DEVELOPING WEED MANAGEMENT STRATEGIES IN TRUVERA SUGARBEET AND DESICCATION STRATEGIES IN SOYBEAN

By

Ian Gregory Waldecker

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ABSTRACT

Weed management is one of the most challenging facets of sugarbeet production. ‘Truvera’ is a new herbicide-resistant sugarbeet trait package with resistance to dicamba, glufosinate, and glyphosate. Six site-years of field experiments were established to evaluate crop tolerance and weed control of 15 herbicide programs that included dicamba and glufosinate in comparison with current weed management programs in glyphosate-resistant (GR) sugarbeet. GR waterhemp control was 90% or greater in herbicide programs with at least two postemergence (POST) applications of glufosinate or dicamba tank-mixed with acetochlor, 49% greater than the current strategy for GR waterhemp control. Additionally, herbicide programs with POST dicamba followed by (fb.) glufosinate also provided good waterhemp control. GR horseweed control was 95% or greater from herbicide programs that contained at least two applications of an effective POST (glufosinate, dicamba, or clopyralid). Truvera sugarbeet provides growers with two additional herbicide options that will improve control of several problematic weed species, including GR weeds, and protect profitability in sugarbeet production. Variable fall weather patterns can delay harvest of early planted longer maturity group (MG) soybeans resulting in potential yield loss. Field research was conducted over four site-years to evaluate two preharvest desiccation timings (early, label) of the harvest aids paraquat, saflufenacil, and sodium chlorate on typical and late MG soybeans for soybean desiccation, yield, seed quality, and seed dry down. Early applications of paraquat and sodium chlorate improved soybean desiccation by as much as 26% compared with nontreated soybean, however desiccation was only improved between 3-9% at the label timing. Applications of harvest aids resulted in soybean yield losses of 8 and 9% in two out of four site-years. The risk of soybean yield loss from harvest aid applications may outweigh potential benefits from accelerated maturity.

Dedicated to my parents, Mark and Kathi Waldecker

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CHAPTER I: LITERATURE REVIEW

Sugarbeet Production

Sugarbeet (*Beta vulgaris L.*) is a high input specialty row crop grown across several distinct temperate regions: the Great Plains (Alberta, Colorado, Montana, Nebraska, western North Dakota, and Wyoming), the Great Lakes (Michigan and Ontario), the Red River Valley (Minnesota and eastern North Dakota), and the Mountain West (California, Idaho, Oregon, and Washington). Roughly 55% of all sugar in the United States is derived from sugarbeet, with the remaining derived from sugarcane (*Saccharum* spp.) (Abadam 2025). A biennial crop, sugarbeet is harvested for sucrose at the end of its first year of growth prior to its reproductive stage. In 2022, the United States ranked third for global sugarbeet production behind Russia and France, with production on 469,000 ha (FAOSTAT 2022; USDA-NASS 2024a). The most concentrated sugarbeet growing region in North America is the Red River Valley, on the border of North Dakota and Minnesota, where roughly 50% of production occurs (Ali 2004). In Michigan, sugarbeets are grown on 56,650 ha across 17 counties.

In 2000, annual sugarbeet production costs were estimated between \$1,000 to \$1,400 ha^{-1} (Ali 2004; Kniss 2004). In 2023, average yield for the U.S. was 69.9 Mg ha^{-1} and 75.95 Mg ha^{-1} for Michigan (USDA-NASS 2024a). Sugarbeet prices typically range between \$38 and \$44 Mg^{-1}, however in 2022 as a result of the COVID-19 pandemic, prices spiked to \$71.85 Mg^{-1} (USDA-NASS 2024b). When managed properly, sugarbeet can be one of the most profitable crops in a grower's rotation.

Sugarbeet planting occurs as early as field conditions allow, with the potential for higher yields outweighing the risk of frost injury. In Michigan, planting typically begins in early April, with harvest beginning in late August and continuing through October. Depending on a farm's equipment and crop rotation sugarbeet is planted in 50-, 55-, or 76-cm row widths. In general, planting population targets 575 to 655 plants $(100\ m)^{-1}$ of row at harvest for best yields, with an estimate of 68% stand establishment (Branch et al. 2024).

Proper pest management in sugarbeet is the most critical aspect for protecting yields and profitability. Sugarbeet is highly susceptible to competition from weeds as well as several crown, root, and leaf diseases. Cercospora leaf spot (*Cercospora beticola*) and rhizoctonia root and crown rot (*Rhizoctonia solani*) can cause up to 30-50% yield reductions, Cercospora can also decrease root storability by up to 50% (Harveson 2008; Khan and Smith 2005; Smith and Ruppel 1971; Tan et al. 2023). The short growth habit and slow canopy closure of sugarbeet make weed control particularly challenging for growers. When chemical weed control fails, growers may resort to mechanical methods of control or labor for hand weeding, significantly reducing profitability.

Weed Control in Sugarbeet. Prior to 2008, chemical weed control relied heavily on multiple applications of selective herbicides. Timing of weed control was critical, with most herbicides only effective on weeds with two-true leaves or smaller (Dale and Renner 2005). With limited chemical options and crop injury a concern, herbicide rate reduction through split postemergence (POST) applications was developed in the Red River Valley in the 1980s. This method became a popular across many sugarbeet producing regions. Split applications of desmedipham and phenmedipham, made 5-7 days after each other at half-labeled rates, reduced sugarbeet injury while also increasing weed control (Dexter 1994).

In the late 1990s, the registration of triflusulfuron and clopyralid, both selective broadleaf herbicides, for postemergence use in sugarbeet improved in-season broadleaf weed control and further refined the split application strategy. Tank-mix combinations of desmedipham +

phenmedipham + triflusulfuron + clopyralid at quarter-labeled rates plus a full rate of methylated seed oil were registered and termed "micro-rate" applications (Dale et al. 2006). Three to five applications of this micro-rate program provided good weed control at reduced herbicide rates. This strategy was used widely across sugarbeet growing regions from the late 1990s to 2008.

In 2008, glyphosate-resistant (GR) sugarbeet was commercialized, resulting in significant changes in weed control practices (Morishita 2018). Adoption of GR sugarbeet was rapid and widespread. In 2008, roughly 60% of all sugarbeet acreage in the U.S. was GR, increasing to 95% the following season. Currently 99% of all sugarbeet acreage is GR (Fernandez-Cornejo et al. 2016). Applications of glyphosate two to four times throughout the growing season quickly replaced the micro-rate strategy (Kniss et al. 2004).

Glyphosate, a non-selective broad-spectrum herbicide, was far more effective at controlling a wide range of broadleaf and grass weed species at larger sizes compared with the micro-rate strategy. Glyphosate use also allowed for fewer applications, spaced further apart in the season, to increase the number of weeds controlled. Glyphosate effectively controlled weeds that were 20 cm in height, 8-11 weeks after planting, with no significant yield differences compared with weed free plots (Kemp et al. 2009). Guza et al. (2002) found that one application of glyphosate tank-mixed with dimethenamid-P provided similar control to the standard micro-rate treatment, reducing the number of applications by three. While one application of glyphosate alone was not effective at controlling some weed species such as redroot pigweed (*Amaranthus retroflexus L.*), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), and hairy nightshade (*Solanum physalifolium* Rusby) from new emergence or poor coverage from leaf interference. Additional applications of glyphosate or addition of residual herbicides significantly improved control. Additionally, sugarbeet injury was significantly reduced from glyphosate applications compared with micro-rate applications. Injury from the micro-rate herbicide strategy caused between 6-8% lower root yields and 15% lower sucrose yield (Wilson et al. 2002). Overall, for best weed control, recommendations included making initial glyphosate applications when weeds were 10 cm tall or less with follow up applications made as necessary. Narrower row widths (38- or 51-cm) provided higher yield and better weed control (Armstrong and Sprague 2010).

While GR sugarbeet initially simplified weed control, high adoption rates of GR crops increased the selection pressure for GR weed populations. In Michigan, several weed species were identified as glyphosate resistant including: horseweed (marestail) (*Erigeron canadensis L.*), Palmer amaranth (*Amaranthus palmeri* S. Watson), waterhemp (*Amaranthus tuberculatus* (Moq.)), and common- (*Ambrosia artemisiifolia L.*) and giant ragweed (*Ambrosia trifida L.*) (Heap 2024; Hill 2024). Horseweed and waterhemp are the most threatening to the sugarbeet growing region in Michigan. Based off samples that have been submitted to the Michigan State University Plant and Pest Diagnostic Clinic, GR horseweed and waterhemp populations have been confirmed in 11 and 8 out of the 17 sugarbeet producing counties in the state, respectively. However, GR horseweed and waterhemp populations are likely more widespread, since samples must be submitted to the clinic to be screened for resistance.

Horseweed Biology and Development of Glyphosate Resistance. Horseweed is a broadleaf weed species that exhibits both winter and summer annual growth types. Historically, horseweed emerged in the fall and formed a basal rosette that overwintered and then bolted the following spring. In the spring, limited new emergence of horseweed could occur, spring-emerged horseweed either briefly formed rosettes before bolting, or immediately bolted upwards with the potential to grow up to 2 m (Loux et al. 2006; Regehr and Bazzaz 1979). Recently, primary emergence has shifted from fall to spring, with most plants exhibiting immediate upright growth patterns. However, both rosette and upright growth types have been observed emerging during the summer (Schramski et al. 2021). In sugarbeet production, the increase in summer annual growth types is problematic since they escape effective spring tillage.

Across the North Central region of the U.S. and southern Canada, horseweed is generally considered to have broad emergence timing in the spring. In Iowa, horseweed was observed emerging into early June, in southern Ontario, peak spring emergence was May 14-27, with plants emerging as late as June 3 (Buhler and Owen 1997; Tozzi and Van Acker 2014). Specifically in Michigan, spring horseweed emergence occured between April 25 and May 14 (Schramski et al. 2020). Primarily self-pollinated, horseweed can produce up to 200,000 seeds at a density of 10 plants m^{-2}. These seeds can disperse via wind, but most seeds stay within 100 m of the mother plant (Bhowmik and Bekech 1993; Dauer et al. 2007)

Horseweed was the first major weed identified as glyphosate-resistant, when several populations from Delaware were not controlled by glyphosate applications in soybean in 2000 (VanGessel 2001). GR horseweed populations now occur in 25 states, with most populations identified in field crops (Heap 2024). The first confirmed case of GR horseweed in Michigan was identified in 2007. Since then, GR horseweed has been confirmed in 32 counties across the state (Hill 2024).

Overwhelmingly, the primary mechanism of glyphosate resistance in horseweed is caused by a non-target site mutation resulting in rapid glyphosate sequestering in the vacuole and increased glyphosate metabolism, resulting in impaired glyphosate translocation to the meristem (Dinelli et al. 2006; Feng et al. 2004; Ge et al. 2010; González-Torralva et al. 2012; Koger and Reddy 2005; Moretti and Hanson 2017). However, the first report of target site resistance was recently confirmed by Beres et al. (2020) in the United States. A proline to serine mutation at position 106 of the *EPSPS2* gene was observed in highly resistant biotypes from Ohio and Iowa. EPSPS (5-enolpyruvalshikimate-3-phosphate synthase), the target for glyphosate, is an important enzyme in the shikimate acid pathway, which is responsible for aromatic amino acid synthesis (Duke and Powles 2008). Mutations in the *EPSPS2* gene, one of three *EPSPS* genes, as described in Beres et al. (2020) can cause glyphosate insensitivity in the EPSPS enzyme. Additionally, recent research comparing dose responses among horseweed biotypes indicated that a mechanism other than reduced translocation and vacuole sequestration causes differences in sensitivity to glyphosate between resistant upright and rosette biotypes (Fisher et al. 2023; Schramski et al. 2021). Schramski et al. (2021) found that GR upright growth biotypes were 4- to 3-fold less sensitive to glyphosate compared with related GR rosette growth types. Further research found no difference in glyphosate absorption, translocation, or interception between horseweed growth types, indicating that the primary mechanism of glyphosate-resistance in horseweed is caused by an undescribed resistance mechanism causing differences in sensitivity between growth types (Fisher et al. 2023).

Other confirmed herbicide resistance cases of horseweed in Michigan include resistance to ALS inhibitors (WSSA Group 2) and PSII inhibitors (WSSA Group 5) (Heap 2024). Overall, horseweed is problematic weed in sugarbeet as its growth type shifts towards spring/summer emergence and glyphosate-resistant populations continue to spread across many growing regions. Additionally, it appears that there are several resistance mechanisms causing high levels of glyphosate resistance well-above field application levels.

Waterhemp Biology and Development of Glyphosate Resistance. Waterhemp is a particularly difficult-to-manage weed across the corn and soybean producing regions of the

Midwest. Since the early 2000s, GR populations have expanded northward and now are increasingly problematic in Michigan sugarbeet production.

Waterhemp is a summer annual dioecious broadleaf weed species with a broad emergence time beginning in May and often continuing into the summer (Leon and Owen 2006). In competitive field crops such as corn and soybean, later-emerging waterhemp plants are commonly shaded out and do not survive to maturity (Hartzler et al. 2004). Steckel and Sprague (2004b) reported that as interception of photosynthetic active radiation increased, waterhemp mortality following emergence approached 100% when soybean canopy was fully developed. However, sugarbeet has a low growth habit and the crop canopy is slower to develop compared with corn and soybean, so later emerging weeds are more problematic throughout the season.

Waterhemp seed production varies depending on crop competition and emergence timing. Waterhemp emerging at the same time as soybean produced 23,000 seeds per plant in both narrow and wide rows (Steckel and Sprague, 2004b). In corn, female plants produced up to 16,000 seeds (Steckel and Sprague, 2004a). Uncontrolled waterhemp populations reduced corn and soybean yield by 74 and 44%, respectively (Steckel and Sprague 2004a, 2004b).

The first GR waterhemp population was identified in Missouri in 2005, since then resistant populations have been identified in 20 states (Legleiter & Bradley, 2008; Heap 2024). In Michigan, the first GR waterhemp population was identified in Isabella County in 2011 (Hill 2024). GR waterhemp populations have now been identified from submitted samples by the Michigan State University Plant and Pest Diagnostic Clinic in 21 Michigan counties, with 8 of these counties in the sugarbeet growing region of the state (Hill 2024). But as with horseweed, GR waterhemp likely occurs in more Michigan counties than have been reported, since samples must be submitted to be screened and confirmed for each county.

There are several mechanisms that have been identified for glyphosate resistance in waterhemp populations including EPSPS gene amplification, a target-site proline to serine mutation at position 106 of the *EPSPS2* gene as described in horseweed, and reduced translocation (Bell et al. 2013; Nandula et al. 2013). The most common of these mechanisms appears to be EPSPS gene amplification, where a normal field dose of glyphosate is overwhelmed by a high number of target sites due to several copies of the EPSPS gene (Powles 2010). This gene amplification mechanism for glyphosate resistance was first-identified in Palmer amaranth, a closely-related species to waterhemp (Gaines et al. 2010).

A study conducted on Illinois waterhemp populations found that 91% of resistant populations had elevated EPSPS copy number (Chatham et al. 2015b). Gene amplification was also the primary resistance mechanism for GR waterhemp in four of five states from a multistate study (Chatham et al. 2015a). While gene amplification is likely the most common mechanism for glyphosate-resistance, a combination of several target- and non-target site mechanisms are present in many resistant populations (Tranel 2021).

In addition to glyphosate resistance, several waterhemp populations in Michigan are resistant to multiple herbicide sites of action including ALS inhibitors (WSSA Group 2), PSII inhibitors (WSSA Group 5), and PPO inhibitors (WSSA Group 14) (Hill 2024). Of these, PPO resistance is particularly concerning since the only effective product for emerged waterhemp in sugarbeet is acifluorfen, a PPO inhibitor (Barker et al. 2023). The long emergence window, rapid growth, and widespread glyphosate resistant populations make waterhemp difficult to manage in sugarbeet.

Management of GR Horseweed and Waterhemp in Sugarbeet. The increase and spread of GR weeds into sugarbeet growing regions has complicated weed control. With the development of the split application and micro-rate herbicide strategies followed by the release of GR sugarbeet, use of preemergence (PRE) herbicides had decreased because of cost, reliance on incorporating rainfall, and crop injury concerns (Dale et al. 2006). Additionally, following the release of GR sugarbeet studies suggested that the use of PRE herbicides were not necessary due to the effectiveness of glyphosate (Kemp et al. 2009).

Since GR weeds have become widespread, the use of PRE and selective POST herbicides have become necessary for chemical weed control programs in sugarbeet. Multiple applications of residual chloroacetamide herbicides (WSSA Group 15) such as S-metolachlor, acetochlor, and dimethenamid-P, tank-mixed with glyphosate is the most effective strategy for GR waterhemp management (Lueck et al. 2020; Peters et al. 2016). Notably, this strategy relies completely on residual waterhemp control and timely rainfall, as chloroacetamide herbicides exhibit no control of emerged weeds. In most studies, overlapping residual strategies provided between 60-85% waterhemp control depending on the application timing, chloroacetamide herbicide applied, and location (Peters et al. 2017). The only effective herbicide for emerged waterhemp is acifluorfen, which is only labeled for one rescue application through a Section 18 emergency exemption (Anonymous 2024). In addition to these strategies, some growers are falling back on inter-row cultivation or manual waterhemp removal in hopes to improve control (Haugrud and Peters 2021). For emerged horseweed control, applications of clopyralid have increased in sugarbeet and can provide good control (Sprague and Burns 2024). While chemical control strategies have been developed to help manage GR weed populations, many of these strategies do not provide complete control, cause higher sugarbeet injury, and are reliant on timely rainfall.

In other crops, advancement of herbicide resistant traits has provided growers with more herbicide options during the growing season. In cotton and soybean, transgenic varieties with resistance to three herbicides (HT3; dicamba or 2,4-D + glufosinate + glyphosate) are widely used (Nandula 2019). These varieties have allowed growers greater flexibility in managing GR weeds by rotating multiple herbicide sites of action. However, similar to glyphosate, with increased use of these herbicides, selection of resistant weed populations is a concern. There are currently 19 documented weed species populations resistant to dicamba or 2,4-D across the U.S., some of which developed as a direct result of HT3 crops (Heap 2024).

Commercial release of an HT3 sugarbeet variety with resistance to glyphosate, glufosinate, and dicamba is imminent. Following its release, this variety will likely be adopted rapidly across sugarbeet growing regions. Understanding the herbicide site of action and selectivity of glufosinate and dicamba, while promoting an effective herbicide rotation, will be crucial to minimize weed control failures and protect the profitability of sugarbeet production.

Dicamba Mode of Action and Weed Control. Dicamba belongs to the benzoate chemical family in the synthetic auxin herbicide group (WSSA Group 4). The synthetic auxin herbicides include several widely-used herbicides for selective broadleaf control. Historically, several of the synthetic auxin herbicides were used in cereal crop production for control of broadleaf weed species.

Plant produced auxins are a class of phytohormone that help regulate plant growth, metabolism, and response to abiotic and biotic conditions (Vanneste and Friml 2009; Woodward and Bartel 2005). Synthetic auxin herbicides mimic the action of plant auxins and at sufficient doses, cause uncontrolled growth, epinasty, and plant death. These auxin mimic herbicides block auxin repressive proteins, creating an overexpression of certain ethylene and abscisic acid producing genes and pathways. Overexpression of ethylene causes the epinasty symptoms associated with auxin mimic herbicides, but accumulation of abscisic acid is responsible for root and shoot growth inhibition and promoting leaf senescence (Grossmann 2010; Grossmann et al. 2001). On the plant level, decline and death following application of auxin mimic herbicides can be split into three phases. The first phase begins within hours of application where ethylene biosynthesis is stimulated and stem curling and leaf epinasty is observed. By 24 hours following application the second phase is in effect and plant root and shoot growth is inhibited. In phase three foliar senescence and tissue decay and symptoms may begin to appear as soon as 72-hours after application, although these symptoms are typically not observed under field conditions until 10-14 d after application.

Dicamba has both residual and foliar activity on broadleaf species. While residual activity is typically short-lived, dicamba can provide control of small-seeded broadleaf weeds (Sprague and Burns, 2024). This short-lived residual activity is a result of high solubility causing dicamba to quickly move and leach through the soil (Gazola et al. 2022; Menasseri et al. 2004). Typically, residual activity of dicamba is significantly reduced once 25 mm of rainfall have been received following application (Norsworthy et al. 2009). As a result, drier conditions following application favor longer residual activity.

A multi-state study that analyzed PRE applications of dicamba found that waterhemp control was 35% and horseweed control was greater than 90%, 3 weeks after application (Johnson et al. 2010). In the same study, POST applications of dicamba tank-mixed with glyphosate were also evaluated, GR waterhemp and horseweed control was 95% and 98%, respectively (Johnson et al. 2010).

With the benefit of having both residual and postemergence activity on broadleaf weeds, dicamba will be very useful as an early season herbicide that can control emerged GR horseweed and waterhemp and provide residual activity in dicamba-resistant sugarbeet.

Glufosinate Mode of Action and Weed Control. A broad-spectrum herbicide that provides control of both broadleaf and grass species, glufosinate-ammonium (glufosinate) is a member of the phosphonic acid chemical family in the glutamine synthetase inhibitor herbicide group (WSSA Group 10) (Zhou et al. 2020). Glufosinate use has increased substantially since its release in 1993 with an estimated use of 17 million pounds in 2018 (USGS-NAWQA 2024a). This increase in use can be largely attributed to the rise of glufosinate-resistant crops.

Glufosinate inhibits glutamine synthetase, a protein that provides nitrogen metabolism by catalyzing ATP and converting glutamate into glutamine by incorporating ammonia (Takano and Dayan 2020). For many years, ammonia accumulation and toxicity in the plant was attributed as the main mode of action. Recently it was discovered that inhibition of glutamine synthetase creates a cascading reaction that ultimately causes light-dependent reactive oxygen species to over accumulate in the mitochondria, causing rapid lipid peroxidation in the cell membrane, and subsequent cell death (Takano et al. 2019, 2020; Takano and Dayan 2020). This series of events best explains the rapid symptomology seen after glufosinate applications as well as the necessity of sunlight for its herbicide action (Martinson et al. 2005).

Glufosinate is a broad-spectrum herbicide, although its efficacy on grass weed species can be reduced under certain circumstances (Sprague and Burns 2024). Green foxtail and large crabgrass control was 61 and 67%, respectively, at soybean harvest following a single application of glufosinate(Aulakh and Jhala 2015). Two applications of glufosinate improved green foxtail and large crabgrass control to 87%. Jhala et al. (2017), found that two POST applications of glufosinate provided only 76% waterhemp control 14 d after treatment (DAT), whereas PRE applications of residual herbicides followed by (fb.) POST applications of glufosinate provided 93% waterhemp control. In Mississippi, glufosinate applied alone provided up to 97% horseweed control 28 DAT.

Glyphosate Mode of Action and Weed Control. Glyphosate is a broad-spectrum non-selective herbicide known to inhibit EPSPS synthase (WSSA Group 9). With the adoption of transgenic GR crops, glyphosate use increased dramatically from less than 50 million pounds in 1996 to over 250 million pounds beginning in 2011 (USGS-NAWQA 2024b).

Glyphosate binds to EPSPS, an enzyme in the shikimate pathway that produces tyrosine, tryptophan, and plastoquinone, amino acids that are necessary for plant growth and development and photosynthesis (Duke 2021). Disrupting the production of these amino acids causes a relatively slow plant death.

