INTEGRATED WEED MANAGEMENT STRATEGIES IN EARLY PLANTED SOYBEAN

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ABSTRACT

Variable weather patterns paired with increasing farm size have prompted soybean growers to explore new strategies such as early planting to minimize delays and subsequent yield loss. Field experiments were conducted in 2022 and 2023 to evaluate the effectiveness and crop safety of commonly used PRE herbicides and the effects of soybean row width on weed suppression and soybean yield in soybeans planted earlier than the current standard. Planting soybeans in early to mid-April slowed crop emergence and heavy precipitation created an environment favorable for reduced stands and PRE herbicide injury compared with those planted at a normal time. However, PRE herbicides controlled susceptible weed species when sufficient rainfall occurred for incorporation in both early and normal planted soybeans. Soybean establishment and yield were only lower in early planted soybeans when heavy precipitation resulted in soil surface crusting and high amounts of crop injury. The effects of soil crusting on stand were most evident when soybeans were planted in 19 cm row widths compared to 38 and 76 cm. Soybeans drilled in 19 cm row widths were superior to 38 and 76 cm for weed suppression at the time of POST. However, season-long weed suppression was only observed when 19 cm rows were planted at 494,000 seeds ha^{-1}. Similarly, higher soybean yield occurred only when 19 cm rows were planted at 494,000 seed ha^{-1}. Regardless of planting date, a complete PRE followed by POST weed management program was beneficial for weed control and soybean yield. Planting soybeans in early to mid-April will allow growers to reduce planting delays, without affecting soybean yield assuming weather conditions are not exceptionally poor during initial soybean establishment.

Dedicated to my parents, Dale and Linda Goddard, and my late grandfather, Ronald Goddard

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CHAPTER I: LITERATURE REVIEW

Introduction

Soybean (*Glycine Max* (L.) Merr.) is an important source of food, protein, and oil. In 2023, soybeans were planted on over 809 thousand hectares in Michigan, nearly double the number of soybean hectares produced 50 years ago (USDA-NASS 2024a). Across the U.S. soybean was planted on 33.8 million hectares in 2023, second only to corn (USDA-NASS 2024b). In Michigan and much of the Midwest, soybean is commonly grown in rotation with grass crops such as corn (*Zea mays* L.) and double-cropped following winter wheat (*Triticum aestivum* L.). The economic impacts of soybeans go beyond production. A recent study funded by the United Soybean Board and National Oilseed Producers Association revealed the economic impact of the U.S. soybean sector including production, processing and jobs supported averaged \$124 billion year^{-1} from 2019 to 2022, 0.6% of total U.S. gross domestic product (LMC International 2023). Nonetheless, soybeans have an immense impact on agricultural production and the economy, thus evaluation of best management practices is essential to optimize efficiency and profitability.

Soybean Planting Date

When to plant is one of the first decisions a grower must make in the production of soybeans. Robinson et al. (2009) indicated that the date of planting is one of the most important, and least expensive cultural management decisions that influences soybean yield. The potential for planting soybeans earlier continues to increase as climate variability increases. Based on climatological data collected from 1,218 sites from 1900 to 2014 Kukal and Irmak (2018) indicated that in the upper Midwest, the last spring frost is 9 days earlier, contributing to a 14.5 day increase in the length of the growing season. The combination of earlier last spring frost, the need to spread out the field workload, and avoid delays in planting from heavy precipitation events have prompted soybean producers to plant soybeans earlier than the historical standard.

Soybean Establishment. High amounts of precipitation before or soon after soybean planting and cool soil temperatures can lead to delayed and poor soybean establishment (DeWerff et al. 2015; Oplinger and Philbrook 1992; Schmitz and Kandel 2021). Average annual precipitation in the Midwest has increased by 5-15% between 1901-1960 and 2002-2021, while heavy precipitation events have increased by 45% from 1958 to 2016 (Marvel et al. 2023). The combination of high amounts of precipitation, cool temperatures, and delayed emergence when soybeans are planted early increases seedling vulnerability to insects including bean leaf beetle (*Cerotoma trifurcta* Förster) and seed corn maggot (*Delia platura* Meigen) (Hammond and Cooper 1993; Zeiss and Pedigo 1996). Furthermore, these conditions are conducive for diseases such as damping off or root rot from *Pythium* spp. (Serrano and Robertson 2018) and *Fusarium* spp. (Yan and Nelson 2022), as well as sudden death syndrome (*Fusarium virguliforme* O'Donnell & T. Aoki) (Gongora-Canul and Leandro 2011). Despite potential challenges, planting soybean early has been demonstrated to have a positive impact on yield (Arsenijevic et al. 2022; De Bruin and Pedersen 2008a; Siler and Singh 2023).

Early-Season Weed Competition. Weed competition increases when soybean planting occurs earlier in the growing season. Coulter & Nafziger (2007) reported higher weed densities when soybean planting occurred in late April compared with mid-late May in all five site-years of an Illinois study, and these increases were a result of higher broadleaf compared with grass weed species. Biennial, perennial, and winter annual weed species are effectively controlled mechanically in conventionally tilled soybean systems (Buhler 1995). In contrast, summer annuals emerge at the same time or after spring planted crops resulting in weed-crop competition. Early season weed control in soybeans is essential to prevent yield loss. The critical weed free period has been defined as the time between soybean emergence up to V4 in soybean (Van Acker et al. 1993). Although the length of this period is variable when influenced by environmental conditions, and soybean row width, preemergence herbicides (PRE) can be of great value to ensure adequate weed control is maintained and yield potential is protected (Knezevic et al. 2003, 2019). Initial weed emergence, as well as the length of the emergence period, is variable across species and will influence the benefit and selection of PRE herbicides. Among summer annual weed species, common ragweed (*Ambrosia artemisiifolia* L.) and common lambsquarters (*Chenopodium album* L.) are two of the earliest emerging species in the Midwest, beginning in April (Werle et al. 2014). Whereas velvetleaf (*Abutilon theophrasti* Medik.), *Setaria* and *Amaranthus* species emerge later, beginning in May and extending into June and July. Selecting a preemergence herbicide that will not only effectively control the species in the weed seedbank, but more specifically the weeds that will be emerging during the period following planting is critical in early-planted soybeans. In addition to selectivity, crop safety should be considered as well (Poston et al. 2008).

Soybean Yield Benefits of Early Planting. The benefit of early planting for soybean yield is most evident when paired with later maturing varieties (Mourtzinis et al. 2017; Siler and Singh 2022; Vossenkemper et al. 2015). However, yield advantages of planting soybeans early have been reported regardless of maturity group (Arsenijevic et al. 2022; Matcham et al. 2020; Schmitz and Kandel 2021). Delaying soybean planting past the regionally targeted window can result in significant yield loss (De Bruin and Pedersen 2008a; Siler and Singh 2023). Planting soybeans earlier advances the onset of vegetative and reproductive stages, allowing for earlier accrual of reproductive nodes, and induction of flowering (Bastidas et al. 2008). Delayed soybean planting resulted in soybean yield losses of 70 kg ha^{-1} per week between late April and early May in Iowa (De Bruin and Pedersen 2008a). As soybean planting was delayed even further, yield losses of 404 kg ha^{-1} per week were reported between late May and early June. Research in Wisconsin reported 188-902 kg ha^{-1} higher soybean yield when planted in mid-April compared with mid-May (Arsenijevic et al. 2022). Similarly, research specific to Michigan indicates that delaying soybean planting beyond mid-May can result in significant yield loss, with an average of 131 kg ha^{-1} wk^{-1} between mid-May and early June, and 326 kg ha^{-1} wk^{-1} between early and late June (Siler and Singh 2023). Nonetheless, planting date determines the conditions soybean seedlings are required to establish in, the weeds they will compete with, the length of the growing season, as well as the environmental conditions in yield impactful reproductive stages.

Soybean Row Width

Before the development and adoption of herbicides, weed control was dominated by mechanical methods including interrow cultivation. As a result, soybeans in the past have predominately been planted in 76 cm rows, which offered more equipment accessibility after crop emergence (Wax et al. 1977; Wax and Pendleton 1968). Today, soybeans are commonly planted in 19, 38, and 76 cm row widths. Rows that are 38 and 76 cm wide can be planted using a traditional row crop planter that precisely meters seed allowing for more consistent placement and seed singulation. However, farmers in Michigan often own grain drills to plant wheat or other small grains, which can be used to plant soybeans in 19 cm wide rows. The seed is metered with wearable fluted wheels, resulting in less precise populations, placement, and singulation of soybean seed. Although precision drills are available to producers, they are not as widely adopted as standard flute-metered models or air seeders. Holshouser et al. (2006) found that a vacuum planter and precision drill were similar in uniformity of seed placement, while noticeable gaps between seeds occurred when soybean was planted with a standard flute-metered drill. However, the differences observed in stand uniformity did not result in yield differences between the precision methods and standard drill. Despite inconsistent speed placement in some cases, narrow row widths can be beneficial for weed suppression and soybean yield.

Canopy Closure. Planting soybeans in narrow row widths (< 76 cm) allows for more rapid canopy closure compared with wider row widths (Arsenijevic et al. 2022; Dalley et al. 2004; Fisher and Sprague 2023; Hock et al. 2006; Nelson and Renner 1999). Narrow rows (19 cm) decrease the amount of available photosynthetic active radiation reaching the soil surface, early in the season compared with wide rows (76 cm) (Steckel and Sprague 2004). Similarly, Hock et al. (2006) found canopy closure in 76 cm rows was delayed by 20 days compared with 19 cm rows. Other research reported similar delays in canopy development where soybean in 19 and 38 cm row widths achieved canopy closure 1-2 weeks earlier than soybean planted in 76 cm rows depending on population (Harder et al. 2007).

Depending on growing conditions such as planting date and precipitation, wide row widths (76 cm) may not reach full canopy closure. Planting soybeans in narrow row widths allows for more complete canopy closure and interception of more sunlight (Dalley et al. 2004; Rich and Renner 2007; Yelverton and Coble 1991). Dalley et al (2004) found that when growing conditions were conducive to crop development, soybean canopy intercepted a maximum of 98% in 19 and 38 cm rows widths, while 76 cm rows only intercepted 84%. Under drought conditions, the canopy benefits of narrow row widths were even more evident where 19 cm rows intercepted 89% compared with 63% in 76 cm rows. This indicates that the benefits of narrow row widths may be even more advantageous when soybeans are under moisture-limited growing conditions. Another study reported similar findings where narrow row widths (23 cm) reached full canopy closure 10 weeks after planting and the wide row widths (91 cm) only reached 75% closure when the soybeans reached vegetative maturity (Yelverton and Coble 1991). Additionally, planting soybeans in narrow row widths increases leaf area index and biomass per plant (Cox and Cherney 2011; Légère and Schreiber 1989).

Weed Suppression. Weed control is a critical component in soybean production worldwide. Planting in narrow row widths is a practice that has been utilized by many to aid in the suppression of yield-limiting weed competition. Advanced soybean canopy development in narrow rows (19 and 38 cm) reduces weed emergence and resurgence compared with wider rows (76 cm) by limiting the quantity and quality of available sunlight at the soil surface (Fisher and Sprague 2023; Mickelson and Renner 1997; Steckel and Sprague 2004; Yelverton and Coble 1991). Some weeds possess a seed dormancy mechanism that is regulated by phytochrome and the presence of red light from direct sun and far-red light that reaches the soil-surface after it is filtered through a crop canopy. Common waterhemp (*Amaranthus rudis* Sauer*)* germination is decreased in the presence of far-red light (Leon and Owen 2003). Steckel and Sprague (2004) reported a two-fold increase in common waterhemp density when soybeans were planted in 76 cm rows compared with narrow row widths that were 19 cm wide. In Michigan, soybean planted in 19 and 38 cm row widths reduced horseweed (Conyza canadensis L.) density by 2-fold at the time of postemergence herbicide application (POST) compared with 76 cm rows (Fisher and Sprague 2023). Hock et al. (2006) attributed higher weed biomass in 76 cm compared with 19 cm row widths to a 20 day delay in canopy closure in the wider row spacing. In a meta-analysis, it was reported that planting soybean in row widths less than 76 cm resulted in a 42% reduction in weed density, and 71% lower weed biomass (Singh et al. 2023). Narrow row widths provide some degree of weed suppression, but they do not eliminate the need for herbicide-based weed control. Harder et al. (2007) reported lower weed density and biomass in narrow row widths (19 and 38 cm) compared with wide rows (76 cm) after a POST application of glyphosate. However, reduction in weed densities within narrow row widths were not apparent in the absence of a POST application. Soybeans planted in 76 cm rows, intercept less light and advance the critical time for weed removal by 60 and 200 growing degree days earlier on average compared with 38 and 19 cm row widths, respectively (Knezevic et al. 2003).

Impact of Row Width on Soybean Yield. Soybean yield response to row spacing is variable, and most evident when weed competition is occurring. In general, it has been concluded that soybeans planted in narrow rows are more competitive against weeds compared with wider row widths (Fisher and Sprague 2023; Hock et al. 2006; Knezevic et al. 2003; Légère and Schreiber 1989; Singh et al. 2023; Steckel and Sprague 2004). When season-long weed competition occurred, planting soybeans in narrow row widths (19 and 38 cm) increased yield (Hock et al. 2006; Knezevic et al. 2003). Similarly, Steckel and Sprague (2004) reported that early-season waterhemp competition reduced soybean yield by 44% in wide rows compared with 37% in narrow row widths. Field studies conducted in West Lafayette, IN reported similar trends in the presence of weed competition, as well as higher soybean yields in narrow row widths in a weed-free environment compared with wider rows (Légère and Schreiber 1989). Research in Iowa reported a 6% increase in soybean yield by decreasing row width from 76 to 38 cm in a weed-free environment (De Bruin and Pedersen 2008b). The results of a meta-analysis revealed that across 20 studies planting soybeans in narrow row widths (< 76 cm) resulted in an average of 12% higher yield (Singh et al. 2023). However, Arsenijevic et al. (2022) did not observe any yield advantages of narrow row widths, even with advanced canopy closure. Furthermore, Schultz et al. (2015) reported 8% lower yield when soybeans were planted in 19 cm row widths, even with reduced waterhemp density compared with wide row widths (76 cm), attributed to inconsistent seed placement.

Herbicide Trends in Soybean

The presence of weeds, their competition with cash crops, and the development of resistance to herbicides poses significant challenges to soybean producers. Weeds compete with all crops for light, water, and nutrients (Krausz et al. 2001). Methods of weed control have evolved from the reliance on mechanical cultivation to the wide adoption of synthetic herbicides. Preplant incorporated, preemergence, and postemergence herbicide applications are important tools for effective weed control and resistance management throughout all phases of the growing season.

The introduction of herbicide-resistant crops has given producers more postemergence weed control options to use throughout the growing season. Glyphosate-resistant soybean was introduced by Monsanto in 1996, giving producers added flexibility with a new, effective postemergence weed control option (Harper 1995). Instead of increasing the diversity of herbicide sites of action utilized in weed control programs, glyphosate-resistant soybean brought forward a cropping system that could be managed with a broad spectrum, non-selective, postemergence herbicide as the primary or exclusive component for weed control. The wide adoption of glyphosate and genetically engineered soybean that were resistant to it, led to the declined use of preemergence herbicides and mechanical-based weed control (Norsworthy et al. 2012; Young 2006). The extensive use of glyphosate, often being applied multiple times in a growing season resulted in high selection pressure for glyphosate-resistant weed populations (Heap and Duke 2018; Powles 2008; Reddy 2001; Young 2006). The evolution of glyphosate-resistant weed species has become widespread, reducing the overall utility of glyphosate and glyphosate-resistant crops (Heap 2024). Since the introduction of glyphosate-resistant soybean, trait packages resistant to glufosinate, dicamba, 2,4-D, and isoxaflutole have been made available to growers (Behrens et al. 2007; Nandula 2019; Siehl et al. 2014; Wright et al. 2010). To prolong the viability of these systems, weed resistance management is essential. Soil-applied, preemergence herbicides are a valuable tool that can increase the diversity of weed management programs. Additionally, preemergence herbicides extend the period between planting and postemergence herbicide application, allowing for more timely postemergence applications and reduced quantity of weeds that are subjected to recurrent selection by postemergence products (Johnson et al. 2012; Knezevic et al. 2019; Oliveira et al. 2017).

Preemergence Herbicides in Soybean

Commonly used herbicide sites of action for preemergence weed control in soybean include acetolactate synthase (ALS) inhibitors (WSSA Group 2), microtubule inhibitors (WSSA Group 3), photosystem II (PSII) inhibitors (WSSA Group 5), deoxy-d-xyulose phosphate synthase (DOXP) inhibitors (WSSA Group 13), protoporphyrinogen oxidase (PPO) inhibitors (WSSA Group 14), and very long-chain fatty acid synthesis (VLCFA) inhibitors (WSSA Group 15). Foliar activity of most preemergence herbicides is limited, thus incorporation into the soil solution is needed before weed germination to be effective. Rainfall allows these herbicides to move from the soil surface and into the soil solution, making them available to germinating weed seeds and seedlings for uptake (Knake et al. 1967; Mueller et al. 2014).

Mobility and Availability. The inability to accurately predict precipitation and in some growing seasons the absence of rainfall poses significant challenges in the use of preemergence herbicides. The amount of precipitation required for adequate incorporation is dependent on multiple characteristics of the herbicide molecule itself, as well as factors of the soil and environment.

Water solubility is the measure of a chemical substance, in this case, a herbicide that can dissolve in water and has been classified as follows: low (<10 ppm), medium (10-1,000 ppm) and high (>1,000 ppm) (Ney 1995). Though herbicides must be relatively soluble to be incorporated by rainfall, adsorption of the herbicide to soil colloids is an important factor in initial mobility and plant availability once the herbicide is in the soil solution.

The organic carbon-water partition coefficient (K_{OC}) represents the ratio of a chemical that is soil-bound compared to available in the soil solution. K_{OC} is a common metric used to measure the adsorption of pesticides, and mobility potential has been categorized as very high (0-5), high (50-150), medium (150-500), low (500-2,000), slight (2,000-5,000), and immobile (>5,000) (McCall et al. 1980). In general, herbicides are less bound to coarse soils with low organic matter, and readily adsorbed in heavy soils with high organic matter (Sheng et al. 2001). However, herbicides may be more readily adsorbed by clay or organic matter depending on the specific molecule. Though they will adsorb to both, non-ionizable herbicides (i.e. flumioxazin, pyroxasulfone, and s-metolachlor) generally have a higher affinity for organic matter compared with clay particles (Glaspie et al. 2021; Weber et al. 2000). Production field soils with high organic matter and clay content may require increased herbicide rates to avoid decreased activity of preemergence herbicides due to increased adsorption (Glaspie et al. 2021).

Soil pH also has a significant effect on the mobility and activity of herbicides, affecting their net charge and in turn, their affinity for soil colloids (adsorption), resulting in altered behaviors in the soil (Corbin et al. 1971). However, the impact of variable soil pH is molecule specific. Flumioxazin, a non-ionic PPO inhibitor (WSSA Group 14), showed no response in adsorption when soil pH was adjusted (Ferrell et al. 2005). In contrast, metribuzin, a PSII inhibitor (WSSA Group 5) with a pK_a of 1.0 (weak base) possesses an inverse relationship between soil adsorption and soil pH, whereas when soil pH increases adsorption decreases (Ladlie et al. 1976).

Many preemergence herbicide labels lack definitive information on the quantity of precipitation required for sufficient incorporation into the soil solution. For herbicides that don't have precipitation-specific label recommendations, rainfall has been estimated based on the water solubility and soil mobility of herbicides. Herbicides with high water solubility and soil mobility are estimated to require 0.6 cm of precipitation and herbicides with low solubility and mobility require approximately 1.9 cm (Anonymous 2023). These precipitation estimates are consistent with the findings of Nagy (2008) for acetochlor, a group 15, α-chloroacetamide herbicide with moderate solubility and high soil mobility, which was reported to need 1.4 cm of rainfall for optimal incorporation and weed control. Previous research has found that when precipitation was limited the week before and after application, weed control was reduced across seven preemergence herbicides belonging to WSSA groups 2, 5, and 15 (Stewart et al. 2010). In contrast, weed control from soil-applied metribuzin was also reduced when high amounts of precipitation occurred within a week of application due to its high solubility and mobility in the soil. Thus, characteristics of the herbicide, soil and environment should be considered when utilizing a PRE herbicide in a weed control program.

