INTEGRATED WEED MANAGEMENT

IN ORGANIC NO-TILL PLANTED SOYBEAN

A Thesis

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Degree of Master in Science

by

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BIOGRAPHICAL SKETCH

Before Annika began her master's program at Cornell University, she experienced a year of exploration into the US food system. In June 2020, she began a six-month apprenticeship with the Boston Area Gleaners, where she harvested fresh produce from farms around the Boston area intended for hunger relief organizations. Annika realized the extent to which the changing climate was influencing the decisions farmers made about what crops to keep. She began to understand the sustainable practices farmers were taking to reduce crop loss as she learned about the negative effects of monocropping and intensive soil tillage. Once her apprenticeship ended, Annika began working in a food pantry north of Boston, where she got to know the individuals receiving the produce she had gleaned in the farms that summer. Working at a food pantry exposed her to even more cracks in the US food system, for she was giving out food that came from large food banks, which are subsidized by the US government. Annika questioned why the government was buying meals for food banks rather than putting more money into programs that would allow individuals to afford to buy their own food. She understands now that she was thinking deeply about the social pillar of agroecology.

All the while, Annika missed the process of scientific exploration. She obtained her bachelor's degree in biology at Vassar College, where she investigated scientific questions at the intersection of apiculture, biochemistry, and the food system. Equipped with knowledge of sustainable farming and food justice, Annika applied for graduate programs where she could pursue questions of agroecology in a scientific context. Annika entered the graduate program at Cornell University in the lab of Dr. Matthew Ryan and chose a project focused on multi-tactic

weed management in organic no-till soybean systems. This thesis is the result of two years of Annika's research and experiences at Cornell.

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PROLOGUE

Modern agriculture has led to record breaking yields of mass-produced crops (Ikerd 2023; USDA – NASS, 2023). However, land use and management changes associated with using high-input, intensive methods can lead to several negative outcomes, including soil degradation, habitat loss, and pest resistance (Azarbad, 2022; Powers and Jetz, 2019; Heap, 2014; Montgomery, 2012; Foley, 2005). Organic agriculture is a method of production that has the potential to solve some of these problems (Edwards, 2007; Heckman, 2006; Horrigan et al., 2002). The concept of organic farming was pioneered by Sir Albert Howard in the 1940's with his book *An Agricultural Testament*, where he described the importance of using residues from plants and animal waste to build and maintain soil health in agricultural systems (Heckman, 2006). Howard's ideas were adopted and promoted by various individuals, including Jerome Rodale, who began experimenting with building soil health on his farm in Allentown, PA in the early 1940's (Heckman, 2006; Hepperly et al., 2006). Rodale began publishing his magazine *Organic Farming and Gardening* soon after, which disseminated organic farming information to producers (Heckman, 2006).

The concept of organic agriculture was not immediately supported in the United States. In the mid-20th century, synthetic fertilizers and pesticides began to be widely used by producers to solve problems of soil fertility and pest control (Heckman, 2006). These new technologies encouraged a substantial increase in technological optimism among producers and researchers, fostering the belief that current and future technologies would continue to lead to higher crop yields (Dentzman et al., 2016; Heckman, 2006). Given that synthetic fertilizers and pesticides were excluded from principles of organic farming, it took several decades and substantial

encouragement from consumers for land grant universities to begin experimenting with organic practices (Heckman, 2006; Delate and DeWitt, 2004). In the late 1970s, USDA researchers began to study organic farming and reported that the practices used by organic farmers (i.e., crop rotations, cover crops, conservation tillage) had been cited as best management practices by a separate USDA/EPA report on improving soil health (USDA, 1980, 1978). The organic farming report stated that more could be learned from the innovative practices organic farmers were using, such as organic recycling and pest management, and that research and education should be developed to support organic farmers (USDA, 1980). Consequently, after several years of surveys, symposiums, and publications, the USDA passed the Organic Foods Production Act in 1990 (Heckman, 2006). This act established the National Organic Program (NOP), which set production and marketing standards for organic producers and encouraged the development of commerce between states for fresh and processed organic food (EPA, 2022; Heckman, 2006). In 2002, after substantial debate and integration of organic farmer feedback, the USDA NOP standards were defined (Heckman, 2006). Organic production has increased since the start of the USDA NOP, with area under organic production increasing from half a million hectares in 2002 to 2 million hectares in 2021 (Cardinia, 2021; Greene, 2013; Kuminoff and Wossink, 2010).