Following the release of GR crops, glyphosate was considered the ideal herbicide, with broad spectrum weed control, a translocation-based mode of action, and low mammal toxicity that replaced more toxic selective herbicides (Duke and Powles 2008). However, the rise of the GR weed species has reduced its efficacy and usefulness as an effective herbicide. As of 2020, 48 weed species are resistant to glyphosate across 30 countries, 17 of these weed species have GR populations in the United States (Baek et al. 2021). Much of this resistance is due to the widespread planting of GR crops and the subsequent reliance on glyphosate for weed control (Green and Siehl 2021).

Despite its decreasing usefulness on problematic GR weeds such as horseweed and waterhemp, glyphosate is still a useful herbicide for control of many non-GR weeds. Glyphosate provides excellent control of many grass species including green and yellow foxtail, crabgrass, and perennial species such as quackgrass, all of which are not as effectively controlled from glufosinate (Sprague and Burns 2024).

The introduction of dicamba, glufosinate, and glyphosate-resistant sugarbeet will provide more chemical options for control of several problematic weed species. However, growers will need to adopt strategies to minimize the risk of dicamba and glufosinate resistant weed populations. Safeguarding the usefulness of these herbicides will be key for improved weed control and protecting the profitability of sugarbeet production.

Questions that remain to be answered:

1. Will the addition of glufosinate and dicamba in sugarbeet improve control of problematic GR weeds?
2. Can dicamba provide useful PRE residual broadleaf weed control in sugarbeet?
3. Can chloroacetamide residual herbicides improve season long weed control in sugarbeets when tank-mixed with glufosinate?

Soybean Production

Soybean (*Glycine max (L.) Merr.*) is an oilseed legume crop grown on 33.8 million hectares (ha.) in the U.S., second only in production hectares to corn (38.3 million ha) (USDA-NASS 2024a). Soybean is grown widely across the Midwest and Southeastern U.S., with Illinois ranked 1st in overall production area. In 2023, Michigan ranked 13th in statewide soybean production area, with soybeans planted on 826 thousand ha (USDA-NASS 2024a). In Michigan, soybean is typically preceded in rotation by corn and often followed by winter wheat.

Soybeans are processed for their high protein and oil content for use in soybean meal, vegetable oil, and biodiesel. Soybeans have the highest protein content of any other field crop (~40%) along with a very high oil content (~20%) (Pagano and Miransari 2016). Being rich in critical nutrients has cemented soybean as a valuable field crop around the world. In the United States, soybean production, processing, and job creation were responsible for \$124 billion year^{-1}

between 2019 to 2022 which was 0.6% of U.S. gross domestic product (LMC International 2023). Soybean production in South Dakota and Iowa was responsible for nearly 8% of their statewide economies.

Significant research efforts have investigated nearly every facet of soybean production including pest and nutrient management, planting timing, row spacing, and plant populations. Recently, agronomic research has focused on adjusting planting dates for maximizing yields. As planting dates are adjusted, impacts on soybean harvest should also be addressed.

Soybean Planting Date and Maturity Group. Historically, recommendations in the northern U.S. were to plant soybean in May, depending on location and field conditions (Wilcox and Frankenberger 1987). Growers have typically planted soybean after corn in fear of frost damage on soybean, although soybean can survive temperatures as low as -3 C, roughly 1 C colder than corn can tolerate (Helsel et al. 1981). Despite these practices, it was understood for some time that planting soybean earlier resulted in higher yields, while delayed planting lowered yields. Studies investigating planting dates from late-March through early-June in Iowa and Indiana have found delaying planting to late-May or June reduced yields up to 41% compared with planting dates from late-April and early-May (De Bruin and Pedersen 2008; Robinson et al. 2009). Additionally in Kentucky, delaying planting of soybean after May 9 resulted in a yield reduction of 0.5% d^{-1}, and late-April and early-May planting dates had the highest yields (Knott et al. 2019).

Earlier soybean planting is increasingly possible as climate variability has resulted in earlier frost-free dates across the Midwest. Between 1900 to 2014, the last spring frost occurred 9 d earlier (Kukal and Irmak 2018). Further climate research indicated that the frost-free season in the Great Lakes Region increased by 16 days from 1951 to 2017 (GLISA 2019). This climate data agrees with the most-recent planting date studies. Mourtzinis et al. (2019) found that planting soybean 8-10 days earlier than normal could improve yield up to 10% across the U.S. Furthermore, Siler and Singh (2022) investigated combining earlier soybean planting dates with longer maturing varieties; when soybean was planted early, a +1.0 increase in maturity group over the optimal resulted in an average yield increase of 521 kg ha^{-1}, which equated to a 14% increase in yield. Growers have started adopting these earlier planting strategies to attain higher yields as well as to spread-out spring workloads.

Soybean maturity groups (MG) are classified from 000 to 10, however MG from 00 through 6 are commonly grown from north to south, respectively (Mourtzinis and Conley 2017). In general, early maturing varieties (MG = 000-4) have indeterminate growth, while later maturing (MG = 5-10) varieties are determinant. Indeterminant soybeans continue to grow vegetatively during early reproductive stages, while determinant varieties cease vegetative growth at the beginning of reproductive growth (Stowe and Vann 2022).

Maturity groups are highly sensitive to photoperiod length and temperature, and as a result are adapted to specific latitude ranges (Cober et al. 2001; Major et al. 1975). Scott and Aldrich (1970) were the first to propose the hypothetical ranges for soybean MGs across the United States. These ranges are still widely used today. Recently, revised regions for MGs have been adjusted to more adequately reflect modern production practices and climatic conditions. The largest shift in MGs occurred in the far south, where MG 5 and 6 were identified as better adapted, replacing the previous range of varieties in MG 7 and 8 (Mourtzinis and Conley 2017). This shift is largely due to grower adoption of “shorter” MGs and earlier planting dates to avoid extreme summer temperatures during reproductive growth.

In Michigan, MG recommendations from Scott and Aldrich (1970) suggested planting MG 2 soybeans in the southern lower peninsula, and MG 1 soybean varieties in the northern lower peninsula. Since then, optimal MGs have shifted slightly, with MG 3 soybean optimal in the extreme southern portion of the state, and MG 2 optimal for nearly all of the lower peninsula (Mourtzinis and Conley 2017; Zhang et al. 2007). If the early planting and longer MG strategy recommendations described in Siler & Singh (2022) were implemented, an increase of 0.5 to 1 would be added to the optimal MGs outlined in Mourtzinis and Conley (2017).

Impacts from Soybean Harvest Delays. While early planting and longer MG varieties can be utilized to increase soybean yields in the Midwest, understanding how this strategy affects soybean harvest is important for minimizing harvest delays and the potential for yield and soybean seed quality decline. Despite the potential for higher yields from early planting, growers continue to struggle with soybean harvest because of variable fall weather. The total annual precipitation in the Great Lakes region has increased 13.6% since 1951, with a 35% increase in severe storms (GLISA, 2019). Greater fall precipitation and potential mechanical failures at harvest can delay soybean harvest resulting in a subsequent decline in soybean yield and quality (Dao and Ram 1996; Jaureguy et al. 2013; Wilcox et al. 1974). Furthermore, harvest delays are problematic for growers looking to plant winter wheat following soybean harvest, causing wheat yield reductions of 17-21% if planting is delayed past mid-October (Copeland et al. 2023).

Delayed soybean harvest has long been associated with yield and seed quality losses. (Philbrook and Oplinger 1989) reported an average soybean yield loss of 10% from delayed harvest across several varieties ranging from MG 0 to 2. Soybean yield losses increased by 0.2% per day, with an average yield loss of 13.9% when harvest was delayed 42 d. Of the reported harvest losses, 60% were attributed to the action of the combine header. An additional study found up to 50% yield loss after harvest was delayed 25 d after R8 soybean(Larcher 1985). Losses occurred from natural pod shattering and harvest operations. Since these studies have been published, limited research has been conducted on the impacts of delayed harvest and potential soybean yield loss for modern soybean varieties.

In addition to potential yield losses, a decline in soybean quality and composition is also a concern when harvest is delayed. Reduced seed germination, greater incidences of fungal infection, variation in oil and protein content, and lower sugar content have all been reported when soybeans are harvested past the optimal time (Krober and Collins 1948; Wilcox et al. 1974; Yaklich 1985). Despite previous research strongly supporting declines in seed quality, a recent study found that while delayed harvest negatively impacted oleic and saturated fat content in food grade soybean, these changes were not significant enough to affect marketability (Jaureguy et al. 2013). The decline in soybean quality and composition have been well documented, however whether these declines affect marketability is not always consistent.

Soybean Desiccation. Desiccation of soybeans could be a method for minimizing harvest delays in Midwest soybean production. Preharvest herbicides (harvest aids) are applied prior to soybean harvest to hasten soybean maturity, desiccate weeds, and improve harvest efficiency. Soybean desiccation is a practice that is commonly used in the Southeastern U.S. and in dry edible bean production in Michigan, but it has not been extensively used in Midwest soybean production.

There are currently six registered active ingredients that can be applied as harvest aids in soybean: carfentrazone, dicamba, glyphosate, paraquat, saflufenacil, and sodium chlorate (Sprague and Burns 2024). While potentially effective for weed desiccation, some of these herbicides may not be effective options for soybean desiccation. For example, glyphosate would not a viable option for soybean desiccation, since most varieties are GR. Additionally, concerns of off-target movement from dicamba applications would likely result in low adoption.

In dry edible bean, paraquat and saflufenacil provided rapid dry bean desiccation compared with glyphosate (Goffnett et al. 2016). However, yield reductions up to 55% were observed when saflufenacil and paraquat were applied early (50% yellow pods). When applications were made at the label recommendation (80% yellow pods) fewer yield reductions were observed, with saflufenacil and glyphosate reducing yield by 9% in 1 of 2 planting times. In soybean, paraquat was the most effective desiccant evaluated compared with glyphosate and ametryn (Whigham and Stoller 1979). Similar to dry edible bean research, when paraquat was applied 3-4 weeks prior to harvest, soybean yield and seed weight were reduced by at least 37 and 28%, respectively. However, when paraquat was applied only two weeks prior to harvest yields were not reduced. Additionally, formulations of sodium chlorate have been shown to provide effective soybean, cotton, and weed desiccation (Ellis et al. 1998; Larson et al. 2005).

Previous research showed that the time of harvest aid application (i.e., soybean growth stage) can negatively impact soybean yield and quality. In a Louisiana study, indeterminate (MG 4) soybean yield and seed weight were reduced 15.4% and 1.8 g 100 seeds^{-1}, respectively, when applications were made at 60% seed moisture (~R6 soybean stage) (Boudreaux and Griffin 2011). However, when applications were delayed to 50% seed moisture (~R6.5), yield was not affected. This agrees with research that ~R6.5 and ~50% seed moisture represent soybean physiological maturity, so yield losses from desiccation at this growth stage are less likely (Boudreaux and Griffin 2008; TeKrony et al. 1979).

Given previous research in dry bean, soybean, and cotton, paraquat, saflufenacil, and sodium chlorate are the most common and effective harvest aids evaluated.

Paraquat Desiccation Characteristics and Action. Paraquat is a fast-acting, broad-spectrum herbicide that is most commonly used for non-selective weed control prior to planting, inter-row directed applications, and weed control under fruit trees. A member of the pyridinium chemical family, paraquat is classified as a photosystem I (PSI) electron diverter (WSSA group 22). Paraquat is unique since it is one of only three herbicides (with glyphosate and glufosinate) that are fully non-selective and do not have soil activity (Hawkes 2014). Upon application, paraquat accepts a single electron from PSI which creates a reaction that forms a superoxide (Farrington et al. 1973; Hawkes 2014). When this superoxide comes into contact with sunlight, reactive oxygen species are quickly formed through a chemical reaction and rupture cell membranes. This leads to rapid water loss, wilting, and desiccation of affected foliar tissue (Babbs et al. 1989).

Paraquat can be used as a harvest aid in soybean when seed moisture is 30% or less and 65% of soybean pods have mature color (Anonymous 2021). If used as a harvest aid there is a preharvest interval of 15 d. Despite the label's application directions, previous studies have recommended earlier application timings at 50% seed moisture (Boudreaux and Griffin 2008, 2011; Whigham and Stoller 1979). Following application, rapid wilting and desiccation of foliar tissue occurs within hours under ideal sunny conditions (Griffin et al. 2010). Within 3 d, foliar tissue is fully desiccated, and soybeans can reach harvestable moisture within 7-10 d, 14 d before non-desiccated soybean.

Saflufenacil Desiccation Characteristics and Action. Another cell membrane disruptor, saflufenacil is part of the N-phenyl-imide chemical family. Saflufenacil inhibits the protoporphyrinogen IX oxidase (PPO) enzyme (WSSA group 14) (Grossmann et al. 2010). The PPO enzyme acts as a catalyst for the conversion of protoporphyrinogen to protoporphyrin. When this reaction is inhibited, the synthesis of chlorophylls, hemes, and cytochromes are prevented. Heme regulates the protoporphyrin pathway (Duke et al. 1991; Matsumoto 2002). This leads to high concentrations of protoporphyrin accumulating in green tissue. When exposed to light, protoporphyrin interacts with oxygen to form oxygen radicals. These oxygen radicals peroxidize the unsaturated fatty acids of the cell membrane, leading to rapid water loss from the cell (Grossmann et al. 2010; Wakabayashi and Böger 1999). This leads to the characteristic symptomology of PPO inhibitors observed with contact leaf burning, tissue necrosis, and eventual plant death.

Saflufenacil is typically used for burndown and preemergence broadleaf weed control in corn and soybean, with lower rates used in soybean for improved crop tolerance. As a harvest aid, saflufenacil can be applied to soybean when seed moisture is at 30% and soybean pods are at 65% mature color (Anonymous 2022). There is a 3 d preharvest interval if saflufenacil is applied as a harvest aid. The shorter preharvest interval of saflufenacil compared with paraquat (15 d) could provide greater flexibility for desiccation applications.

Sodium Chlorate Desiccation Characteristics and Action. Sodium chlorate is labeled as a preharvest chemical desiccant for several field crops including corn, cotton, dry edible bean, and soybean. When applied, sodium chlorate acts as a strong oxidizing agent while also blocking protein sulfation (Griffin et al. 2010). Readily, absorbed into foliar tissue, sodium chlorate will cause rapid desiccation.

Sodium chlorate is labeled for preharvest applications to improve weed desiccation and facilitate soybean dry down for improved harvestability. Applications should be made 7-10 d before anticipated harvest (Anonymous 2024b). Sodium chlorate is commonly applied in combination with paraquat for more rapid desiccation, however no yield or economic benefits have been observed from combinations of sodium chlorate and paraquat (Griffin et al. 2010; Orlowski 2018).

Questions that remain to be answered:

1. How does delayed harvest affect soybean yield and quality in modern soybean varieties?
2. Will soybean desiccation be a feasible method of minimizing harvest delays in the Northern U.S.?
3. Will preharvest herbicide (harvest aid) activity in a cooler climate be similar to previous research conducted in the southeastern U.S.?
4. Will preharvest herbicides affect soybean yield and quality when applied at R6.5 compared with label recommendations in the Northern U.S.

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CHAPTER II: WEED CONTROL SYSTEMS IN TRUVERA SUGARBEET

Abstract

Weed control is one of the most challenging aspects of sugarbeet production. Overreliance of glyphosate-based weed control has led to the development of glyphosate-resistant (GR) weed species. ‘Truvera’ is a new herbicide-resistant sugarbeet trait package with resistance to dicamba, glufosinate, and glyphosate. Six site-years of field experiments were established to evaluate crop tolerance and weed control of 15 herbicide programs that included dicamba and glufosinate in comparison with current weed management programs in GR sugarbeet. Mid-season GR waterhemp control was 87% or greater from all herbicide programs that had at least two applications of glufosinate or dicamba. At harvest GR waterhemp was 90% or greater in herbicide programs that included a minimum of one postemergence (POST) application of acetochlor with at least two applications of glufosinate or dicamba, 49% greater than the current strategy for GR waterhemp control. Additionally, herbicide programs with a POST application of dicamba fb. glufosinate also provided similar control at harvest. Common lambsquarters control was greater than 79 and 90% with all herbicide programs at Richville in 2023 and East Lansing except for glufosinate only programs which provided 54 and 78% control, respectively. At harvest horseweed control was 95% or greater from herbicide programs that contained at least two POST applications of either dicamba or glufosinate, which was comparable to the grower standard with two applications of clopyralid. In general, common purslane and velvetleaf were not effectively controlled when glufosinate was applied alone at the last application. In one site-year, five of the 15 herbicide programs had less than 70% annual grass (giant foxtail and barnyardgrass) control. This poor grass control resulted in sugarbeet yield reductions up to 52%. The inclusion of glufosinate and dicamba in weed management programs

in Truvera sugarbeet improves control of several problematic weed species, protecting the profitability of sugarbeet production.

Introduction

Sugarbeet (*Beta vulgaris L.*) is a specialty row crop grown specifically for its recoverable sugar that is refined from the roots (Panella et al. 2015). Sugarbeet is grown across the northern temperate latitudes of the United States, Europe, and Russia. In the United States, 55% of sugar is derived from sugarbeet, and is indistinguishable from sugar derived from sugarcane (Abadam 2025; Morishita 2018). Since sugarbeet is highly susceptible to infestations from disease, insects, and weeds, proper pest management is one of the most challenging and critical facets for protecting sugarbeet yield and profitability.

Weed management has historically been the greatest pest management challenge in United States sugarbeet production (Carlson et al. 2008). If left uncontrolled, weeds can reduce yield by 70% leading to a $1.25 billion loss in value to United States sugarbeet growers (Soltani et al. 2018). Since sugarbeet has a low growth habit and is slower to develop a crop canopy, it is a far less competitive crop than corn or soybean. The reduced competitiveness of sugarbeet increases the impact of weeds, especially when sugarbeets are planted in wider row widths (Armstrong and Sprague 2010). This puts increased pressure on chemical weed control programs to extend control later into the growing season, which often necessitates additional herbicide applications, and the use of residual herbicides.

Prior to the release of glyphosate-resistant (GR) sugarbeet varieties in 2008, chemical weed control programs relied heavily on “micro-rates” , where multiple applications of selective herbicides such as desmedipham, phenmedipham, triflusulfuron, and clopyralid were applied at quarter- to half-labeled rates (Dale and Renner 2005; Dexter 1994). The “micro-rate” strategy required up to six applications per season since labeled herbicides rarely controlled weeds larger than two-true leaves. If correct application timings were not made, weed control was poor. Following the commercial release of GR sugarbeet in 2008, growers quickly adopted this technology. By 2009 95% of United States sugarbeet hectares were planted to GR sugarbeet (Fernandez-Cornejo et al. 2016), with two to four applications of glyphosate quickly replacing the "micro-rate" strategy for weed control (Kniss et al. 2004; Morishita 2018). Glyphosate provided consistent broad-spectrum control of weeds up to 10 cm in height, and season-long weed control was possible with one application of glyphosate tank-mixed with a chloroacetamide herbicide such as dimethenamid-P (Guza et al. 2002; Kemp et al. 2009).

The simplification of weed control with glyphosate was short-lived. Selection pressure from high adoption of GR crops led to the development of GR weed populations across the United States (Green and Siehl 2021). As of 2020, a total of 48 weed species have documented resistance to glyphosate world-wide; in the U.S., 17 weed species have confirmed GR populations (Baek et al. 2021). In Michigan, five weed species have been identified as glyphosate resistant (Heap 2024; Hill 2024). The most problematic GR weed species in Michigan sugarbeet production are horseweed (marestail) (*Conyza canadensis* L.) and waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer). Glyphosate-resistant horseweed and waterhemp populations have been confirmed in 65% and 47% of sugarbeet producing counties in the state, respectively. Although GR populations have not been identified in Michigan, common lambsquarters (*Chenopodium album* L.) and annual grass species such as giant foxtail (*Setaria faberi* Herrm.) and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) can also be problematic weeds to manage in sugarbeet.

The onset of GR weed populations has changed weed management strategies across all GR crops. In sugarbeet, growers have needed to use multiple applications of clopyralid for GR horseweed control and implement overlapping preemergence (PRE) and postemergence (POST) applications of WSSA Group 15 residual products for GR waterhemp control (Peters et al. 2016, 2017). The only herbicide that provides control of emerged waterhemp in sugarbeet is acifluorfen, labeled under a Section 18 emergency exemption for rescue application (Anonymous 2025). These strategies rely on the timeliness of incorporating rainfall, which can lead to weed escapes, and can increase the risk of herbicide injury to sugarbeet.

The advancement of herbicide resistance traits in corn, soybean, and cotton has provided growers with broad spectrum POST herbicide options during the growing season (Nandula 2019). In cotton and soybean, transgenic varieties with three-way herbicide resistance to glufosinate, glyphosate, and dicamba/2-4,D have been released and widely adopted to improve weed control (Cahoon et al. 2015a; Striegel and Jhala 2022; Werle et al. 2018). Since the release of these crops, management recommendations have focused on two-pass herbicide programs that include a PRE application of a residual herbicide followed by (fb.) applications of glufosinate alone or tank-mixes of glyphosate and dicamba for GR horseweed and waterhemp control (Duenk et al. 2023; Soltani et al. 2020).

The projected release of sugarbeet varieties with resistance to dicamba, glufosinate, and glyphosate will provide growers with two new additional active ingredients with different sites of action for weed control. However, the anticipated widespread adoption of this technology will require increased stewardship of dicamba and glufosinate to maintain effective weed control with the goal of preventing the further evolution of herbicide-resistant weeds. As a result, herbicide program recommendations in Truvera sugarbeet will need to include herbicides from multiple sites of action and mimic herbicide program design in similarly traited cotton and soybean, combined with application timings commonly used in sugarbeet production. Sugarbeet injury from labeled residual products tank-mixed with glufosinate or dicamba is also a concern and has been observed in dicamba, glufosinate, and glyphosate resistant cotton (Samples et al. 2021).

Specific herbicide application timing for adequate weed control in dicamba, glufosinate and glyphosate-resistant sugarbeet is unknown. The interaction between these herbicides and labeled residual products when tank-mixed, have not been investigated for sugarbeet tolerance and weed control. Therefore, the objectives of this research were to (1) investigate optimal dicamba and glufosinate application timings and impact on sugarbeet tolerance and weed control in dicamba, glufosinate, and glyphosate-resistant sugarbeet, (2) evaluate the need for residual herbicides to achieve season-long weed control, and (3) compare herbicide programs that include dicamba and glufosinate to current grower standard herbicide programs used in GR sugarbeet.

Methods and Materials

Field research was conducted in 2023 and 2024 at three different locations for a total of six site-years. Research locations included the Michigan State University (MSU) Agronomy Farm in East Lansing in 2023 (MSU-23 = 42.684^o N, -84.497^o W) and 2024 (MSU-24 = 42.685^o N, -84.490^o W), the Saginaw Valley Research and Extension Center near Richville in 2023 (SVREC-23 = 43.393^o N, -83.696^o W) and 2024 (SVREC-23 = 43.398^o N, -83.694^o W), and on commercial fields near Morrice, Michigan in 2023 (AMATU-23 = 42.837^o N, -84.149^o W) and Durand, Michigan in 2024 (AMATU-24 = 43.008^o N, -83.985^o W). Soil at MSU was a Conover loam (fine-loamy, mixed, active, mesic aquic hapludalfs) with pH 5.7 in 2023 and 2024 and 2.8% organic matter in 2023 and 2.7% in 2024. Soil at SVREC was a Tappan-Londo loam (fine-loamy, mixed active calcareous, mesic typic epiaquolls) with pH 7.6 and 2.1% organic matter in

2023 and pH 7.5 and 2.3% organic matter in 2024. Soil at AMATU-23 was a Kendallville sandy loam (fine-loamy, mixed, superactive, mesic typic hapludalfs) with pH 6.1 and 1.3% organic matter. Soil at AMATU-24 was a Brookston loam (fine-loamy, mixed, superactive, mesic typic argiaquolls) with pH 7.2 and 2.3% organic matter.