Selectivity and Control. The spectrum of weed species controlled is herbicide-specific and varies within and between sites of action. In some cases, seed size influences the efficacy of preemergence herbicides on weed species. Scott and Phillips (1971) explained that some herbicides control small-seeded broadleaves due to a larger surface area to seed volume ratio, whereas the inverse can be inferred from the lack of control for larger seeded weeds. Unlike postemergence herbicides, preemergence products partially rely on spatial selectivity where the crop is germinating below the lethal dose of herbicide in the soil (Krähmer et al. 2021).

Herbicides belonging to WSSA Group 15 inhibit very long-chain fatty acid (VLCFA) synthesis. Specifically, they have been reported to target one or more elongase enzymes that facilitate the elongation of fatty acids (Böger 2003; Tanetani et al. 2013). VLCFAs are essential components in pollen coats, cuticle waxes, sphingolipids, and phospholipids (Cassagne et al. 1994). The depletion of complete VLCFA's and buildup of precursors results in weakened and leaky cells, and ultimately results in plant death (Matthes and Böger 2002). Group 15 herbicides are absorbed by emerging shoots, roots, and cotyledons, and while germination is not inhibited, weeds often fail to emerge due to inhibited growth. This group provides residual control of annual grasses and some small-seeded broadleaves (Böger et al. 2000).

PPO-inhibiting herbicides, classified in WSSA Group 14 inhibit protoporphyrinogen oxidase, resulting in the accumulation of protoporphyrinogen-IX substrate, where it then moves to the cytoplasm and is oxidized (Dan Hess 2000). This oxidation produces a light-activated protoporphyrin IX, generating singlet oxygen molecules that cause lipid peroxidation and cell death. Most herbicides belonging to this group are applied postemergence, however, flumioxazin, saflufenacil, and sulfentrazone are registered for preemergence application in soybean and provide control of economically impactful annual broadleaf species such as common waterhemp, palmer amaranth *(Amaranthus palmeri* S. Watson*),* redroot pigweed *(Amaranthus retroflexus* L.*),* horseweed and common lambsquarters (Niekamp et al. 1999; Norsworthy et al. 2009; Ribeiro et al. 2022).

Herbicides in WSSA Group 5 inhibit photosystem II by binding with the Q_B binding site of the D1 protein, blocking electron transport and preventing CO_2 fixation. This ultimately results in photooxidation and plant death (Ma et al. 2020). Inhibiting the PS II pathway, metribuzin is an effective preemergence herbicide that is widely used in row crops such as soybean, and corn as well as specialty crops. Metribuzin provides preemergence control of annual broadleaf weed species including common lambsquarters, velvetleaf, *Amaranthus* spp., and horseweed, as well as *Setaria* spp. (Oliveira et al. 2017).

Soybean Injury. Though spatial selectivity is an advantage of preemergence applications, crops will encounter these herbicides when emerging if soil moisture is sufficient. Soybeans can rapidly metabolize these herbicides, rendering the molecule inactive and conferring additional tolerance. Exact metabolism steps and relative speed are herbicide specific and complex but involve a series of cleavage, conjugation, and oxidation reactions facilitated by various enzymes within the plant (Breaux 1986, 1987; Jaworski 1969; Lamoureux and Rusness 1989). However, soybean injury can occur if varietal tolerance is low, herbicide splashing occurs and when growing conditions are cool and wet (Arsenijevic et al. 2021; Griffin and Habetz 1989; Payne and Koszykowski 1977; Wise et al. 2015).

Under cool, wet soil conditions Niekamp et al. (1999) observed 11-20% soybean injury from preemergence applied flumioxazin, attributed to slowed soybean metabolism and microbial breakdown. Similarly, Poston et al. (2008) reported a high incidence of soybean injury from both grass and broadleaf controlling herbicides under cool, wet (4.6 cm within 8 d) growing conditions. Research in Wisconsin found flumioxazin + metribuzin + pyroxasulfone delayed canopy development by 4 days under similar, stressful growing conditions (Arsenijevic et al. 2022). Decreased adsorption of metribuzin in alkaline soils results in higher concentrations of the herbicide being plant available, which can lead to soybean injury when rates aren't adjusted accordingly (Moomaw and Martin 1978). Utilizing preplant herbicide applications has been shown to reduce the risk of soybean injury, but also reduces the length of residual weed control of herbicides that are less persistent and highly mobile (Moshier and Russ 1981; Priess et al. 2020). Soybean yield correlation to early-season preemergence herbicide injury is variable. Mild soybean yield reductions, and delays in soybean canopy development have been reported as a result of severe preemergence herbicide soybean injury (Arsenijevic et al. 2022; Poston et al. 2008; Taylor-Lovell et al. 2001). Though yield reductions can occur, many studies have found that soybean yield is unaffected when initial injury from preemergence herbicides is observed (Arsenijevic et al. 2021; Barlow et al. 2018; Krausz et al. 2001; Osborne et al. 1995).

As environmental conditions continue to change and farm size increases, growers need alternate management strategies to improve timeliness of field operations and profitability. Although the length of growing season has increased in the upper Midwest, increased heavy precipitation events pose significant challenges for growers in the spring. Further research is needed to evaluate the implications of planting soybeans earlier than the current standard on integrated weed management strategies.

Questions that remain to be answered:

1. How does early planting affect soybean establishment in Michigan?
2. How does the early season environment affect crop/weed competition as well as the length of residual weed control and crop safety of preemergence herbicides?
3. Can the length of residual control be increased if preemergence herbicide applications are delayed in early planted soybean?

4. Will narrow row widths provide the same weed suppression and yield benefits if soybeans are planted earlier than the current standard?
5. Does soybean planting date affect crop performance and best management strategies in soybean production?

LITERATURE CITED

Anonymous (2023) Conditions Affecting PRE Herbicide Activation | Crop Science US. https://www.cropscience.bayer.us/articles/bayer/conditions-affecting-pre-herbicide-activation. Accessed January 30, 2024

Arsenijevic N, De Avellar M, Butts L, Arneson NJ, Werle R (2021) Influence of sulfentrazone and metribuzin applied preemergence on soybean development and yield. Weed Technol 35:210–215

Arsenijevic N, DeWerff R, Conley S, Ruark M, Werle R (2022) Influence of integrated agronomic and weed management practices on soybean canopy development and yield. Weed Technol 36:73–78

Barlow BR, Shergill LS, Bish MD, Bradley KW (2018) Investigations of the Potential Interactions Between Pre-emergence Residual Herbicides, Variety, and Seed Treatments in Soybean. Weed Technol 32:570–578

Bastidas AM, Setiyono TD, Dobermann A, Cassman KG, Elmore RW, Graef GL, Specht JE (2008) Soybean Sowing Date: The Vegetative, Reproductive, and Agronomic Impacts. Crop Sci 48:727–740

Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, LaVallee BJ, Herman PL, Clemente TE, Weeks DP (2007) Dicamba Resistance: Enlarging and Preserving Biotechnology-Based Weed Management Strategies. Science 316:1185–1188

Böger P (2003) Mode of Action for Chloroacetamides and Functionally Related Compounds. J Pestic Sci 28:324–329

Böger P, Matthes B, Schmalfuβ J (2000) Towards the primary target of chloroacetamides -new findings pave the way. Pest Manag Sci 56:497–508

Breaux EJ (1986) Identification of the initial metabolites of acetochlor in corn and soybean seedlings. J Agric Food Chem 34:884–888

Breaux EJ (1987) Initial Metabolism of Acetochlor in Tolerant and Susceptible Seedlings. Weed Sci 35:463–468

Buhler DD (1995) Influence of Tillage Systems on Weed Population Dynamics and Management in Corn and Soybean in the Central USA. Crop Sci 35:1247–1258

Cassagne C, Lessire R, Bessoule JJ, Moreau P, Creach A, Schneider F, Sturbois B (1994) Biosynthesis of very long chain fatty acids in higher plants. Prog Lipid Res 33:55–69

Corbin FT, Upchurch RP, Selman FL (1971) Influence of pH on the Phytotoxicity of Herbicides in Soil. Weed Sci 19:233–239

Coulter JA, Nafziger ED (2007) Planting Date and Glyphosate Timing on Soybean. Weed Technol 21:359–366

Cox WilliamJ, Cherney JH (2011) Growth and Yield Responses of Soybean to Row Spacing and Seeding Rate. Agron J 103:123–128

Dalley CD, Kells JJ, Renner KA (2004) Effect of Glyphosate Application Timing and Row Spacing on Weed Growth in Corn (Zea mays) and Soybean (Glycine max). Weed Technol 18:177–182

Dan Hess F (2000) Light-dependent herbicides: an overview. Weed Sci 48:160–170

De Bruin JL, Pedersen P (2008a) Soybean Seed Yield Response to Planting Date and Seeding Rate in the Upper Midwest. Agron J 100:696–703

De Bruin JL, Pedersen P (2008b) Effect of Row Spacing and Seeding Rate on Soybean Yield. Agron J 100:704–710

DeWerff RP, Conley SP, Colquhoun JB, Davis VM (2015) Weed Control in Soybean as Influenced by Residual Herbicide Use and Glyphosate-Application Timing Following Different Planting Dates. Weed Technol 29:71–81

Ferrell JA, Vencill WK, Xia K, Grey TL (2005) Sorption and desorption of flumioxazin to soil, clay minerals and ion-exchange resin. Pest Manag Sci 61:40–46

Fisher JL, Sprague CL (2023) Contributions of shading, soybean (*Glycine max*) row width, and planting green on horseweed (*Conyza canadensis*) management compared with soil-applied residual herbicides. Weed Technol 37:383–393

Glaspie CF, Jones EAL, Penner D, Pawlak JA, Everman WJ (2021) Effect of Clay, Soil Organic Matter, and Soil pH on Initial and Residual Weed Control with Flumioxazin. Agronomy 11:1326

Gongora-Canul CC, Leandro LFS (2011) Effect of Soil Temperature and Plant Age at Time of Inoculation on Progress of Root Rot and Foliar Symptoms of Soybean Sudden Death Syndrome. Plant Dis 95:436–440

Griffin JL, Habetz RJ (1989) Soybean (Glycine max) Tolerance to Preemergence and Postemergence Herbicides. Weed Technol 3:459–462

Hammond RB, Cooper RL (1993) Interaction of planting times following the incorporation of a living, green cover crop and control measures on seedcorn maggot populations in soybean. Crop Prot 12:539–543

Harder DB, Sprague CL, Renner KA (2007) Effect of Soybean Row Width and Population on Weeds, Crop Yield, and Economic Return. Weed Technol 21:744–752

Harper DR (1995) Roundup Ready Soybeans: An Overview of the Technology. Page 11934380 *in* Proceedings of the Integrated Crop Management Conference. Iowa State University, Digital Press

Heap I (2024) The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed January 30, 2024

Heap I, Duke SO (2018) Overview of glyphosate-resistant weeds worldwide. Pest Manag Sci 74:1040–1049

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean Row Spacing and Weed Emergence Time Influence Weed Competitiveness and Competitive Indices. Weed Sci 54:38–46

Holshouser DL, Grisso Jr. RD, Pitman RM (2006) Uniform Stand and Narrow Rows are Needed for Higher Double-crop Soybean Yield. Crop Manag 5:CM-2006-0417-01-RS

Jaworski EG (1969) Analysis of the mode of action of herbicidal .alpha.-chloroacetamides. J Agric Food Chem 17:165–170

Johnson WG, Chahal GS, Regehr DL (2012) Efficacy of Various Corn Herbicides Applied Preplant Incorporated and Preemergence. Weed Technol 26:220–229

Knake EL, Appleby AP, Furtick WR (1967) Soil Incorporation and Site of Uptake of Preemergence Herbicides. Weeds 15:228

Knezevic SZ, Evans SP, Mainz M (2003) Row Spacing Influences the Critical Timing for Weed Removal in Soybean (Glycine max). Weed Technol 17:666–673

Knezevic SZ, Pavlovic P, Osipitan OA, Barnes ER, Beiermann C, Oliveira MC, Lawrence N, Scott JE, Jhala A (2019) Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. Weed Technol 33:393–399

Krähmer H, Walter H, Jeschke P, Haaf K, Baur P, Evans R (2021) What makes a molecule a pre- or a post-herbicide – how valuable are physicochemical parameters for their design? Pest Manag Sci 77:4863–4873

Krausz RF, Young BG, Kapusta G, Matthews JL (2001) Influence of Weed Competition and Herbicides on Glyphosate-Resistant Soybean (Glycine max)1. Weed Technol 15:530–534

Kukal MS, Irmak S (2018) U.S. Agro-Climate in 20th Century: Growing Degree Days, First and Last Frost, Growing Season Length, and Impacts on Crop Yields. Sci Rep 8:6977

Ladlie JS, Meggitt WF, Penner D (1976) Effect of pH on Metribuzin Activity in the Soil. Weed Sci 24:505–507

Lamoureux GL, Rusness DG (1989) Propachlor metabolism in soybean plants, excised soybean tissues, and soil. Pestic Biochem Physiol 34:187–204

Légère A, Schreiber MM (1989) Competition and Canopy Architecture as Affected by Soybean (Glycine max) Row Width and Density of Redroot Pigweed (*Amaranthus retroflexus*). Weed Sci 37:84–92

Leon RG, Owen MDK (2003) Regulation of Weed Seed Dormancy through Light and Temperature Interactions. Weed Sci 51:752–758

LMC International (2023) The Economic Impact of U.S. Soybeans and End Products on the U.S. Economy - 2023 Update

Ma H, Lu H, Han H, Yu Q, Powles S (2020) Metribuzin resistance via enhanced metabolism in a multiple herbicide resistant Lolium rigidum population. Pest Manag Sci 76:3785–3791

Marvel K, Su W, Delgado R, Aarons S, Chatterjee A, Garcia ME, Hausfather Z, Hayhoe K, Hence DA, Jewett EB, Robel A, Singh D, Tripati A, Vose RS (2023) Climate trends. Washington, DC, USA: U.S. Global Change Research Program

Matcham EG, Mourtzinis S, Conley SP, Rattalino Edreira JI, Grassini P, Roth AC, Casteel SN, Ciampitti IA, Kandel HJ, Kyveryga PM, Licht MA, Mueller DS, Nafziger ED, Naeve SL, Stanley JD, Staton MJ, Lindsey LE (2020) Management strategies for early- and late-planted soybean in the north-central United States. Agron J 112:2928–2943

Matthes B, Böger P (2002) Chloroacetamides Affect the Plasma Membrane. Z Für Naturforschung C 57:843–852

McCall PJ, Swann RL, Laskowski DA, Unger SM, Vrona SA, Dishburger HJ (1980) Estimation of chemical mobility in soil from liquid chromatographic retention times. Bull Environ Contam Toxicol 24:190–195

Mickelson JA, Renner KA (1997) Weed Control Using Reduced Rates of Postemergence Herbicides in Narrow and Wide Row Soybean. J Prod Agric 10:431–437

Moomaw RS, Martin AR (1978) Interaction of Metribuzin and Trifluralin with Soil Type on Soybean (Glycine max) Growth. Weed Sci 26:327–331

Moshier LJ, Russ OG (1981) Metribuzin Injury in Soybeans as Influenced by Application Timing and Cultivation1. Agron J 73:677–679

Mourtzinis S, Gaspar AP, Naeve SL, Conley SP (2017) Planting Date, Maturity, and Temperature Effects on Soybean Seed Yield and Composition. Agron J 109:2040–2049

Mueller TC, Boswell BW, Mueller SS, Steckel LE (2014) Dissipation of Fomesafen, Saflufenacil, Sulfentrazone, and Flumioxazin from a Tennessee Soil under Field Conditions. Weed Sci 62:664–671

Nagy P (2008) Efficacy of Acetochlor as Affected by Different Rainfall Conditions. Cereal Res Commun 36:2019–2022

Nandula VK (2019) Herbicide Resistance Traits in Maize and Soybean: Current Status and Future Outlook. Plants 8:337

Nelson KA, Renner KA (1999) Weed Management in Wide- and Narrow-Row Glyphosate Resistant Soybean. J Prod Agric 12:460–465

Ney RE (1995) Fate and transport of organic chemicals in the environment : a practical guide. Rockville, Md. : Government Institutes. 322 p

Niekamp JW, Johnson WG, Smeda RJ (1999) Broadleaf Weed Control with Sulfentrazone and Flumioxazin in No-Tillage Soybean (Glycine max). Weed Technol 13:233–238

Norsworthy JK, McClelland M, Griffith GM (2009) Conyza canadensis (L.) Cronquist response to pre-plant application of residual herbicides in cotton (Gossypium hirsutum L.). Crop Prot 28:62–67

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. Weed Sci 60:31–62

Oliveira MC, Feist D, Eskelsen S, Scott JE, Knezevic SZ (2017) Weed Control in Soybean with Preemergence- and Postemergence-applied Herbicides. Crop Forage Turfgrass Manag 3:cftm2016.05.0040

Oplinger E s., Philbrook B d. (1992) Soybean Planting Date, Row Width, and Seeding Rate Response in Three Tillage Systems. J Prod Agric 5:94–99

Osborne BT, Shaw DR, Ratliff RL (1995) Soybean (Glycine max) Cultivar Tolerance to SAN 582H and Metolachlor as Influenced by Soil Moisture. Weed Sci 43:288–292

Payne RC, Koszykowski TJ (1977) Differentiation of Soybean Cultivars by Metribuzin Sensitivity. J Seed Technol 2:1–10

Poston DH, Nandula VK, Koger CH, Matt Griffin R (2008) Preemergence Herbicides Effect on Growth and Yield of Early-Planted Mississippi Soybean. Crop Manag 7:1–14

Powles SB (2008) Evolved glyphosate-resistant weeds around the world: lessons to be learnt. Pest Manag Sci 64:360–365

Priess GL, Norsworthy JK, Roberts TL, Gbur EE (2020) Weed control and soybean injury from preplant vs. preemergence herbicide applications. Weed Technol 34:718–726

Reddy KN (2001) Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. Weed Biol Manag 1:193–202

Ribeiro V, Coura Oliveira M, Smith DH, Barbosa dos Santos J, Werle R (2022) Control of common weeds in Wisconsin soybean cropping systems with pre-emergence herbicides. Crop Forage Turfgrass Manag 8:e20153

Rich AM, Renner KA (2007) Row Spacing and Seeding Rate Effects on Eastern Black Nightshade (*Solanum Ptycanthum*) and Soybean. Weed Technol 21:124–130

Robinson AP, Conley SP, Volenec JJ, Santini JB (2009) Analysis of High Yielding, Early-Planted Soybean in Indiana. Agron J 101:131–139

Schmitz PK, Kandel HJ (2021) Individual and Combined Effects of Planting Date, Seeding Rate, Relative Maturity, and Row Spacing on Soybean Yield. Agronomy 11:605

Schultz JL, Myers DB, Bradley KW (2015) Influence of Soybean Seeding Rate, Row Spacing, and Herbicide Programs on the Control of Resistant Waterhemp in Glufosinate-Resistant Soybean. Weed Technol 29:169–176

Scott HD, Phillips RE (1971) Diffusion of Herbicides to Seed. Weed Sci 19:128–132

Serrano M, Robertson AE (2018) The Effect of Cold Stress on Damping-Off of Soybean Caused by *Pythium sylvaticum*. Plant Dis 102:2194–2200