Weeds are often more abundant on organic farms compared with conventional farms. Increased weed abundance can be a major production constraint contributing to lower yields in organic production (Seufert et al., 2012; Cavigelli et al., 2008). Many organic farmers use tillage for weed management (Baker and Mohler, 2015). Tillage is the process of mechanically disturbing the soil before planting a crop. Tilling the soil can manage weeds and create a clean seedbed through the burying, uprooting, or chopping of weeds and crop residue (Mohler et al., 2021; Mitchell et al., 2016; Al-Kaisi et al., 2004). Often, additional soil disturbance through

cultivation may be needed during a growing season to manage weeds that regrow after primary tillage events (Mohler et al., 2021). However, if tillage is performed frequently and without soil conservation measures, topsoil can be rapidly lost to erosion because of the breakdown of soil aggregates and soil organic matter (Magdoff and Van Es, 2021; Rust and Williams, 2010; Liebman et al., 2001; Govers et al., 1996). Loss of soil aggregates and organic matter can lead to decreased water infiltration, which can result in water runoff in the event of heavy rain (Zuzel et al., 1990). Consequently, intensive tillage has been linked to increases in soil erosion and decreases in soil health, both of which can dramatically decrease crop growth and yields (Rust and Williams, 2010; Biggelaar et al., 2004; Pierce and Lal, 1994).

In the mid 20th century, in response to the dust bowl and increased knowledge about the negative effects of tillage, some farmers began to adopt "no-till" methods, where the soil is minimally disturbed (Huggins and Regnaold, 2008). Farmers can eliminate all soil disturbance (i.e., no-till), or practice reduced-tillage, when less intensive tillage practices are used to manage troublesome weeds or other pests (Mohler et al., 2021; Mirsky et al., 2012; Derpsch et al., 2010). Rotational no-till is considered a form of reduced tillage, where a farmer tills the soil before some but not all crops, resulting a reduction in tillage frequency (Ryan et al., 2021). As of 2017, 42.3 million hectares are under no-till practices and 39.6 million hectares are under reduced tillage in the United States. In New York state, 337,968 acres of land were under no-till practices in 2017, which increased by 12% from 2012 (USDA – NASS, 2017).

Implementing both organic and no-till practices in row-crops can be difficult. Mulch from mechanically terminated cover crops serves as the basis for weed suppression in an organic no-till system that has emerged over the past several decades and is now used by some organic grain crop farmers (Mirsky et al., 2012; Ashford and Reeves, 2009; Teasdale et al., 1991). Cover

crop mulch can suppress weeds through light interception, physical interference of weed emergence, and allelopathy (Teasdale and Mohler, 2000; Putnam et al., 1983). Mulch also conserves soil moisture, adds organic matter to the soil, and reduces the risk of soil erosion (Ryan et al., 2021; Teasdale and Mohler, 2000; Papendick and Parr, 1997). A commonly used cover crop for organic no-till is cereal rye (*Secale cereale* L.), which is planted in the fall, overwinters, and then grows vigorously in early spring. Organic farmers often terminate the cereal rye cover crop in the spring with a roller-crimper to create a thick mulch that will persist throughout the growing season (Silva and Delate, 2017; Mirsky et al., 2013).