Dicamba, glufosinate, and glyphosate-resistant sugarbeet seed (KWS Seeds, Inc. Bloomington, MN) was planted at 118,000 seeds ha^{-1} in 76 cm rows with a four-row John Deere MaxEmerge2 vacuum planter (John Deere, Moline, IL). Planting dates ranged from early April to mid-May depending on site-year (Table 2.1). All fields were fall chisel plowed, then spring soil finished with a field cultivator twice prior to sugarbeet planting. Each location was arranged in randomized complete block design with 4 replications and plot size 3 m wide by 9 m long.

Locations were selected based on the presence of specific weed species. At MSU-23, annual grass species (giant foxtail and barnyardgrass), common lambsquarters, common purslane (*Portulaca oleracea* L.), and GR horseweed were present at mid-season densities of 4-, 2-, 37-, and 2 plants m^2, respectively. At MSU-24, annual grass species, common lambsquarters, common purslane, velvetleaf (*Abutilon theophrasti* Medik.) and GR horseweed were present at densities of 11-, 7-, 9-, 6-, and 13 plants m^{-2}, respectively. At AMATU-23 and AMATU-24, GR waterhemp was present at densities of 61 and 86 plants m^{-2}, respectively. At SVREC-23 and SVREC-24, common lambsquarters was the predominant weed species present at 23 and 15 plants m^{-2}, respectively.

Twenty different herbicide programs including an untreated control were each evaluated for sugarbeet injury and control of several key weed species (Table 2.2). Herbicide programs were grouped into three different strategies based on herbicide application timings commonly used in sugarbeet production. Eight herbicide programs followed a PRE fb. two POST application timings at 2 leaf (lf) and 8 lf sugarbeets. Five herbicide programs had two POST applications at 2 lf and 8 lf sugarbeets. Six herbicide programs had three POST applications at 2, 6, and 12 lf sugarbeet. In 2023, herbicide applications to 6- and 8 lf sugarbeets were applied separately; however in 2024 the 6- and 8 lf applications were applied at the same time (Table 2.1). Four of the herbicide programs evaluated aligned with current weed management strategies in GR sugarbeet: 1) three POST applications of glyphosate, 2) three POST applications of glyphosate plus the inclusion of a Group 15 herbicide (acetochlor) with the second glyphosate application, 3) the current recommendation for horseweed control that includes two applications of clopyralid, and 4) an overlapping residual herbicide program for waterhemp control (Table 2.2). Herbicide trade names, WSSA site of action group numbers, and manufacturer information can be found in Table 2.3.

Average weed heights for annual grass, common lambsquarters, horseweed, and velvetleaf at the 2, 6-8, and 12 lf applications were approximately 5-, 10-, and 25 cm, respectively. Average common purslane height at the 12 lf application was <5 cm. Average waterhemp heights at the 2-, 6-8, and 12 lf applications were 5-, 18-, and 38 cm, respectively. All herbicide applications were made with a tractor mounted compressed air sprayer calibrated to deliver 177 L ha^{-1}. Non-dicamba herbicides were applied using AIXR 11003 nozzles (TeeJet Spraying Systems CO., Wheaton, IL) at 207 kPa. Herbicide treatments that contained dicamba were applied using TTI 11003 nozzles at 186 kPa (TeeJet Spraying Systems CO.).

Data Collection. Sugarbeet injury and weed control were evaluated on a scale of 0 to 100%, with 0 indicating no injury or weed control and 100 indicating complete crop death or all weeds controlled. Sugarbeet injury and weed control from PRE herbicide treatments were evaluated just prior to the 2 lf application. Additional evaluations were 7 and 14 d after treatment (DAT) following the 2- and 6-8 lf applications. The 14 DAT evaluation following the 6-8 lf application was deemed the "mid-season" weed control evaluation. At this time, weed counts were recorded from two 0.25 m^2 quadrats per plot. Sugarbeet injury and weed control was also evaluated 14 and 28 d after the 12 lf application. Final weed control evaluations were taken just prior to sugarbeet harvest and aboveground weed biomass was collected from two 0.25 m^2 quadrats per plot. Biomass samples were dried at 65º C for 7 d and dry aboveground weed biomass was recorded. Sugarbeet was harvested for yield from the middle two rows at MSU-24, SVREC-23, and SVREC-24 by mechanically removing the sugarbeet leaves and digging the roots with a custom built two-row pull behind sugarbeet plot harvester.

Rainfall data were obtained throughout the growing season from the nearest Michigan Automated Weather Network (https://mawn.geo.msu.edu/, Michigan State University, East Lansing, MI) for each trial location (Table 2.4).

Statistical Analysis. All data were analyzed in R v. 4.3.1 using linear mixed effects models (lmer) (R Development Core Team 2024). Means were separated using Tukey's HSD post hoc test in the EMMEANS package in R ($\alpha \leq 0.05$) (Lenth 2023). For all statistical analyses, herbicide treatment was considered a fixed effect, with replication and replication nested within site-year (when years were combined) considered random effects. When site-year interactions were not significant, data was combined across site-year. Normality and unequal variance assumptions were verified by examining normality histograms, side-by-side box plots of the residuals, and normality probability plots.

Results and Discussion

Sugarbeet Injury. Sugarbeet injury from herbicide applications was relatively low in 5 of the 6 site-years of this research. At all locations, the standard program for horseweed control containing clopyralid caused 6-10% injury, 7 DAT (data not shown). Sugarbeet injury from clopyralid applications is common and results in elongated sugarbeet petioles (Dale et al. 2006; Wilson 1995, 1999).

The one site-year where injury did occur other than the standard program for horseweed control was at AMATU-24, where acetochlor applications to 2-lf sugarbeet tank-mixed with glyphosate or glufosinate resulted in significant sugarbeet injury 7 DAT compared with the untreated control (Table 2.5). Sugarbeet injury from acetochlor tank-mixed with glyphosate was 5-8%. Peters et al. (2017) reported an average sugarbeet injury and growth reduction of 29% when tank-mixes of glyphosate and labeled Group 15 herbicides (acetochlor, dimethenamid-P, and *S*-metolachlor) were applied at the 2 lf stage. This injury was the result of 25 mm of rainfall occurring in one event within 7 DAT, causing herbicide leaching into the seedling zone of actively growing plants. AMATU-24 received 16 mm of rainfall within 7 DAT of the 2 lf application (data not shown), likely causing the increase in injury from glyphosate and acetochlor tank-mixes compared with other site-years.

Greater sugarbeet injury occurred when acetochlor was tank-mixed with glufosinate (15-16%). These symptoms consisted of plant stunting and abnormal leaf formation. However, by 14 DAT sugarbeet injury was 7% or less with this tank-mixture and was not apparent later in the season. While injury from tank-mixtures of acetochlor and glufosinate has not been previously reported in sugarbeet, tank-mixtures of acetochlor and glufosinate resulted in up to 10% growth reduction 7 DAT when applied to 1- to 2-leaf glufosinate-resistant cotton (Cahoon et al. 2015a). As seen in sugarbeet, cotton injury symptoms subsided by 14 DAT. Additionally, cotton yield was not affected from this injury. Rainfall was not discussed as a factor leading to injury from acetochlor and glufosinate tank-mixtures in glufosinate-resistant cotton (Cahoon et al. 2015a).

Acetochlor and glufosinate tank-mixtures at AMATU-24 enhanced injury compared with applications of acetochlor and glyphosate. Tank-mixtures of acetochlor and glufosinate has caused injury in other glufosinate-resistant crops but did not reduce yield. While sugarbeets were not harvested at this site, since injury symptoms subsided by 14 DAT, chances of yield reduction from glufosinate and acetochlor tank-mixtures were low.

Waterhemp Control. Glyphosate-resistant waterhemp control from PRE applications of dicamba or *S*-metolachlor differed between AMATU-23 and AMATU-24 as a result of low precipitation (5 mm) within 20 d following PRE herbicide application at AMATU-23 (Table 2.4). For both site-years, waterhemp control was greater from PRE dicamba than *S*-metolachlor 20 DAT (data not shown). Waterhemp control at AMATU-23 was 51 and 76% from PRE *S*-metolachlor and dicamba, respectively, and 89 and 95% at MSU-24 (data not shown). There was 13 mm of rainfall within 7 d of the PRE applications at MSU-24 (Table 2.4). Most soil-applied PRE herbicides need 13-25 mm of rainfall within 14 d of application for adequate incorporation (Jhala 2017). Specifically, *S*-metolachlor usually requires at least 13 mm of rainfall for acceptable residual weed control (Anonymous 2023).

Waterhemp control from PRE dicamba applications in this study was greater than reported by Johnson et al. (2010), where dicamba provided an average of 35% waterhemp control 20 DAT. However, waterhemp control from dicamba varied significantly between site-years from >90% to <10%. While rainfall information was not discussed in Johnson et al. (2010), dicamba has only short-lived residual activity on broadleaf weeds, that is significantly reduced once 25 mm of rainfall has been received (Norsworthy et al. 2009). The variability seen between site-years in Johnson et al. (2010) may be a result of differing amounts of precipitation. While waterhemp control from PRE applications of dicamba was greater than applications of *S*-

metolachlor at AMATU-23 and AMATU-24, the short-lived residual activity of dicamba can result in variable control. Growers should take caution if applying dicamba without an additional residual herbicide.

Waterhemp control from PRE *S*-metolachlor was significantly lower than previous studies in corn, soybean, and fallow-ground, which reported >90% waterhemp control 28 DAT (Steckel et al. 2002; Strom et al. 2022; Vyn et al. 2007). Differences in waterhemp control between our research and previous research could be attributed to the lower PRE *S*-metolachlor application rate allowed in sugarbeet (0.53 kg ai ha^{-1}) compared with corn and soybean (1.4 kg ai ha^{-1}) due to sugarbeet tolerance concerns (Dexter and Luecke 2004; Lueck et al. 2020). Additionally, differences in weed control from PRE applications can be highly dependent on several factors including soil characteristics, precipitation following application, and the specific herbicide applied. Soil texture, organic matter, and pH can all have significant impacts on a specific herbicide's residual activity (Corbin et al. 1971; Sheng et al. 2001). Overall, both dicamba and *S*-metolachlor reduced early season waterhemp competition compared with the untreated control.

Mid-season and at harvest waterhemp control were similar for both site-years. Mid-season waterhemp control was evaluated 14 d after the 6-8 lf POST herbicide application, which was the final application for the PRE fb. two POST and two POST only herbicide program strategies. At this time, waterhemp control was 87% or greater and similar for all herbicide programs that contained at least two applications of glufosinate or dicamba (Table 2.5). Waterhemp control from current standard herbicide programs used in GR sugarbeet, was unacceptable (51% or less). This included the current waterhemp control strategy of overlapping residual herbicides. For waterhemp control to be successful with this strategy, timely rainfall after the application of the residual herbicide is needed. Additionally, since none of the herbicides in this program had foliar activity against GR waterhemp, there was nothing to control newly emerged waterhemp.

At harvest, the herbicide programs that provided the greatest season-long waterhemp control (90% or greater) included a minimum of one application of POST acetochlor for late season residual waterhemp control in addition to at least two applications of glufosinate or dicamba (Table 2.5). There were two additional programs that resulted in similar control, these included dicamba (PRE) fb. dicamba + glyphosate (2 lf) fb. glufosinate (6-8 lf) and dicamba + glyphosate (2 lf) fb. glufosinate (6-8 lf) fb. glyphosate (12 lf). The 2 lf application of dicamba in these programs likely provided residual waterhemp control. Similarly, certain POST application timings of dicamba in cotton improved palmer amaranth (*Amaranthus palmeri*) control by 13% compared to glufosinate-only treatments, likely as a result of its residual activity (Cahoon et al. 2015b). Dicamba PRE fb. one or two applications of glufosinate resulted in good waterhemp control (~80%). Schryver et al. (2017) also reported good control of waterhemp when PRE herbicides were followed by glufosinate applications in soybean. However, in the present study where two POST applications of glufosinate were applied alone or tank-mixed with glyphosate waterhemp control was unacceptable (70% or less). This has also been observed in glufosinate-resistant soybean where waterhemp control was 76% 14 d after two applications of glufosinate (Jhala et al. 2017).

Waterhemp dry biomass at harvest was similar for all herbicide programs that included at least two applications of glufosinate or dicamba applications (Table 2.5). Waterhemp biomass was at least 75% lower from herbicide programs that included at least two applications of glufosinate or dicamba compared with the current standard program used for waterhemp control in GR sugarbeet. However, this strategy did reduce waterhemp biomass by 44% compared with the untreated control. Three applications of glyphosate had no effect on late-season waterhemp biomass compared with the untreated control.

The lower waterhemp control observed from mid-season to at harvest evaluations among the herbicide programs can be attributed to new emerging waterhemp. Waterhemp emergence can continue into August under conditions with adequate soil temperature and moisture (Schryver et al. 2017; Symington et al. 2023). Late-season rainfall at both locations likely increased waterhemp emergence, in July AMATU-23 and AMATU-24 received 176 and 142 mm of rainfall, respectively (Table 2.4). July precipitation was an increase of at least 75% compared with the 30-year average at these locations. Additionally, regrowth of larger waterhemp plants following glufosinate applications can occur if spray coverage of the entire plant is not complete, leading to reduced control later in the season (Haarmann et al. 2020). Season-long waterhemp control was improved significantly when acetochlor was applied at the 2 or 6-8 lf stage in combination with glufosinate. These herbicide programs provided good POST waterhemp control, with acetochlor providing residual control of late emerging waterhemp. Herbicide programs with PRE applications fb. glufosinate applications had higher control compared to programs that only had POST applications of glufosinate. Glyphosate-resistant waterhemp control from this study largely agrees with results from previous studies conducted in glufosinate, glyphosate, and dicamba/2,4-D resistant soybean. PRE fb. POST herbicide programs are generally regarded as the most effective at providing season-long waterhemp control in soybean while also alternating herbicide site of action to limit the selection of herbicide-resistant weeds (Duenk et al. 2023; Soltani et al. 2020). In sugarbeet a PRE fb. POST strategy should also be followed, however in sugarbeet two POST applications may be necessary for season-long waterhemp control due to the low growth habit and reduced competitiveness of sugarbeet compared with other field crops.

Common Lambsquarters Control. Common lambsquarters was present in 4 of the 6 site-years of this research. However, differences in common lambsquarters control and late-season biomass resulted in SVREC-23 and SVREC-24 being analyzed separately from the combined MSU-23 and MSU-24 data. Common lambsquarters biomass was included with the total weed biomass collected at MSU-23 and MSU-24.

Dicamba PRE controlled common lambsquarters greater than 98% at the 2 lf application at SVREC-23 and SVREC-24 (data not shown). This differed from MSU-24 where dicamba PRE only provided 58% common lambsquarters control. The reduced common lambsquarters control from PRE dicamba at MSU-24 was likely due to high amounts of precipitation, 47 and 74 mm, within 7 and 21 DAT, respectively. SVREC-23 and SVREC-24 received 23 and 19 mm of rainfall 7 DAT, and 39 and 37 mm 21 DAT, respectively. Dicamba is highly water soluble and large amounts of precipitation dissipate its residual activity resulting in reduced weed control, which likely occurred at MSU-24 (Cahoon et al. 2015b; Silva et al. 2023).

Mid-season common lambsquarters control at SVREC-23 was 90% or greater from herbicide programs that contained either dicamba PRE or glyphosate at the 2 or 6-8 lf application (Table 2.6). Herbicide programs that only relied on glufosinate for common lambsquarters control were not as effective (74-78%). By harvest, herbicide programs that had an additional glyphosate application at the 12 lf stage provided 98% or greater common lambsquarters control. Additionally, several other herbicide programs where the last application was to 6-8 lf sugarbeet also provided similar common lambsquarters control. Herbicide programs with two POST applications of glufosinate alone only provided 54% common lambsquarters control. Variability and overall lower control of common lambsquarters from glufosinate can be caused by cooler temperatures at application, lower humidity, the time of day applications were made, larger weed size, and application rates (Steckel et al. 1997; Takano and Dayan 2020).

At harvest common lambsquarters biomass at SVREC-23 followed similar results to the at harvest common lambsquarters control evaluations (Table 2.6). Herbicide programs that did not reduce common lambsquarters biomass similar to the programs with greatest control included two applications of glufosinate and dicamba PRE fb. glufosinate + acetochlor at 2 lf fb. glufosinate at 6-8 lf sugarbeet.

At SVREC-24, mid-season and at harvest common lambsquarters control was 99% or greater across all herbicide programs (Table 2.6). This resulted in 1 g m^{-2} or less of common lambsquarters biomass for all herbicide programs.

Common lambsquarters control was similar for MSU-23 and MSU-24, therefore evaluations were combined across site-years. Mid-season common lambsquarters control was 99% or greater from all herbicide programs with dicamba PRE or at least one application of glyphosate (Table 2.7). Control ranged from 92-97% in herbicide programs that only had glufosinate applied at the 2 and 6-8 leaf sugarbeet stages. At harvest common lambsquarters control was at least 90% among all herbicide programs that had at least one application of glyphosate or a PRE application of dicamba fb. a tank-mixture of glufosinate and acetochlor at the 2-lf application. Common lambsquarters control ranged from 78-79% among herbicide programs that only had glufosinate applied at the 2 and 6-8 lf timings. The poor common lambsquarters control from glufosinate applications agrees with the results observed at SVREC-23 along with what has been reported in previous research (Steckel et al. 1997; Takano and Dayan 2020).

Velvetleaf Control. Velvetleaf was only present at MSU-24. Mid-season velvetleaf control was 92% or greater across all herbicide programs (Table 2.7). At harvest, velvetleaf control ranged from 90-100% for all herbicide programs, with the exception of two POST applications of glufosinate alone that provided only 78% control. Similarly, Aulakh and Jhala (2015) reported between 73-80% velvetleaf control at harvest from two POST applications of glufosinate in soybean. While single POST application of dicamba was not specifically evaluated in this study, Sanctis and Jhala (2021) reported 74% control of emerged velvetleaf from a single dicamba application, while a single application of glyphosate provided 93% control, 56 DAT.

Common Purslane Control. An extremely high population (37 plants m^{-2}) of common purslane was present following the mid-season evaluation at MSU-23. At harvest, common purslane control ranged between 81-100% from herbicide programs that had either a 12-leaf application of glyphosate or an application of acetochlor at the 2 or 6-8 lf timing (Table 2.7). All other herbicide programs provided unacceptable common purslane control (65% or less).

At MSU-24, a much lower population of common purslane (9 plants m^{-2}) was present. However, control followed similar trends as observed at MSU-23. Greatest common purslane control was observed from herbicide programs that had either a 12-leaf application of glyphosate or an application of acetochlor at the 2 or 6-8 lf timing. Herbicide programs that included only applications of glyphosate or glufosinate at the 2 and 6-8 lf timing provided between 89-84% control. In previous research, PRE applications of *S*-metolachlor provided 84-98% common purslane control (Norsworthy and Smith 2005). While common purslane emerged later in the growing season and well after PRE applications in this study, the application of acetochlor, a chloroacetamide herbicide like *S*-metolachlor, at the 2 and 6-8 lf application timings significantly improved late-season common purslane control.

Horseweed Control. Emergence of GR horseweed was not consistent prior to the 2 lf application, so control from the PRE herbicide applications was not evaluated. Horseweed control was similar for MSU-23 and MSU-24, so data was combined over the site-years. All herbicide programs, with the exception of two, provided 95% or greater mid- and late-season horseweed control (Table 2.8). The two programs that did not provide good control included three applications of glyphosate alone or when acetochlor was tank-mixed with the 6-8 lf glyphosate application. These programs provided only 27 and 56% GR horseweed control, respectively. At harvest, GR horseweed biomass followed similar trends as control evaluations. Herbicide programs with excellent control reduced GR horseweed biomass by at least 90%. However, the glyphosate only programs only reduced horseweed biomass by 50% compared with the untreated control.

Herbicide programs that provided excellent horseweed control contained at least two applications of glufosinate, two applications of dicamba, two applications of clopyralid, or separate applications of glufosinate or dicamba, regardless of application timing (Table 2.8). This data strongly agrees with previous research where each of these products were found to effectively control GR horseweed. Dicamba applications in soybean controlled 96 to 98% of GR horseweed 5-8 weeks after treatment (Johnson et al. 2010; Soltani et al. 2022), and GR horseweed control with glufosinate in cotton and soybean was 91 and 96%, respectively (Eubank et al. 2008; Steckel et al. 2006). More importantly, the standard recommendation for horseweed control in GR sugarbeet provided excellent season-long control and was comparable to the herbicide programs that contained dicamba or glufosinate. In Mahoney et al. (2016), applications of clopyralid provided 96% GR horseweed control 8 weeks after treatment in winter wheat.

While clopyralid has been used to effectively manage GR horseweed in sugarbeet, injury can occur following application.

Annual Grass Control. The annual grass population was low (4 plants m^{-2}) at MSU-23, and control was 93% or greater across all herbicide programs for both the mid- and late-season evaluation (Table 2.9). As a result, total weed biomass, excluding GR horseweed, at MSU-23 was mainly affected by the level of common purslane control. Herbicide programs that only had glyphosate or glufosinate applied at the 2 and 6-8 lf timings and did not have a 12 lf application of glyphosate had similar weed biomass to the untreated control. These were the herbicide programs that had poor common purslane control (Table 2.7). Herbicide programs that provided 86% or higher common purslane control had at least a 74% reduction in weed biomass (Table 2.7 and 2.10).

At MSU-24, the average annual grass population was 11 plants m^{-2} leading to differences in control between herbicide programs. *S*-metolachlor applied PRE provided 100% annual grass control 30 DAT (data not shown). This is consistent with previous research that reported excellent control of annual grasses with *S*-metolachlor and other WSSA Group 15 herbicides (Clewis et al. 2006). Mid-season annual grass control was 90% or greater from all herbicide programs (Table 2.9). For adequate annual grass control at harvest, a PRE application of *S*-metolachlor, a POST residual application of acetochlor + glyphosate at 6-8 lf sugarbeet, or an application of glyphosate at 12 lf sugarbeet was needed. Control was 78% or lower for most herbicide programs that only received glufosinate applications at the 6-8 lf timing, except dicamba PRE fb. glufosinate + acetochlor fb. glufosinate that had 88% annual grass control.

Lower control of several annual grass species from one or more glufosinate applications has been frequently reported (Corbett et al. 2004; Gardner 2006; Whitaker et al. 2011). In our study, tank-mixture combinations of glyphosate and glufosinate applied twice resulted in only 63% annual grass control. Reduced control was likely caused by glufosinate antagonizing glyphosate activity on annual grasses, which is well-documented in greenhouse trials. Glyphosate translocation was reduced from 52.4 to 21.6% when glufosinate was tank-mixed with glyphosate compared with glyphosate applied alone (Besançon et al. 2018). Previous research has shown that glufosinate tank-mixtures with glyphosate provided similar annual grass control to glufosinate alone, while glyphosate applied alone provided the greatest annual grass control (Whitaker et al. 2011).

At MSU-24, the weed community consisted of more annual grass than common purslane, thus weed biomass (excluding horseweed) was more closely associated with the level of annual grass control. Herbicide programs that resulted in 98% or greater annual grass control reduced weed biomass by at least 94% compared with herbicide programs that had below 68% annual grass control (Table 2.9). Herbicide programs that resulted in 63% or lower annual grass control had similar weed biomass compared with the untreated control.