Sheng G, Johnston CT, Teppen BJ, Boyd SA (2001) Potential Contributions of Smectite Clays and Organic Matter to Pesticide Retention in Soils. J Agric Food Chem 49:2899–2907

Siehl DL, Tao Y, Albert H, Dong Y, Heckert M, Madrigal A, Lincoln-Cabatu B, Lu J, Fenwick T, Bermudez E, Sandoval M, Horn C, Green JM, Hale T, Pagano P, Clark J, Udranszky IA, Rizzo N, Bourett T, Howard RJ, Johnson DH, Vogt M, Akinsola G, Castle LA (2014) Broad 4-Hydroxyphenylpyruvate Dioxygenase Inhibitor Herbicide Tolerance in Soybean with an Optimized Enzyme and Expression Cassette. Plant Physiol 166:1162–1176

Siler TB, Singh MP (2022) Optimal soybean maturity group selection is influenced by planting date in northern production systems. Crop Sci 62:2462–2475

Siler TB, Singh MP (2023) Soybean seeding rate and seed treatment that maximize yield and profitability based on planting date. Agron J 115:759–769

Singh M, Thapa R, Singh N, Mirsky SB, Acharya BS, Jhala AJ (2023) Does narrow row spacing suppress weeds and increase yields in corn and soybean? A meta-analysis. Weed Sci 71:520–535

Steckel LE, Sprague CL (2004) Late-Season Common Waterhemp (*Amaranthus rudis*) Interference in Narrow- and Wide-Row Soybean. Weed Technol 18:947–952

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and Soil Conditions Influence Pre- and Postemergence Herbicide Efficacy in Soybean. Weed Technol 24:234–243

Tanetani Y, Kaku K, Ikeda M, Shimizu T (2013) Action mechanism of a herbicide, thiobencarb. J Pestic Sci 38:39–43

Taylor-Lovell S, Wax LM, Nelson R (2001) Phytotoxic Response and Yield of Soybean (*Glycine max*) Varieties Treated with Sulfentrazone or Flumioxazin [1]. Weed Technol 15:95–102

USDA-NASS (2024a) Soybeans - Acres Planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/75D59937-EC6F-3CE3-8542-0F82121309A7. Accessed February 22, 2024

USDA-NASS (2024b) Field Crops - US Total. https://quickstats.nass.usda.gov/results/BCED657A-002D-3397-BCD8-F8C984B49AA1. Accessed March 8, 2024

Van Acker RC, Swanton CJ, Weise SF (1993) The Critical Period of Weed Control in Soybean [Glycine max (L.) Merr.]. Weed Sci 41:194–200

Vossenkemper JP, Nafziger ED, Wessel JR, Maughan MW, Rupert ME, Schmidt JP (2015) Early Planting, Full-season Cultivars, and Seed Treatments Maximize Soybean Yield Potential. Crop Forage Turfgrass Manag 1:1–9

Wax LM, Nave WR, Cooper RL (1977) Weed Control in Narrow and Wide-Row Soybeans. Weed Sci 25:73–78

Wax LM, Pendleton JW (1968) Effect of Row Spacing on Weed Control in Soybeans. Weed Sci 16:462–465

Weber JB, Wilkerson GG, Michael Linker H, Wilcut JW, Leidy RB, Senseman S, Witt WW, Barrett M, Vencill WK, Shaw DR, Mueller TC, Miller DK, Brecke BJ, Talbert RE, Peeper TF (2000) A proposal to standardize soil/solution herbicide distribution coefficients. Weed Sci 48:75–88

Werle R, Sandell LD, Buhler DD, Hartzler RG, Lindquist JL (2014) Predicting Emergence of 23 Summer Annual Weed Species. Weed Sci 62:267–279

Wise K, Kandel Y, Young B, Johnson B, Legleiter T (2015) Soybean seedling damage: is there an interaction between the ILeVO seed treatment and pre-emergence herbicides? Integr Crop Manag News Iowa State Univ

Wright TR, Shan G, Walsh TA, Lira JM, Cui C, Song P, Zhuang M, Arnold NL, Lin G, Yau K, Russell SM, Cicchillo RM, Peterson MA, Simpson DM, Zhou N, Ponsamuel J, Zhang Z (2010) Robust crop resistance to broadleaf and grass herbicides provided by aryloxyalkanoate dioxygenase transgenes. Proc Natl Acad Sci 107:20240–20245

Yan H, Nelson B (2022) Effects of Soil Type, Temperature, and Moisture on Development of Fusarium Root Rot of Soybean by *Fusarium solani* (FSSC 11) and *Fusarium tricinctum*. Plant Dis 106:2974–2983

Yelverton FH, Coble HD (1991) Narrow Row Spacing and Canopy Formation Reduces Weed Resurgence in Soybeans (Glycine max). Weed Technol 5:169–174

Young BG (2006) Changes in Herbicide Use Patterns and Production Practices Resulting from Glyphosate-Resistant Crops1. Weed Technol 20:301–307

Zeiss MR, Pedigo LP (1996) Timing of Food Plant Availability: Effect on Survival and Oviposition of the Bean Leaf Beetle (Coleoptera: Chrysomelidae). Environ Entomol 25:295–302

CHAPTER II: EFFECTS OF RESIDUAL PREEMERGENCE HERBICIDE PROGRAMS ON EARLY VERSUS NORMAL PLANTED SOYBEAN

Abstract

Variable weather patterns pose significant challenges on timely soybean planting, prompting growers to plant earlier than the current standard. Four site-years of experiments were conducted in Michigan to evaluate weed control and crop safety of six preemergence (PRE) herbicide treatments in soybeans planted in early to mid-April (early) compared with soybeans planted 4 wk later (normal). At East Lansing in 2022 (MSU-22), heavy precipitation resulted in soil surface crusting in the early planting and reduced stand by 25% compared with the normal planting date. In three of four site-years, soybean injury 14 d after emergence was the highest in the early planted soybean from treatments that included flumioxazin with 18-20%. However, when soil surface crusting occurred, high amounts of injury were observed with all PRE treatments in early planted soybeans at MSU-22 (20-31%). Early planting resulted in higher weed biomass in the untreated controls at POST herbicide application; however, all PRE treatments reduced weed biomass by 73 and 67% or more in the early and normal planted soybeans, respectively, except for s-metolachlor in the early planting date which only provided 32% reduction, due to poor common ragweed control. In all site-years, delaying PRE applications reduced crop safety up to 8% across all treatments, and resulted in 3.3-fold more weed biomass in the pyroxasulfone treatment. Planting soybeans early did not result in yield differences compared with the normal planting date in three of four site-years. However, at MSU-22 yield was 15% lower in the early compared with normal planted soybeans, and 10% lower when PRE applications were delayed in the early planted soybean specifically. Although poor weather and soil conditions resulted in lower stands and reduced crop tolerance of residual

herbicides, utilizing an effective PRE treatment is beneficial for weed management, and soybean yield in both early and normal planted soybean.

Introduction

Soybean (*Glycine Max* (L.) Merr.) is an important source of food, protein, and oil and was planted on over 809 thousand hectares in Michigan in 2023, nearly double the number of soybean hectares produced 50 years ago (USDA-NASS 2024). Over the last century in the upper Midwest, the growing season has been lengthened by nearly 15 d due to changes in climatic conditions (Kukal and Irmak 2018). Extreme precipitation events in the Midwest, defined as the top 1% of heaviest rainstorms have increased by 45% since the 1950s, despite only a 14% rise in annual precipitation (Marvel et al. 2023). These heavy precipitation events paired, with larger farm sizes on average can lead to delayed soybean planting, prompting producers in Michigan to start planting as early as mid-April (USDA-NASS 2023).

Planting date determines the soil conditions soybean seedlings are required to establish in (DeWerff et al. 2015; Schmitz and Kandel 2021), the weeds they will compete with (Coulter and Nafziger 2007), and insect and disease pressure, potentially presenting challenges when planting soybean early. Environmental conditions such as heavy rainfall and cool air and soil temperatures can greatly affect early-season soybean establishment. Research in Wisconsin reported that heavy precipitation following early planting resulted in soil surface crusting, reducing soybean stand by 50% (DeWerff et al. 2015). Additionally, these soil conditions can delay soybean emergence leaving soybean seedlings vulnerable to bean leaf beetle (*Cerotoma trifurcta* Förster) (Zeiss and Pedigo 1996) and seed corn maggot (*Delia platura* Meigen) (Hammond and Cooper 1993) and diseases such as damping off or root rot from *Pythium* spp. (Serrano and Robertson 2018) and *Fusarium* spp. (Yan and Nelson 2022), as well as sudden death syndrome (*Fusarium virguliforme* O'Donnell & T. Aoki) (Gongora-Canul and Leandro 2011).

The efficacy and crop safety of preemergence (PRE) herbicides are especially of interest in early planted soybean in response to widespread glyphosate and other postemergence herbicide-resistant weeds (Heap 2024). Planting soybeans earlier can result in higher weed competition; however, an effective PRE herbicide can reduce early season weed interference, add flexibility to postemergence (POST) herbicide application timings (Coulter and Nafziger 2007; Oliveira et al. 2017; Reddy 2001), and limit the number of weeds subjected to POST herbicide selection (Johnson et al. 2012; Knezevic et al. 2019). Although PRE herbicides rely on rainfall to be incorporated into the soil (Knake et al. 1967; Mueller et al. 2014), high amounts of precipitation can be problematic (Griffin and Habetz 1989; Salzman and Renner 1992). Soybeans tolerance of PRE herbicides is largely due to the crops ability to rapidly metabolize them (Breaux 1986; Jaworski 1969; Taylor-Lovell et al. 2001). Cool, wet growing conditions that are often associated with early planted soybeans create an environment conducive to high crop injury due to increased herbicide availability (Salzman and Renner 1992) and slowed soybean metabolism (Niekamp et al. 1999; Wise et al. 2015). Furthermore, excessive rainfall can lead to herbicide dissipation and in turn reduced weed control (Johnson et al. 2012; Oliver et al. 1993; Priess et al. 2020). Research in Wisconsin found that sulfentrazone applied PRE reduced soybean canopy growth at V2 by 22% compared with the untreated control, due to cool, wet environmental conditions (Arsenijevic et al. 2021). Herbicides belonging to WSSA Group 15 are often considered to be safer to soybean (Osborne et al. 1995) than WSSA Group 5 and 14 herbicides (Taylor-Lovell et al. 2001) when applied PRE however, reduced crop safety has been observed in WSSA Group 5, 14 and 15 herbicides when temperatures were cooler and high amounts of rainfall had occurred (Poston et al. 2008). Although early season injury is common from PRE herbicides, it often has been reported to have no impact on soybean yield (Arsenijevic et al. 2021, 2022; Norsworthy 2004).

Soybean planting date is one of the first decisions a producer makes in the spring and has been demonstrated to consistently affect soybean yield (Kessler et al. 2020; Oplinger and Philbrook 1992; Robinson et al. 2009; Siler and Singh 2023). Studies throughout the Midwest have found that planting soybeans between late April and mid-May minimizes the risk of yield loss (De Bruin and Pedersen 2008; Mourtzinis et al. 2017; Robinson et al. 2009). Similarly, research specific to Michigan indicates that delaying soybean planting beyond mid-May can result in significant yield loss, with an average of 131 kg ha^{-1} wk^{-1} between mid-May and early June, and 326 kg ha^{-1} wk^{-1} between early and late June (Siler and Singh 2023). Planting soybeans earlier advances the onset of vegetative and reproductive stages, allowing for earlier accrual of reproductive nodes, and induction of flowering (Bastidas et al. 2008).

As weather conditions continue to change, planting soybeans earlier than the current standard in Michigan and throughout the Midwest could be a valuable tactic to spread out a producer's spring workload and limit the yield loss due to inclement weather delays in the typical planting window. Although PRE herbicides reduce early-season weed competition and extend the period before a POST application must be made, soybean injury is still a concern in weather conditions associated with early to mid-April. Therefore, the objectives of this research were to 1) evaluate the effectiveness of six PRE herbicide programs in soybean planted in early to mid-April versus 4 wk later, and 2) determine if delaying PRE herbicide applications in early planted soybean just prior to soybean emergence would provide longer residual weed control without increasing crop injury.

Methods and Materials

Field experiments were conducted at the Michigan State University (MSU) farm in East Lansing, Michigan in 2022 (MSU-22 = 42.685556º N, -84.488056º W) and 2023 (MSU-23 = 42.70515º N, -84.46886º W) and at the Saginaw Valley Research and Extension Center (SVREC) near Richville, Michigan in 2022 (SVREC-22 = 43.39472º N, -83.67861º W) and 2023 (SVREC-23 = 43.39553º N, -83.67805º W). Soybeans were planted under conventional tillage conditions. Fields were chisel plowed in the fall and soil finished twice in the spring. Soil characteristics for each site-year can be found in Table 2.1.

All experiments were arranged in a randomized complete block, split-plot design with four replications. Plot sizes ranged from 3 m wide x 9 to 12 m long. The main plot factor was soybean planting date, and the subplot factor was PRE herbicide treatment. The main plots included two planting dates: mid-April or as soon as field soil conditions were conducive for field operations (Early), and 4 wk after the early planting, near the regionally targeted planting window in the second wk of May (Normal). Glyphosate, glufosinate, and 2,4-D-resistant soybean 'P24T35E' or 'P25A16E' (Enlist E3®; Corteva Agriscience, Indianapolis, IN) were planted in 76 cm rows with a four-row John Deere MaxEmerge2 vacuum planter (John Deere, Moline, IL) at 370,650 seeds ha^{-1} in 2022 and 2023, respectively. Soybean seed had a full spectrum seed treatment including oxathiapiprolin (Lumisena® Fungicide; Corteva Agriscience, Indianapolis, IN), penflufen + prothioconazole + metalaxyl (Evergol Energy® Fungicide; Bayer Crop Science, St. Louis, MO), *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 fluopyram (ILEVO® Fungicide/Nematicide; BASF Corporation, Research Triangle Park, NC). The subplots included six different PRE herbicide treatments that were applied immediately after each planting. Since soybeans have been found to require ~130 growing degree days (GDD) for emergence to occur (Gauck 2019), four of the PRE herbicides were also applied as a delayed PRE (DPRE) 80 GDDs (base 10 C) after planting, in the early planted soybean only. All PRE and DPRE treatments received a POST herbicide application when the average weed height was ~10 cm tall. Herbicide applications were made with a tractor-mounted compressed air sprayer calibrated to deliver 177 L ha^{-1} at 207 kPa of pressure using AIXR 11003 nozzles (TeeJet Spraying Systems CO., Wheaton, IL). Untreated as well as weed-free controls were included in all experiments. Dates of all field operations can be found in Table 2.1. Herbicide treatments, rates, and manufacturer information can be found in Table 2.2.

Data Collection. Soybean stand was assessed by counting the number of plants in 6 m of row when soybean had two fully developed trifoliate leaves (V2). Soybean injury was evaluated at 14 and 28 d after crop emergence, and weed control was evaluated at the time of POST herbicide application which occurred 8-9 and 5-7 wk after planting in the early and normal planted soybean, respectively. Soybean injury and weed control were evaluated on a scale of 0 to 100%, with 0 indicating no crop injury or weed control and 100 meaning complete crop and weed death. Weed species evaluated at MSU included: common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), giant foxtail (*Setaria faberi* Hermm.), and velvetleaf (*Abutilon theophrasti* Medik.). At SVREC the predominant weed species was common lambsquarters. Weed densities of the untreated controls for each planting date at the time of POST herbicide application are listed in Table 2.3. Weed counts and aboveground weed biomass were collected from two 0.25 m^2 quadrats per plot at the time of POST herbicide application and soybean harvest. Biomass samples were placed in a 65 C dryer for 7 d and dry weed biomass was recorded for each sample. The center two rows of soybean for each plot were harvested using a small-plot research combine (Massey-Ferguson 8XP, AGCO, Duluth, GA) with a 1.5-m header. Soybean yields were adjusted to 13% moisture.

Growing degree day (GDD) and rainfall data were collected throughout the growing season from the nearest weather station to each research location from the Michigan Automated Weather Network (https://mawn.geo.msu.edu, Michigan State University, East Lansing, MI) (Table 2.4).

Statistical Analysis. Statistical analysis was performed using PROC MIXED in SAS 9.4 (SAS Institute Inc., Cary, NC). The statistical model to compare the early and normal planted soybeans consisted of planting date, herbicide treatment, and their interactions as fixed effects. Additionally, the model for the effects of application timing in the early planted soybean consisted of PRE herbicide application timing and PRE treatment. Replications were used as an error term for testing the effects of site-year. Replications and replication nested within site-year were considered random effects when data were combined over site-years. Soybean stand, injury, and soybean yield data were analyzed separately for MSU-22 and combined across the other three site-years. Weed control data for all species except for common ragweed were combined across applicable site-years. Weed biomass data at the time of POST herbicide application and soybean harvest were combined across all site-years. Normality and unequal variance assumptions were checked using PROC UNIVARIATE and examining the residuals' histogram, normal probability plots, and side-by-side box plots. Further assessment of the unequal variance assumption was conducted with Levene’s Test. When interactions were not significant, data was combined over main effects. Treatment means were separated using Fisher’s Protected LSD at $\alpha \leq 0.05$.

Results and Discussion

Early-Season Soybean Establishment. Early planted soybean emerged 25-30 d after planting, while soybean planted at the normal time emerged 11-14 d after planting (data not shown). The effects of planting date on soybean establishment and stand were similar in all site-years except MSU-22. At this site, soybean stand was 25% lower when soybeans were planted early compared with those planted at normal time (Table 2.5). However, soybean stand was not different between planting dates in the other three site-years. Differences in soybean stand between early and normal planted soybean at MSU-22 were largely due to conditions during soybean emergence. During the 30 d between early soybean planting and emergence, 102 mm of rainfall occurred at MSU-22 (Table 2.4). This resulted in the development of severe soil surface crusting and poor emergence conditions. When high amounts of precipitation occur soon after planting and emergence is delayed by cool temperatures, the formation of a crust on the soil surface has been reported to reduce harvest stands by 50% (DeWerff et al. 2015). Similarly, Schmitz & Kandel (2021) observed significant stand reductions when planting soybeans earlier than the standard, due to poor seeding and emergence conditions caused by heavy precipitation. The main effect of PRE herbicide did not reduce soybean stand compared with the weed-free control in all site-years. Delaying PRE herbicide applications in early planted soybean reduced soybean stand an additional 9% at MSU-22, regardless of PRE herbicide (Table 2.6). The negative effects of delayed PRE herbicide applications on soybean stand were not observed in the other three site-years.

Soybean injury from PRE herbicides was dependent on planting date and herbicide treatment (Table 2.7). At 14 d after emergence (DAE), there was a planting date by PRE herbicide treatment interaction for all site-years. Soybean injury was the highest at MSU-22, and all treatments in the early planting had between 20-31% injury (Table 2.7). Averaged across the other three site-years, soybean injury was significantly lower, but the highest injury was from flumioxazin (20%) and metribuzin + flumioxazin (18%) in the early planted soybean. Injury 14 DAE in the normal planted soybean was minimal with 9% or less, in all site-years. By 28 DAE soybean injury was less than 10 and 5% at MSU-22 and the other three site-years, respectively (data not shown). Higher crop injury in the early planted soybean can be explained by cooler, wet growing conditions compared with the normal planting date (Table 2.4). Cool, wet growing conditions create an environment conducive for crop injury due to slower soybean metabolism, and slower microbial degradation of soil-applied herbicides (Arsenijevic et al. 2022; Niekamp et al. 1999). Similarly, Poston et al. (2008) reported noticeable soybean injury from s-metolachlor (11%), metribuzin (16%), and flumioxazin (31%) when growing conditions were cool, and 78 mm of rainfall had occurred with 15 d of planting.