Cover crop roller-crimpers were first developed in Brazil and then popularized in the United States in the early 2000s (Ashford and Reeves, 2003; Derpsch et al., 1991). Although several variations of the machine have been developed, most consist of a hollow cylindrical barrel that can be filled with water for additional weight (Ryan et al., 2021). Around the barrel are dull blades in a chevon pattern that apply downward force when rolled over cereal rye (Davis, 2010; Raper and Simionescu, 2005). Farmers can save fuel and labor by attaching roller-crimpers to the front of a tractor so that one can simultaneously terminate the cover crop and no-till plant cash crops in a single pass operation at planting (Ryan et al., 2021; Crowley et al., 2018). Rolling terminates the cereal rye cover crop but the plant roots remain in the soil, which stabilizes soil and prevents the mulch from moving (Crowley et al., 2018). When compared to traditional tillage-based production that involves primary tillage and secondary cultivation, no-till planting organic soybean into rolled-crimped cereal rye can save farmers labor and fuel costs (Ryan et al., 2021; Mirsky et al., 2013). In most cases, rotational no-till management is used, where tillage is used to establish the cover crop, but cash crops such as soybean are no-till planted into the mulch. Research has found that soybeans can produce relatively high yields

when a cereal rye cover crop is used (Mirsky et al., 2013; Delate et al., 2012), as soybean can fix its own nitrogen through association with bacteria and is not impacted by nitrogen immobilization from cereal rye (Williams et al., 2018; Mirsky et al., 2013).

Optimizing weed suppression in organic no-till planted soybean is important for maximizing yields. Several cultural management practices have been studied to increase cereal rye biomass, including earlier fall planting dates, higher seeding rates, and later spring termination timing (Keene et al., 2017; Mirsky et al., 2013, 2011; Ryan et al., 2011). Results from research conducted in the Northeast US suggest that cereal rye should be planted in late August or early September at 135 to 269 kg seed ha^{-1} and that termination should be delayed until cereal rye reaches 50% anthesis, which typically occurs in late May or early June (Ryan et al., 2021; Keene et al., 2017; Mirsky et al., 2013, 2011; Ryan et al., 2011). Implementing these strategies can produce cereal rye biomass greater than or equal to 8000 kg ha^{-1}, a recommended biomass that can lead to adequate weed suppression (Ryan et al., 2021; Silva and Delate, 2017; Mirsky et al., 2012; Teasdale and Mohler, 2000). However, cover crop biomass may be suboptimal because of poor weather, soil fertility limitations, or planting constraints imposed by crop rotations (Mirsky et al., 2013). When cover crop biomass is low, weeds are more likely to emerge, compete with soybean, and reduce yield (Mirsky et al., 2013; Ryan et al., 2011). Therefore, additional weed management strategies are needed for organic no-till planted soybean production (Mirsky et al., 2013).

Integrated weed management (IWM) is an approach to weed management that can allow farmers to decrease risk and reduce selection for dominant weed species. IWM typically involves the use of several weed management practices, which can fall under the categories of prevention, monitoring, cultural practices (cropping system diversification, cultivar selection and planting),

direct control (mechanical or physical practices), and chemical use (Riemens et al., 2021; Liebman and Gallandt, 1997). Using several weed management tactics can allow farmers to target varied weed species traits across time and space, which lessens the likelihood of a dominant species emerging and becoming resistant to a tactic (Mohler et al., 2021; Liebman & Gallandt, 1997; Swanton and Murphy, 1996). A concept that stems from IWM is the 'many little hammers' approach, where multiple weed management tactics that may not be effective when used in isolation are combined to achieve more complete management (Liebman and Gallandt, 1997). Using several tactics can decrease risk of crop failure, for if one tactic fails to manage weeds, others can fill in management gaps (Cordeau et al., 2022; Liebman & Gallandt, 1997). Furthermore, using multiple strategies has the potential to result in synergistic interactions, when tactic efficacy is greater in combination than what could be predicted based on an understanding of tactic performance in isolation (Cordeau et al., 2022; Ryan et al., 2011).