Sugarbeet Yield. Sugarbeet was harvested at 3 of the 6 site-years. At SVREC, there was no interaction with site-year, so yield data was combined across SVREC-23 and SVREC-24 (Table 2.6). Yield reductions from weed competition among herbicide programs were not observed. This was likely because of excellent weed control across all herbicide programs at SVREC-24 and minimal early season weed interference at SVREC-23. Average yield across herbicide programs was 63.0 Mg ha^{-1} compared to 28.8 Mg ha^{-1} in the untreated control, a 54% reduction in yield when weeds were left uncontrolled for the entire season.

At MSU-24, the glufosinate fb. glufosinate + acetochlor fb. glyphosate program had the highest yield at 97.9 MG ha^{-1} (Table 2.9). Sugarbeet yield was reduced the most when annual grass was not adequately controlled. The lowest yielding herbicide program was dicamba PRE fb. dicamba + glyphosate fb. glufosinate, which averaged 46.8 Mg ha^{-1}, a 52% yield reduction compared with the highest yielding program. Similarly, dicamba PRE fb. glyphosate fb. glufosinate averaged 51.8 Mg ha^{-1}, which was a 47% reduction in yield. These herbicide programs had 50 and 58% annual grass control at harvest, respectively. The glufosinate fb. glufosinate treatment was not significantly different from these two programs and yielded 64.7 Mg ha^{-1}, a 34% yield reduction from the highest yielding treatment. Interestingly, the interference from uncontrolled GR horseweed in glyphosate only herbicide programs did not significantly reduce yield.

In conclusion, sugarbeet varieties resistant to glyphosate, glufosinate, and dicamba will offer more herbicide options for growers to manage problematic and GR weeds. However, because of the low growth habit of sugarbeet and delayed canopy development, weed control systems will likely need a PRE herbicide fb. two effective POST herbicide applications for season-long control of difficult to manage weeds such as GR waterhemp. Notably, applying a POST residual herbicide, such as acetochlor, will be critical in this system to reduce selection pressure on glufosinate and dicamba, and to provide season-long weed control of GR waterhemp and annual grasses. Furthermore, programs with a PRE herbicide also effectively reduced early-season weed competition compared with programs without a PRE application. While control from POST applications of dicamba or glufosinate can provide effective control of GR horseweed, glyphosate was still necessary for providing effective control of non-GR weed species such as annual grass species, common lambsquarters, velvetleaf, and common purslane. All of these species were not as effectively controlled from glufosinate applications. While sugarbeet root yield between herbicide programs was not significantly different in 2 of the 3 site-years, control of annual grass species was critical for protecting yield at MSU-24, where up to a 52% yield reduction was observed in herbicide programs with poor annual grass control. Combining currently labeled WSSA group 15 residual products such as acetochlor, *S*-metolachlor, or dimethenamid-P with glyphosate, glufosinate and dicamba will be crucial for improving weed control as a part of an integrated weed management strategy that will prevent the development of herbicide-resistant weeds in sugarbeet and protect the profitability of sugarbeet production in Michigan.

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APPENDIX A: CHAPTER II TABLES

Table 2.1. Field operation dates for the six site-years of research.

	Locations					
Operation	AMATU-23[a]	AMATU -24	MSU-23	MSU-24	SVREC-23	SVREC-24
Planting date	May 23	May 9	April 27	April 9	April 26	April 16
PRE application	May 23	May 9	April 27	April 10	April 26	April 22
2 lf application	June 14	May 30	May 30	May 10	May 22	May 16
6 lf application[b]	June 29	-	June 13	-	June 7	-
8 lf application	July 11	June 14	June 20	May 30	June 19	May 30
12 lf application	July 19	June 27	July 10	June 19	July 5	June 12
Sugarbeet harvest[c]	-	-	-	September 5	September 19	September 19

[a] Abbreviations: AMATU-24 = waterhemp site 2023 (Morrice, MI); AMATU-24 = waterhemp site 2024 (Durand, MI); MSU = Michigan State University (East Lansing, MI); SVREC = Saginaw Valley Research and Extension Center (Richville, MI); PRE = preemergence; lf = sugarbeet leaf stage.
[b] The 6- and 8 lf herbicide applications timing were combined in 2024 and applied on the same date.
[c] Sugarbeet was not harvested at MSU-23, AMATU-23, and AMATU-24.

Table 2.2. Herbicide programs, application rates, and abbreviated herbicide programs organized by application timing strategy.

Herbicide programs[a]	Rates	Abbreviated herbicide programs
PRE fb. 2 lf fb. 8 lf[b]	——— kg ai/ae ha^{-1} ———	
dicamba fb. glyphosate fb. glufosinate	0.56 fb. 1.26 fb. 0.66	dicam fb. glyph fb. glufo
dicamba fb. glyphosate + acetochlor fb. glufosinate	0.56 fb. 1.26 + 1.26 fb. 0.66	dicam fb. glyph + aceto fb. glufo
dicamba fb. glufosinate fb. glufosinate	0.56 fb. 0.59 fb. 0.59	dicam fb. glufo fb. glufo
dicamba fb. glufosinate + acetochlor fb. glufosinate	0.56 fb. 0.59 + 1.26 fb. 0.59	dicam fb. glufo + aceto fb. glufo
dicamba fb. dicamba + glyphosate fb. glufosinate	0.56 fb. 0.56 + 1.26 fb. 0.66	dicam fb. dicam + glyph fb. glufo
dicamba fb. glufosinate + glyphosate + acetochlor fb. glufosinate + glyphosate + acetochlor	0.56 fb. 0.59 + 1.26 + 1.26 fb. 0.59 + 0.84 + 1.26	dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto
S-metolachlor fb. glyphosate + acetochlor fb. glyphosate + acetochlor[c]	0.53 fb. 1.26 + 1.26 fb. 0.84 + 1.26	*S*-met fb. glyph + aceto fb. glyph + aceto
S-metolachlor fb. glufosinate + glyphosate + acetochlor fb. glufosinate + glyphosate + acetochlor	0.53 fb. 0.59 + 1.26 + 1.26 fb. 0.59 + 0.84 + 1.26	*S*-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto
2 lf fb. 8 lf		
glufosinate fb. glufosinate	0.59 fb. 0.59	glufo fb. glufo
glufosinate + glyphosate fb. glufosinate + glyphosate	0.59 + 1.26 fb. 0.59 + 0.84	glufo + glyph fb. glufo + glyph
glufosinate + glyphosate + acetochlor fb. glufosinate + glyphosate	0.59 + 1.26 + 1.26 fb. 0.59 + 0.84	glufo + glyph + aceto fb. glufo + glyph
glufosinate + glyphosate fb. glufosinate + glyphosate + acetochlor	0.59 + 1.26 fb. 0.59 + 0.84 + 1.26	glufo + glyph fb. glufo + glyph + aceto
glufosinate + glyphosate + acetochlor fb. glufosinate + glyphosate + acetochlor	0.59 + 1.26 + 1.26 fb. 0.59 + 0.84 + 1.26	glufo + glyph + aceto fb. glufo + glyph + aceto
2 lf fb. 6 lf fb 12 lf		
glyphosate fb. glyphosate fb. glyphosate[d]	1.26 fb. 0.84 fb. 0.84	glyph fb. glyph fb. glyph
glyphosate fb. glyphosate + acetochlor fb. glyphosate[e]	1.26 fb. 0.84 + 1.26 fb. 0.84	glyph fb. glyph + aceto fb. glyph
dicamba + glyphosate fb. glufosinate fb. glyphosate	0.56 + 1.26 fb. 0.66 fb. 0.84	dicam + glyph fb. glufo fb. glyph
glufosinate fb. glufosinate fb glyphosate	0.59 fb. 0.59 fb. 0.84	glufo fb. glufo fb. glyph

Table 2.2 (cont'd)

glufosinate fb. glufosinate + acetochlor fb glyphosate	0.59 fb. 0.59 + 1.26 fb. 0.84	glufo fb. glufo + aceto fb. glyph
clopyralid + glyphosate fb. clopyralid + glyphosate + acetochlor fb. glyphosate[f]	0.052 + 1.26 fb. 0.105 + 0.84 + 1.26 fb. 0.84	clopy + glyph fb. clopy + glyph + aceto fb. glyph

[a] All treatments that contained dicamba included drift-reducing and volatility reducing agents at 0.5% and 1% v v^{-1}, respectively. All other POST applications included ammonium sulfate at 2% w w^{-1}.

[b] Abbreviations: PRE = preemergence; fb. = followed by; lf = sugarbeet leaf stage; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid

[c] Current standard for GR waterhemp control using overlapping residual herbicides.

[d] Current standard herbicide program.

[e] Current standard glyphosate + residual standard herbicide program.

[f] Current standard for GR horseweed control.

Table 2.3. Common names, trade names, herbicide site of action groups and manufacturer information for products used in this research.

Common name	Trade name	Site of Action	Manufacturer[a]
ammonium sulfate	Sulf-N	-	AdvanSix Inc.
acetochlor	Warrant	15	Bayer Crop Science
clopyralid	Stinger HL	4	Corteva Agriscience
drift-reducing agent	Cognitive 1	-	CHS Inc.
dicamba	XtendiMax	4	Bayer Crop Science
glufosinate	Liberty 280 SL	10	BASF Corporation
glyphosate	Roundup PowerMax 3	9	Bayer Crop Science
s-metolachlor	Dual Magnum	15	Syngenta Crop Protection
vapor-reducing agent	Suralta	-	CHS Inc.

[a] Manufacturer information: AdvanSix Inc., Parsippany, NJ, BASF Corporation, Research Triangle Park, NC; Bayer Crop Science, St. Louis, MO; CHS Inc., Inver Grove Heights, MN; Corteva Agriscience, Indianapolis, IN; Syngenta Crop Protection LLC, Greensboro, NC.

Table 2.4. Monthly[a] and the 30-year average rainfall[b] for the six site-years of this research.

Month	Rainfall						30-year average rainfall		
	AMATU-23	AMATU-24	MSU-23	MSU-24	SVREC-23	SVREC-24	AMATU	MSU	SVREC
	mm						mm		
April	-	-	88(5)[c]	87(74)	78(14)	70(32)	83	90	75
May	27(0)	87(62)	25	48	25	105	104	111	87
June	20	108	18	86	38	100	98	96	100
July	176	142	155	126	139	108	81	86	93
August	203	108	150	74	150	86	82	88	86
September	48	35	50	16	34	38	75	81	98
Total	572	561	486	437	464	507	523	552	539

[a] Monthly rainfall data was retrieved from the closest Michigan State Enviroweather station (https://mawn.geo.msu.edu/).
[b] Monthly 30-year average rainfall data was retrieved from the National Oceanic and Atmospheric Administration, U.S. Climate Normals (https://www.ncei.noaa.gov/access/us-climate-normals/).
[c] Numbers in parentheses represent the rainfall after planting for that month.

Table 2.5. Sugarbeet injury following the 2 lf[a] application at AMATU-24, and GR waterhemp control and biomass at the combined AMATU-23 and AMATU-24 locations.

	AMATU-24		AMATU-23/24		
	Sugarbeet injury		Waterhemp control		Waterhemp biomass
Herbicide program[b]	7 DAT[c]	14 DAT	Mid-season[e]	At harvest[f]	At harvest
PRE fb. 2 lf fb. 6-8 lf	%				g m^{-2}
dicam fb. glyph fb. glufo	0 d[d]	0 d	97 a	82 bc	50 (29)[g] d
dicam fb. glyph + aceto fb. glufo	8 b	4 abc	98 a	96 ab	15 (13) d
dicam fb. glufo fb. glufo	0 d	0 d	97 a	83 bc	35 (13) d
dicam fb. glufo + aceto fb. glufo	15 a	5 d	99 a	98 a	4 (3.2) d
dicam fb. dicam + glyph fb. glufo	4 bcd	1 cd	100 a	94 ab	11 (5.7) d
dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto	15 a	6 ab	99 a	100 a	2 (1.6) d
S-met fb. glyph + aceto fb. glyph + aceto[h]	5 bc	3 bcd	51 b	41 e	304 (61) bc
S-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto	15 a	4 ab	97 a	96 ab	9 (3.6) d
2 lf fb. 6-8 lf					
glufo fb. glufo	0 d	0 d	91 a	60 d	109 (21) d
glufo + glyph fb. glufo + glyph	0 d	0 d	93 a	70 cd	75 (26) d
glufo + glyph + aceto fb. glufo + glyph	16 a	7 a	97 a	91 ab	21 (14) d
glufo + glyph fb. glufo + glyph + aceto	0 d	0 d	97 a	91 ab	60 (30) d
glufo + glyph + aceto fb. glufo + glyph + aceto	15 a	6 ab	96 a	92 ab	25 (15) d
2 lf fb. 6-8 lf fb 12 lf					
glyph fb. glyph fb. glyph	0 d	0 d	27 c	21 f	487 (51) ab

Table 2.5 (cont'd)

glyph fb. glyph + aceto fb. glyph	1 cd	0 d	38 bc	27 ef	313 (72) bc
dicam + glyph fb. glufo fb. glyph	5 bc	1 cd	97 a	90 ab	38 (17) d
glufo fb. glufo fb glyph	0 d	0 d	87 a	69 cd	156 (44) cd
glufo fb. glufo + aceto fb. glyph	0 d	0 d	94 a	90 ab	45 (26) d
clopy + glyph fb. clopy + glyph + aceto fb. glyph	6 b	4 ab	36 bc	32 ef	340 (77) bc
Untreated	0 d	0 d	0 d	0 g	545 (51) a

[a] Abbreviations: PRE = preemergence; fb. = followed by; lf = sugarbeet leaf stage; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid.
[b] Herbicide programs can be found in Table 2.2.
[c] 7 d after the 2-leaf application.
[d] Means followed by the same letter within a column are not statistically different at $a \leq 0.05$.
[e] Mid-season evaluations were taken 14 d after the 6-8 leaf application.
[f] At harvest evaluations were taken just prior to typical sugarbeet harvest.
[g] Numbers in (SE) are the standard errors of the mean.
[h] Current strategy recommended for GR waterhemp control using overlapping residual herbicides.

Table 2.6. Common lambsquarters control, biomass, and sugarbeet yield at SVREC-23 and SVREC-24.

	Common lambsquarters control				Common lambsquarters biomass		Sugarbeet yield
	SVREC-23		SVREC-24				
Herbicide program[a]	Mid-Season[bc]	At harvest[d]	Mid-season	At harvest	SVREC-23	SVREC-24	SVREC-23/24
PRE fb. 2 lf fb. 6-8 lf[e]	%				$g\ m^{-2}$		$Mg\ ha^{-1}$
dicam fb. glyph fb. glufo	96 a	84 bcd	100 a	99 a	97 (65)[f] bcd	0 b	64.8 (5.0) a
dicam fb. glyph + aceto fb. glufo	100 a	97 ab	100 a	99 a	0 (0.2) d	1 (1.0) b	66.2 (5.5) a
dicam fb. glufo fb. glufo	100 a	86 abcd	100 a	100 a	58 (31) cd	0 (0.3) b	58.8 (7.7) a
dicam fb. glufo + aceto fb. glufo	95 a	72 d	100 a	100 a	247 (146) bc	0 b	59.6 (8.7) a
dicam fb. dicam + glyph fb. glufo	100 a	99 ab	100 a	100 a	0 d	0 b	67.7 (6.3) a
dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto	98 a	97 ab	100 a	100 a	2 (1.6) d	0 b	61.9 (6.1) a
S-met fb. glyph + aceto fb. glyph + aceto	90 ab	88 abcd	100 a	100 a	24 (24) d	0 b	64.1 (7.2) a
S-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto	98 a	98 ab	100 a	99 a	1 (0.6) d	0 b	61.4 (6.2) a
2 lf fb. 6-8 lf							
glufo fb. glufo	78 bc	54 e	100 a	100 a	350 (121) b	1 (1.4) b	58.7 (8.1) a
glufo + glyph fb. glufo + glyph	93 a	79 cd	100 a	99 a	85 (33) bcd	0 (0.3) b	60.1 (6.9) a
glufo + glyph + aceto fb. glufo + glyph	97 a	86 abcd	100 a	100 a	38 (21) d	0 b	65.6 (5.7) a
glufo + glyph fb. glufo + glyph + aceto	97 a	90 abc	100 a	100 a	40 (39) d	0 b	63.5 (7.2) a
glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	90 abc	100 a	100 a	5 (3.9) d	0 b	55.8 (7.7) a
2 lf fb. 6-8 lf fb 12 lf							
glyph fb. glyph fb. glyph	94 a	100 a	100 a	100 a	0 d	0 b	66.2 (7.9) a

Table 2.6 (cont'd)

glyph fb. glyph + aceto fb. glyph	89 ab	100 a	100 a	100 a	0 d	0 b	63.5 (6.2) a
dicam + glyph fb. glufo fb. glyph	98 a	100 a	100 a	100 a	0 (0.3) d	0 b	64.0 (6.7) a
glufo fb. glufo fb glyph	79 bc	98 ab	100 a	100 a	0 d	0 b	65.6 (6.8) a
glufo fb. glufo + aceto fb. glyph	74 c	98 ab	100 a	100 a	0 d	0 b	66.6 (5.7) a
clopy + glyph fb. clopy + glyph + aceto fb. glyph	97 a	100 a	100 a	100 a	0 d	0 b	62.1 (6.7) a
Untreated	0 d	0 f	0 b	0 b	850 (106) a	826 (34) a	28.8 (5.6) b

[a] Herbicide programs can be found in Table 2.2.
[b] Means followed by the same letter within a column are not statistically different at $a \leq 0.05$.
[c] Mid-season ratings were taken 14 d after the 6-8 leaf application.
[d] At harvest evaluations were taken just prior to sugarbeet harvest.
[e] PRE = preemergence; fb. = followed by; lf = sugarbeet leaf stage; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid.
[f] Numbers in (SE) are the standard errors of the mean.

Table 2.7. Common lambsquarters, velvetleaf, and common purslane control at MSU-23 and MSU-24.

	Common lambsquarters		Velvetleaf		Common purslane	
	MSU-23/24		MSU-24		At harvest	
Herbicide program[a]	Mid-season[bc]	At harvest[d]	Mid-season	At harvest	MSU-23	MSU-24
PRE fb. 2 lf fb. 6-8 lf[e]	% control					
dicam fb. glyph fb. glufo	100 a	94 ab	99 a	91 a	30 cd	84 d
dicam fb. glyph + aceto fb. glufo	99 ab	98 ab	100 a	98 a	91 a	96 abc
dicam fb. glufo fb. glufo	99 ab	79 c	98 ab	93 a	39 c	89 bcd
dicam fb. glufo + aceto fb. glufo	100 a	94 ab	95 ab	90 a	86 a	98 ab
dicam fb. dicam + glyph fb. glufo	100 ab	100 a	100 a	98 a	65 b	95 abc
dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	99 a	99 ab	98 a	94 a	98 a
S-met fb. glyph + aceto fb. glyph + aceto	100 ab	100 ab	100 a	100 a	97 a	98 a
S-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	98 a	99 a	97 a	94 a	100 a
2 lf fb. 6-8 lf						
glufo fb. glufo	92 d	78 c	94 ab	78 b	19 d	88 cd
glufo + glyph fb. glufo + glyph	99 ab	90 b	100 a	93 a	24 cd	86 d
glufo + glyph + aceto fb. glufo + glyph	100 a	97 ab	100 a	93 a	90 a	95 abc
glufo + glyph fb. glufo + glyph + aceto	100 a	93 ab	100 a	100 a	91 a	97 abc
glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	97 ab	100 a	95 a	90 a	96 abc
2 lf fb. 6-8 lf fb 12 lf						
glyph fb. glyph fb. glyph	100 ab	100 a	99 a	100 a	81 a	99 a
glyph fb. glyph + aceto fb. glyph	100 a	100 a	100 a	100 a	93 a	98 ab

Table 2.7 (cont'd)

dicam + glyph fb. glufo fb. glyph	100 a	100 a	99 ab	100 a	88 a	88 cd
glufo fb. glufo fb glyph	97 bc	95 ab	94 ab	99 a	89 a	89 bcd
glufo fb. glufo + aceto fb. glyph	95 c	100 a	92 b	100 a	91 a	100 a
clopy + glyph fb. clopy + glyph + aceto fb. glyph	100 a	100 a	100 a	100 a	95 a	100 a
Untreated	0 e	0 d	0 c	0 b	0 e	0 e

[a] Herbicide programs can be found in Table 2.2.

[b] Means followed by the same letter within a column are not statistically different at $a \leq 0.05$.

[c] Mid-season ratings were taken 14 d after the 6-8 leaf application.

[d] At harvest evaluations were taken just prior to sugarbeet harvest.

[e] Abbreviations: PRE = preemergence; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid.

Table 2.8. GR horseweed control and biomass for the combined site-years of MSU-23 and MSU-24.

	MSU-23/24		
	Horseweed control		Horseweed biomass
Abbreviated herbicide programs[a]	Mid-season[bc]	At harvest[d]	At harvest
PRE fb. 2 lf fb. 6-8 lf[e]	——— % ———		— g m^{-2} —
dicam fb. glyph fb. glufo	99 a	96 a	2 (2.2)[f] d
dicam fb. glyph + aceto fb. glufo	100 a	99 a	0 (0) d
dicam fb. glufo fb. glufo	100 a	100 a	5 (4.9) d
dicam fb. glufo + aceto fb. glufo	100 a	100 a	0 (0) d
dicam fb. dicam + glyph fb. glufo	100 a	100 a	0 (0) d
dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	0 (0) d
S-met fb. glyph + aceto fb. glyph + aceto	99 a	98 a	27 (27) cd
S-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	0 (0) d
2 lf fb. 6-8 lf			
glufo fb. glufo	98 a	97 a	0 (0) d
glufo + glyph fb. glufo + glyph	100 a	99 a	1 (0.5) d
glufo + glyph + aceto fb. glufo + glyph	100 a	99 a	11 (9.9) d
glufo + glyph fb. glufo + glyph + aceto	100 a	98 a	0 d
glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	0 d
2 lf fb. 6-8 lf fb 12 lf			
glyph fb. glyph fb. glyph	27 c	16 b	107 (41) bc
glyph fb. glyph + aceto fb. glyph	56 b	14 b	129 (48) b
dicam + glyph fb. glufo fb. glyph	100 a	98 a	5 (5.4) d
glufo fb. glufo fb glyph	100 a	95 a	0 (0) d
glufo fb. glufo + aceto fb. glyph	100 a	100 a	0 (0) d
clopy + glyph fb. clopy + glyph + aceto fb. glyph[g]	99 a	99 a	1 (0.4) d
Untreated	0 d	0 c	249 (66) a

[a] Herbicide programs can be found in Table 2.2.
[b] Means followed by the same letter within a column are not statistically different at $a \leq 0.05$.
[c] Mid-season ratings were taken 14 d after the 6-8 leaf application.
[d] At harvest evaluations were taken just prior to sugarbeet harvest.

Table 2.8 (cont'd)

[e] Abbreviations: PRE = preemergence; fb. = followed by; lf = sugarbeet leaf stage; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid.

[f] Numbers in (SE) are the standard errors of the mean.

[g] Current strategy recommended for GR horseweed control.

Table 2.9. Annual grass control and weed biomass at MSU-23 and MSU-24 and sugarbeet yield at MSU-24.