In the early planted soybean, delaying PRE herbicide applications further reduced crop safety (Table 2.6). Pooled across PRE herbicides, soybean injury 14 DAE from delayed PRE applications, was 8 and 2% higher compared with PRE at MSU-22 and the other three site-years, respectively. Additionally, averaged across application timing flumioxazin resulted in the highest injury 14 DAE in the early planted soybean with injury of 42% at MSU-22, and 22% at the other three site-years. However, by 28 DAE injury from delayed PRE applications was less than 12% at MSU-22 and less than 4% at the other three site-years (data not shown). Reduced crop safety from delayed PRE applications can be attributed to a higher concentration of herbicide being available for soybean uptake closer to emergence. Reduced crop safety of PRE herbicides belonging to WSSA Group 5, 14 and 15 has been reported when applied closer to soybean emergence (Priess et al. 2020).

Weed Control at POST Herbicide Application.

Common lambsquarters. Common lambsquarters control at the time of POST herbicide application was 82 and 78% in the early and normal planted soybean, respectively, averaged across PRE herbicides (Table 2.5). The main effect of PRE herbicide treatment resulted in 92 to 97% common lambsquarters control in all treatments, except for s-metolachlor (76%) and pyroxasulfone (83%). The main effect of application timing resulted in minimal control differences with 2% higher control from the PRE compared with the delayed PRE herbicide applications in early planted soybean (Table 2.8). Averaged across application timing, flumioxazin and metribuzin provided excellent common lambsquarters control (96-97%), while s-metolachlor and pyroxasulfone provided only 72 and 79% control, respectively. Lower control of common lambsquarters with Group 15 herbicides in this study is similar to findings of previous research (Odero and Wright 2013).

Common ragweed. Common ragweed control differed between MSU-22 and MSU-23 and there was an interaction between planting date and PRE herbicide treatment at both locations (Table 2.7). Control from effective broadleaf PRE herbicide treatments (WSSA Group 5/14), at MSU-22 ranged from 83-98% and 97-100% in the early and normal planted soybean, respectively. Lower control in the early planting at MSU-22 could be a result of high and moderate amounts of rainfall in April and May, encouraging herbicide dissipation and new weed emergence (Table 2.4). High amounts of precipitation can reduce herbicide persistence, resulting in reduced residual control and more weed escapes (Johnson et al. 2012; Oliver et al. 1993; Priess et al. 2020). Interestingly, control in the combination treatment of saflufenacil + metribuzin + pyroxasulfone, was not different between the early and normal planting dates with control of 98 and 100%, respectively. Regardless of planting date, the lowest control of common ragweed was observed in s-metolachlor and pyroxasulfone treatments. Though activity of WSSA Group 15 herbicides on large-seeded broadleaves is limited, pyroxasulfone provided 63 and 80% control compared with 51 and 56% from s-metolachlor in the early and normal planting, respectively. Similarly, previous research has indicated that pyroxasulfone provides better control of large-seeded broadleaf species such as common ragweed and velvetleaf compared to s-metolachlor (Geier et al. 2006; Knezevic et al. 2009). Control of common ragweed was similar in most treatments across planting date at MSU-23 (Table 2.7). Differences in control were not present between planting date for all effective single active ingredient PRE herbicide treatments and greatest control was from metribuzin (76-82%) and flumioxazin (70-73%). However, control of common ragweed was higher in the early planted soybean from tank mixes of metribuzin + flumioxazin and saflufenacil + metribuzin + pyroxasulfone with 85 and 93% control compared with 70 and 80% in the normal planting, respectively.

Delaying PRE herbicide applications improved common ragweed control at MSU-22 by 8% for flumioxazin and 10% for metribuzin, but reduced control of s-metolachlor by 8% and pyroxasulfone by 20% compared with PRE applications (Table 2.8). Between planting and the delayed PRE application 82 mm of rainfall had occurred. This may have resulted in longer residual control of flumioxazin and metribuzin when the PRE application was delayed. Furthermore, both metribuzin and flumioxazin have foliar activity unlike s-metolachlor and pyroxasulfone, which may have controlled newly emerged common ragweed. In contrast, there was no advantage of delaying the PRE herbicide application at MSU-23, where control was reduced in all delayed treatments at this site (Table 2.8). Decreased efficacy of delayed PRE applications at MSU-23 may be due to higher common ragweed pressure (Table 2.3) and lower initial soil moisture when delayed applications were made (Table 2.4).

Giant foxtail. Averaged across two site-years, giant foxtail control was higher in the early planted soybean compared with the normal planting time for most treatments (Table 2.7). Treatments in the early planting, that included s-metolachlor or pyroxasulfone had the greatest giant foxtail control ranging from 95-100% at the time of POST application. Control in the normal planted soybean was similar for pyroxasulfone (86%), however control from s-metolachlor was lower with 88% control compared to 100% in the early planted soybean. Giant foxtail control was not affected by the delayed PRE applications of s-metolachlor and pyroxasulfone in early planted soybean (Table 2.8). Giant foxtail is not an early emerging species, with 50% emergence occurring by approximately 245 growing degree days (Werle et al. 2014). These applications were likely made and incorporated into the soil solution before any significant giant foxtail emergence had occurred.

Velvetleaf. Overall, velvetleaf densities were low in this research (Table 2.3). Velvetleaf control was not different between early and normal planted soybean and was greatest with treatments that contained metribuzin (Table 2.5). However, there was an interaction between application timing and PRE herbicide treatment on velvetleaf control (Table 2.8). Delayed PRE applications of s-metolachlor and pyroxasulfone resulted in 5 and 14% lower velvetleaf control, respectively, compared with PRE applications.

POST herbicide applications occurred 8-9 wk after planting (WAP) in the early and 6-7 WAP in the normal planted soybean. Weed control of large seeded broadleaf species such as common ragweed seemed to be more responsive to varying amounts of incorporating rainfall. MSU-22 received 60 and 39 mm of rainfall in the 7d before and after application in the early and normal planted soybean, respectively. However, rainfall at MSU-23 7 d before and after application was much less with 12 and 4 mm in the early and normal planting, respectively

(Table 2.4). Stewart et al. (2010) reported PRE herbicides that rely on precipitation for incorporation may have reduced efficacy when rainfall is low 7 d before and after application. Furthermore, PRE herbicides have been shown to have better efficacy on large-seeded broadleaf weeds specifically, when higher amounts of precipitation have occurred within 1 wk of application (Taylor-Lovell et al. 2002). Although velvetleaf is a larger seeded broadleaf weed species, pressure was relatively low therefore significant differences in control across years were not observed. Accounting for incorporation into the soil and the general selectivity of the PRE herbicide treatments, soil-applied herbicide programs were effective on susceptible species when sufficient rainfall occurred.

Total Weed Biomass. Though control of individual weeds were site specific for common ragweed, trends in total weed biomass were consistent, therefore data were combined across site-years. Total weed biomass at POST herbicide application was 52% lower in the normal compared with early planted soybean in the untreated control (Table 2.7). Later planting allows for control of early emerging weed species with tillage, such as common lambsquarters and common ragweed which were present in this research (Coulter and Nafziger 2007; Werle et al. 2014). All PRE herbicides reduced weed biomass by 73% or more in the early planting with the exception of s-metolachlor which only reduced weed biomass by 32%. This was a result of higher weed densities in the early planting and limited activity of s-metolachlor on broadleaf weeds such as common ragweed, common lambsquarters and velvetleaf. Biomass reductions in the normal planted soybean were similar across all PRE herbicides and reduced biomass by 67% or more compared with the untreated control. Delaying PRE herbicide application in the early planted soybean did not result in higher weed biomass reductions compared to PRE application and provided similar reductions across application timing for all herbicides, except pyroxasulfone (Table 2.8). Delaying the PRE application of pyroxasulfone resulted in a 3.3-fold increase in weed biomass. Pyroxasulfone has some activity on large seeded broadleaf weeds (Nakatani et al. 2016) however, when applications were delayed these weed species had likely germinated prior to herbicide incorporation resulting in common lambsquarters and common ragweed escapes.

Weed Biomass at Harvest and Soybean Yield. The POST application of glyphosate + 2,4-D choline reduced weed biomass at soybean harvest by 89-99% following all PRE herbicide treatments compared with the untreated controls across soybean planting date, and PRE application timing (Table 2.9-10).

Planting soybeans early did not result in higher yields in any site-year (Table 2.9). The main effect of planting date influenced soybean yield at MSU-22 and was 2,868 kg ha^{-1} in the early compared with 3,389 kg ha^{-1} in the normal planting date (Table 2.9). Additionally, averaged across planting date soybean yield was 18% lower for metribuzin + flumioxazin compared with the weed-free control. Delaying the PRE herbicide application at MSU-22 resulted in 277 kg ha^{-1} lower soybean yield compared with the PRE application in the early planted soybean (Table 2.10). Similarly, Poston et al. (2008) reported yield losses of up to 13% due to high amounts of crop injury, which was observed in both PRE and delayed PRE applications at MSU-22 in the early planted soybean. In contrast, DeWerff et al. (2015) did not observe yield reductions across planting dates even with substantial soybean stand loss when planted early. It appears that the combination of emergence stress, PRE herbicide injury and stand loss due to initial soil surface crusting may have acted in concert to reduce soybean yield at this location.

Soybean yield was not different between planting dates or application timing at the other three site-years and ranged from 4,071 to 4,177 kg ha^{-1} (Table 2.9-10). Higher soybean yield in the three site-years can be attributed to higher amounts of rainfall in July and August compared to MSU-22, in which time pod and seed set occurred (Table 2.4). These results are similar to research conducted in Wisconsin in which higher yields across years were attributed to increased rainfall in yield impactful reproductive stages (Arsenijevic et al. 2022). The effects of planting soybean early for higher soybean yield reported by many others was not observed in this study, even under favorable emergence and growing conditions (Arsenijevic et al. 2022; Schmitz and Kandel 2021). However, research conducted in Michigan reported similar findings to our results, where planting soybean by mid-May in Michigan resulted in the highest soybean yield but did not observe any further yield increase from planting in late April (Siler and Singh 2023). Similarly, De Bruin and Pedersen (2008) reported higher soybean yield in Iowa for soybean planted in late April and early May compared with late May and early June. It is likely that the lack of yield increases from planting soybean early was due to the normal planting date occurring at near optimal time with little yield loss potential. The main effect of PRE herbicide resulted in 451 kg ha^{-1} lower yield in the s-metolachlor treatment compared with the weed-free, regardless of planting date (Table 2.9). Lower soybean yield in the s-metolachlor treatment can be attributed to the lack of broadleaf weed control from this treatment and early season weed competition. Weed competition as early as V1 has been shown to negatively affect soybean yield (Green-Tracewicz et al. 2012).

In conclusion, planting soybean earlier than the current standard will allow producers to spread out their spring workload and maximize the number of days to conduct field operations. However, extending the growing season into early April comes with risk. When heavy precipitation occurred soon after early planting, soil crusting had a significant effect on soybean stand. Additionally, the cool, wet soil conditions associated with planting soybeans early reduced the crop safety of most PRE herbicides. However, this injury did not affect soybean yield in three of four site-years. Preemergence herbicides controlled susceptible weed species when sufficient incorporating rainfall occurred and reduced the effects of weed competition on soybean yield. Delaying PRE herbicide applications further reduced crop safety and did not consistently improve residual weed control. Utilizing an effective PRE herbicide was equally important in the early and normal planted soybean for a complete weed control program. For example, when s-metolachlor was applied PRE in an early season environment with high pressure of large seeded broadleaf species, weed biomass was only reduced by 32% at the time of POST herbicide application. This resulted in 10% lower soybean yield compared with the weed-free in three of four site-years, regardless of planting date. Planting soybeans earlier than the current standard (i.e. early- to mid-April) will give producers an additional option to adjust to more variable weather conditions and avoid delayed planting and the penalties associated with planting delays. Even with increased risk for crop injury, applying an effective PRE herbicide treatment according to the weed species present is paramount, and these applications should not be delayed. Combining early soybean planting with a complete weed control program including an effective PRE herbicide, followed by a timely POST application will allow producers to limit delays in planting and optimize soybean yield and overall profitability.

LITERATURE CITED

Arsenijevic N, De Avellar M, Butts L, Arneson NJ, Werle R (2021) Influence of sulfentrazone and metribuzin applied preemergence on soybean development and yield. Weed Technol 35:210–215

Arsenijevic N, DeWerff R, Conley S, Ruark M, Werle R (2022) Influence of integrated agronomic and weed management practices on soybean canopy development and yield. Weed Technol 36:73–78

Bastidas AM, Setiyono TD, Dobermann A, Cassman KG, Elmore RW, Graef GL, Specht JE (2008) Soybean Sowing Date: The Vegetative, Reproductive, and Agronomic Impacts. Crop Science 48:727–740

Breaux EJ (1986) Identification of the initial metabolites of acetochlor in corn and soybean seedlings. J Agric Food Chem 34:884–888

Coulter JA, Nafziger ED (2007) Planting Date and Glyphosate Timing on Soybean. Weed Technology 21:359–366

De Bruin JL, Pedersen P (2008) Soybean Seed Yield Response to Planting Date and Seeding Rate in the Upper Midwest. Agronomy Journal 100:696–703

DeWerff RP, Conley SP, Colquhoun JB, Davis VM (2015) Weed Control in Soybean as Influenced by Residual Herbicide Use and Glyphosate-Application Timing Following Different Planting Dates. Weed technol 29:71–81

Gauck S (2019) Agronomy Talk: Corn and Soybean Early-Season Emergence. https://www.beckshybrids.com/resources/agronomy-talk/agronomy-talk-corn-and-soybean-early-season-emergence. Accessed March 20, 2024

Geier PW, Stahlman PW, Frihauf JC (2006) KIH-485 and *S* -metolachlor Efficacy Comparisons in Conventional and No-Tillage Corn. Weed technol 20:622–626

Gongora-Canul CC, Leandro LFS (2011) Effect of Soil Temperature and Plant Age at Time of Inoculation on Progress of Root Rot and Foliar Symptoms of Soybean Sudden Death Syndrome. Plant Disease 95:436–440

Green-Tracewicz E, Page ER, Swanton CJ (2012) Light Quality and the Critical Period for Weed Control in Soybean. Weed sci 60:86–91

Griffin JL, Habetz RJ (1989) Soybean (Glycine max) Tolerance to Preemergence and Postemergence Herbicides. Weed Technology 3:459–462

Hammond RB, Cooper RL (1993) Interaction of planting times following the incorporation of a living, green cover crop and control measures on seedcorn maggot populations in soybean. Crop Protection 12:539–543

Heap I (2024) The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed January 30, 2024

Jaworski EG (1969) Analysis of the mode of action of herbicidal .alpha.-chloroacetamides. J Agric Food Chem 17:165–170

Johnson WG, Chahal GS, Regehr DL (2012) Efficacy of Various Corn Herbicides Applied Preplant Incorporated and Preemergence. Weed technol 26:220–229

Kessler A, Archontoulis S v., Licht M a. (2020) Soybean yield and crop stage response to planting date and cultivar maturity in Iowa, USA. Agronomy Journal 112:382–394

Knake EL, Appleby AP, Furtick WR (1967) Soil Incorporation and Site of Uptake of Preemergence Herbicides. Weeds 15:228

Knezevic SZ, Datta A, Scott J, Porpiglia PJ (2009) Dose–Response Curves of KIH-485 for Preemergence Weed Control in Corn. Weed technol 23:34–39

Knezevic SZ, Pavlovic P, Osipitan OA, Barnes ER, Beiermann C, Oliveira MC, Lawrence N, Scott JE, Jhala A (2019) Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. Weed Technol 33:393–399

Kukal MS, Irmak S (2018) U.S. Agro-Climate in 20th Century: Growing Degree Days, First and Last Frost, Growing Season Length, and Impacts on Crop Yields. Sci Rep 8:6977

Marvel K, Su W, Delgado R, Aarons S, Chatterjee A, Garcia ME, Hausfather Z, Hayhoe K, Hence DA, Jewett EB, Robel A, Singh D, Tripati A, Vose RS (2023) Climate trends. Washington, DC, USA: U.S. Global Change Research Program

Mourtzinis S, Gaspar AP, Naeve SL, Conley SP (2017) Planting Date, Maturity, and Temperature Effects on Soybean Seed Yield and Composition. Agronomy Journal 109:2040–2049

Mueller TC, Boswell BW, Mueller SS, Steckel LE (2014) Dissipation of Fomesafen, Saflufenacil, Sulfentrazone, and Flumioxazin from a Tennessee Soil under Field Conditions. Weed Science 62:664–671

Nakatani M, Yamaji Y, Honda H, Uchida Y (2016) Development of the novel pre-emergence herbicide pyroxasulfone. Journal of Pesticide Science 41:107–112

Niekamp JW, Johnson WG, Smeda RJ (1999) Broadleaf Weed Control with Sulfentrazone and Flumioxazin in No-Tillage Soybean (Glycine max). Weed Technology 13:233–238

Norsworthy JK (2004) Soil-applied herbicide use in wide- and narrow-row glyphosate-resistant soybean (Glycine max). Crop Protection 23:1237–1244

Odero DC, Wright AL (2013) Comparison of Pyroxasulfone, S-metolachlor, and Mesotrione for Weed Control in Sweet Corn on Organic Soils. Crop manag 12:1–8

Oliveira MC, Feist D, Eskelsen S, Scott JE, Knezevic SZ (2017) Weed Control in Soybean with Preemergence- and Postemergence-applied Herbicides. Crop, Forage & Turfgrass Management 3:cftm2016.05.0040

Oliver LR, Klingaman TE, McClelland M, Bozsa RC (1993) Herbicide Systems in Stale Seedbed Soybean (Glycine max) Production. Weed Technology 7:816–823

Oplinger E s., Philbrook B d. (1992) Soybean Planting Date, Row Width, and Seeding Rate Response in Three Tillage Systems. Journal of Production Agriculture 5:94–99

Osborne BT, Shaw DR, Ratliff RL (1995) Soybean (Glycine max) Cultivar Tolerance to SAN 582H and Metolachlor as Influenced by Soil Moisture. Weed Science 43:288–292

Poston DH, Nandula VK, Koger CH, Matt Griffin R (2008) Preemergence Herbicides Effect on Growth and Yield of Early-Planted Mississippi Soybean. Crop Management 7:1–14

Priess GL, Norsworthy JK, Roberts TL, Gbur EE (2020) Weed control and soybean injury from preplant vs. preemergence herbicide applications. Weed Technol 34:718–726

Reddy KN (2001) Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. Weed Biology and Management 1:193–202

Robinson AP, Conley SP, Volenec JJ, Santini JB (2009) Analysis of High Yielding, Early-Planted Soybean in Indiana. Agronomy Journal 101:131–139

Salzman FP, Renner KA (1992) Response of Soybean to Combinations of Clomazone, Metribuzin, Linuron, Alachlor, and Atrazine. Weed Technology 6:922–929

Schmitz PK, Kandel HJ (2021) Individual and Combined Effects of Planting Date, Seeding Rate, Relative Maturity, and Row Spacing on Soybean Yield. Agronomy 11:605

Serrano M, Robertson AE (2018) The Effect of Cold Stress on Damping-Off of Soybean Caused by *Pythium sylvaticum*. Plant Disease 102:2194–2200

Siler TB, Singh MP (2023) Soybean seeding rate and seed treatment that maximize yield and profitability based on planting date. Agronomy Journal 115:759–769

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and Soil Conditions Influence Pre- and Postemergence Herbicide Efficacy in Soybean. Weed Technology 24:234–243

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence Flumioxazin and Pendimethalin and Postemergence Herbicide Systems for Soybean (Glycine max) [1]. Weed Technology 16:502–511

Taylor-Lovell S, Wax LM, Nelson R (2001) Phytotoxic Response and Yield of Soybean (*Glycine max*) Varieties Treated with Sulfentrazone or Flumioxazin [1]. Weed Technology 15:95–102

USDA-NASS (2023) Soybeans-Progress, measured in pct planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/FD7F25B2-D751-3B3F-9B2C-22BEB14059C4. Accessed February 15, 2024

USDA-NASS (2024) Soybeans - Acres Planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/75D59937-EC6F-3CE3-8542-0F82121309A7. Accessed February 22, 2024

Werle R, Sandell LD, Buhler DD, Hartzler RG, Lindquist JL (2014) Predicting Emergence of 23 Summer Annual Weed Species. Weed sci 62:267–279

Wise K, Kandel Y, Young B, Johnson B, Legleiter T (2015) Soybean seedling damage: is there an interaction between the ILeVO seed treatment and pre-emergence herbicides? Integrated Crop Management News: Iowa State University

Yan H, Nelson B (2022) Effects of Soil Type, Temperature, and Moisture on Development of Fusarium Root Rot of Soybean by *Fusarium solani* (FSSC 11) and *Fusarium tricinctum*. Plant Disease 106:2974–2983

Zeiss MR, Pedigo LP (1996) Timing of Food Plant Availability: Effect on Survival and Oviposition of the Bean Leaf Beetle (Coleoptera: Chrysomelidae). Environmental Entomology 25:295–302

APPENDIX A: CHAPTER II TABLES

Table 2.1. Enlist E3® soybean varieties, planting dates, herbicide application dates, and soybean harvest dates for the four field experiments.