Several studies have tested IWM in organic no-till systems with a high residue (HR) cultivator as one of the management tactics (Wallace et al., 2018; Zinati et al., 2017; Snyder et al., 2016). HR cultivators have coulters that can cut through cereal rye mulch followed by a narrow shank with wide, low-angle cultivator sweeps that separate underground roots from aboveground weed biomass (Mirsky et al., 2013). Studies have shown that using HR cultivation in a no-till cover crop system can manage early-emerging summer annual weeds (Wallace et al., 2018; Mirsky et al., 2013). Wallace et al. (2018) also found that performing HR cultivation in 76 cm rows decreased weed biomass compared to no cultivation in plots with 38 cm spacing. Researchers have found that yield improvements after HR cultivation vary depending on degree of weed infestation and timing of cultivation (Zinati et al., 2017; Mirsky et al., 2013). However, HR cultivation is likely to disrupt the cereal rye mulch and the soil surface, which can induce

germination of later-emerging summer annual weeds (Wallace et al., 2018; Teasdale and Mirsky, 2015). Like other forms of cultivation, HR cultivation can also reduce soil moisture and degrade soil organic matter, negative outcomes that are avoided when cereal rye mulch is not disturbed (Peigné et al., 2007; Rasmussen and Collins, 1991). Moreover, studying the effectiveness and profitability of additional weed management tools in organic no-till cover cropped systems could be valuable (Mirsky et al., 2013).

My research builds upon the demonstrated need for additional weed management strategies in organic rotational no-till systems. Too this end, an experiment was conducted in organic no-till planted soybean to test the integrated weed management of three practices: a high soybean seeding rate, inter-row mowing, and electrical weeding. These practices do not disturb the cereal rye mulch and were implemented alone and in combination in nine different treatments. We collected weed-by-species biomass, percent weed cover, weed seed production, and soybean yield data to investigate the effects of treatments. We also compared which weed traits were targeted by the tactics that were tested. This chapter provides a detailed examination into the use of novel weed management tactics for organic no-till planted soybean.

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CHAPTER 1

MULTI-TACTIC WEED MANAGEMENT IN ORGANIC NO-TILL PLANTED SOYBEAN

ABSTRACT

No-till planting organic soybean [*Glycine max* (L.) Merr.] into rolled-crimped cereal rye (*Secale cereale* L.) can have several advantages over traditional tillage-based production. However, suboptimal cereal rye growth in fields with large populations of weeds may result in reduced weed suppression, weed-crop competition, and soybean yield loss. Ecological weed management theory suggests that integrating multiple management practices that may be weakly effective on their own can provide high levels of weed suppression. In 2021 and 2022, field experiments were conducted in central New York to evaluate the performance of three weed management tactics implemented alone and in combination in organic no-till planted soybean: 1) increasing crop seeding rate, 2) inter-row mowing, and 3) weed electrocution. An untreated control and weed free treatment that did not receive any weed management were also included. All treatments that included inter-row mowing had lower weed biomass and higher soybean yield than the untreated control. Using a high seeding rate or weed electrocution did not improve weed suppression or soybean yield. Soybean yield across all treatments was at least 22% lower than the weed free control plot. Inter-row mowing was effective at controlling annual broadleaf weed species that grew between soybean rows, however, few weeds grew above soybean plants before canopy closure, which limited the effect of weed electrocution. Future research should explore the direct effects of the multiple tactics on weed population and community dynamics over an extended period and the indirect effects from tactics such as improved harvestability and impacts of weed electrocution on weed seed viability and soil organisms.

Key Words: Agroecology, Integrated Weed Management, Inter-row Mower, Many Little Hammers, Synergism, Weed Zapper

INTRODUCTION

Organic farmers who do not use synthetic herbicides often rely on mechanical weed management, primarily soil tillage and cultivation (Lowry and Brainard, 2019; Peigné et al., 2007; Teasdale et al., 2007; Bàrberi, 2002). However, tillage can lead to soil erosion and degrade soil health (Magdoff and Van Es, 2021; Pimentel and Burgess, 2013; Montgomery, 2012). Cover crops can be used to manage weeds in organic no-till soybean [*Glycine max* (L.) Merr.] production (Vincent-Caboud et al., 2017; Mirsky et al., 2009). In cover crop based organic no-till systems, a fall-planted winter cover crop, often cereal rye (*Secale cereale* L.), is mechanically terminated in the spring with a roller-crimper to create a weed suppressive mulch on the soil surface (Mirsky et al., 2009; Ashford and Reeves, 2003). Summer cash crops, like soybean, are then no-till planted directly into the mulch. Benefits of the system include increased soil health, weed suppression, and lower labor and fuel costs compared to tillage-based production (Ryan et al., 2011a, 2011b; Davis, 2010; Mirsky et al., 2009; Ashford and Reeves, 2003).