	Annual grass control				Weed biomass[a]		Sugarbeet yield
	MSU-23		MSU-24				
Herbicide program[b]	Mid-Season[cd]	At harvest[e]	Mid-season	At harvest	MSU-23	MSU-24	MSU-24
PRE fb. 2 lf fb. 6-8 lf[f]	%				g m^{-2}		Mg ha^{-1}
dicam fb. glyph fb. glufo	98 a	93 a	91 a	58 ef	240 (58) a	148 (35) abc	51.7 (3.7)[g] cd
dicam fb. glyph + aceto fb. glufo	100 a	100 a	95 a	78 bcde	43 (14) c	57 (24) bcde	65.3 (2.6) abcd
dicam fb. glufo fb. glufo	100 a	98 a	95 a	68 def	193 (17) ab	67 (5.2) bcde	68.2(2.9) bcd
dicam fb. glufo + aceto fb. glufo	100 a	100 a	99 a	88 abcd	51 (24) c	96 (14) bcde	74.5 (6.4) bcd
dicam fb. dicam + glyph fb. glufo	100 a	98 a	93 a	50 f	78 (41) bc	146 (23) abcd	46.8 (2.9) d
dicam fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	99 a	87 abcd	7 (4.2) c	30 (13) cde	64.3 (4.5) bcd
S-met fb. glyph + aceto fb. glyph + aceto	100 a	100 a	100 a	99 a	4 (2.6) c	2 (1.5) e	80.7 (1.1) abc
S-met fb. glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	100 a	98 a	7 (5.5) c	4 (2.0) e	75.5 (4.5) abcd
2 lf fb. 6-8 lf							
glufo fb. glufo	98 a	96 a	100 a	68 cdef	259 (48) a	120 (16) bcd	64.7 (10) bcd
glufo + glyph fb. glufo + glyph	99 a	96 a	93 a	63 ef	223 (53) a	155 (69) ab	67.1 (1.6) abcd
glufo + glyph + aceto fb. glufo + glyph	100 a	98 a	96 a	77 bcde	10 (4.9) c	58 (9.9) bcde	80.6 (9.1) abc
glufo + glyph fb. glufo + glyph + aceto	100 a	100 a	99 a	87 abcd	11 (7.3) c	17 (6.1) cde	81.2 (4.9) abc
glufo + glyph + aceto fb. glufo + glyph + aceto	100 a	100 a	100 a	90 abc	9 (4.4) c	28 (6.9) cde	79.3 (5.7) abcd
2 lf fb. 6-8 lf fb 12 lf							
glyph fb. glyph fb. glyph	100 a	100 a	99 a	100 a	24 (8.6) c	1 (0.8) e	87.7 (7.3) ab

Table 2.9 (cont'd)

glyph fb. glyph + aceto fb. glyph	100 a	100 a	100 a	99 a	6 (2.5) c	0 (0.3) e	84.4 (7.9) abc
dicam + glyph fb. glufo fb. glyph	100 a	100 a	95 a	91 ab	27 (19) c	7 (3.2) e	86.9 (4.3) ab
glufo fb. glufo fb glyph	100 a	96 a	94 a	89 abc	34 (9.3) c	20 (8.6) cde	81.8 (5.3) abc
glufo fb. glufo + aceto fb. glyph	98 a	100 a	90 a	100 a	12 (5.0) c	0 e	97.9 (0.6) a
clopy + glyph fb. clopy + glyph + aceto fb. glyph	100 a	100 a	100 a	100 a	12 (6.6) c	1 (1.0) e	84.6 (4.0) ab
Untreated	0 b	0 b	0 b	0 g	224 (58) a	269 (81) a	14.3 (5.3) e

[a] Weed biomass includes annual grass, velvetleaf, and common purslane, but excludes horseweed.
[b] Herbicide programs can be found in Table 2.2.
[c] Means followed by the same letter within a column are not statistically different at $a \leq 0.05$.
[d] Mid-season ratings were taken 14 d after the 6-8 leaf application.
[e] At harvest evaluations were taken just prior to sugarbeet harvest.
[f] Abbreviations: PRE = preemergence; dicam = dicamba; glyph = glyphosate; glufo = glufosinate; aceto = acetochlor; *S*-met = *S*-metolachlor; clopy = clopyralid.
[g] Numbers in (SE) are the standard errors of the mean.

CHAPTER III: DEVELOPING SOYBEAN DESICCATION STRATEGIES IN THE NORTHERN U.S.

Abstract

The longer frost-free seasons in the northern U.S. has allowed soybean growers to pair early planting with longer maturity group (MG) soybeans for increased yield potential. However, harvest of longer MG soybean may occur later into the fall which could result in harvest delays and potential yield losses. Field research was conducted over four site-years in Michigan to evaluate two preharvest desiccation timings (early, label) of the harvest aids paraquat, saflufenacil, and sodium chlorate on typical and late MG soybeans for soybean desiccation, yield, seed quality, and seed dry down. Following the early application (R6.5), paraquat and sodium chlorate soybean desiccation was between 60-73%, 3 d after treatment (DAT), which was 26 and 19% greater than the nontreated control. However, by 14 DAT differences between paraquat and sodium chlorate desiccated soybean compared with nontreated soybean were only 5% in three of four site-years. Paraquat applied at the label timing improved soybean desiccation between 9-3% from 3-7 DAT compared with nontreated soybean. Depending on location, by 10-14 DAT all soybeans were at 95% desiccation or greater. Saflufenacil was not effective at desiccating soybean compared with paraquat and sodium chlorate. An early application of harvest aids (prior to R6.5) reduced soybean yield by 9%. Additionally, at one location yield was reduced up to 8% from applications of paraquat and sodium chlorate. Reductions in soybean yield were a function of reduced seed weight, since seed number was already set by the time applications were made. Early applications of paraquat reduced seed moisture to 20% sooner than nontreated soybean in 2024. However, paraquat did not effectively reduce seed moisture at either application timing in 2023. While paraquat and sodium chlorate desiccated soybean

quicker, potential yield losses from harvest aid applications nullifies advantages of harvest aid applications for quicker soybean harvestability in the northern U.S.

Introduction

In recent years, warmer spring temperatures have shifted optimal soybean seed planting dates 8 to 10 d earlier across the northern U.S. (Mourtzinis et al. 2019). Additional climate research indicates that the frost-free season in the Great Lakes region has increased by 16 d from 1951 to 2017 (GLISA 2019). As a result of a lengthening growing season, current strategies for maximizing yield recommend coupling earlier soybean planting dates with longer maturing varieties (Siler and Singh 2022).

Despite the potential for higher yields from earlier planting, growers continue to struggle with end of season management and delayed soybean harvest from variable fall weather. The Great Lakes region experienced a 13.6% increase in total annual precipitation since 1951, plus a 35% increase in severe storm intensity (GLISA 2019). Early spring planting of longer maturity group (MG) soybeans can still result in a later fall harvest, which can lead to harvest delays, soybean yield loss, and impact the timeliness of winter wheat planting, a common rotational crop planted following soybean harvest. Yield losses from delayed harvest can cause up to a 13.9% reduction in soybean yield compared with the optimal time for soybean harvest (Philbrook and Oplinger 1989). Furthermore, soybean yield losses can increase by 0.2% per day delayed. Additionally, winter wheat yield losses of 17-21% have been reported in Michigan when winter wheat planting is delayed beyond mid-October (Copeland et al. 2023). Developing strategies that will optimize soybean yields, minimize harvest delays while allowing adequate time for winter wheat planting would increase farm productivity across the Northern U.S.

The application of harvest aids (also referred to as preharvest herbicides or desiccants) have traditionally been used to improve harvest efficiency and crop quality by desiccating uncontrolled weeds in soybean, cotton, and grain sorghum prior to harvest (Griffin et al. 2010). The presence of uncontrolled weeds at harvest can cause higher soybean seed moisture, delayed harvest, and increase foreign material in harvested in soybean (Ellis et al. 1998; Mcwhorter and Anderson 1993). Additionally, weeds that are still green when the soybean crop has matured can reduce harvest efficiency and increase wear on harvest equipment (Burnside 1973; Burnside et al. 1969; Griffin et al. 2010).

Harvest aid use in soybean has shifted in focus in the southeastern U.S. in recent years as a result of planting shorter MG soybean early, a strategy to avoid extreme high temperatures and drought stress during soybean reproductive stages (Heatherly and Elmore 2004; Mourtzinis and Conley 2017). In this system, harvest aids defoliate green leaves and promote uniform maturity across the field for improved harvest efficiency. Well-timed applications of harvest aids in soybean have been shown to reduce harvest date by as much as 15 d compared with soybean that were not treated with harvest aids (Boudreaux and Griffin 2011). The earlier harvest timing allowed growers to take advantage of higher market prices early in the season (Boudreaux and Griffin 2008). Harvest aids are also used in dry edible bean production in the northern U.S. and southern Canada to desiccate green crop tissue after plants have reached physiological maturity (Goffnett et al. 2016; Soltani et al. 2013). If the advantages of harvest aids for hastening soybean and dry edible bean maturity are also applicable to northern soybean production systems, it could be a strategy for improving end of season soybean management and harvest.

There are several herbicides labeled for use as a harvest aid in soybean. Of these, paraquat, saflufenacil, and sodium chlorate ($NaClO_3$) are perhaps the most intensively studied

(Bellaloui et al. 2022; Boudreaux and Griffin 2011; McNeal et al. 2024). These harvest aids differ in chemical composition and their activity within plants, resulting in differences in the speed and effectiveness of plant desiccation. Both paraquat and saflufenacil are cell membrane disrupters (WSSA Group 22 and 14, respectively) that rely on sunlight to form reactive oxygen species to rapidly desiccate plant tissue (Babbs et al. 1989; Grossmann et al. 2010). Specifically, paraquat applications can result in rapid foliar necrosis, and complete foliar desiccation within 3 d under ideal sunny conditions (Griffin et al. 2010). Sodium chlorate is a strong oxidizing agent that acts as a desiccant when applied at sufficient concentrations (Larson et al. 2005). While specific effectiveness of each of these herbicides can be affected by differences in environmental conditions, paraquat is generally considered the most effective at desiccating soybean (McNeal et al. 2024; Orlowski 2018; Whigham and Stoller 1979).

The application timing of a harvest aid is especially important. When applications were made during soybean seed pod fill when seed development is not complete, yield losses of 15% were reported in Louisiana and Illinois (Boudreaux and Griffin 2011; Whigham and Stoller 1979). Conversly, if applications are delayed, harvest aids may not meaningfully reduce the time to soybean maturity compared with non-desiccated soybean. The paraquat and saflufenacil labels state that applications should be made to indeterminate soybean varieties when 65% of pods have reached mature color or seed moisture has reached 30% for indeterminate soybean varieties (Anonymous 2021, 2022). The sodium chlorate label states that applications should be made 7 to 10 d before anticipated harvest, when soybean is mature (Anonymous 2024). Several studies propose that applications of harvest aids can be made earlier than defined in the labels without risk of soybean yield reduction (Boudreaux and Griffin 2011; Griffin et al. 2010; Ratnayake and Shaw 1992).

Soybean physiological maturity, defined as the time when dry matter accumulation in the seed has reached its peak, occurs between 50-60% seed moisture and corresponds to soybean growth stage R6.5-R7 (TeKrony et al. 1979). Visually, this can be observed when the white membrane inside the pod begins to separate from seeds on the four uppermost nodes of a plant (Griffin et al. 2010). Soybeans typically reach physiological maturity before reaching 65% mature pods, and research generally supports that harvest aid applications made at or immediately following physiological maturity will not reduce soybean yield (Boudreaux and Griffin 2011; Griffin et al. 2010; McNeal et al. 2024).

The use of harvest aids to hasten maturity and optimize harvest of later MG soybean has not been effectively investigated in the northern U.S. Additionally, the effect of harvest aid application timing with respect to soybean desiccation and potential yield reduction is unknown in this region. As growers continue to struggle with harvest delays from weather, options for promoting earlier soybean harvest need to be evaluated so that growers can avoid harvest losses and plant winter wheat on time. While harvest aids have been shown to decrease the time for soybean to reach harvestable maturity, the potential for significant yield loss and quality decline is high if applications are made at the incorrect timing and could negate any benefit from earlier harvest. Therefore, the objectives of this research were to 1) evaluate the effectiveness of paraquat, sodium chlorate, and saflufenacil on desiccation of typical and later MG soybean varieties at early (physiological maturity) and label defined application timings, 2) determine the effect of paraquat on soybean seed dry down compared, with non-desiccated soybean in late maturing varieties, and 3) determine the potential for soybean yield and quality losses from desiccated and non-desiccated soybean when harvest aids are applied at early and label application timings.

Materials and Methods

Field research was conducted at the Michigan State University (MSU) Agronomy Farm in East Lansing, Michigan in 2023 (MSU-23 = 42.709^o N, -84.473^o W) and 2024 (MSU-24 = 42.686^o N, -84.490^o W) and at the Saginaw Valley Research and Extension Center (SVREC) near Richville, Michigan in 2023 (SVREC-23 = 43.395^o N, 83.677^o W) and 2024 (SVREC-24 = 43.395^{o}N, 83.678^{o}W) for a total of four site-years. The soil type at MSU was a Conover loam (fine-loamy, mixed, active, mesic aquic hapludalfs) with a pH of 7.8 and organic matter of 2.6% in 2023 and pH of 5.4 and organic matter of 3.2% in 2024. The soil type at SVREC was a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic typic epiaquolls) with a pH of 7.5 and organic matter of 3.2% in 2023 and pH of 7.5 and organic matter of 2.5% in 2024. Each site-year was arranged in a split-split plot design with four replications. Each replication was divided into two randomized main plots (soybean MG). Each MG was divided into two randomized subplots (harvest aid application timing), and each harvest aid application timing was divided into four randomized sub-subplots (harvest aid product). Each plot measured 3 m wide by 10-12 m in length.

Fields were fall chisel plowed and spring soil finished twice prior to soybean planting in late April. Two varieties of glyphosate, glufosinate, and 2,4-D-resistant soybean (Enlist E3®, Corteva Agriscience, Indianapolis, IN) from two MGs, typical and late (typical + 1.0) for each location were planted on April 27 and 26 in 2023 and 2024, respectively. ‘P25A16E’ and ‘P35T15E’ (MG = 2.5 and 3.5) soybean were planted in 38-cm rows at 370,650 seeds ha^{-1} with a seven-row John Deere vacuum planter (John Deere, Moline, IL) at MSU. ‘P21A53E’ and ‘P31A73E’ (MG = 2.1 and 3.1) soybean were planted in 76-cm rows at 356,330 seeds ha^{-1} with a four-row John Deere MaxEmerge2 vacuum planter (John Deere, Moline, IL) at SVREC. The soybean seed treatment for all varieties included ipconazole + oxathiapiprolin + picoxystrobin (LumiTreo® Fungicide; Corteva Agriscience, Indianapolis, IN), fluopyram (ILEVO® Fungicide/Nematicide; BASF Corporation, Research Triangle Park, NC), metalaxyl (Sebring 480 FS®; Nufarm Americas Inc, Alsip, IL), *Bacillus amyloliquefaciens* strain MBI 600 + *Bacillus pumilus* strain BU F-33 (L-2030 G® Bio-Fungicide; BASF Corporation, Research Triangle Park, NC), imidacloprid (Gaucho® Insecticide; Bayer Crop Science, St. Louis, MO), and cyantraniliprole (Lumiderm®; Corteva Agriscience, Indianapolis, IN). Plots were kept weed-free with multiple postemergence applications of glyphosate (Roundup PowerMax 3; Bayer Crop Science, St. Louis, MO) at 1.25 kg ae ha^{-1} + ammonium sulfate (Sulf-N; Advansix Inc., Parsippany, NC) at 2% w w^{-1} tank-mixed with either glufosinate (Liberty 280 SL; BASF Corporation; Research Triangle Park, NC) at 0.65 kg ai ha^{-1} or 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.06 kg ae ha^{-1} when weeds were <5 cm tall.

Harvest aid applications were made at two different timings for each soybean MG: early (growth stage R6.5, when filled beans separate from the white membranes inside pods from the four uppermost nodes; Fehr and Caviness 1977), and at the label application timing (when 65% of pods were mature color or when seed moisture was 30% or less). Harvest aid application dates for each timing are listed in Table 3.1. Soybean growth stage was assessed for each soybean MG at the time of the harvest aid applications. The three harvest aid treatments examined were 1) paraquat (Gramoxone SL 3.0, Syngenta Crop Protection) at 0.28 kg ai ha^{-1} + 0.25% v v^{-1} non-ionic surfactant (Activator 90, Loveland Products Inc., Greely, CO), 2) saflufenacil (Sharpen, BASF Corp.) at 0.05 kg ai ha^{-1} + 1% v v^{-1} methylated seed oil (Hot-MES, Drexel Chemical Company, Memphis, TN) + 2% w w^{-1} ammonium sulfate (Sulf-N; Advansix Inc., Parsippany, NC), and 3) sodium chlorate (DeFol 5, Drexel Chemical Co.) at 6.72 kg ai ha^{-1} + 1% v v^{-1}

methylated seed oil. The treatments were compared with a nontreated control for each soybean MG. Treatments were applied using a tractor mounted $C0_2$ sprayer calibrated to deliver 177 L ha^{-1} at 207 kPa of pressure using AIXR 11003 nozzles (TeeJet Spraying Systems Co., Wheaton, IL).

Soybean seed dry down. Additional plots of paraquat-desiccated and nontreated 'P35T15E' soybean were established at MSU in 2023 and 2024 to measure soybean seed moisture following early and label application.

Data Collection. Soybean desiccation was evaluated 3, 7, 10, and 14 d after treatment (DAT) on a scale from 0-100%, with 0 indicating all tissue was green, and 100 indicating complete plant desiccation. Once the nontreated controls for the later MG reached full-maturity, soybeans were harvested from the center 1.5 m with a small-plot research combine (Massey-Ferguson 8XP, AGCO, Duluth, GA). Soybean yields were adjusted to 13% moisture. Soybean seed subsamples were collected from each plot for further analysis.

Soybean seed subsamples were measured for 100 seed-weight (g), percent germination, protein, and oil content. Germination percentages were determined by planting 25 seeds in a 25 x 25 x 2.5 cm germination tray with a peat and perlite mixture (SureMix, Michigan Grower Products Inc., Galesburg, MI). Germinated plants were counted 14 d after planting. Greenhouse temperatures were set at 25+/-5°C, with an 18-hour photoperiod. Soybean seed protein and oil content were measured using near infrared reflectance spectroscopy (NIRS, Model DS2500, Foss, Eden Prairie, MN).

To measure soybean seed dry down, seed moisture was recorded beginning 1 DAT from the additional paraquat and non-desiccated plots by sampling seed from a 1 m section from the middle three rows. Soybeans were sampled every 2-3 d until soybeans from the nontreated controls reached 13% moisture. Soybean seed moisture was determined by placing 100 g of fresh weight soybean seed in a 100° C oven for 72 h. Dry seed samples were then immediately weighed to determine moisture content at sampling (Equation 1).

$$seed\ moisture\ \% = \frac{fresh\ weight - dry\ weight}{fresh\ weight} * 100 \quad [1]$$

Maximum and minimum air temperature and precipitation data were retrieved from the nearest Michigan Automated Weather Network for each trial location during desiccation and harvest operations (September 1-November 1, https://mawn.geo.msu.edu/, Michigan State University, East Lansing, MI) (Figures 3.1 and 3.2).

Statistical Analysis. Soybean desiccation, yield, seed weight, germination, and protein and oil content were analyzed using ANOVA in R v. 4.3.1 using linear mixed effects models (lmer) (R Core Team 2024). Differences in means were tested using Tukey's HSD post hoc tests in the EMMEANS package in R using an $\alpha \leq 0.05$ (Lenth 2023).

For soybean desiccation evaluations, soybean MG and harvest aid were considered fixed effects. Due to differences in soybean maturity between application timings, desiccation evaluations were analyzed separately for the early and label applications. Due to an earlier than R6.5 application timing at SVREC-23 for the later MG soybean, this site-year was analyzed separately with replication considered a random effect. Since applications at MSU-23, MSU-24, and SVREC-24 were made at the R6.5 application timing, these site-years were combined, and site-year and replication were considered random effects.

For soybean yield, seed weight, germination, protein, and oil, soybean MG, application time, and harvest aid were considered fixed effects. Due to differences in yield at SVREC-23 and MSU-24 these site-years were each analyzed separately, and replication was considered a random effect. MSU-23 and SVREC-23 were combined, and replication and site-year were considered random effects.

When interactions were not significant data was combined over main effects. Normality and unequal variance assumptions were verified by examining normality histograms, side-by-side box plots of the residuals, and normality probability plots.

Soybean seed moisture was regressed over time with a three parameter, log-logistic model (LL.3) (Equation 2) to assess seed dry down using the drc package in R v. 4.3.1 (R Core Team 2024). This model was selected by the mselect function lack of fit test, followed by inspections of estimates and standard errors associated with the estimates.

$$y = \frac{d}{1 + \exp\left(b(\log(x) - \log(e))\right)} \qquad [2]$$

In the model, *y* is the average soybean moisture, *d* is the upper limit, *x* is the number of days after the early application, *b* is the slope, and *e* is the inflection point (Ritz et al. 2015). The time to reach 20 and 13% moisture between paraquat desiccated and non-desiccated soybean was determined using the ED function for each application timing. The EDcomp function was used to determine differences in time between treatments using a t-statistic ($a \leq 0.05$).

Results and Discussion

Soybean Desiccation. At SVREC-23, harvest aids were applied to the late MG before reaching the target growth stage of R6.5 for the early application. This resulted in lower overall soybean desiccation in the late MG following the early application at SVREC-23. Additionally, at the label application, harvest aids were applied after the typical MG reached growth stage R8 (full maturity). This resulted in higher overall soybean desiccation in the typical MG following the label application at SVREC-23. As a result, desiccation evaluations from SVREC-23 were analyzed separately. For the other three site-years (MSU-23, MSU-24, and SVREC-24) harvest aid applications were made at the appropriate targeted growth stages and there was not a site-year interaction for soybean desiccation, so these site-years were combined and will be referred to hereafter as MSU/SVREC-24.

Following the early application (R6.5) at MSU/SVREC-24, only the main effects of soybean MG and harvest aid were significant (Table 3.2). Soybean desiccation, 7-14 DAT, resulted in 4-6% greater desiccation for the typical MG soybean compared with the late MG (Table 3.3). Additionally, paraquat and sodium chlorate applications resulted in greater soybean desiccation compared with nontreated soybean following the early application, 3-14 DAT. At 3 DAT, paraquat or sodium chlorate resulted in 73 and 72% soybean desiccation, respectively, compared with 53% maturity for the nontreated soybean. Similarly, by 7 DAT, desiccation was greatest with paraquat (90%) and sodium chlorate (87%) which was 14% greater than the nontreated control. Total desiccation (98% or greater) was reached with early applications of paraquat and sodium chlorate by 14 DAT, when the nontreated soybean were still at 93% maturity. Soybean treated with saflufenacil was not different than the non-desiccated soybean between 3-10 DAT (Table 3.3). The effectiveness of paraquat over other harvest aids has been well documented (McNeal et al. 2024; Orlowski 2018; Whigham and Stoller 1979). McNeal et al. (2024) reported that while sodium chlorate and paraquat defoliated soybean similarly, paraquat was more effective at desiccating green soybean tissue. While differences between defoliation and desiccation at MSU/SVREC-24 were not separately evaluated, paraquat and sodium chlorate were shown to provide similar desiccation 3-14 DAT. Interestingly, Goffnett et al. (2016) found that applications of paraquat and saflufenacil provided similar levels of desiccation in dry edible bean. In this study applications of saflufenacil provided significantly lower desiccation compared with paraquat.