	Sites[a]			
	MSU-22	MSU-23	SVREC-22	SVREC-23
Soybean variety[b]	P24T35E	P25A16E	P24T35E	P25A16E
Early planting date	April 21	April 12	April 20	April 13
PRE	April 22	April 14	April 20	April 14
DPRE	May 5	April 20	May 5	April 19
POST	June 20	June 13	June 24	June 19
Normal planting date	May 20	May 9	May 19	May 11
PRE	May 20	May 9	May 19	May 12
POST	June 28	June 23	July 7	June 19
Soybean harvest	October 24	October 20	October 11	October 8
Soil series	Conover loam	Marlette fine sandy loam	Tappan-Londo loam	Tappan-Londo loam
Soil type	clay loam	clay loam	clay loam	clay loam
Soil pH	7.4	6.8	7.9	7.5
Organic matter (%)	2.7	2.3	2.4	3.2

[a] Abbreviations: MSU = Michigan State University (East Lansing, MI); SVREC = Saginaw Valley Research and Extension Center (Richville, MI); PRE = preemergence; DPRE = delayed preemergence; POST = postemergence.
[b] Pioneer, Corteva Agriscience, Indianapolis, IN.

Table 2.2. Herbicide products, application rates and timings, and manufacturer information for weed control treatments.

Common name	Trade name	SOA[a]	Rates	Timings	Manufacturer[b]
			kg ai or ae ha^{-1}		
s-metolachlor	Dual II Magnum	15	2.14	PRE, DPRE	Syngenta Crop Protection
metribuzin	Dimetric DF	5	0.42	PRE, DPRE	WinField Solutions
flumioxazin	Valor SX	14	0.09	PRE, DPRE	Valent U.S.A. LLC
pyroxasulfone	Zidua SC	15	0.15	PRE, DPRE	BASF Corporation
metribuzin + flumioxazin	Dimetric DF + Valor SX	5/14	0.32 + 0.07	PRE	WinField + Valent
saflufenacil + metribuzin + pyroxasulfone	Sharpen + Dimetric DF + Zidua SC	14/5/15	0.02 + 0.32 + 0.15	PRE	BASF + WinField + BASF
glyphosate + 2,4-D choline + AMS	Roundup PowerMax 3 + Enlist One + Actamaster	9/4	1.35 + 1.06 + 2% w w^{-1}	POST	Bayer + Corteva + Loveland

[a] Abbreviations: SOA = WSSA site of action group; PRE = preemergence; DPRE = delayed preemergence; POST = postemergence; AMS = ammonium sulfate.

[b] Manufacturer information: BASF Corporation, Research Triangle Park, NC; Bayer Crop Science, St. Louis, MO; Corteva Agriscience, Indianapolis, IN; Loveland Products Inc., Loveland, CO; Syngenta Crop Protection LLC, Greensboro, NC; Valent U.S.A. LLC, San Ramon, CA; WinField Solutions, LLC, St. Paul, MN.

Table 2.3. Densities of weed species present at the time of POST herbicide application in the untreated controls in both soybean planting dates for all four site-years.

Planting Date	MSU-22	MSU-23	SVREC-22	SVREC-23
Early		plants m^{-2}		
Common lambsquarters	19	11	8	50
Common ragweed	13	55	-	-
Giant foxtail	47	4	-	-
Velvetleaf	4	1	-	-
Normal				
Common lambsquarters	19	3	3	14
Common ragweed	4	12	-	-
Giant foxtail	21	4	-	-
Velvetleaf	1	1	-	-

Table 2.4. Monthly[a] rainfall, GDDs[b] and the 30-year mean rainfall[c] for the four site-years.

	MSU-22		MSU-23		SVREC-22		SVREC-23		30-year average rainfall	
Month	Rainfall	GDD[d]	Rainfall	GDD	Rainfall	GDD	Rainfall	GDD	MSU	SVREC
	— mm —	— 10 C —	— mm —	— 10 C —	— mm —	— 10 C —	— mm —	— 10 C —	—— mm ——	
April	98 (56)[e]	109 (65)[g]	88 (33)	150 (99)	61 (19)	109 (70)	78 (31)	166 (100)	90	75
May	71 (25)[f]	387 (182)[h]	25 (10)	317 (242)	42 (14)	409 (201)	25 (9)	343 (272)	111	87
June	62	540	18	495	55	523	38	506	96	100
July	43	651	155	645	59	644	139	628	86	93
August	65	616	152	536	76	599	150	495	88	86
September	50	409	45	412	65	420	34	407	81	98
October	45	208	127	195	50	207	66	201	79	74
Total	434	2,920	610	2,750	408	2,911	530	2,746	631	613

[a] Monthly GDDs and rainfall data were collected from the closest weather station in the Michigan State University Enviroweather network (https://enviroweather.msu.edu).
[b] Abbreviations: GDDs = growing degree days.
[c] Monthly 30-year mean rainfall data were collected from the National Oceanic and Atmospheric Administration (https://www.ncei.noaa.gov/access/us-climate-normals).
[d] Growing degree days (GDD) minimum 10 C, maximum 30 C, and base 10 C.
[e] Rainfall after early planting.
[f] Rainfall after normal planting.
[g] GDDs after early planting.
[h] GDDs after normal planting.

Table 2.5. Main effects of soybean planting date and PRE herbicide treatment on soybean stand at V2 and weed control of common lambsquarters and velvetleaf at the time of POST herbicide application.

			Weed control	
	Soybean stand		Common lambsquarters	Velvetleaf
Main effects	MSU-22	3 SY[a]	4 SY	2 SY
Planting date	—— plant ha^{-1} ——		—— % ——	
Early	248,076 b[b]	284,658	82 a	83
Normal	331,144 a	282,442	78 b	84
PRE herbicide				
s-metolachlor	299,338 ab	285,445	76 e	84 d
metribuzin	311,608 a	289,111	93 c	98 ab
flumioxazin	289,973 ab	288,338	92 c	94 c
pyroxasulfone	297,400 ab	282,261	83 d	95 bc
metribuzin + flumioxazin	291,588 ab	284,347	97 ab	98 ab
saflufenacil + metribuzin + pyroxasulfone	303,536 ab	279,884	96 bc	99 a
weed-free	270,276 bc	283,530	100 a	100 a
untreated	253,162 c	275,482	0 f	0 e
Effects (p-values)				
Planting date	<0.0001	0.4414	0.0008	0.6272
PRE herbicide	0.0311	0.3241	<0.0001	<0.0001
Planting date * PRE herbicide	0.5097	0.3335	0.2451	0.2672

[a] Abbreviations: 3 SY = SVREC-22, SVREC-23, and MSU-23; 4 SY = MSU-22, MSU-23, SVREC-22, and SVREC-23; 2 SY = MSU-22 and MSU-23.
[b] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

Table 2.6. Main effects of application timing and PRE herbicide treatment on soybean stand at V2 and soybean injury 14 d after emergence (DAE), in the early planted soybean.

	Soybean stand		Soybean injury	
Main effects	MSU-22	3 SY[a]	MSU-22	3 SY
Application timing	plant ha^{-1}		%	
PRE	242,721 a[b]	285,382	24 b	7 b
Delayed PRE (80 GDD's)	219,687 b	282,545	32 a	9 a
PRE herbicide				
s-metolachlor	251,870 ab	285,109 a	26 b	8 b
metribuzin	264,141 a	288,641 a	23 b	0 c
flumioxazin	211,829 cd	287,195 a	42 a	22 a
pyroxasulfone	242,829 abc	286,342 a	21 b	3 c
weed-free	227,329 cd	286,903 a	0 c	0 c
untreated	189,225 d	269,591 b	0 c	0 c
Effects (p-values)				
Application timing	0.0173	0.3688	0.0209	0.0366
PRE herbicide	0.0005	0.0061	0.0001	<0.0001
Application timing * PRE herbicide	0.1208	0.8474	0.0728	0.1469

[a] 3 SY = SVREC-22, SVREC-23, and MSU-23; GDD = growing degree days (base 10 C).

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

Table 2.7. Interaction between planting date and PRE herbicide treatment on soybean injury 14 d after emergence (14 DAE), and giant foxtail and common ragweed control, and total weed biomass at POST herbicide application.

		Soybean injury		Weed control			Weed biomass at POST[b]
				Common ragweed		Giant foxtail	
Planting date	PRE herbicide	MSU-22	3 SY[a]	MSU-22	MSU-23	2 SY	
		%		%			g m^{-2}
Early	s-metolachlor	25 abc[c]	6 b	51 g	36 h	100 a	30 b
	metribuzin	21 bc	0 de	83 de	82 bc	84 cd	12 c
	flumioxazin	31 a	20 a	88 cd	73 de	83 cd	5 cde
	pyroxasulfone	20 c	3 cd	63 f	63 f	95 ab	9 cd
	metribuzin + flumioxazin	24 abc	18 a	91 bc	85 b	67 f	4 cde
	saflufenacil + metribuzin + pyroxasulfone	29 ab	2 cde	98 ab	93 a	99 a	1 de
	weed-free	0 e	0 e	100 a	100 a	100 a	0 e
	untreated	0 e	0 e	0 h	0 i	0 g	44 a
Normal	s-metolachlor	1 de	2 cde	56 fg	44 g	88 bc	6 cde
	metribuzin	1 de	0 cde	97 ab	76 cde	87 bc	3 de
	flumioxazin	9 d	3 cd	97 ab	70 ef	73 ef	7 cde
	pyroxasulfone	1 de	1 cde	80 de	65 f	86 bc	6 cde
	metribuzin + flumioxazin	6 de	3 bc	100 a	70 ef	76 de	3 de
	saflufenacil + metribuzin + pyroxasulfone	5 de	2 cde	100 a	80 cde	79 cde	3 de
	weed-free	0 e	0 e	100 a	100 a	100 a	0 e
	untreated	0 e	0 e	0 h	0 i	0 g	21 b
Effects (p-values)							
Planting date		<0.0001	<0.0001	<0.0001	0.0030	0.0050	<0.0001
PRE herbicide		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Planting date * PRE herbicide		0.0018	<0.0001	0.0029	<0.0001	0.0008	<0.0001

[a] Abbreviations: 3 SY = SVREC-22, SVREC-23, and MSU-23; 2 SY = MSU-22 and MSU-23.
[b] Weed biomass was combined over all four site-years.
[c] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

Table 2.8. Interaction between application timing and PRE treatment on weed control of common lambsquarters, common ragweed, giant foxtail, velvetleaf, and total weed biomass at the time of POST herbicide application.

Application timing	PRE herbicide	Common lambsquarters[a]	Common ragweed		Giant foxtail	Velvetleaf	Weed biomass at POST
		4 SY[b]	MSU-22	MSU-23	2 SY	2 SY	4 SY
		% control					$g\ m^{-2}$
PRE	s-metolachlor	77	51 f[c]	36 ef	100 a	82 c	30 bc
	metribuzin	97	83 d	82 b	85 b	96 ab	12 de
	flumioxazin	96	88 cd	73 c	83 b	94 b	5 e
	pyroxasulfone	83	63 e	63 d	95 a	97 ab	9 e
	weed-free	100	100 a	100 a	100 a	100 a	0 e
	untreated	0	0 h	0 g	0 d	0 e	44 a
Delayed PRE	s-metolachlor	67	43 g	4 g	99 a	77 d	23 cd
(80 GDD's)	metribuzin	98	93 bc	58 e	63 c	95 ab	5 e
	flumioxazin	96	96 a	65 d	68 c	99 ab	3 e
	pyroxasulfone	75	43 g	49 e	98 a	83 c	39 ab
	weed-free	100	100 a	100 a	100 a	100 a	0 e
	untreated	0	0 h	0 g	0 d	0 e	44 a
Effects (p-values)							
Application timing		0.0500	0.1787	<0.0001	<0.0001	0.0133	0.3455
PRE herbicide		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Application timing * PRE herbicide		0.0586	<0.0001	<0.0001	<0.0001	<0.0001	0.0006

[a] The main effects of application timing and PRE herbicide were significant and control of common lambsquarters was 75 and 73% in the PRE and delayed PRE applications, respectively. Flumioxazin and metribuzin provided 96-97% control, while control from s-metolachlor and pyroxasulfone was 72 and 79%, respectively.

[b] 4 SY = MSU-22, MSU-23, SVREC-22, and SVREC-23; 2 SY = MSU-22 and MSU-23; GDD = growing degree days (base 10 C).

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

Table 2.9. Main effects of soybean planting date and PRE herbicide treatment on weed biomass at soybean harvest and soybean yield.

Main effects	Weed biomass at harvest[a]	Soybean yield	
	4 SY[b]	MSU-22	3 SY
Plant date	g m^{-2}	kg ha^{-1}	
Early	43	2,868 b[c]	4,177
Normal	21	3,389 a	4,127
PRE herbicide			
s-metolachlor	20	3,282 ab	3,998 b
metribuzin	4	3,576 ab	4,370 a
flumioxazin	5	3,602 a	4,292 ab
pyroxasulfone	12	3,679 a	4,274 ab
metribuzin + flumioxazin	5	2,944 b	4,286 ab
saflufenacil + metribuzin + pyroxasulfone	1	3,167 ab	4,432 a
weed-free	0	3,610 a	4,449 a
untreated	231	1,166 c	3,118 c
Effects (p-values)			
Planting date	0.0012	0.0015	0.5810
PRE herbicide	<0.0001	<0.0001	<0.0001
Planting date * PRE herbicide	<0.0001	0.2908	0.0878

[a] The interaction of planting time and PRE treatment was significant for weed biomass. The biomass of the untreated control was 307 and 154 g m^{-2} for the early and normal plantings, respectively. Weed biomass was reduced similarly in all other treatments.
[b] Abbreviations: 4 SY = MSU-22, MSU-23, SVREC-22, and SVREC-23; 3 SY = SVREC-22, SVREC-23, and MSU-23.
[c] Means followed by the same letter in the same column are not statistically different ($\alpha \leq 0.05$).

Table 2.10. Main effects of herbicide application timing and PRE herbicide treatment on weed biomass at soybean harvest and soybean yield in the early planted soybean.

	Weed biomass at harvest	Soybean yield	
Main effects	4 SY[a]	MSU-22	3 SY
Application timing	—— $g\ m^{-2}$ ——	—— $kg\ ha^{-1}$ ——	
PRE	63	2,880 a	4,130
Delayed PRE (80 GDD's)	63	2,603 b	4,071
PRE herbicide			
s-metolachlor	33 b[b]	3,121 a	4,070 b
metribuzin	3 b	3,342 a	4,584 a
flumioxazin	18 b	2,949 a	4,451 ab
pyroxasulfone	18 b	3,270 a	4,341 ab
weed-free	0 b	3,306 a	4,402 ab
untreated	307 a	461 b	2,756 c
Effects (p-values)			
Application timing	0.9502	0.0225	0.6512
PRE herbicide	<0.0001	<0.0001	<0.0001
Application timing * PRE herbicide	0.9891	0.5942	0.9977

[a] Abbreviations: 4 SY = MSU-22, MSU-23, SVREC-22, and SVREC-23; 3 SY = SVREC-22, SVREC-23, and MSU-23; GDD = growing degree days (base 10 C).

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

CHAPTER III: IMPACT OF PLANTING DATE AND SOYBEAN ROW WIDTH ON WEED SUPPRESSION AND YIELD

Abstract

More variable weather patterns and an increase in the length of the growing season over the last couple of decades have prompted growers to plant soybeans earlier than the historical standard. An experiment was conducted over three site-years to evaluate the effects of soybean planting date, row spacing, and herbicide program on weed suppression and soybean yield. The effect of planting date on soybean establishment was limited except when heavy precipitation resulted in soil surface crusting, resulting in 44-52% lower stand in 19 cm rows compared with those planted at the normal time; however, no reductions in stand were observed in soybean planted in 38 and 76 cm rows. Weed densities and biomass at POST herbicide application were substantially higher when soybeans were planted early compared with the normal planting time in all site-years. Soybean planted in 19 cm rows (370,500 and 494,000 seeds ha^{-1}) reduced weed biomass by 29-47% compared with 76 cm rows (370,500 seeds ha^{-1}) in 2 of 3 site-years when weeds were not controlled; however, the effects of soybean row width were not observed when a PRE herbicide was applied. Similarly, narrow row widths resulted in more advanced canopy development compared with 76 cm rows in 2 of 3 site-years, where soil crusting did not affect initial soybean establishment. Regardless of row width, a PRE followed by POST herbicide program provided the most consistent weed control. Soybean yield was 7% higher for soybean planted in 19 cm rows at the high population compared with 76 cm rows in 2 of 3 site-years. However, soybean planting date did not affect soybean yield when weed control was good in all site-years. Combining narrow row widths (< 76 cm) with a complete herbicide program for an

integrated weed management system is equally beneficial for both early and normal planted soybeans.

Introduction

Trends surrounding production agriculture such as variable weather patterns, increasing farm size, and pest management require growers to adapt their production practices in an effort to maximize efficiency and profitability. Soybean (*Glycine max* (L.) Merr.) is an economically important, leguminous crop that was planted on over 0.8 million hectares in Michigan in 2023 (USDA-NASS 2024). While many variables affect soybean production, timely planting is one of the most important cultural practices that has an immense impact on soybean yield potential (De Bruin and Pedersen 2008a; Robinson et al. 2009; Siler and Singh 2023). Planting soybean beyond mid-May in Michigan can result in yield losses up to 326 kg ha^{-1} wk^{-1} (Siler and Singh 2023). Although the growing season in the upper Midwest has increased by 15 d in length in the last century, the frequency of heavy precipitation events has increased by nearly 45% since the 1950s (Kukal and Irmak 2018; Marvel et al. 2023). Thus, producers need strategies to maximize the number of days for field operations in the spring to avoid soybean planting delays.

Planting soybeans earlier than the current standard has been shown to be a promising strategy to avoid yield loss from planting delays and even increase the yield potential of soybeans (Arsenijevic et al. 2022; De Bruin and Pedersen 2008a; Robinson et al. 2009; Siler and Singh 2022). However, cool wet growing conditions associated with early planted soybean can pose establishment risks associated with poor emergence conditions (DeWerff et al. 2015; Schmitz and Kandel 2021), PRE herbicide injury (Arsenijevic et al. 2021; Poston et al. 2008; Taylor-Lovell et al. 2001), soilborne diseases (Gongora-Canul and Leandro 2011; Serrano and Robertson 2018; Yan and Nelson 2022), and increased susceptibility to pests (Hesler et al. 2018).

Under exceptionally cool and wet growing conditions often associated with early planted soybean, seed treatments (Siler and Singh 2023; Vosberg et al. 2017) and increased seeding rates (Schmitz and Kandel 2021) have aided in sufficient crop establishment. In addition to increased disease and insect pressure, increased weed interference has also been reported when soybeans are planted earlier than the current standard (Coulter and Nafziger 2007).

Early methods of weed control were dominated by tillage and interrow cultivation, thus soybeans were grown in 76 cm or wider rows for equipment accessibility following crop emergence (Wax et al. 1977). However, the development and wide adoption of synthetic herbicides provided growers added flexibility, and in turn the option to plant soybeans in narrow rows, less than 38 cm. Precision planters are often used to plant soybean in 38 and 76 cm rows, thus allowing for accurate seed placement and singulation. However, one concern with planting soybeans in 19 cm rows is less precise seed placement and singulation due to wearable seed metering components of a drill used to plant small grains (Holshouser et al. 2006). Even with less precise seed placement, narrow row soybeans have demonstrated beneficial weed suppression, advanced canopy closure, and increased light interception (Arsenijevic et al. 2022; Fisher and Sprague 2023; Harder et al. 2007; Singh et al. 2023; Steckel and Sprague 2004). Although the weed suppression benefits of narrow row soybeans are often limited when a preemergence herbicide is utilized (Fisher and Sprague 2023), using an integrated weed management program combining narrow row widths and a complete herbicide program is beneficial for sustainable weed management and soybean yield (Norsworthy et al. 2012; Schultz et al. 2015). Yield responses of soybean to narrow row widths are well documented; with much of the research indicating that soybean planted in rows less than 76 cm wide often results in increased soybean yield in the Midwest (De Bruin and Pedersen 2008b; Schmitz and Kandel

2021; Singh et al. 2023). Although, poor initial soybean establishment can negate the yield benefits of narrow row widths (Young et al. 2001).

Soybean planting date and row spacing have been shown to have a significant impact on soybean growth, canopy development and yield. However, there is little research regarding the effects of narrow row widths when soybean is planted earlier than the regional standard. Thus, the objectives of this study were to compare the effects of soybean row width and herbicide program on weed suppression and soybean yield in early versus normal planted soybean.

Methods and Materials

Field experiments were conducted at the Michigan State (MSU) Agronomy farm in East Lansing, MI in 2022 (MSU-22 = 42.685556º N, -84.4875º W) and 2023 (MSU-23 = 42.70952º N, -84.46609º W) and at the Saginaw Valley Research and Extension Center (SVREC) near Richville, MI in 2023 (SVREC-23 = 43.39556º N, -83.67865º W). Soybeans were planted under conventional tillage conditions consisting of fall chisel plowed and soil finished, and soil finished twice in the spring before each planting. Soil characteristics can be found in Table 3.1.

Experiments were arranged in a randomized complete block split-split-plot design with four replications. Plot sizes ranged from 3 m wide x 9-12 m long. The main plot factor was soybean planting time, the subplot factor was soybean row width system, and the sub-subplot factor was herbicide program. The main plot consisted of two planting times: mid-April or as soon as field soil conditions were conducive for soil cultivation and planting (Early), and approximately 4 wk after the early planting time in early-to-mid May (Normal). The sub-plot factor included four row width systems of 19 cm rows at 494,000 seeds ha^{-1}, and 19, 38, and 76 cm rows at 370,500 seeds ha^{-1}. The sub-subplots consisted of four herbicide programs, untreated or no herbicide application, preemergence application only, preemergence followed by a postemergence application, and weed-free. The preemergence herbicide (PRE) was s-metolachlor at 1.47 kg ha^{-1} + metribuzin at 0.35 kg ha^{-1} (Boundary 6.5 EC; Syngenta Crop Protection, Greensboro, NC). The PRE followed by postemergence (POST) herbicide program included s-metolachlor + metribuzin (1.47 + 0.35 kg ha^{-1}), followed by a POST application of glyphosate (Roundup PowerMax 3; Bayer Crop Science, St. Louis, MO) at 1.35 kg ae ha^{-1} + 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.06 kg ae ha^{-1} + ammonium sulfate (AMS) (Actamaster; Loveland Products, Inc., Greely, CO) at 2% w w^{-1}, when weeds were ~10 cm tall. The weed-free treatments were maintained by multiple applications of glyphosate at 1.35 kg ae ha^{-1} + AMS at 2% w w^{-1}.

Glyphosate, glufosinate, and 2,4-D-resistant soybean ‘P24T35E’ or ‘P25A16E’ (Enlist E3®; Corteva Agriscience, Indianapolis, IN) were planted in 19 cm wide rows using a John Deere 1560 no-till small grain drill, and in 38 and 76 cm rows with a split-row John Deere MaxEmerge2 vacuum planter (John Deere, Moline, IL). Soybean seed used in this study had a full spectrum seed treatment including oxathiapiprolin (Lumisena® Fungicide; Corteva Agriscience, Indianapolis, IN), penflufen + prothioconazole + metalaxyl (Evergol Energy® Fungicide; Bayer Crop Science, St. Louis, MO), *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 fluopyram (ILEVO® Fungicide/Nematicide; BASF Corporation, Research Triangle Park, NC). All herbicide applications were made with a rear tractor-mounted compressed air sprayer calibrated to apply 177 L ha^{-1}at 207 kPa of pressure using AIXR 10003 nozzles (TeeJet Spraying Systems CO., Wheaton, IL). Soybean planting, herbicide application, and soybean harvest dates can be found in Table 3.1.

Data Collection. Soybean stand was estimated by counting the number of plants in 9 and 6 m of row for 38 and 76 cm row widths, respectively, and from three 0.9 m hoop sub-samples plot^{-1} for 19 cm rows when the majority of soybeans had two fully developed trifoliate leaves (V2). Soybean injury from the PRE herbicide treatments was evaluated 14 and 28 d after crop emergence on a scale of 0 to 100%, where 0 was no crop injury and 100% was complete crop death. Weed species that were present and collected for weed biomass at MSU were common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), giant foxtail (*Setaria faberi* Hermm.), and velvetleaf (*Abutilon theophrasti* Medik.). At SVREC the predominant weed species was common lambsquarters. Individual weed species were counted, and aboveground weed biomass was harvested from two 0.25 m^2 quadrats plot^{-1} at the time of POST herbicide application and just prior to soybean harvest. Weed biomass samples were then placed into a 65 C dryer for approximately 7 d, and dry weight was recorded in grams for each sub-sample. Weed densities of the untreated controls of each planting date at the time of POST are listed in Table 3.2.

Canopy closure was measured in the weed-free treatments beginning 8 and 4 wk after planting in the early and normal planted soybeans, respectively, and measurements continued approximately every 7-10 d until the majority of plots reached 95 percent closure. Two photos were taken per plot using a smartphone (iPhone 13 Pro, Apple®) 1.2 m above the soil surface. The photos were uploaded to the mobile phone app Canopeo (Oklahoma State University, Stillwater, OK) and analyzed for percent green cover based on the ratios of R/G, B/G with thresholds of 0.95, and the excess green index with a minimum threshold of 20 (Patrignani and Ochsner 2015). The result of this analysis was a fractional green canopy closure ranging from 0, or no green canopy, and 1, or 100% green canopy cover.

Prior to harvest, 10 representative soybean plants were hand-harvested from the center rows of each plot to evaluate yield components. Reproductive branches were separated from the main stems and the total number of branches was recorded. Pods from the branches and main stems were counted separately, and seeds were removed from pods using a stationary thresher (Almaco, Nevada, IA). Total seed count, 100-seed weight, and total seed weight were measured and recorded for both reproductive branches and main stems in each plot. The number of seeds plant^{-1} for both main stem and reproductive branches was calculated by dividing the total number by 10. The removed soybean seed was adjusted to 13% moisture and added to the overall yield for each plot. The center 1.5 m of each plot was harvested at the same time for both planting dates when they had reached physiological maturity using a small-plot research combine (Massey-Ferguson 8XP, AGCO, Duluth, GA). Soybean yields are reported at an adjusted moisture of 13%.

Growing degree days (GDD) and precipitation data were collected from the nearest Michigan Automated Weather Network weather station for each trial location (https://mawn.geo.msu.edu, Michigan State University, East Lansing, MI) (Table 3.3).

Economic Analysis. The net profit of each treatment was calculated by subtracting the estimated total costs including treated soybean seed, herbicides, adjuvants, and application costs from gross income. Gross income was calculated in USD ($) ha^{-1} at two market prices $0.37 kg^{-1} ($10 bu^{-1}) and $0.55 kg^{-1} ($15 bu^{-1}). Input costs were calculated based on June 2023 price sheets from multiple agricultural input suppliers in the Midwest. The cost of 140,000 treated soybean seeds was estimated at $90. Herbicide application costs were included at a rate of $24.70 ha^{-1} application^{-1}. Total treatment costs can be found in Table 3.4.

Statistical Analysis. Statistical analysis was conducted using lmer in R v. 4.3.2 (R Development Core Team, 2023). The statistical model consisted of planting date, row width system, herbicide program, and their interactions as fixed effects. Replication and replication nested within site-year when years were combined, were considered random effects. Replications were used as an error term for testing the effects of site-year. Data from MSU-23 and SVREC-23 were combined over site-year, referred to as 2023 for all data except economic return, where all three site-years were analyzed separately. Normality and unequal variance assumptions were checked by examining the residuals' histogram, normal probability plots, and side-by-side box plots. Further assessment of the unequal variance assumption was conducted with Levene's Test. When interactions were not significant data was combined over main effects. Treatment means were separated using Tukey's HSD at $\alpha \leq 0.05$.

Canopy closure data were analyzed using the drc package in R v. 4.3.2 (R Development Core Team, 2023). As selected by the mselect function lack of fit test, followed by inspection of estimates and standard errors associated with the estimates, four-parameter Weibull 2 models (Equation 1) were fit to average percent soybean canopy closure for each planting date and row width system combination, regressed over the number of days after the respective planting date:

$$y = c + (d - c)(1 - \exp(-\exp(b(\log(x) - \log(e))))) \qquad \text{[Eq. 1]}$$

where y is the average percentage of soybean canopy cover, c is the lower limit fixed at 0, d is the upper limit fixed at 100, b is the slope, x is the number of days after planting, and e is the inflection point (Ritz et al. 2015). The time to reach 50 and 95 percent canopy closure was determined using the ED function for each planting date and row width system combination. Differences in days to 50 and 95 percent canopy cover between planting date and row width systems combinations were compared based on a t-statistic ($\alpha \leq 0.05$) using the EDcomp function. The two sites in 2023 were combined in the analysis based on lack of differences from results given by the EDcomp function for planting date and row width combinations between the two site-years.

Results and Discussion

Soybean Establishment. Environmental conditions were notably different between planting dates and years (Table 3.3). In all site-years cooler growing conditions in April resulted in early planted soybean emergence occurring 25-30 d after planting, while soybean planted at normal time emerged 9-14 d after planting. While soil conditions were conducive for soybean emergence at both sites in 2023, heavy rainfall following the early planted soybean at MSU-22 resulted in severe soil crusting (Table 3.3). These emergence conditions led to an interaction between planting date and row width system on soybean stand at MSU-22 (Figure 3.1). Soybean establishment was most affected in the early planted soybean when drilled in 19 cm rows, where stand was 27 and 29% of seeds planted in the low and high populations, respectively. Poor soil conditions such as surface crusting have been reported to reduce soybean stands by up to 50% (DeWerff et al. 2015). However, soybean stand in 38 and 76 cm row widths were similar across planting dates. Decreased seed spacing has been shown to increase soybean emergence under unfavorable soil conditions (Hyatt et al. 2007). Our observed higher soybean stand in wider row widths (38 and 76 cm) in the early planting was likely a function of reduced seed spacing allowing for a facilitated emergence effort. In 2023, soybean establishment was less affected by planting date with only 5% lower stand in the early compared with normal planted soybean (Table 3.5). Similarly, the effect of row width was less evident where the percent soybean stand was 76% or greater for all row width systems in 2023. Soybean injury 14 d after emergence from the PRE herbicide was limited, with the highest injury observed being 11 and 5% at MSU-22 and

2023, respectively, in early planted soybean (data not shown). Injury in the normal planted soybean was 4% or less in all site-years (data not shown). Cool, wet growing conditions associated with early planted soybean can result in decreased crop safety from PRE herbicides (Arsenijevic et al. 2022; Poston et al. 2008).

Early-Season Weed Suppression and Soybean Canopy Development. At the time of POST herbicide application total weed biomass in the untreated controls was 16-75% and 79-93% lower in the normal compared with early planted soybean at MSU-22 and 2023, respectively (Table 3.6). Similarly, weed numbers in the untreated controls were higher in the early compared with normal planted soybean at all site-years (Table 3.2). Delaying planting until initial weed emergence occurs allows for control of early emerging weed species such as common lambsquarters and common ragweed with tillage prior to planting (Werle et al. 2014). Lower weed biomass in the normal planted soybean in 2023 compared with MSU-22 can be attributed to limited precipitation observed in mid-late May and early June in 2023 (Table 3.3). At MSU-22, row width had little effect on weed biomass at the time of POST, and the PRE herbicide application reduced weed biomass by 51-92% and 96-100% in the early and normal planted soybeans, respectively (Table 3.6). In 2023, early planted soybean drilled in 19 cm rows, regardless of population reduced weed biomass by 29-47% compared with soybean planted in 76 cm rows, when weeds were not controlled. Narrow row widths have been shown to provide better weed suppression compared with wide rows (76 cm) through advanced canopy development and shading of the soil surface (Fisher and Sprague 2023; Harder et al. 2007; Hock et al. 2006; Steckel and Sprague 2004). However, when a PRE was applied in the early planting weed biomass was reduced by 95-100% and there was no effect of row width. Fisher and Sprague (2023) reported similar findings where the addition of a residual herbicide eliminated the weed suppression effect of narrow row widths. Low weed numbers and the lack of incorporating rainfall in 2023 resulted in no observed weed biomass reductions from the PRE herbicide in the normal planted soybean.

Common lambsquarters, common ragweed, giant foxtail and velvetleaf densities were unaffected by soybean row width (data not shown). It can be inferred that lower weed biomass from narrow row widths was a result of increased competition and not reduced weed emergence. These findings are similar to previous research that has reported lower weed biomass with narrow row widths in the absence of reduced weed density (Harder et al. 2007; Rich and Renner 2007). In contrast, some research has reported reduced horseweed and common waterhemp densities when soybeans were planted in narrow row widths (Fisher and Sprague 2023; Steckel and Sprague 2004).

The effects of row width on weed biomass in 2023 and the lack thereof at MSU-22 can be attributed to differences in soybean canopy development (Figure 3.2). At MSU-22, canopy closure reached 50% 78 d after planting for the 19 cm rows planted at the high population (Table 3.7). However, soybeans drilled in 19 cm rows at the low population required 85 d compared with 80 and 82 d for the 38 and 76 cm row widths in early planted soybean, respectively. Although the high population of drilled soybean in 19 cm rows reached 50% closure earlier than the low population and 76 cm rows, the presence of randomly distributed openings in the canopy likely negated the shading benefits on weed suppression. Similarly, Harder et al. (2007) reported delayed canopy closure in 19 cm rows when soybean populations were reduced. Soybean planted at normal time at MSU-22 reached 50% closure 50 to 51 d after planting when planted in 38 and 76 cm rows, while 19 cm rows occurred 5-6 d and 2-3 d earlier in the high and low populations, respectively. In contrast, canopy development in 2023 was much more uniform, a result of better initial soybean establishment. In the early planted soybean, 19 and 38 cm rows reached 50% closure 77-78 d after planting regardless of population, while 76 cm rows occurred 3-4 d later (Table 3.7). Similarly, the normal planted soybean in 19 (high and low) and 38 cm rows reached 50% closure 50-52 d after planting, 5-7 d before the 76 cm rows. Narrow row widths (19 and 38 cm) have been shown to consistently result in faster canopy closure compared with 76 cm rows (Arsenijevic et al. 2022; Fisher and Sprague 2023; Harder et al. 2007). The lack of weed suppression benefits observed in the normal planted soybean in all site-years is likely due to lower weed pressure and fewer days after planting to 50% closure compared with the early planted soybean, across all row widths.

Late-Season Soybean Canopy Development and Weed Suppression. While 50% canopy closure is of interest for measuring effects of early season weed suppression and crop competitiveness, 95% or near complete canopy closure can be used as a measure of crop productivity in terms of accumulation of light, season-long competitiveness with weeds, and suppression of weed species with extended emergence windows (Arsenijevic et al. 2022; Schmitz and Kandel 2021). Amongst the early planted soybean at MSU-22, 38 cm rows reached 95% canopy closure 99 d after planting while both populations of 19 cm rows and 76 cm rows occurred 103-110 d after planting (Table 3.7). In contrast, 19 and 38 cm rows, regardless of population reached 95% closure 69 to 70 d after planting which was 10 to 11 d earlier than 76 cm rows in the normal planted soybean. Canopy closure in 2023, was consistently faster for narrow row widths. Early planted soybean in narrow rows (19 and 38 cm) reached 95% canopy closure 95 d after planting, while 76 cm rows required 101 d. A similar trend in the normal planting was observed where 76 cm rows required 78 d after planting to reach 95% canopy closure which was 12 d longer than 19 and 38 cm row widths.

Although the number of days after the respective planting date provides insight to the relative rate of canopy development between the planting dates, calendar date is an important aspect to consider. When maximum canopy closure occurs earlier in the growing season soybean accumulation of light increases, which is most impactful on yield beginning in the early reproductive stages (Andrade et al. 2002; Board et al. 1992; Schmitz and Kandel 2021). The number of days after planting required for 95% closure were significantly lower in the normal planting for all site-years, however calendar date of closure differed between planting date and site-years. At MSU-22, the early planted soybean reached 95% closure between July 29 and August 9, while the normal planted soybean ranged between July 21 and August 1. Earlier canopy closure in the normal compared with the early planted soybean was likely due to lower stand establishment and stressful growing conditions early in the season at MSU-22. In 2023, narrow row widths (19 and 38 cm) achieved 95% closure July 17 across both planting dates. However, early planted soybean in 76 cm rows reached 95% closure on July 23, 6 d earlier than those planted at normal time. Fewer days required for canopy development in the normal planted soybean can be attributed to warmer soil temperatures and greater GDD accumulation during germination and early vegetative stages (Table 3.3).

At MSU-22 weed biomass at soybean harvest was not influenced by row width system and weed biomass was reduced similarly by PRE fb. POST programs compared with the weed-free (Table 3.8). Interestingly, in the normal planted soybean the PRE only treatment reduced weed biomass by 62% compared with the untreated and was similar to the PRE fb. POST and weed-free treatments. In 2023, the main effect of row width system resulted in 39% lower weed biomass in the 19 cm high population system compared with 38 and 76 cm rows (Table 3.9). However, when soybeans were planted in 19 cm rows at the low population weed biomass was similar to both 38 and 76 cm row widths. Although canopy development in 19 and 38 cm rows progressed at a similar rate in the weed-free plots, apparently the combination of decreased row width and higher population increased soybeans competitiveness with weeds. These findings are inconsistent with previous research that has found soybean planted in 19 cm rows do not benefit from increased plant populations and suppress weeds even at suboptimal populations (Rich and Renner 2007; Schultz et al. 2015). Harder et al. (2007) reported lower weed biomass when soybean populations were 296,000-309,000 plant ha^{-1}, but no reductions occurred as seeding rate was increased further. Furthermore, weed biomass was reduced similarly across planting dates by the PRE fb. POST program (99-100%); however, no reductions were observed in the normal planted PRE only program compared with the untreated (Table 3.8). In 2023, poor weed control from the PRE herbicide in the normal planting can be attributed to limited incorporating rainfall following application (Table 3.3).