Following the label application at MSU/SVREC-24, the main effects of MG and harvest aid on soybean desiccation were significant 3 and 7 DAT. However, there was an interaction between MG and harvest aid 10 DAT (Table 3.2). Desiccation for the typical MG soybean was 10 and 3% greater than the late MG, 3 and 7 DAT, respectively (Table 3.3). Similar to the early application timing, paraquat and sodium chlorate provided greater soybean desiccation (91% or greater) than saflufenacil (88%) and nontreated (85%) soybeans 3 DAT (Table 3.3). At 7 DAT, all harvest aids provided similar soybean desiccation. However, paraquat (98%) was the only harvest aid significantly greater than the nontreated soybean (95%). By 10 DAT, soybean desiccation was 98% or greater for all harvest aids including the non-desiccated control (Table 3.3).

At MSU/SVREC-24 following the label application, paraquat was the only harvest aid that significantly improved desiccation compared with the nontreated (Table 3.3). Notably, the improvement in desiccation from the label application was lower in comparison to when harvest aids were applied at the early application, indicating that there may be less benefit for increasing soybean desiccation from applying harvest aids at the recommended label timing.

Several studies advocate that the paraquat and sodium chlorate labels are open to interpretation, and since reasonable crop safety exists once soybeans reach physiological maturity, applications can be made earlier than defined in the label (Boudreaux and Griffin 2011; Griffin et al. 2010). These studies argue that the label application timing for paraquat and sodium chlorate are written solely to eliminate potential for yield loss and there is increased benefit of applying desiccants earlier, while still allowing for crop safety. In this study, earlier application of harvest aid products was more effective at desiccating soybean compared with the label timing. Future research efforts would need to investigate application times that meaningfully improve soybean desiccation but do not reduce yield or increase harvest aid residue in harvested soybean across a wide range of conditions.

At SVREC-23, following the early application, the main effects of soybean MG and harvest aid were significant for soybean desiccation 3 DAT, while there were interactions between soybean MG and harvest aid 7-14 DAT (Table 3.2). At 3 DAT, averaged across harvest aid, soybean desiccation for the typical and late soybean MGs were 75 and 25%, respectively (Figure 3.3a). Similar to desiccation at MSU/SVREC-24, desiccation 3 DAT at SVREC-23 averaged across soybean MG was greatest with paraquat (61%) and sodium chlorate (60%) treated soybean and there was no difference between soybean desiccated with saflufenacil (46%) and the nontreated (35%) (Figure 3.3b).

At 7 DAT, when there was an interaction between soybean MG and harvest aid for the early application timing (Table 3.2), there was no difference between harvest aids for the typical MG (Table 3.4). However, when the harvest aids were applied earlier than R6.5 for the late MG, paraquat provided the greatest soybean desiccation (73%) followed by sodium chlorate (55%). At this time the non-desiccated control was only at 11% maturity. By 10 DAT, regardless of harvest aid, all soybeans within the typical MG were at least 98% desiccated. Within the late MG, soybean desiccation was 89 and 83% from paraquat and sodium chlorate, respectively, which was 45% greater than the nontreated control. By 14 DAT, desiccation for the late MG was 93 and 91% from paraquat and sodium chlorate which was at least 20% greater than the nontreated control, respectively, and significantly better than saflufenacil (80%).

At SVREC-23 following harvest aid applications at the label timing, there was an interaction between soybean MG and harvest aid 3 and 7 DAT (Table 3.2). Since harvest aids were applied to the typical MG after reaching the R8 growth stage, soybean were 100%

desiccated regardless of harvest aid beginning 3 DAT (Table 3.4). For the late MG, all three harvest aids provided similar desiccation 86-92%, 3 DAT. Paraquat (92%) and sodium chlorate (90%) were the only harvest aids that were different from the nontreated control (83%). By 7 DAT, paraquat (94%) was the only harvest aid within the late MG with greater soybean desiccation than the nontreated control. By 14 DAT, all soybean, regardless of soybean MG or harvest aid, were at 99% or greater desiccation.

Despite differences in application timings and lower overall soybean desiccation at SVREC-23, the three harvest aids evaluated followed similar trends compared with the MSU/SVREC-24 site-year. In general, paraquat and sodium chlorate significantly improved soybean desiccation compared with saflufenacil, with differences varying in overall desiccation depending on specific d after harvest aid application. While this study did not separately evaluate soybean defoliation compared with soybean desiccation as described in McNeal et al. (2024), the effectiveness of paraquat and sodium chlorate cannot be reasonably differentiated from each other in this study.

Soybean Yield and Seed Quality. In two (MSU-23 and SVREC-24) of the four site-years, there was no significant difference in soybean yield from soybean MG, application time, or harvest aid (Table 3.5). These two site-years were combined for the analysis of soybean yield, seed weight, seed germination, and oil and protein content and will be referred to as MSU-23/SVREC-24. At MSU-24 and SVREC-23, there was a significant interaction between soybean MG and harvest aid on soybean yield (Table 3.5). Additionally, at SVREC-23, there was a significant interaction between soybean MG and application timing. As a result of these interactions, SVREC-23 and MSU-24 were each analyzed separately for soybean yield, seed weight, seed germination, and oil and protein content.

There was no difference in soybean yield for any main effect or interaction at MSU-23/SVREC-24 and average soybean yield was 5294 kg ha^{-1} (Table 3.6). Among the seed quality measurements taken, differences were strictly dictated by soybean variety, and only the main effect of soybean MG was significant (Table 3.5). Soybean seed quality aspects are determined by both soybean variety (genotype) and specific responses to environmental conditions and stresses (Brummer et al. 1997; MacMillan and Gulden 2020; Rotundo and Westgate 2009; Yaklich 1985). In the absence of significant stress, it is expected that varietal differences would be present. As a result, soybean seed weight, germination, and oil and protein content were significantly lower in the late MG compared with the typical MG at MSU-23/SVREC-24 (Table 3.6).

At SVREC-23, the interaction between soybean MG and application timing was significant for soybean yield (Table 3.5). The early application timing for the late MG was at R6.0, slightly before the R6.5 targeted application timing. This resulted in a 9 and 12% reduction in soybean yield compared with the label application timing for the late MG and the typical MG within the early timing, respectively (Figure 3.4). For the interaction between soybean MG and harvest aid at SVREC-23, there was no difference in yield between harvest aids within each respective MG. Typical MG soybeans desiccated with saflufenacil yielded 4618 kg ha^{-1}, which was 14% or more than late MG soybean desiccated with paraquat (3826 kg ha^{-1}), saflufenacil (3972 kg ha^{-1}), and sodium chlorate (4042 kg ha^{-1}) (Table 3.8). Soybeans from the typical MG that were desiccated with paraquat yielded 4398 kg ha^{-1}, which was 15% more than soybean from the late MG desiccated with paraquat, which yielded 3826 kg ha^{-1}.

There was an interaction between MG, application timing, and harvest aid for soybean seed weight at SVREC-23 (Table 3.5). Soybean seed weight was similar for the typical MG for the different application timings of the harvest aid products, which is consistent with no differences in soybean yield (Table 3.9). However, soybean seed weight was 11% lower when paraquat was applied early (R6) compared with the nontreated control for the late MG soybean. Similarly, seed weight was reduced by 15% when sodium chlorate was applied at early compared with the nontreated control. All three harvest aids significantly reduced seed weight by at least 11% when they were applied to the late MG at R6 as compared with the typical MG. When harvest aids were applied at the label timing to the late MG there was no difference in soybean seed weight.

Only the main effect of soybean MG was significant for soybean germination and oil content at SVREC-23 (Table 3.5). The main effects of soybean MG and harvest aid were significant for soybean protein. Similar to MSU-23/SVREC-24, soybean germination and seed oil content were all lower in the late MG compared with the typical MG (Table 3.7). However, protein content was lower in the typical MG compared with the late MG. While this contradicts the results observed at MSU-23/SVREC-24, protein and oil content are typically inversely related to each other (Brummer et al. 1997; Mourtzinis et al. 2017). Additionally, soybean protein averaged across application time and soybean maturity was also higher in soybean treated with saflufenacil (37.6%) compared with the nontreated soybean (37.1%).

There was a significant interaction between soybean MG and harvest aid for soybean yield at MSU-24 (Table 3.5). Soybean yield for the typical MG was not affected by harvest aid (Table 3.8). However, soybean yield for the late MG was reduced by 8 and 7% from applications of paraquat and sodium chlorate, respectively, compared with the nontreated soybean. Soybean seed weight was affected by a soybean MG and application time interaction (Table 3.5). Seed weight was at least 5% lower for the late MG compared with the typical MG for both application timings (Figure 3.5). The early harvest aid application resulted in a 4% reduction in seed weight compared with the label application timing for late MG soybean. Similar to MSU-23/SVREC-24 and SVREC-23, only the main effect of soybean MG was significant for soybean oil and protein content (Table 3.5). Soybean oil content was 21.5% in late MG soybean, significantly higher than in the early MG which was 20.2% (Table 3.10). Conversely, soybean protein was 40.3% in the typical MG, compared with 37.6% in the late MG. This inverse relationship between protein and oil content was also noted at SVREC-23.

Yield reductions from harvest aid applications have been widely reported when applications are made before soybean reaches physiological maturity (R6.5). Boudreaux and Griffin (2011) reported an average yield reduction of 15.4% when harvest aids were applied to soybean at 60% seed moisture, once soybean reached 50% seed moisture no yield losses were recorded. Whigham and Stoller (1979) also found that soybean yield was reduced when paraquat applications were made 3-4 weeks before estimated harvest, but did not report yield losses when harvest aids were applied once soybeans reached physiological maturity. Additionally, Goffnett et al. (2016) reported up to 55% yield loss in dry edible bean when harvest aids were applied early, when pods were 50% yellow. In contrast, Bellaloui et al. (2022) reported yield losses when soybean were desiccated with paraquat up until soybean reached the R7 growth stage.

Reduced seed weight is closely associated with yield reductions observed from harvest aid applications (Bellaloui et al. 2022; Boudreaux and Griffin 2011; Ratnayake and Shaw 1992). Since seed number is usually already determined by the time harvest aid application occurs, yield reductions from harvest aid applications occur as a function of reduced seed weight (Bellaloui et al. 2022). Boudreaux and Griffin (2011) reported a 12.4% reduction in seed weight when harvest aids were applied at 60% seed moisture. Similarly, seed weight was reduced up to 15% when sodium chlorate was applied to R6 soybean at SVREC-23. Additionally, at MSU-24 a 9 and 5% reduction in seed weight was recorded when desiccants were applied to soybean at the early and label application timings, respectively. This further supports the conclusion that harvest aid application was responsible for the yield reduction observed in the late MG, even though applications were made at the correct timing. For the two combined site-years, seed weight was solely influenced by soybean maturity, reinforcing the conclusion that no negative impacts on yield were recorded from harvest aid application at MSU-23 and SVREC-24.

Previous research agrees that the 9-12% yield reduction recorded at SVREC-23 was a result of harvest aid application being made too early. However, the yield losses observed at MSU-24 regardless of application timing, more closely support the conclusions of Bellaloui et al. (2022) where yield losses are possible through soybean stage R7, compared with those of Boudreaux and Griffin (2011).

The results from this study reaffirm that the timing of when dry matter accumulation in soybean seed ceases (physiological maturity) remains somewhat unclear, with arguments supporting anywhere from 50-60% seed moisture. Likely, seed moisture at physiological maturity differs between soybean cultivars and regions, and seed moisture sampling will need to be conducted to adequately understand true moisture at physiological maturity for different soybean varieties. Regardless, yield reductions observed across application timing could indicate that soybean physiological maturity occurs later in soybean growth and development, or that physiological maturity is not an indication that soybean can be desiccated without reducing yield. Additionally, environmental differences between site-years could be responsible for the differences in yield response to harvest aid application observed in this study, as yield at MSU-23 and SVREC-24 was not reduced following desiccation.

Differences in soybean germination, oil, and protein were primarily caused by differences between soybean maturity (variety) across site-years, and differences between these quality aspects caused by harvest aids were generally not detectable. This contrasts with Bellaloui et al. (2020) who reported increased protein and oil content following the application of harvest aids. While others have reported decreases in seed oil content when harvest aid applications were made 3-4 weeks before harvest (Whigham and Stoller 1979). In the current study, the only instance where harvest aid affected protein or oil content was at SVREC-23, where soybean desiccated with saflufenacil had significantly higher protein compared with the nontreated soybeans.

Applications of harvest aids at R6 will reduce soybean yield compared with nontreated soybean. Additionally, while applications of paraquat and sodium chlorate were generally the most effective at desiccating soybean, these products also have the potential to reduce yield, regardless of application timing as observed at MSU-24.

Soybean Seed Dry Down. All soybean marketing is based on a moisture content of 13%, which ensures stability of the crop for short term storage (de Alencar and D'Antonino Faroni 2011). In Michigan, depending on grain elevator, soybean above 18-21% moisture are subject to load rejection (Musgrove Grain 2024; Zeeland Farm Services 2024). At MSU-23 and MSU-24, seed samples were compared between paraquat-desiccated and nontreated soybean for the time to reach 20% (maximum marketable moisture) and 13% (optimal) moisture.

In 2023, there was no significant difference in the time to reach 20% and 13% moisture between paraquat desiccated and nontreated soybean at either application timing (Table 3.11 and Figure 3.6). Averaged across desiccated and nontreated soybean, seed reached 20% moisture on November 2 for both application times. Soybean reached 13% moisture on November 8 for the early and label applications, averaged across desiccated and nontreated soybean in 2023. In 2024 following the early application, paraquat-desiccated soybean reached 20% moisture 2 d before nontreated soybean. Soybean reached 13% moisture on October 7 for paraquat desiccated soybean and on October 8 for nontreated soybean. There was no significant difference between paraquat and nontreated soybean to reach 13% moisture following the early application or to reach 20% and 13% moisture following the label application in 2024. Soybean moisture reached 20% moisture on October 6 following the label application. Averaged across application timings and paraquat and nontreated soybean reached 13% moisture on October 8 in 2024.

Seed dry down is primarily determined by weather conditions as soybean plants mature. Low relative humidity and higher temperatures increase the rate of seed dry down via physical evaporation from the seed surface (Kiesselbach and Walker 1952; Martinez-Feria et al. 2019). During ideal conditions, soybean lose roughly 3% moisture per day (Ciampitti and Sittel 2024; Martinez-Feria et al. 2019). Notably, harvest aid applications occurred earlier in the fall in 2024 compared with 2023, which was the result of a warm and dry weather pattern preceding and following harvest aid applications in 2024. These weather conditions resulted in less time for soybean to reach 20 and 13% moisture compared with 2023, which was cool and wet (Figure 3.1 and Figure 3.2).

Following paraquat application, seed moisture was generally not meaningfully reduced compared with the nontreated control. Only following the early application in 2024 did paraquat desiccated soybean reach 20% moisture faster than the nontreated. Interestingly, following the label application, while not significantly different, nontreated soybean moisture did appear lower than soybean moisture following paraquat application. The results from this study indicate that paraquat applications do not consistently improve the rate of soybean seed dry down compared with nontreated soybean and may inhibit normal seed dry down to a limited extent.

In conclusion, paraquat and sodium chlorate were the most effective harvest aids when applied at the early application timing. At the label timing, differences in desiccation between desiccated and nontreated soybean were generally smaller, and paraquat was the most consistent at improving desiccation across evaluations and site-years. While harvest aids did improve soybean desiccation, this did not necessarily correspond to differences in measured seed moisture between paraquat desiccated and nontreated soybean. Time to reach 20 and 13% moisture was only significantly quicker in paraquat treated soybean following the early application in 2024. At this application timing, paraquat only gave a 2 d advantage over nontreated soybean. Harvest aids did not reduce yield in two of four site-years, however at MSU-24 and SVREC-23, yield was reduced from applications of paraquat and sodium chlorate. At, SVREC-23 yield was reduced by 9% from desiccant applications made to the late MG at R6. Yield losses up to 8% were recorded in the late MG at MSU-24, regardless of application timing. In both cases yield losses were a function of reduced seed weight, with harvest aids generally not affecting soybean germination, oil, and protein. Harvest aids were not able to improve soybean seed dry down by a significant margin to justify application purely for improving soybean desiccation, especially when factoring in the risk of yield reduction. Based on the research provided, to justify application of a harvest aid, a factor that would cause significant harvesting issues would need to be present, such as high weed populations at harvest. For harvest aids to have a significant impact on improving soybean production in the Northern U.S., further research will need to address specific application times with respect to the harvest aid labels. Research investigating application times should focus on specific soybean moisture at application and should not rely purely on visual soybean stage evaluation.

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APPENDIX A: CHAPTER III TABLES

Table 3.1. Planting, harvest aid application, and soybean harvest dates for the four site-years of this research in 2023 and 2024. Harvest aid applications were based on early (soybean growth stage R6.5) and label timings for the individual typical and late maturity groups (MG)[a].

Operation	MSU-23[b]	MSU-24	SVREC-23	SVREC-24
Planting	April 27	April 26	April 26	April 26
Typical MG - early application	September 25	September 16	September 21	September 3
Typical MG - label application	October 10	September 20	October 3	September 12
Late MG - early application	October 10	September 20	September 21	September 16
Late MG - label application	October 17	October 1	October 3	September 19
Harvest	November 1	October 8	October 18	October 3

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.
[b] Abbreviations: MSU = Michigan State University (East Lansing, MI); SVREC = Saginaw Valley Research and Extension Center (Richville, MI).

Table 3.2. P-values for soybean desiccation 3, 7, 10, and 14 d after harvest aid applications (DAT) to typical and later maturity group (MG) soybeans[a] applied early (soybean stage = R6.5) and at label timings. Due to differences in application timing, SVREC-23 was analyzed separately from the combined MSU-23, MSU-24, and SVREC-24 site-years.

	Early application timing (R6.5)				Label application timing		
Effects	3 DAT	7 DAT	10 DAT	14 DAT	3 DAT	7 DAT	10 DAT
MSU/SVREC-24	*p-values*				*p-values*		
Soybean MG	0.4588	<0.0001	0.0001	<0.0001	<0.0001	0.0002	0.0626
Harvest aid	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0424	0.0002
MG*Harvest aid	0.9142	0.8500	0.8877	0.2392	0.1180	0.6946	<0.0001
SVREC-23							
Soybean MG	<0.0001	<0.0001	<0.0001	<0.0001	0.0196	0.0443	0.1781[b]
Harvest aid	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0399
MG*Harvest aid	0.2428	<0.0001	<0.0001	<0.0001	0.0196	0.0443	0.1781

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.
[b] There was no 10 DAT evaluation at SVREC-23, p-values are from the 14 DAT evaluation.

Table 3.3. Soybean desiccation 3, 7, 10, and 14 d after harvest aid applications (DAT) to typical and later maturity group (MG) soybeans[a] applied early (soybean = R6.5) and at label timings for the combined site-year of MSU-23, MSU-24, and SVREC-24.

	Early application timing (R6.5)				Label application timing		
Main effects	3 DAT[b]	7 DAT	10 DAT	14 DAT	3 DAT	7 DAT	10 DAT[c]
Soybean MG	% desiccation				% desiccation		
Typical	65 (2.6)[d]	85 (1.5) a	93 (1.0) a	98 (0.4) a	94 (0.8) a	98 (0.4) a	99 (0.2)
Late	63 (2.1)	79 (1.5) b	87 (1.2) b	94 (0.9) b	84 (0.9) b	95 (0.7) b	98 (0.4)
Harvest aid							
paraquat	73 (3.7) a	90 (1.3) a	96 (0.9) a	99 (0.4) a	92 (1.2) a	98 (0.5) a	100 (0)
saflufenacil	58 (3.8) b	78 (1.8) b	88 (1.5) bc	96 (1.0) b	88 (1.5) b	97 (0.8) ab	100 (0.3)
sodium chlorate	72 (3.7) a	87 (1.0) a	93 (0.8) ab	98 (0.5) ab	91 (1.2) a	97 (0.7) ab	99 (0.4)
nontreated	53 (4.8) b	73 (2.6) b	84 (2.1) c	93 (1.5) c	85 (2.0) c	95 (1.2) b	98 (0.8)

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.

[b] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).

[c] The interaction between MG and harvest aid was significant for the label application 10 DAT at the three combined site-years. All MG*harvest aid combinations were similar (99% desiccated or greater) except for the nontreated late MG soybean which was 95%.

[d] Numbers within parenthesis represent standard errors.

Table 3.4. Soybean desiccation 3, 7, 10, and 14 d after harvest aid applications (DAT) to typical and later maturity group (MG) soybeans[a] applied early (soybean = R6) and at label timings for SVREC-23.

		Early application timing (R6)			Label application timing		
Soybean MG	Harvest aid	7 DAT[bc]	10 DAT	14 DAT	3 DAT	7 DAT	14 DAT[d]
		% desiccation			% desiccation		
Typical	paraquat	96 (2.1)[e] a	98 (0.7) a	100 (0) a	100 (0) a	100 (0) a	100
	saflufenacil	93 (1.8) ab	98 (1.2) a	100 (0) a	100 (0) a	100 (0) a	100
	sodium chlorate	98 (1.4) a	100 (0.5) a	100 (0) a	100 (0) a	100 (0) a	100
	nontreated	85 (3.1) b	98 (1.2) a	100 (0) a	100 (0) a	100 (0) a	100
Late	paraquat	73 (2.5) c	89 (1.3) ab	93 (2.2) ab	92 (2.0) b	94 (1.7) b	100
	saflufenacil	29 (2.4) e	71 (5.5) c	80 (2.2) c	86 (2.7) bc	90 (2.4) bc	99
	sodium chlorate	55 (5.4) d	83 (4.3) bc	91 (4.1) b	90 (2.4) b	92 (2.0) bc	100
	nontreated	11 (1.3) f	38 (2.6) d	71 (2.4) d	83 (3.2) c	88 (1.9) c	99

[a] The typical and late maturity groups for SVREC are 2.1 and 3.1.
[b] The interaction between soybean MG and harvest aid was not significant 3 DAT. The main effects for soybean MG and harvest aid are presented Figure 3.3.
[c] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).
[d] Only the main effect of soybean MG was significant 14 DAT of the label application. Desiccation was 99 and 100% for the late and typical MG.
[e] Numbers within parenthesis represent standard errors.

Table 3.5. P-values for soybean yield, seed weight, germination, and oil and protein content for the main effects and interactions for soybean maturity group (MG)[a], application time, and harvest aid. Due to differences in yield SVREC-23 and MSU-24 were analyzed separately from the combined MSU-23/SVREC-24 site-years.

Effects	Yield[b]	Seed weight	Germination	Oil	Protein
MSU-23/SVREC-24			*p-values*		
Soybean MG	0.6556	<0.0001	0.0038	<0.0001	0.0038
Application time	0.2336	0.2760	0.6767	0.3442	0.7846
Harvest aid	0.7510	0.8244	0.5314	0.6147	0.6047
MG*Time	0.4147	0.3062	0.1048	0.2274	0.5672
MG*Harvest aid	0.9980	0.8337	0.0515	0.8676	0.9185
Time*Harvest aid	0.9859	0.8926	0.0957	0.9238	0.9431
MG*Time*Harvest aid	0.7799	0.8544	0.6494	0.7433	0.8769
SVREC-23					
Soybean MG	<0.0001	<0.0001	<0.0001	<0.0001	0.0010
Application time	0.0058	0.0015	0.5042	0.1317	0.1820
Harvest aid	0.1105	0.0521	0.5895	0.7633	0.0464
MG*Time	0.0279	0.0012	0.2188	0.6092	0.1975
MG*Harvest aid	0.0182	0.0260	0.5735	0.2826	0.1305
Time*Harvest aid	0.6231	0.4508	0.5793	0.4232	0.1917
MG*Time*Harvest aid	0.5510	0.0043	0.2614	0.5173	0.3136
MSU-24					
Soybean MG	0.1639	<0.0001	0.2749	<0.0001	<0.0001
Application time	0.2073	0.0140	0.8752	0.4650	0.5795
Harvest aid	0.0054	0.3613	0.2137	0.9196	0.6485
MG*Time	0.2472	0.0264	0.8752	0.1475	0.5851
MG*Harvest aid	0.0058	0.5711	0.2307	0.7364	0.0801
Time*Harvest aid	0.7855	0.1833	0.4882	0.7509	0.3737
MG*Time*Harvest aid	0.9851	0.7422	0.2307	0.2901	0.4278

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.
[b] Interactions and main effects were deemed significant if the P-value $\leq$0.05.