Soybean Yield and Economic Return. Despite poor establishment of the early planted soybean at MSU-22, soybean yield was not reduced compared with the normal planting when a complete weed control program was utilized (i.e. PRE fb. POST, weed-free) and ranged from 3,450 to 3,571 kg ha^{-1} (Table 3.8). Soybean yield was 52 and 38% lower in the untreated and PRE only treatments when soybeans were planted early compared with normal time, consistent with observed weed biomass and competition. The early planted soybean appeared to compensate for lower populations with an increase in the number of seeds produced on the branches (Table 3.10). Averaged across row width system, the number of seeds $plant^{-1}$ on branches ranged between 1.4 to 3.6-fold higher in the early compared with normal planted soybean in all herbicide programs except for the untreated. Additionally, the main effect of planting date resulted in a 5% increase in 100-weight of branch seeds in the early compared with normal planted soybean (Table 3.11). Furthermore, seeds plant^{-1} on the main stem were similar across planting date and herbicide program, except for the PRE fb. POST where the early planted soybean had 39% more compared with soybean planted at normal time. These findings are in agreement with previous studies that have reported soybeans ability to compensate for substantial stand reductions and produce similar yields, a result of increased plant branching (Board 2000; Cox and Cherney 2011; Mourtzinis et al. 2021).

Soybean yield in 2023 was unresponsive to planting date when a complete weed control program was used and ranged from 4,681 to 4,909 kg ha^{-1} (Table 3.8). Although soybean yield was lowest in the early planted untreated soybean, the PRE only program resulted in 13% higher yield for the early compared with normal planted soybean. The effects of row width were not present at MSU-22; however, in 2023 yield was 7% higher when soybeans were planted in 19 cm rows at the high population compared with 76 cm rows when averaged across planting date and herbicide program (Table 3.9). Soybean planted at the high population in 19 cm rows had 50-54% fewer branch seeds plant^{-1} and similar main stem seeds plant^{-1} to 19 cm (low) and 76 cm row widths (Table 3.11). These findings suggest that higher observed yield was likely an effect of plant populations rather than increased individual plant performance. Previous research in Iowa reported that seeding rates above 400,000 seeds ha^{-1} can increase soybean yield, although population up to 44% lower can achieve 95% of total yield potential (De Bruin and Pedersen 2008b). Similarly, research in the northeastern U.S. indicated that yield potential of soybean in 19 cm rows was greatest at populations greater than 400,000 seeds ha^{-1} (Cox and Cherney 2011).

Soybean yield was 31 to 42% higher in 2023 compared with MSU-22 when weeds were controlled (Table 3.8). Higher yield in 2023 compared with MSU-22 can be explained by below average rainfall at MSU-22 and above average rainfall in 2023 in the months of July and August, from soybean flowering through seed fill (Table 3.3). Adequate precipitation during flowering through pod set is essential for pod development and retention, as well as during the seed fill stage for seed size (Chen and Wiatrak 2010; Veas et al. 2022). Research in Wisconsin reported yield differences across years as result of lower precipitation during seed fill (Arsenijevic et al. 2022). Total seed number was relatively similar across site-years, indicating that higher yield in 2023 was likely an effect of better stand establishment and increased seed weight (Tables 3.5 and 3.10). The absence of early planting yield benefits was likely due to the normal planting occurring within the optimal planting window. This is similar to research studies throughout the Midwest that have reported similar yield when soybean was planted from mid-April through early to mid-May (De Bruin and Pedersen 2008a; Siler and Singh 2023). Soybean yield in this study appeared to be more responsive to seeding rate rather than narrow rows. This is in contrast to much of previous research that has indicated narrow rows (< 76 cm) have increased yield potential (Cox and Cherney 2011; De Bruin and Pedersen 2008b; Schmitz and Kandel 2021; Singh et al. 2023). However, a study in Wisconsin reported early canopy closure in 38 cm row widths compared with 76 cm and observed no yield increase (Arsenijevic et al. 2022). Fisher and Sprague (2023) observed higher soybean yield in 19 cm rows in two site-years, where 75% canopy closure occurred 2.5 wk prior to 76 cm rows. The lack of observed yield benefits in narrow row widths may be due to 95% canopy closure occurring approximately 10 calendar days or less between row widths and planting dates.

Soybean program costs which included treated seed, herbicides, adjuvants, and custom application ranged from \$238 to 408 ha^{-1} and \$318 to 487 ha^{-1} for soybean planted at 370,500 and 494,000 seeds ha^{-1}, respectively (Table 3.4). Although economic return was analyzed for soybean market prices of \$0.37 kg^{-1} (\$10.00 bu^{-1}) and \$0.55 kg^{-1} (\$15.00 bu^{-1}), as expected mean separations did not differ; therefore, reported economic returns are based on \$0.37 kg^{-1}.

Economic returns were the lowest at MSU-22, a result of lower soybean yields compared with the other two site-years (Table 3.12). The interaction of planting date and herbicide program had similar effects on economic returns for both years at MSU (East Lansing, MI). For both years at MSU the PRE fb. POST herbicide program resulted in the highest economic return, regardless of planting date and ranged from \$850-876 ha^{-1} and \$1,338-1,380 ha^{-1} at MSU-22 and MSU-23, respectively. However, the PRE only program was similar to the PRE fb. POST in the normal planted soybean at MSU-22 (\$898 ha^{-1}). When no herbicides were applied (untreated) economic return was \$256-861 ha^{-1} lower when soybean were planted early compared with normal time across all site-years. At SVREC-23 (Richville, MI) economic return was greatest when soybeans were planted early and PRE (\$1,477 ha^{-1}) or PRE fb. POST (\$1,397 ha^{-1}) programs were used. Interestingly, the untreated and PRE fb. POST had similar economic return in the normal planted soybean at SVREC-23 of \$1,268 ha^{-1} and \$1,290 ha^{-1}, respectively.

The effect of row width on economic return was only present at MSU-23 (Table 3.9). When averaged across planting date and herbicide program, economic returns of soybean drilled in 19 cm rows regardless of population, were similar to both 38 and 76 cm row widths (\$1,054-1,118 ha^{-1}). However, return for soybean planted in 38 cm rows (\$1,118 ha^{-1}) was 15% higher than 76 cm rows (\$968 ha^{-1}). Overall, planting date did not affect economic return when a PRE fb. POST program was used when multiple weed species were present. Although yield and weed suppression were higher at MSU-23 for 19 cm rows when planted at a higher population, this did not translate to increased economic return due to higher seed costs. In some cases, a PRE only or untreated program produced similar or greater return than the PRE fb. POST treatment.

However, economic returns reported here were based on one year of production and the long-term effects of weed seed production and the implications on future weed management should be taken into consideration.

In conclusion, planting soybeans early to mid-April will allow producers to increase the number of days they have to conduct spring field operations. However, weather forecast, and soil conditions should be monitored closely, to minimize the risks associated with poor emergence and growing conditions. In the event of heavy rainfall soil crusting reduced stands, most notably in the soybean drilled in 19 cm rows while soybean planted in 38 and 76 cm rows seemed to be more resilient. When the PRE applications were incorporated with sufficient rainfall, they were advantageous for both weed suppression and soybean yield. Cool, wet soil conditions often present in early planted soybean can decrease crop safety of PRE herbicides; however, injury was not a limiting factor in any site-year. When weeds were not controlled in 2023, soybean drilled in 19 cm row widths provided better early season weed suppression compared with 38 and 76 cm rows, but the effects of narrow rows were negated when a PRE herbicide was used. Weed control and soybean yield was consistently the best when a PRE fb. POST herbicide program was utilized. Although this did not always result in the highest economic return, the long-term effects of herbicide program on weed seed production and future management should be considered. Nonetheless, when soybeans were planted early environmental conditions were more challenging than those at the normal planting time, but these conditions did not result in lower soybean yields in any site-year. Implementing a complete herbicide program in early planted soybeans including an effective PRE followed by a timely POST application is beneficial for initial soybean establishment, season-long weed control and crop productivity as well as maximizing soybean yield, regardless of row width.

LITERATURE CITED

Andrade FH, Calviño P, Cirilo A, Barbieri P (2002) Yield Responses to Narrow Rows Depend on Increased Radiation Interception. Agron J 94:975–980

Arsenijevic N, De Avellar M, Butts L, Arneson NJ, Werle R (2021) Influence of sulfentrazone and metribuzin applied preemergence on soybean development and yield. Weed Technol 35:210–215

Arsenijevic N, DeWerff R, Conley S, Ruark M, Werle R (2022) Influence of integrated agronomic and weed management practices on soybean canopy development and yield. Weed Technol 36:73–78

Board JE, Kamal M, Harville BG (1992) Temporal Importance of Greater Light Interception to Increased Yield in Narrow-Row Soybean. Agron J 84:575–579

Chen G, Wiatrak P (2010) Soybean Development and Yield Are Influenced by Planting Date and Environmental Conditions in the Southeastern Coastal Plain, United States. Agron J 102:1731–1737

Coulter JA, Nafziger ED (2007) Planting Date and Glyphosate Timing on Soybean. Weed Technol 21:359–366

Cox WilliamJ, Cherney JH (2011) Growth and Yield Responses of Soybean to Row Spacing and Seeding Rate. Agron J 103:123–128

De Bruin JL, Pedersen P (2008a) Soybean Seed Yield Response to Planting Date and Seeding Rate in the Upper Midwest. Agron J 100:696–703

De Bruin JL, Pedersen P (2008b) Effect of Row Spacing and Seeding Rate on Soybean Yield. Agron J 100:704–710

DeWerff RP, Conley SP, Colquhoun JB, Davis VM (2015) Weed Control in Soybean as Influenced by Residual Herbicide Use and Glyphosate-Application Timing Following Different Planting Dates. Weed Technol 29:71–81

Fisher JL, Sprague CL (2023) Contributions of shading, soybean (*Glycine max*) row width, and planting green on horseweed (*Conyza canadensis*) management compared with soil-applied residual herbicides. Weed Technol 37:383–393

Gongora-Canul CC, Leandro LFS (2011) Effect of Soil Temperature and Plant Age at Time of Inoculation on Progress of Root Rot and Foliar Symptoms of Soybean Sudden Death Syndrome. Plant Dis 95:436–440

Harder DB, Sprague CL, Renner KA (2007) Effect of Soybean Row Width and Population on Weeds, Crop Yield, and Economic Return. Weed Technol 21:744–752

Hesler LS, Allen KC, Luttrell RG, Sappington TW, Papiernik SK (2018) Early-Season Pests of Soybean in the United States and Factors That Affect Their Risk of Infestation. J Integr Pest Manag 9:19

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean Row Spacing and Weed Emergence Time Influence Weed Competitiveness and Competitive Indices. Weed Sci 54:38–46

Holshouser DL, Grisso Jr. RD, Pitman RM (2006) Uniform Stand and Narrow Rows are Needed for Higher Double-crop Soybean Yield. Crop Manag 5:CM-2006-0417-01-RS

Hyatt J, Wendroth O, Egli DB, TeKrony DM (2007) Soil Compaction and Soybean Seedling Emergence. Crop Sci 47:2495–2503

Kukal MS, Irmak S (2018) U.S. Agro-Climate in 20th Century: Growing Degree Days, First and Last Frost, Growing Season Length, and Impacts on Crop Yields. Sci Rep 8:6977

Marvel K, Su W, Delgado R, Aarons S, Chatterjee A, Garcia ME, Hausfather Z, Hayhoe K, Hence DA, Jewett EB, Robel A, Singh D, Tripati A, Vose RS (2023) Climate trends. Washington, DC, USA: U.S. Global Change Research Program

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. Weed Sci 60:31–62

Patrignani A, Ochsner TE (2015) Canopeo: A Powerful New Tool for Measuring Fractional Green Canopy Cover. Agron J 107:2312–2320

Poston DH, Nandula VK, Koger CH, Matt Griffin R (2008) Preemergence Herbicides Effect on Growth and Yield of Early-Planted Mississippi Soybean. Crop Manag 7:1–14

R Core Team (2023). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rich AM, Renner KA (2007) Row Spacing and Seeding Rate Effects on Eastern Black Nightshade (*Solanum Ptycanthum*) and Soybean. Weed Technol 21:124–130

Ritz C, Baty F, Streibig JC, Gerhard D (2015) Dose-Response Analysis Using R. PLOS ONE 10:e0146021

Robinson AP, Conley SP, Volenec JJ, Santini JB (2009) Analysis of High Yielding, Early-Planted Soybean in Indiana. Agron J 101:131–139

Schmitz PK, Kandel HJ (2021) Individual and Combined Effects of Planting Date, Seeding Rate, Relative Maturity, and Row Spacing on Soybean Yield. Agronomy 11:605

Schultz JL, Myers DB, Bradley KW (2015) Influence of Soybean Seeding Rate, Row Spacing, and Herbicide Programs on the Control of Resistant Waterhemp in Glufosinate-Resistant Soybean. Weed Technol 29:169–176

Serrano M, Robertson AE (2018) The Effect of Cold Stress on Damping-Off of Soybean Caused by *Pythium sylvaticum*. Plant Dis 102:2194–2200

Siler TB, Singh MP (2022) Optimal soybean maturity group selection is influenced by planting date in northern production systems. Crop Sci 62:2462–2475

Siler TB, Singh MP (2023) Soybean seeding rate and seed treatment that maximize yield and profitability based on planting date. Agron J 115:759–769

Singh M, Thapa R, Singh N, Mirsky SB, Acharya BS, Jhala AJ (2023) Does narrow row spacing suppress weeds and increase yields in corn and soybean? A meta-analysis. Weed Sci 71:520–535

Steckel LE, Sprague CL (2004) Late-Season Common Waterhemp (*Amaranthus rudis*) Interference in Narrow- and Wide-Row Soybean. Weed Technol 18:947–952

Taylor-Lovell S, Wax LM, Nelson R (2001) Phytotoxic Response and Yield of Soybean (*Glycine max*) Varieties Treated with Sulfentrazone or Flumioxazin [1]. Weed Technol 15:95–102

USDA-NASS (2024) Soybeans - Acres Planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/75D59937-EC6F-3CE3-8542-0F82121309A7. Accessed February 22, 2024

Veas REA, Ergo VV, Vega CRC, Lascano RH, Rondanini DP, Carrera CS (2022) Soybean seed growth dynamics exposed to heat and water stress during the filling period under field conditions. J Agron Crop Sci 208:472–485

Vosberg SK, Marburger DA, Smith DL, Conley SP (2017) Planting Date and Fluopyram Seed Treatment Effect on Soybean Sudden Death Syndrome and Seed Yield. Agron J 109:2570–2578

Wax LM, Nave WR, Cooper RL (1977) Weed Control in Narrow and Wide-Row Soybeans. Weed Sci 25:73–78

Werle R, Sandell LD, Buhler DD, Hartzler RG, Lindquist JL (2014) Predicting Emergence of 23 Summer Annual Weed Species. Weed Sci 62:267–279

Yan H, Nelson B (2022) Effects of Soil Type, Temperature, and Moisture on Development of Fusarium Root Rot of Soybean by *Fusarium solani* (FSSC 11) and *Fusarium tricinctum*. Plant Dis 106:2974–2983

Young BG, Young JM, Gonzini LC, Hart SE, Wax LM, Kapusta G (2001) Weed Management in Narrow- and Wide-Row Glyphosate-Resistant Soybean (*Glycine max*) [1]. Weed Technol 15:112–121

APPENDIX B: CHAPTER III TABLES AND FIGURES

Table 3.1. Enlist E3® soybean varieties, planting dates, herbicide application dates, and soybean harvest dates for the three field experiments conducted in 2022 and 2023.

	Sites[a]		
	MSU-22	MSU-23	SVREC-23
Soybean variety[b]	P24T35E	P25A16E	P25A16E
Early planting date	April 21	April 12	April 13
PRE	April 22	April 14	April 14
POST	June 13	June 13	June 19
Normal planting date	May 23	May 12	May 11
PRE	May 23	May 12	May 11
POST	June 27	June 23	June 19
Soybean harvest	October 24	October 20	October 8
Soil series	Conover loam	Aubbeenaubbee-Capac sandy loam/Colwood-Brookston loam	Tappan-Londo loam
Soil type	clay loam	loam	clay loam
Soil pH	7.4	6.8	7.5
Organic matter (%)	2.7	2.3	3.2

[a] Abbreviations: MSU, Michigan State University (East Lansing, MI); SVREC, Saginaw Valley Research and Extension Center (Richville, MI).
[b] Pioneer, Corteva Agriscience, Indianapolis, IN.

Table 3.2. Weed species present at the time of POST herbicide application in the untreated controls for both early and normal soybean planting dates for the three site-years.

Planting Date	MSU-22	MSU-23	SVREC-23
Early		plants m^{-2}	
Common lambsquarters	7	111	73
Common ragweed	14	23	-
Giant foxtail	45	154	-
Velvetleaf	2	3	-
Normal			
Common lambsquarters	7	9	14
Common ragweed	7	3	-
Giant foxtail	17	17	-
Velvetleaf	0	1	-

Table 3.3. Monthly[a] precipitation, GDDs[b,c] and the 30-year mean precipitation[d] for the three site-years.

	MSU-22		MSU-23		SVREC-23		30-year average precipitation	
Month	Precipitation	GDD	Precipitation	GDD	Precipitation	GDD	MSU	SVREC
	— mm —	– base 10 C –	— mm —	– base 10 C –	— mm —	– base 10 C –	——— mm ———	
April	98 (56)[e]	109 (51)[g]	88 (33)	150 (99)	78 (31)	166 (100)	90	75
May	71 (14)[f]	387 (137)[h]	25 (10)	317 (242)	25 (9)	343 (272)	111	87
June	62	540	18	495	38	506	96	100
July	43	651	155	645	139	628	86	93
August	65	616	152	536	150	495	88	86
September	50	409	45	412	34	407	81	98
October	45	208	127	195	66	201	79	74
Total	434	2,920	610	2,750	530	2,746	631	613

[a] Monthly GDDs and precipitation data were collected from the closest weather station in the Michigan State University Enviroweather network (https://enviroweather.msu.edu).
[b] Abbreviations: GDDs = growing degree days.
[c] Growing degree days (GDD) minimum 10 C, maximum 30 C, and base 10 C.
[d] Monthly 30-year mean precipitation data were collected from the National Oceanic and Atmospheric Administration (https://www.ncei.noaa.gov/access/us-climate-normals).
[e] Precipitation after early planting.
[f] Precipitation after normal planting.
[g] GDDs after early planting.
[h] GDDs after normal planting.

Table 3.4. Treatment costs for the four row width systems and three herbicide programs.

	Treatment costs[a]		
	Untreated	PRE	PRE fb. POST
Row width (cm)[b]		USD \$ ha^{-1}	
19 – high	317.57	396.07	487.15
19 - low	238.18	316.68	407.76
38	238.18	316.68	407.76
76	238.18	316.68	407.76

[a] Treatment costs = soybean seed costs + herbicide costs + adjuvant costs + application costs. Seed, herbicide, and adjuvant costs were calculated from multiple retailer price lists. Herbicide application cost = \$24.7 ha^{-1} $application^{-1}$.

[b] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.

Table 3.5. Main effects of planting date, herbicide program, and row width system on soybean stand for the three site-years.

	Soybean stand	
Main effects	MSU-22[a]	2023[b]
Planting date	——— % of planted ———	
Early	47	77 b
Normal	75	82 a
Herbicide program		
untreated	56 b[c]	76 b
PRE	64 a	81 a
PRE fb. POST	64 a	79 ab
weed-free	61 ab	81 a
Row width (cm)[d]		
19 - high	52	76 b
19 - low	54	77 b
38	74	84 a
76	65	80 b
Effects (p-values)		
Planting date	<0.0001	<0.0001
Herbicide program	0.0227	0.0041
Row width	<0.0001	<0.0001
PD*HERB	0.2782	0.0636
PD*ROW	<0.0001	0.1231
HERB*ROW	0.9947	0.4681
PD*HERB*ROW	0.6187	0.5673

[a] There was planting date by row width system interaction on soybean stand at MSU-22, see Figure 3.1.
[b] Data were combined over MSU-23 and SVREC-23.
[c] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).
[d] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.

Table 3.6. Three-way interaction between soybean planting date, herbicide program, and row width system on weed biomass at POST herbicide application for the three site-years.

		Weed biomass at POST							
		MSU-22				2023[a]			
Planting date	Herbicide program	19 cm-high[b]	19 cm-low	38 cm	76 cm	19 cm-high	19 cm-low	38 cm	76 cm
		g m^{-2}				g m^{-2}			
Early	untreated	88 a[c]	72 ab	42 bcd	74 ab	44 bc	33 c	57 ab	62 a
	PRE	14 c-f	12 c-f	5 ef	36 cde	2 d	0 d	0 d	2 d
	PRE fb. POST[d]	19 c-f	6 ef	8 def	13 c-f	0 d	1 d	0 d	0 d
	weed-free	0 f	0 f	0 f	0 f	0 d	0 d	0 d	0 d
Normal	untreated	22 c-f	30 c-f	35 c-f	45 bc	7 d	7 d	4 d	10 d
	PRE	0 f	1 f	0 f	2 ef	7 d	3 d	3 d	7 d
	PRE fb. POST	0 f	1 f	0 f	2 ef	3 d	3 d	5 d	5 d
	weed-free	0 f	0 f	0 f	0 f	0 d	0 d	0 d	0 d
Effects (p-values)									
Planting date		<0.0001				<0.0001			
Herbicide program		<0.0001				<0.0001			
Row width		0.0134				0.0178			
PD*HERB		<0.0001				<0.0001			
PD*ROW		0.0182				0.1876			
HERB*ROW		0.3899				0.0195			
PD*HERB*ROW		0.0308				0.0143			

[a] Data were combined over MSU-23 and SVREC-23.
[b] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.
[c] Means followed by the same letter within a year are not statistically different ($\alpha \leq 0.05$).
[d] Weed biomass was collected before the POST herbicide application had been made.

Table 3.7. Days after planting to 50 and 95% canopy closure (±SE)[a] in early and normal planted soybeans in four row width systems for the three site-years.

		Time to 50% closure		Time to 95% closure	
Planting date	Row width (cm)[b]	MSU-22	2023[c]	MSU-22	2023
		d after planting			
Early	19 - high	78 (±0.94) c[d]	77 (±0.38) c	103 (±2.65) ab	95 (±0.94) b
	19 - low	85 (±0.87) a	78 (±0.36) b	105 (±2.39) a	95 (±0.89) b
	38	80 (±0.83) bc	78 (±0.36) b	99 (±2.26) b	95 (±0.87) b
	76	82 (±1.00) b	81 (±0.39) a	110 (±2.84) a	101 (±0.94) a
Normal	19 - high	45 (±0.66) f	50 (±0.37) g	69 (±2.23) d	66 (±0.93) d
	19 - low	48 (±0.65) e	51 (±0.35) f	70 (±1.90) d	66 (±0.88) d
	38	50 (±0.60) d	52 (±0.34) e	69 (±1.64) d	66 (±0.86) d
	76	51 (±0.73) d	57 (±0.41) d	80 (±2.29) c	78 (±1.02) c

[a] Abbreviations: SE = standard error.
[b] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.
[c] Data were combined over MSU-23 and SVREC-23.
[d] Estimates followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).

Table 3.8. Interaction between planting date and herbicide program on weed biomass at soybean harvest and soybean yield for the three site-years.

		Weed biomass at harvest		Soybean yield	
Planting date	Herbicide program	MSU-22	2023[a]	MSU-22	2023
		g m^{-2}		kg ha^{-1}	
Early	untreated	449 a[b]	334 a	1,110 c	2,394 d
	PRE	390 ab	187 b	2,065 b	4,472 b
	PRE fb. POST	26 c	2 c	3,450 a	4,909 a
	weed-free	0 c	0 c	3,531 a	4,882 ab
Normal	untreated	297 b	222 b	2,320 b	3,901 c
	PRE	112 c	253 ab	3,336 a	3,948 c
	PRE fb. POST	0 c	0 c	3,524 a	4,708 ab
	weed-free	0 c	0 c	3,571 a	4,681 ab
Effects (p-values)					
Planting date		<0.0001	0.3729	<0.0001	0.0015
Herbicide program		<0.0001	<0.0001	<0.0001	<0.0001
Row width		0.1277	0.0104	0.3412	0.0451
PD*HERB		<0.0001	0.0001	0.0001	<0.0001
PD*ROW		0.8721	0.6030	0.6671	0.7924
HERB*ROW		0.4496	0.2231	0.9488	0.5127
PD*HERB*ROW		0.8962	0.9415	0.9864	0.7708

[a] Data were combined over MSU-23 and SVREC-23.

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

Table 3.9. Main effect of row width system on weed biomass at soybean harvest, soybean yield, and economic return for the three site-years.

	Weed biomass at harvest		Soybean yield		Economic return[a,b]		
Main effects	MSU-22	2023[c]	MSU-22	2023	MSU-22	MSU-23	SVREC-23
Row width (cm)[d]	——— $g\ m^{-2}$ ———		——— $kg\ ha^{-1}$ ———		——— USD $\$\ ha^{-1}$ ———		
19 - high	136	115 b[e]	2,999	4,372 a	638	1,054 ab	1,266
19 - low	134	173 ab	2,744	4,210 ab	608	1,058 ab	1,277
38	184	187 a	2,892	4,284 ab	661	1,118 a	1,267
76	184	190 a	2,818	4,082 b	628	968 b	1,276
Effects (p-values)							
Planting date	<0.0001	0.3729	<0.0001	0.0015	<0.0001	<0.0001	0.0939
Herbicide program	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Row width	0.1277	0.0104	0.3412	0.0451	0.8702	0.0073	0.9880
PD*HERB	<0.0001	0.0001	0.0001	<0.0001	0.0001	<0.0001	<0.0001
PD*ROW	0.8721	0.6030	0.6671	0.7924	0.6671	0.3587	0.9409
HERB*ROW	0.4496	0.2231	0.9488	0.5127	0.9488	0.4150	0.3529
PD*HERB*ROW	0.8962	0.9415	0.9864	0.7708	0.9864	0.2283	0.6722

[a] Economic return = (yield x price) – treatment costs. Crop selling price = \$0.37 kg^{-1} (\$10 bu^{-1}).
[b] No difference in mean separation when crop selling price = \$0.55 kg^{-1} (\$15 bu^{-1}).
[c] Data were combined over MSU-23 and SVREC-23.
[d] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.
[e] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).

Table 3.10. Interaction between planting date and herbicide program on number of seeds plant^{-1} and 100 seed weight on main stem and reproductive branches for the three site-years.

		MSU-22				2023[a]			
Planting date	Herbicide program	MS[b]	BR	MS	BR	MS	BR	MS	BR
		— no. seeds plant^{-1} —		— wt 100 seeds^{-1} (g) —		— no. seeds plant^{-1} —		— wt 100 seeds^{-1} (g) —	
Early	untreated	42 d[c]	17 d	14.5 a	14.6	46 c	9	16.8	16.6
	PRE	58 bcd	48 bc	13.8 a	14.0	74 a	13	17.0	16.8
	PRE fb. POST	93 a	83 a	13.3 ab	13.7	77 a	15	16.8	17.0
	weed-free	79 ab	65 ab	12.0 b	14.2	76 a	14	17.3	17.5
Normal	untreated	48 cd	7 d	13.5 ab	13.1	59 b	7	17.0	17.2
	PRE	68 bc	18 d	13.6 ab	13.8	67 ab	7	17.6	17.4
	PRE fb. POST	67 bc	18 d	14.1 a	13.8	68 ab	13	17.1	17.3
	weed-free	71 ab	20 cd	14.2 a	13.1	69 ab	9	17.7	17.6
Effects (p-values)									
Planting date		0.2136	<0.0001	0.1437	0.0057	0.1735	0.0071	0.0739	0.1519
Herbicide program		<0.0001	<0.0001	0.1437	0.9807	<0.0001	0.0063	0.1250	0.0526
Row width		0.2972	0.5598	0.2172	0.9673	0.0029	0.0001	0.0306	0.6383
PD*HERB		0.0033	0.0013	0.0012	0.0795	<0.0001	0.6559	0.8802	0.8169
PD*ROW		0.0639	0.4775	0.5289	0.1439	0.8251	0.0768	0.3547	0.1115
HERB*ROW		0.6145	0.8350	0.7749	0.5616	0.2624	0.4771	0.8219	0.8117
PD*HERB*ROW		0.5065	0.9120	0.4914	0.2241	0.1010	0.8921	0.5608	0.3865

[a] Data were combined over MSU-23 and SVREC-23.
[b] Abbreviations: MS = main stem; BR = reproductive branches.
[c] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).

Table 3.11. Main effects of planting date, herbicide program, and row width system on number of seeds plant^{-1} and 100 seed weight on the main stem and reproductive branches for the three site-years.

	MSU-22				2023[a]			
Main effects	MS[b]	BR	MS	BR	MS	BR	MS	BR
Planting date	— no. seeds plant^{-1} —		— wt 100 seeds^{-1} (g) —		— no. seeds plant^{-1} —		— wt 100 seeds^{-1} (g) —	
Early	79	53	13.4	14.1 a[c]	68	12 a	17.0	16.9
Normal	64	16	13.8	13.4 b	66	9 b	17.3	17.2
Herbicide program								
untreated	45	12	14.0	13.6	52	8 b	16.9	16.6
PRE	63	33	13.7	13.8	71	10 ab	17.3	16.9
PRE fb. POST	80	50	13.7	13.8	73	14 a	17.0	17.1
weed-free	96	42	13.1	13.8	72	11 ab	17.5	17.6
Row width (cm)[d]								
19 - high	89	30	13.5	13.7	62 b	6 b	17.6 a	17.1
19 - low	65	37	13.6	13.8	68 ab	12 a	17.0 ab	17.1
38	72	38	13.3	13.6	71 a	13 a	16.9 b	16.8
76	59	33	14.1	13.7	66 ab	12 a	17.1 ab	17.2
Effects (p-values)								
Planting date	0.2136	<0.0001	0.1437	0.0057	0.1735	0.0071	0.0739	0.1519
Herbicide program	<0.0001	<0.0001	0.1437	0.9807	<0.0001	0.0063	0.1250	0.0526
Row width	0.2972	0.5598	0.2172	0.9673	0.0029	0.0001	0.0306	0.6383
PD*HERB	0.0033	0.0013	0.0012	0.0795	<0.0001	0.6559	0.8802	0.8169
PD*ROW	0.0639	0.4775	0.5289	0.1439	0.8251	0.0768	0.3547	0.1115
HERB*ROW	0.6145	0.8350	0.7749	0.5616	0.2624	0.4771	0.8219	0.8117
PD*HERB*ROW	0.5065	0.9120	0.4914	0.2241	0.1010	0.8921	0.5608	0.3865

[a] Data were combined over MSU-23 and SVREC-23.
[b] Abbreviations: MS = main stem; BR = reproductive branches.
[c] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$).
[d] Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.

Table 3.12. Interaction between planting date and herbicide program on economic return for soybean marketed at \$0.37 kg^{-1} for the three site-years.

Planting date	Herbicide program	Economic return[a,b] MSU-22	MSU-23	SVREC-23
		USD \$ ha^{-1}		
Early	untreated	152 c[c]	244 c	1,012 d
	PRE	427 b	1,167 b	1,477 a
	PRE fb. POST	850 a	1,380 a	1,397 ab
Normal	untreated	600 b	1,105 b	1,268 bc
	PRE	898 a	1,063 b	1,186 c
	PRE fb. POST	876 a	1,338 a	1,290 bc
Effects (p-values)				
Planting date		<0.0001	<0.0001	0.0939
Herbicide program		<0.0001	<0.0001	<0.0001
Row width		0.8702	0.0073	0.9880
PD*HERB		0.0001	<0.0001	<0.0001
PD*ROW		0.6671	0.3587	0.9409
HERB*ROW		0.9488	0.4150	0.3529
PD*HERB*ROW		0.9864	0.2283	0.6722

[a] Economic return = (yield x price) – treatment costs. Crop selling price = \$0.37 kg^{-1} (\$10 bu^{-1}).
[b] No difference in mean separation when crop selling price = \$0.55 kg^{-1} (\$15 bu^{-1}).
[c] Means followed by the same letter within a column are not statistically different ($\alpha \leq 0.05$)

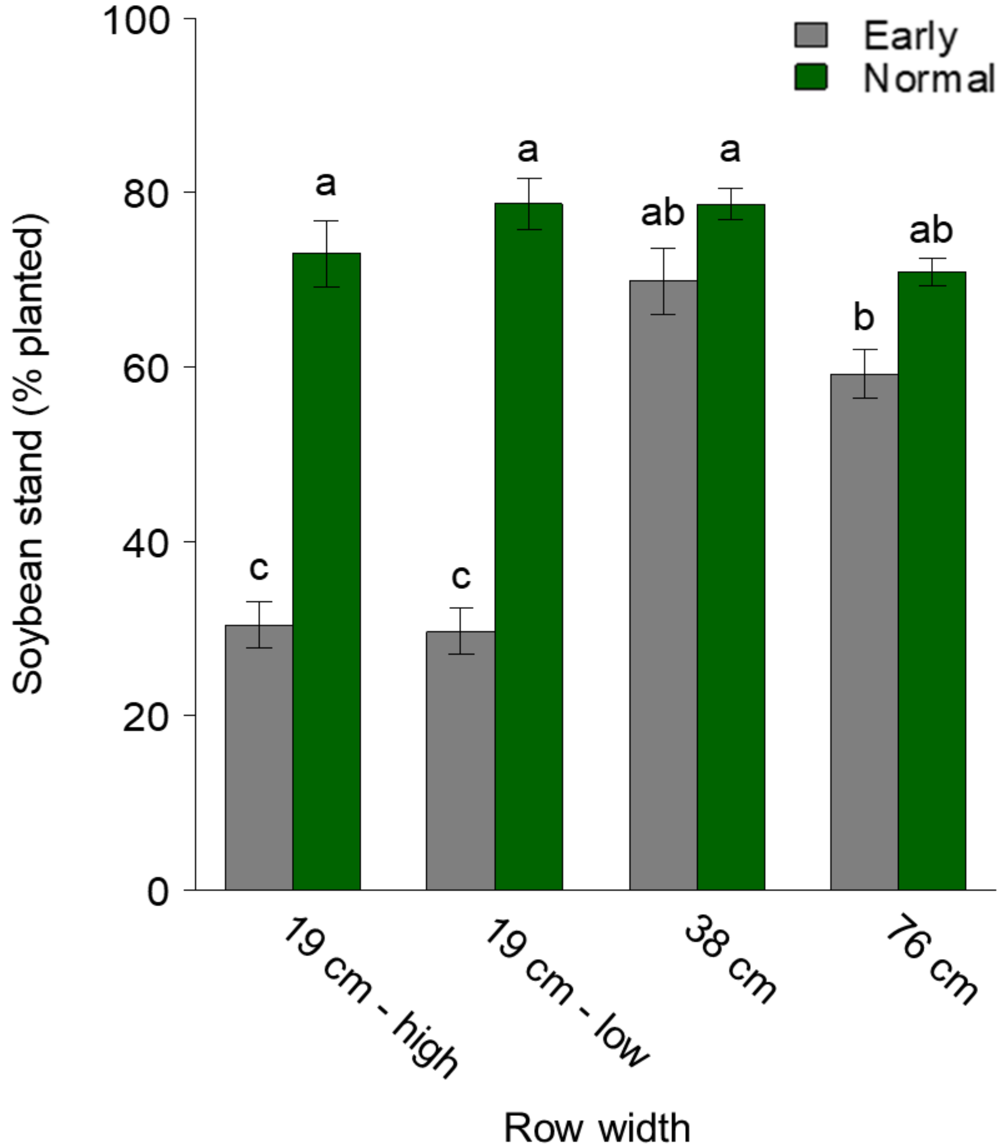

Figure 3.1. Interaction of planting date and row width system on percent soybean stand at MSU-22. Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.

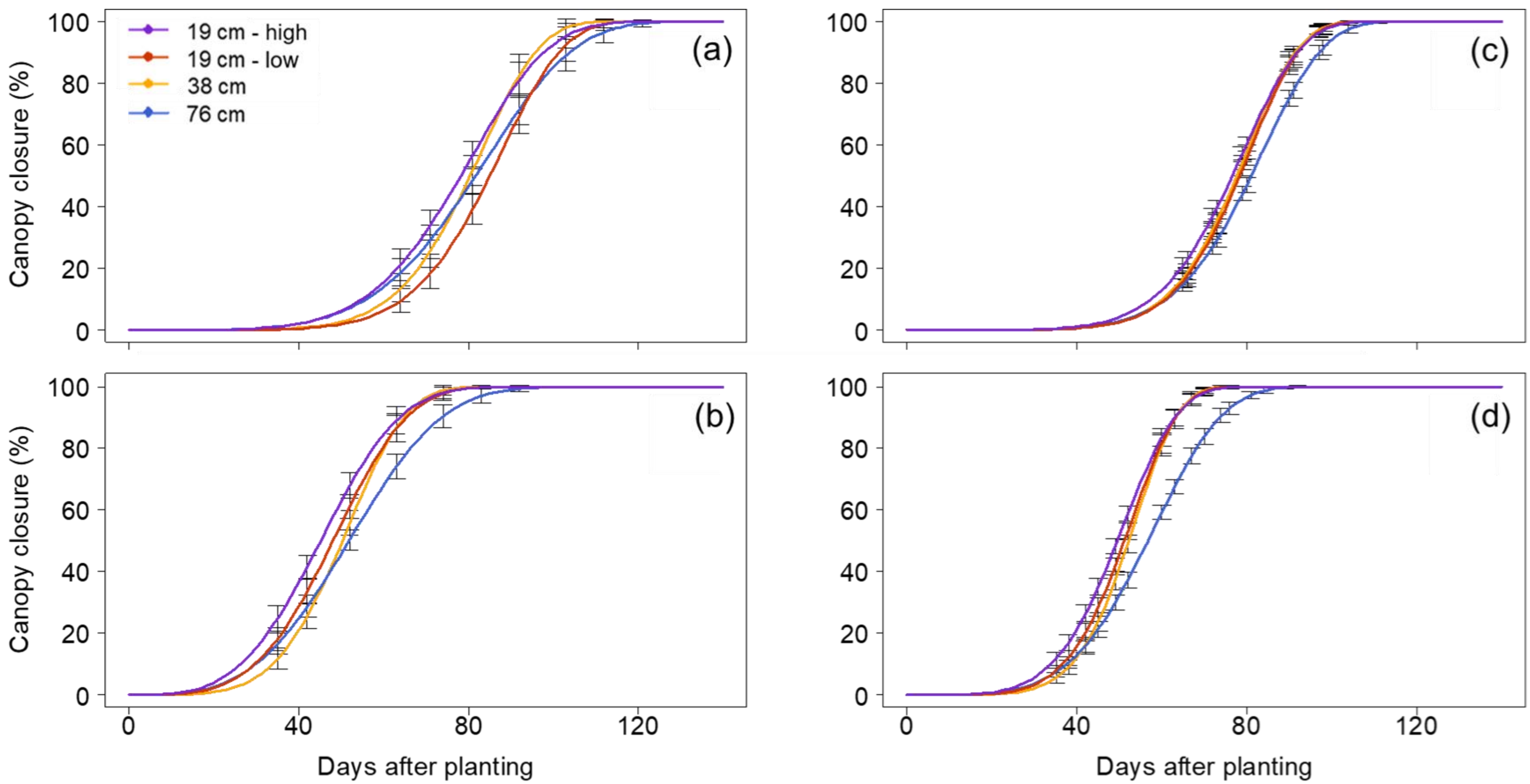

Figure 3.2. The effect of planting date and row width system on canopy closure starting after each planting date in early (a) and normal (b) planted soybean at MSU-22, and early (c) and normal (d) planted soybean combined over both sites in 2023. Soybean populations were 494,000 seeds ha^{-1} in 19 cm (high), and 370,500 seeds ha^{-1} in 19 (low), 38, and 76 cm rows.