Table 3.6. Main effects of soybean maturity group (MG)[a], application time, and harvest aid on soybean yield, seed weight, germination, and oil and protein content for the combined site-years of MSU-23/SVREC-24.

Main effects	Yield	Seed weight[b]	Germination	Oil	Protein
Soybean MG	— $kg\ ha^{-1}$ —	– $g\ 100\text{-}seeds^{-1}$ –		— % —	
Typical	5382 (74)[c]	17.5 (0.12) a	78.4 (2.0) a	21.7 (0.09) a	36.9 (0.13) a
Late	5208 (96)	16.4 (0.12) b	73.9 (2.9) b	21.3 (0.01) b	36.1 (0.39) b
Application time					
Early	5297 (83)	16.9 (0.14)	76.1 (2.4)	21.5 (0.08)	36.5 (0.30)
Label	5289 (91)	17.0 (0.14)	76.2 (2.6)	21.4 (0.07)	36.5 (0.29)
Harvest aid					
paraquat	5202 (116)	17.0 (0.19)	74.2 (4.1)	21.4 (0.11)	36.7 (0.40)
saflufenacil	5312 (132)	16.9 (0.20)	78.6 (3.5)	21.6 (0.13)	36.3 (0.38)
sodium chlorate	5333 (116)	16.9 (0.17)	74.5 (3.7)	21.5 (0.09)	36.7 (0.48)
nontreated	5329 (129)	17.1 (0.21)	77.6 (3.0)	21.5 (0.11)	36.4 (0.45)

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.
[b] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).
[c] Numbers within parenthesis represent standard errors.

Table 3.7. Main effects of soybean MG[a], application time, and harvest aid on soybean yield, seed weight, germination, and oil and protein content at SVREC-23.

Main effects	Yield[b]	Seed weight[c]	Germination[d]	Oil	Protein
Soybean MG	— $kg\ ha^{-1}$ —	– $g\ 100\text{-}seeds^{-1}$ –		%	
Typical	4396	17.1	84.0 (1.6)[e] a	21.6 (0.06) a	37.1 (0.10) b
Late	4039	15.4	63.0 (2.7) b	20.3 (0.05) b	37.6 (0.12) a
Application time					
Early	4105	15.9	74.4 (2.6)	20.9 (0.14)	37.5 (0.15)
Label	4330	16.5	72.6 (3.0)	21.0 (0.13)	37.3 (0.09)
Harvest aid					
paraquat	4112	16.1	72.2 (3.6)	20.9 (0.21)	37.4 (0.15) ab
saflufenacil	4295	16.3	71.5 (3.9)	21.0 (0.16)	37.6 (0.18) a
sodium chlorate	4130	16.0	76.1 (4.8)	20.9 (0.21)	37.4 (0.18) ab
nontreated	4333	15.6	74.2 (3.5)	21.0 (0.20)	37.1 (0.14) b

[a] The typical and late maturity groups for SVREC are 2.1 and 3.1, respectively.
[b] The interactions of soybean MG*application time and soybean MG*harvest aid for soybean yield are presented in Figure 3.4 and Table 3.8, respectively.
[c] The interaction between soybean MG*application time*harvest aid was significant and is presented in Table 3.9.
[d] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).
[e] Numbers within parenthesis represent standard errors.

Table 3.8. Interaction between soybean maturity group (MG)[a] and harvest aid for soybean yield at SVREC-23 and MSU-24.

Maturity	Harvest aid	SVREC-23[b]	MSU-24
		kg ha^{-1}	
Typical	paraquat	4398 (69) ab	6613 (48)[c] ab
	saflufenacil	4618 (92) a	6315 (68) b
	sodium chlorate	4219 (211) abc	6468 (85) b
	nontreated	4350 (114) ab	6581 (89) ab
Late	paraquat	3826 (150) c	6372 (79) b
	saflufenacil	3972 (114) bc	6637 (89) ab
	sodium chlorate	4042 (160) bc	6424 (152) b
	nontreated	4318 (67) abc	6935 (82) a

[a] The typical and late maturity groups for MSU are 2.5 and 3.5 and for SVREC are 2.1 and 3.1, respectively.

[b] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

[c] Numbers within parenthesis represent standard errors.

Table 3.9. Three-way interaction of soybean maturity group (MG)[a], application timing, and harvest aid on soybean seed weight at SVREC-23.

	Typical maturity group		Late maturity group	
Harvest aid	Early timing[b]	Label timing	Early timing	Label timing
	(g 100-seeds^{-1})			
paraquat	17.1 (0.36)[c] a	17.0 (0.38) a	14.4 (0.32) cd	15.8 (0.25) abc
saflufenacil	17.3 (0.34) a	17.2 (0.35) a	14.9 (0.38) bcd	15.7 (0.44) abc
sodium chlorate	17.3 (0.37) a	16.7 (0.61) a	13.8 (0.13) d	16.1 (0.25) ab
nontreated	16.7 (0.58) a	17.3 (0.60) a	16.2 (0.38) ab	16.1 (0.30) ab

[a] The typical and late maturity groups for SVREC are 2.1 and 3.1.

[b] Means followed by the same letter are not statistically different ($\alpha \leq 0.05$).

[c] Numbers within parenthesis represent standard errors.

Table 3.10. Main effects of soybean maturity group (MG)[a], application time, and harvest aid on soybean yield, seed weight, germination, and oil and protein content at MSU-24.

Main effects	Yield[b]	Seed weight[c]	Germination	Oil[d]	Protein
Soybean MG	— kg ha^{-1} —	– g 100-seeds^{-1} –		%	
Typical	6494	18.7	97 (0.7)[e]	20.2 (0.03) b	40.3 (0.08) a
Late	6589	17.4	98 (0.4)	21.5 (0.04) a	37.6 (0.08) b
Application time					
Early	6498	17.9	98 (0.6)	20.8 (0.13)	39.0 (0.26)
Label	6585	18.3	98 (0.6)	20.8 (0.11)	38.9 (0.25)
Harvest aid					
paraquat	6486	18.1	96 (0.2)	20.8 (0.19)	39.0 (0.41)
saflufenacil	6476	18.0	99 (0.2)	20.9 (0.17)	39.0 (0.30)
sodium chlorate	6446	18.0	98 (0.2)	20.8 (0.17)	38.8 (0.30)
nontreated	6758	18.3	98 (0.2)	20.8 (0.18)	38.9 (0.40)

[a] The typical and late maturity groups for MSU are 2.5 and 3.5.
[b] The interaction of soybean MG*harvest aid were significant for soybean yield and results are presented in Table 3.8.
[c] The interaction of soybean MG*application time was significant for seed weight and results are presented in Figure 3.5.
[d] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).
[e] Numbers within parenthesis represent standard errors.

Table 3.11. Days after early application to 20% and 13% seed moisture in paraquat and nontreated late MG soybeans following the early and label application timings at MSU-23 and MSU-24.

		MSU-23[a]		MSU-24[b]	
Application time	Harvest aid	Time to 20% moisture	Time to 13% moisture	Time to 20% moisture	Time to 13% moisture
		——— d after early application ———			
Early					
	paraquat	22 (1.18)[c]	29 (1.86)	14 (0.34) a[d]	17 (0.52)
	nontreated	23 (1.15)	29 (1.82)	16 (0.32) b	18 (0.47)
Label					
	paraquat	23 (1.03)	29 (1.85)	16 (0.35)	18 (0.46)
	nontreated	22 (1.10)	28 (2.05)	15 (0.39)	17 (0.55)

[a] Early application was made on October 10 at MSU-23.
[b] Early application was made on September 20 at MSU-24.
[c] Numbers within parenthesis represent standard errors
[d] Estimates followed by the same letter within an application timing and column are not statistically different ($\alpha \leq 0.05$).

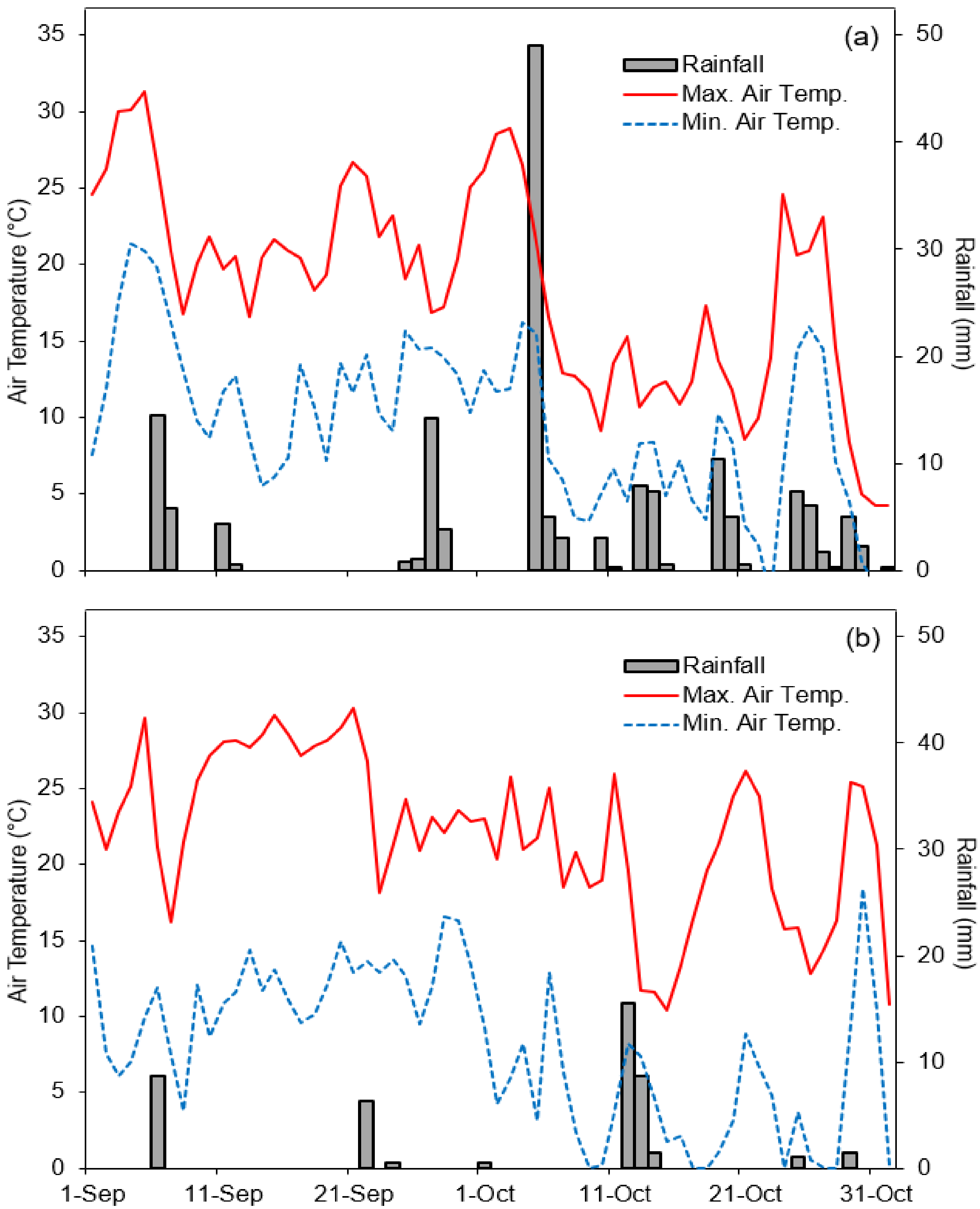

Figure 3.1. Minimum and maximum air temperatures and rainfall from September 1 through November 1 at (a) MSU-23 and (b) MSU-24.

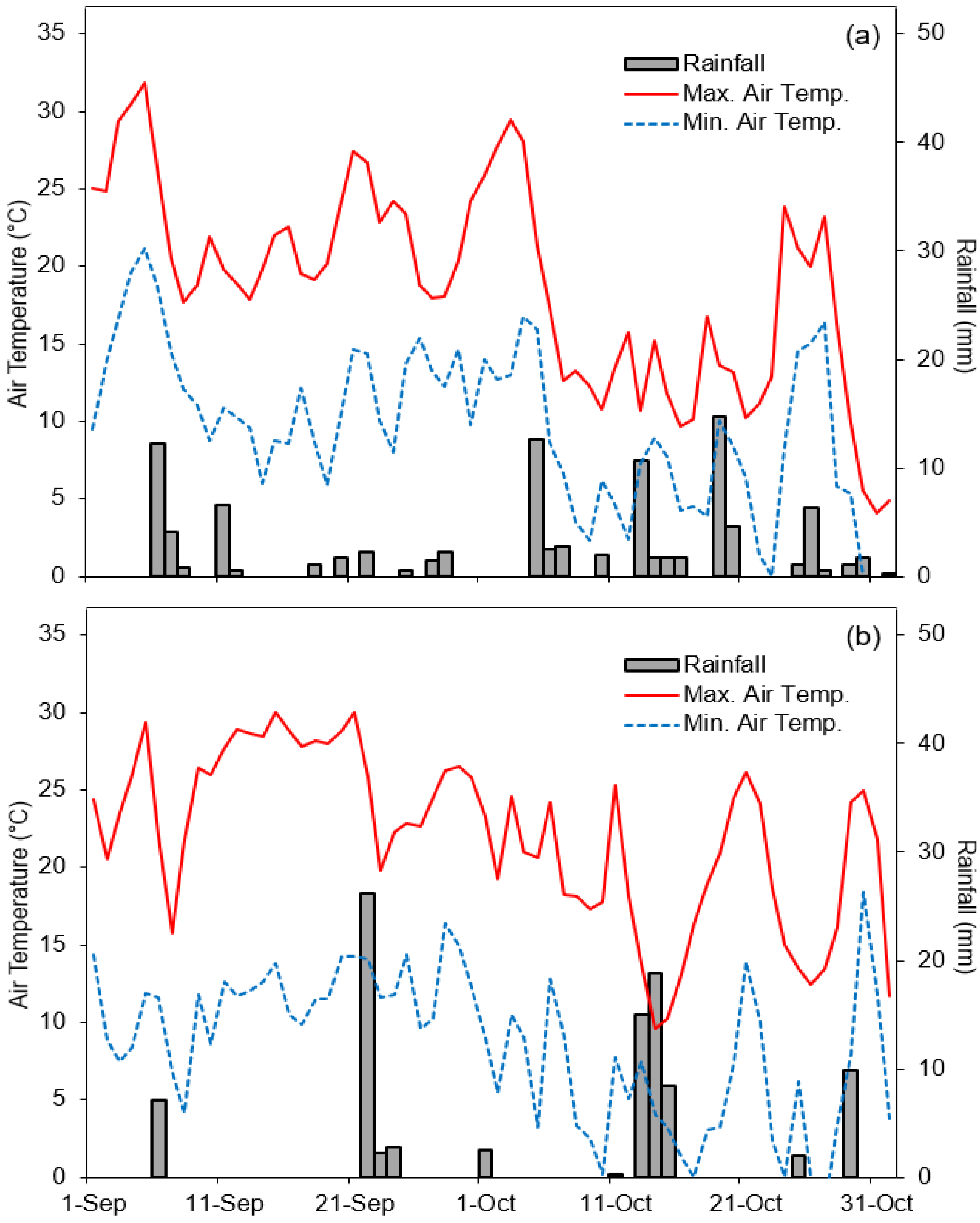

Figure 3.2. Minimum and maximum air temperatures and rainfall from September 1 through November 1 at (a) SVREC-23 and (b) SVREC-24.

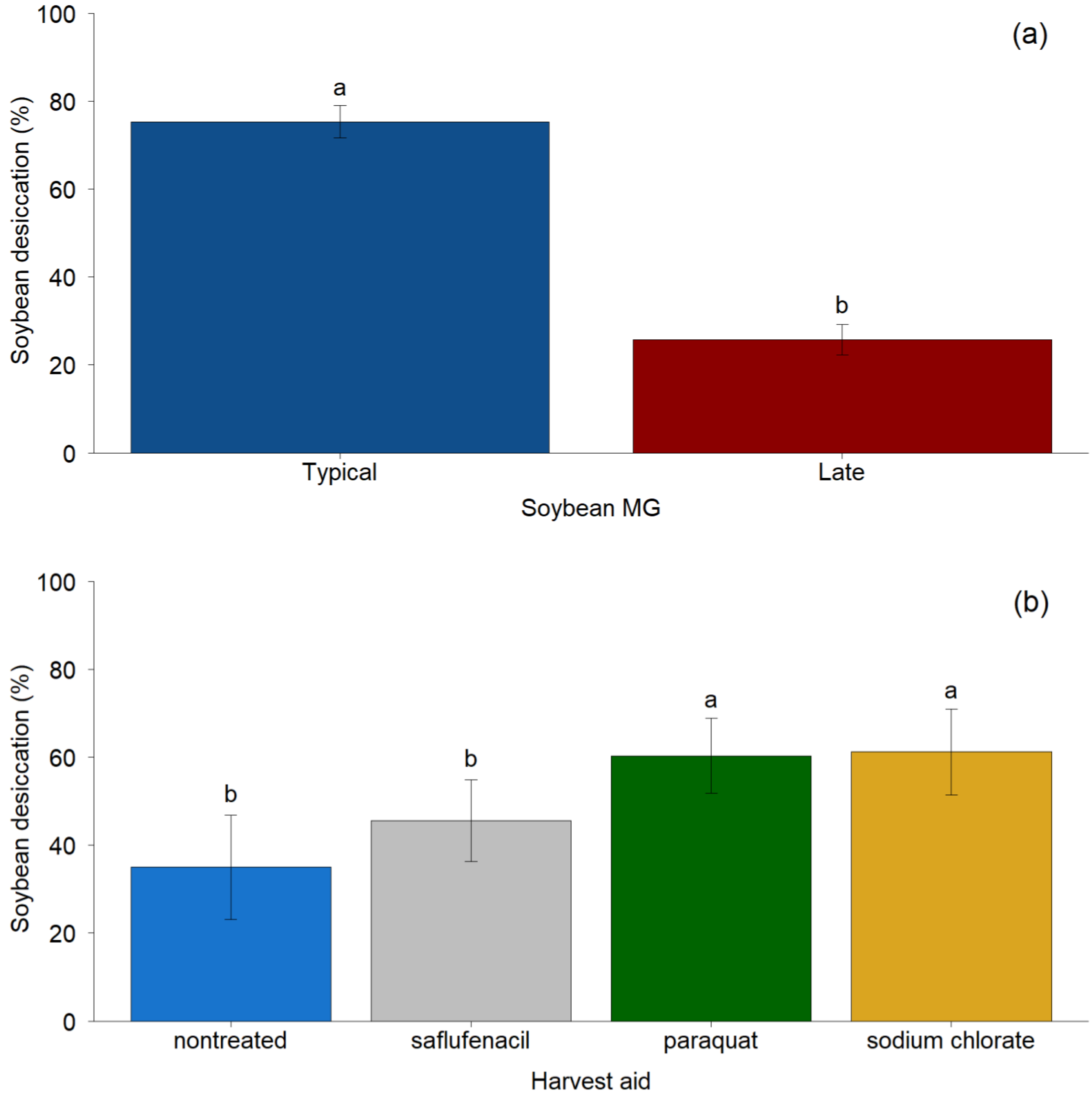

Figure 3.3. Main effects of (a) soybean maturity group (MG) and (b) harvest aid for soybean desiccation following the early application at SVREC-23, 3 d after treatment. The typical and late MG for SVREC are 2.1 and 3.1.

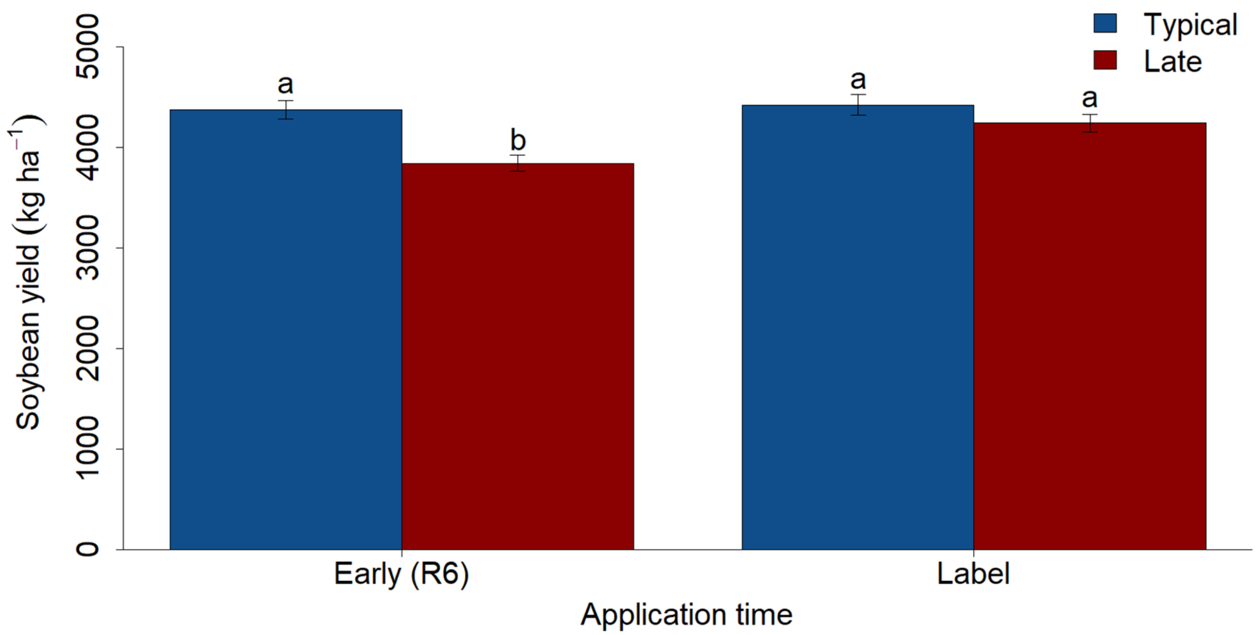

Figure 3.4. Interaction of soybean maturity group (MG) and application time for soybean yield at SVREC-23. Soybean varieties were ‘P21A53E’ (typical) and ‘P31A73E’ (late).

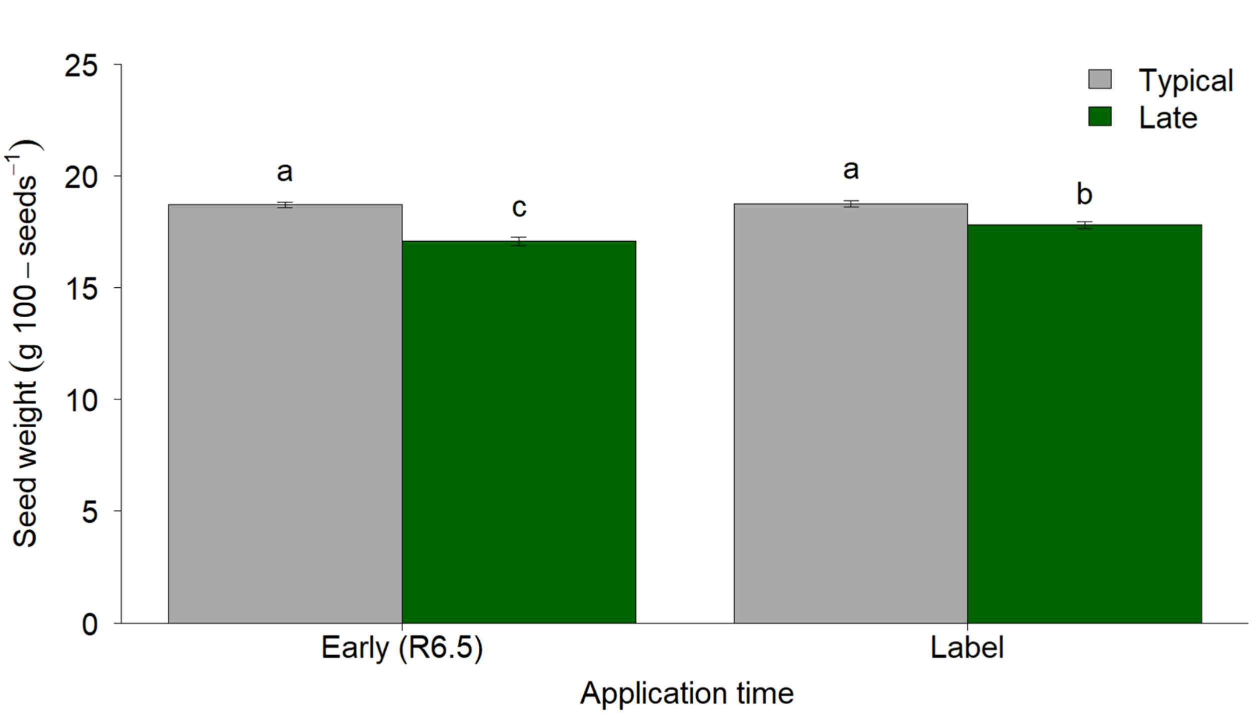

Figure 3.5. Interaction of soybean maturity group (MG) and application time on seed weight at MSU-24. Soybean varieties were 'P25A16E' (typical) and 'P35T15E' (late).

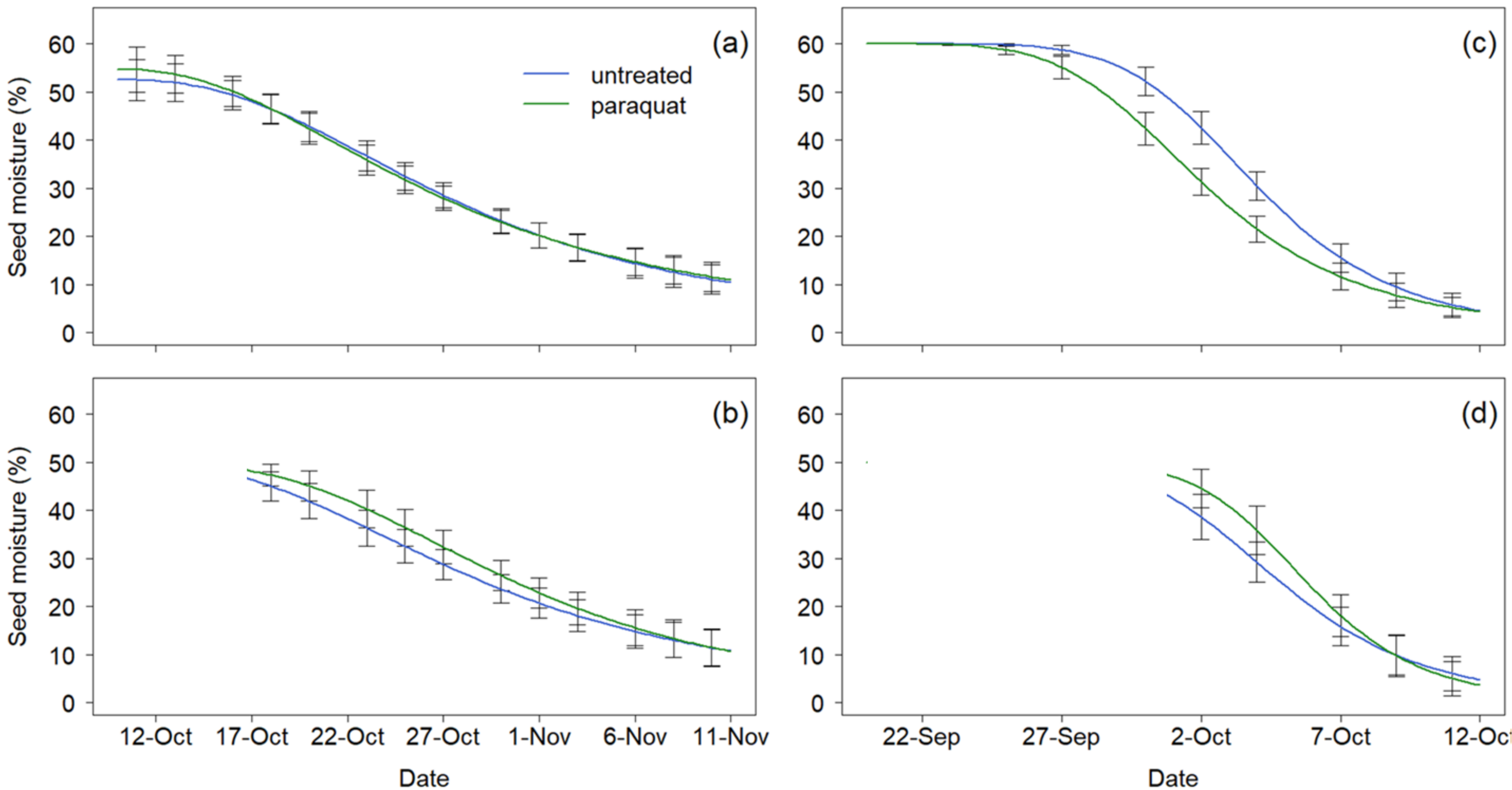

Figure 3.6. Soybean seed moisture from the late maturity group (MG) following paraquat desiccation compared with nontreated soybean at the (a) early and (b) label application timings at MSU-23, and (c) early and (d) label application timings at MSU-24. The soybean variety was 'P35T15E' (late).

APPENDIX B: INFLUENCE OF DELAYED HARVEST ON SOYBEAN YIELD AND QUALITY

Introduction

Changing weather patterns across the Northern U.S. have provided both opportunities and challenges for soybean growers. Since 1951, the frost-free season in the Great Lakes region has increased by 16 days (GLISA 2019). This has shifted soybean planting date recommendations 8-10 d earlier in the spring for optimized yields (Mourtzinis et al. 2019). The shift in planting dates has coincided with the opportunity to plant longer maturing soybean varieties (maturity groups, MG), a +1.0 increase in MG has been reported to increase yield by an average of 521 kg ha^{-1} (Siler and Singh 2022).

Planting longer MG soybean can push harvest later into the season, and harvest can be delayed from variable fall weather patterns. Additionally, larger farm sizes and mechanical failure can impede timely soybean harvest. Delayed soybean harvest has historically been associated with yield and quality reduction from preharvest shatter, stem breakage, lodging, and seed weathering. Philbrook and Oplinger (1989) reported that soybean harvest losses decreased at a rate of 0.2% d^{-1}, from 6.1% at optimal harvest to 13.9% when harvest was delayed by 42 d. Seed quality and composition deterioration has also been reported in weathered and diseased soybean seed (Dao and Ram 1996; Jaureguy et al. 2013; Wilcox et al. 1974). Delayed soybean harvest can also prevent timely winter wheat planting, if winter wheat planting is delayed beyond the beginning of October in Michigan, yield reductions can occur (Copeland et al. 2023).

Currently studies have not assessed the impact of delayed harvest on modern soybean varieties that have improved agronomic traits from modern breeding technologies (Childs et al. 2018; Zhang et al. 2015). Therefore, the objectives of this study were to provide an updated assessment of soybean yield loss and seed quality and composition decline as a result of delayed harvest across multiple MG in early planted modern soybean varieties. In turn, this information can provide growers with useful information regarding end of season management of soybean and provide more clarity on how planting date and soybean MG affect harvest timing.

Material and Methods

Field research was conducted at the Michigan State University (MSU) Agronomy Farm in East Lansing, Michigan in 2023 (MSU-23 = 42.709° N, -84.473° W) and 2024 (MSU-24 = 42.686° N, -84.490° W) and at the Saginaw Valley Research and Extension Center (SVREC) near Richville, Michigan in 2023 (SVREC-23 = 43.395° N, 83.677° W) and 2024 (SVREC-24 = 43.395°N, 83.678°W) for a total of four site-years. The soil type at MSU was a Conover loam (fine-loamy, mixed, active, mesic aquic hapludalfs) with a pH of 7.8 and organic matter of 2.6% in 2023 and pH of 5.4 and organic matter of 3.2% in 2024. The soil type at SVREC was a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic typic epiaquolls) with a pH of 7.5 and organic matter of 3.2% in 2023 and pH of 7.5 and organic matter of 2.5% in 2024. The MSU-23 site-year was arranged in a split-plot design with four replications. The SVREC-23, SVREC-24, and MSU-24 site-years were arranged in a split-plot design with six replications. Each replication was divided into two randomized main plots (soybean MG). Each MG was divided into four randomized subplots (harvest timing). Each plot measured 3 m wide by 10-12 m in length.

Fields were fall chisel plowed followed by spring soil finished twice prior to soybean planting in late April. Two varieties of glyphosate, glufosinate, and 2,4-D-resistant soybean (Enlist E3®, Corteva Agriscience, Indianapolis, IN) from two MGs typical and late (typical, +1.0) for each location were planted on April 27 and 26 in 2023 and 2024, respectively.

‘P25A16E’ and ‘P35T15E’ (MG = 2.5 and 3.5) soybean were planted in 38-cm rows at 370,650 seeds ha^{-1} with a seven-row John Deere vacuum planter (John Deere, Moline, IL) at MSU. ‘P21A53E’ and ‘P31A73E’ (MG = 2.1 and 3.1) soybean were planted in 76-cm rows at 356,330 seeds ha^{-1} with a four-row John Deere MaxEmerge2 vacuum planter (John Deere, Moline, IL) at SVREC. The soybean seed treatment for all varieties included ipconazole + oxathiapiprolin + picoxystrobin (LumiTreo® Fungicide; Corteva Agriscience, Indianapolis, IN), fluopyram (ILEVO® Fungicide/Nematicide; BASF Corporation, Research Triangle Park, NC), metalaxyl (Sebring 480 FS®; Nufarm Americas Inc, Alsip, IL), *Bacillus amyloliquefaciens* strain MBI 600 + *Bacillus pumilus* strain BU F-33 (L-2030 G® Bio-Fungicide; BASF Corporation, Research Triangle Park, NC), imidacloprid (Gaucho® Insecticide; Bayer Crop Science, St. Louis, MO), and cyantraniliprole (Lumiderm®; Corteva Agriscience, Indianapolis, IN). Plots were kept weed-free with multiple postemergence applications of glyphosate (Roundup PowerMax 3; Bayer Crop Science, St. Louis, MO) at 1.25 kg ae ha^{-1} + ammonium sulfate (Sulf-N; Advansix Inc., Parsippany, NC) at 2% w w^{-1} tank-mixed with either glufosinate (Liberty 280 SL; BASF Corporation; Research Triangle Park, NC) at 0.65 kg ai ha^{-1} or 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.06 kg ae ha^{-1}. Herbicide applications were made when weeds were <5 cm tall 2-4 times during the season as needed to maintain weed-free conditions until soybean canopy closure.

Soybean harvest times occurred at optimal soybean harvest (5-7 d after reaching R8 growth stage) followed by delayed harvest timings that targeted 1, 3, and 6 weeks after the optimal harvest timings. In 2023, harvest timings were dictated by overall soybean maturity in the late MG for both locations, and typical and late MG at each location were harvested on the same date for each harvest timing. In 2024, soybean harvest timings were based off the overall maturity for each individual MG for each location, so harvest timings occurred on different dates between MG. Weather conditions and mechanical issues impacted the true harvest date at MSU-24 for the typical and late MG and at SVREC-24 for the late MG. At MSU-24 the 3- and 6-week delayed harvest for the typical MG occurred approximately 2 and 5 weeks after the optimal, respectively, as a result of mechanical issues (Table 4.1). Additionally, the 3- and 6-week harvest of the late MG was delayed by wet field conditions to approximately 4 and 9 weeks at MSU-24, respectively. At SVREC-24, the 3-week harvest of the late MG was delayed to 4 weeks due to weather conditions.

Data Collection. At both locations, soybean were harvested from the center 1.5 m with a small-plot research combine, soybean moisture was recorded and yields are reported at an adjusted moisture of 13% (MSU combine, Kincaid 8XP; Kincaid Equipment Manufacturing, Haven, KS) (SVREC combine, Massey-Ferguson 8XP; AGCO, Duluth, GA). Immediately following each harvest, harvest losses were measured by counting soybean seeds remaining on the ground from 4 randomly placed 0.25 m^2 quadrats per plot.

Soybean seed subsamples were collected from each plot at harvest and measured for 100 seed-weight (g), percent germination, and protein and oil content. Germination percentages were determined by planting 25 seeds in a 25 x 25 x 2.5 cm germination tray with a peat and perlite mixture (SureMix, Michigan Grower Products Inc., Galesburg, MI), germinated plants were counted 14 d after planting. Greenhouse temperatures were set at 25+/-5°C, with an 18-hour photoperiod. Soybean seed protein and oil content were measured using near infrared reflectance spectroscopy (NIRS, Model DS2500, Foss, Eden Prairie, MN).

Statistical Analysis. All data were analyzed in R v. 4.3.1 using linear mixed effects models (lmer) (R Core Team 2024). In the statistical model, soybean MG and harvest time and their interactions were considered fixed effects. Replication was considered a random effect. All four site-years were analyzed separately. Normality and unequal variance assumptions were verified by examining normality histograms and probability plots and side-by-side box plots of the residuals. Differences in means were separated using Tukey's HSD in the EMMEANS package in R at an $\alpha \leq 0.05$ (Lenth 2023).

Table 4.1. Planting and harvest dates for the four site-years of this research in 2023 and 2024. Harvest dates were based on an optimal, 1 week, 3 week, and 6 week delayed harvest for the typical and late maturity groups (MG)[a].

Operation	MSU-23[bc]	MSU-24[d]	SVREC-23	SVREC-24
Planting	April 27	April 26	April 26	April 26
Typical MG Harvest Time				
Optimal	October 24	October 2[e]	October 19	September 19
1 week delay	November 1	-	October 25	September 26
3 week delay	November 15	October 16	November 7	October 10
6 week delay	December 7	November 8	November 30	October 30
Late MG Harvest Time				
Optimal	October 24	October 8	October 19	October 3
1 week delay	November 1	October 16	October 25	October 10
3 week delay	November 15	November 8	November 7	October 30
6 week delay	December 7	December 3	November 30	November 13

[a] The typical and late maturity groups for MSU are MG = 2.5 and 3.5 and for SVREC are MG = 2.1 and 3.1, respectively.
[b] Abbreviations: MSU = Michigan State University (East Lansing, MI); SVREC = Saginaw Valley Research and Extension Center (Richville, MI).
[c] Harvest times at MSU-23 and SVREC-23 began for both MG when the late MG reached optimal harvest, delayed harvest timings occurred on the same date for both MG.
[d] Harvest times at MSU-24 and SVREC-24 were based off the optimal harvest for each individual MG.
[e] As the result of a harvest issue at MSU-24 there were only two delayed harvest times for the typical MG for this location.

Table 4.2. P-values for soybean yield, harvest loss counts, seed moisture at harvest, seed weight, germination, and oil and protein content for the main effects and interaction of soybean maturity group (MG)[a] and harvest time.

Effects	Yield[b]	Harvest loss	Seed weight	Seed moisture	Germination	Oil	Protein
MSU-23				*p-values*			
Soybean MG	0.0131	0.0088	0.0359	0.0002	0.4649	0.0057	<0.0001
Harvest time	0.1504	<0.0001	0.7413	<0.0001	0.0001	0.0592	0.0036
MG*Time	0.5265	0.0768	0.9457	0.0001	0.5871	0.1601	0.9075
MSU-24 Typical MG[c]							
Harvest time	0.2209	<0.0001	0.4808	0.5354	0.6772	0.0015	0.4182
MSU-24 Late MG							
Harvest time	0.0941	0.0009	0.1412	0.2199	0.0238	0.7131	0.4104
SVREC-23							
Soybean MG	0.0058	0.7499	<0.0001	0.6881	0.9248	<0.0001	0.0003
Harvest time	0.6160	0.9362	0.7265	0.0007	<0.0001	0.9396	0.0120
MG*Time	0.1340	0.0941	0.4085	0.8211	0.0012	0.7047	0.5786
SVREC-24							
Soybean MG	0.0002	0.5109	0.0001	<0.0001	0.7921	<0.0001	0.0037
Harvest time	0.0355	<0.0001	0.0135	<0.0001	0.0503	0.3144	0.0704
MG*Time	0.5674	0.0003	0.0973	<0.0001	0.7539	0.3092	0.3625

[a] The typical and late maturity groups for MSU are MG = 2.5 and 3.5 and for SVREC are MG = 2.1 and 3.1, respectively.
[b] Interactions and main effects were deemed significant if the P-value $\leq$0.05.
[c] The late and typical MG were analyzed separately at MSU-24 due to a harvest issue that resulted in only two delayed harvest timings for the typical MG.

Table 4.3. Main effects of soybean maturity group (MG)[a] and harvest time for yield, harvest loss, seed moisture, seed weight, germination, and oil and protein content at MSU-23.

Main effects	Yield[b]	Harvest loss	Seed weight	Seed moisture[c]	Germination	Oil	Protein
Soybean MG	— kg ha^{-1} —	— seeds m^{-2} —	– g 100-seeds^{-1} –	——— % ———			
Typical	5172 b	63 b	12.8	18.7	77	21.6 b	36.6 a
Late	5552 a	75 a	14.4	18.0	73	21.3 a	34.3 b
Harvest time							
Optimal	5087	41 c	13.7	18.3	84 a	21.5	36.1 a
1 week delay	5525	42 c	12.1	18.2	79 a	21.3	35.6 a
3 week delay	5478	75 b	10.1	18.2	91 a	21.6	35.7 a
6 week delay	5357	117 a	18.5	18.6	48 b	21.3	34.4 b

[a] The typical and late maturity groups for MSU are MG = 2.5 and 3.5.

[b] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).

[c] The interaction between soybean MG and harvest time was significant for seed moisture, interaction results are presented in Table 4.8.

Table 4.4. Main effect of harvest time for soybean yield, harvest loss, seed moisture, seed weight, germination, and oil and protein content at MSU-24 for the typical maturity group (MG)[a].

Main effects	Yield	Harvest loss[b]	Seed weight	Seed moisture	Germination	Oil	Protein
Harvest timing	— kg ha^{-1} —	— seeds m^{-2} —	– g 100-$seeds^{-1}$ –	——— % ———			
Optimal	6415	13 c	25.4	15.0	99	20.4 b	39.5
3 week delay	6520	16 b	26.5	14.4	98	20.5 b	39.5
6 week delay	6269	24 a	25.8	15.6	97	20.9 a	39.3

[a] The typical maturity group for MSU is 2.5.

[b] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

Table 4.5. Main effect of harvest time for soybean yield, harvest loss, seed moisture, seed weight, germination, and oil and protein content at MSU-24 for the late maturity group (MG)[a].

Main effects	Yield	Harvest loss[b]	Seed weight	Seed moisture	Germination	Oil	Protein
Harvest time	— $kg\ ha^{-1}$ —	— $seeds\ m^{-2}$ —	– $g\ 100\text{-}seeds^{-1}$ –	——	—— % ——		——
Optimal	6204	17 a	24.4	13.2	97 ab	21.8	37.0
1 week delay	6156	16 a	23.8	12.6	96 ab	21.7	37.3
3 week delay	6010	23 b	24.7	15.6	97 a	21.8	37.6
6 week delay	6636	22 b	26.7	15.7	89 b	21.7	37.5

[a] The late maturity group for MSU is 3.5.

[b] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

Table 4.6. Main effects of soybean maturity group (MG)[a] and harvest timing for yield, harvest loss, seed moisture, seed weight, germination, and oil and protein content at SVREC-23.

Main effects	Yield[b]	Harvest loss	Seed weight	Seed moisture	Germination[c]	Oil	Protein
Soybean MG	— $kg\ ha^{-1}$ —	— $seeds\ m^{-2}$ —	– $g\ 100\text{-}seeds^{-1}$ –		— % —		
Typical	4835 a	21	16.7 a	16.3	91	21.8 a	37.5 b
Late	4554 b	21	15.8 b	16.4	91	20.8 b	36.9 a
Harvest time							
Optimal	4779	22	16.4	17.5 a	89	21.4	37.0 ab
1 week delay	4615	21	16.2	14.8 b	98	21.3	37.6 a
3 week delay	4658	20	16.2	15.9 ab	93	21.3	37.2 ab
6 week delay	4727	21	16.3	17.2 a	85	21.3	36.9 b

[a] The typical and late maturity groups for SVREC are MG = 2.1 and 3.1, respectively.

[b] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).

[c] The interaction between soybean MG and harvest timing was significant for germination, interaction results are presented in Table 4.8.

Table 4.7. Main effects of soybean maturity group (MG)[a] and harvest time for yield, harvest loss, seed moisture, seed weight, germination, and oil and protein content at SVREC-24.

Main effects	Yield[b]	Harvest loss[c]	Seed weight	Seed moisture[d]	Germination	Oil	Protein
Soybean MG	— kg ha^{-1} —	— seeds m^{-2} —	– g 100-seeds^{-1} –		%		
Typical	5572 a	48	19.3 a	12.9	95	22.4 a	37.1 b
Late	5102 b	49	17.5 b	14.1	95	21.9 b	37.9 a
Harvest time							
Optimal	5326 ab	40	18.2 ab	11.5	97	22.1	37.1
1 week delay	5600 a	45	19.5 a	13.5	96	22.1	37.4
3 week delay	5326 ab	52	18.4 ab	12.6	95	22.3	37.4
6 week delay	5097 b	57	17.5 b	16.4	92	22.1	38.1

[a] The typical and late maturity groups for SVREC are MG = 2.1 and 3.1, respectively.

[b] Means followed by the same letter within each main effect in the same column are not statistically different ($\alpha \leq 0.05$).

[c] The interaction between soybean MG and harvest time was significant for harvest loss and seed moisture, interaction results are presented in Table 4.8.

Table 4.8. Interaction between soybean maturity group (MG)[a] and harvest time on seed moisture at MSU-24, germination at SVREC-23, and harvest loss and seed moisture at SVREC-24.

		MSU-23	SVREC-23	SVREC-24	
Maturity	Harvest time	Seed moisture[b]	Germination	Harvest loss	Seed moisture
		——— %	———	— seeds m^{-2} —	— % —
Typical	Optimal	11.1 bc	95 a	42 c	8.7 d
	1 week delay	11.4 bc	98 a	38 c	17.4 a
	3 week delay	10.1 c	93 ab	59 ab	10.4 c
	6 week delay	18.6 a	80 c	52 abc	15.1 b
Late	Optimal	16.4 a	83 bc	38 c	14.3 b
	1 week delay	12.8 b	98 a	52 abc	9.6 cd
	3 week delay	10.1 c	93 ab	45 bc	14.7 b
	6 week delay	18.4 a	90 abc	62 a	17.7 a

[a] The typical and late maturity groups for MSU are MG = 2.5 and 3.5 and for SVREC are MG = 2.1 and 3.1, respectively.
[b] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

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