Cereal rye mulch has the potential to provide adequate weed suppression in organic, no-till planted soybean, depending on cereal rye management, environmental conditions, and weed infestation levels (Mirsky et al., 2011; Ryan et al., 2011b). Previous research has focused on several aspects of cereal rye management, including planting and termination dates, seeding rates, cultivar selection, and fertilizer application (Crowley et al., 2018; Wells et al., 2016; Ryan et al., 2021, 2011a; Mirsky et al., 2013, 2011, 2009; Teasdale and Mohler, 2000). Studies that evaluated fall planting dates found that planting cereal rye in late August - early September allows the crop to reach optimal biomass for weed suppression (above 8000-9000 kg ha^{-1}) at time of roller-crimping (Ryan et al., 2021; Mirsky et al., 2009, 2011; Teasdale and Mohler,

2000). Terminating cereal rye at 50% anthesis (Zadok's growth stage 65) tends to maximize biomass, weed suppression, and soybean yields (Ryan et al., 2021; Mirsky et al., 2009). In addition, seeding cereal rye between 135 to 269 kg ha^{-1}, depending on planting date and location, can provide a thick stand in the spring, leading to cereal rye competition with early emerging weeds and reduced weed biomass (Ryan et al., 2021; Mirsky et al., 2013; Ryan et al., 2011a). The cereal rye variety 'Aroostook' has been found to produce a high amount of biomass by spring termination, although physiological development of cereal rye cultivars could vary depending on regional climates and should be chosen accordingly (Ryan et al., 2021; Wells et al., 2016). Nitrogen applications may be needed to achieve high levels of biomass if planting cereal rye into low fertility soil. Ryan et al. (2011a) found that increased poultry litter applications at planting increased cereal rye biomass, although a subsequent reduction in weed biomass was not observed. Cereal rye mulch will not fully suppress weed emergence if adequate cereal rye biomass is not achieved by time of soybean planting and resulting weed growth could compete with soybean for resources, reduce yield and quality, and complicate harvesting (Silva and Delate, 2017; Keene et al., 2017; Mirsky et al., 2013; Teasdale and Mohler, 2000). Therefore, additional weed management strategies may be needed in cover crop based organic no-till soybean (Vincent-Caboud et al., 2017; Mirsky et al., 2013).

Planting soybean at a higher density is a cultural weed management tactic that has been widely studied (Menalled et al., 2021; Liebert and Ryan, 2017; Ryan et al., 2011a, 2011b; DeBruin and Petersen, 2008; Liebman et al., 2001). Increased soybean density leads to quicker soybean canopy closure, which reduces light penetration—both between and within soybean rows—and enhances crop-weed competition (Liebert and Ryan, 2017; Liebman et al., 2001; Mohler, 1996). Research has found that as soybean planting rates increase, weed biomass is

reduced; however, at higher planting rates, weed biomass reduction reaches a threshold as light interference and competition from soybean is maximized (Menalled et al., 2021; Steckel and Sprague, 2004). Previous work has suggested that seeding food-grade soybean between 646,000 and 728,000 pure live seeds ha^{-1} and feed-grade soybean at 527,800 pure live seeds ha^{-1} can provide the maximum economic return for organic no-till soybean (Liebert and Ryan, 2017; Menalled et al., 2021). Food-grade soybeans are recommended to be planted at a higher rate than feed-grade soybeans because higher market prices provide more offsets to seed costs (Menalled et al., 2021; Coulter et al., 2010). However, partial returns may decrease at rates above 750,000 pure live seeds ha^{-1} because of the increased cost of seed and the law of constant final yield, which states that a yield increase is not observed at higher planting densities (Menalled et al., 2021; Liebert and Ryan, 2017; Ryan, 2010; Mohler, 1996). Rates for organic no-till soybean are higher than recommended rates for tilled organic production because of the reliance on crop density as a weed management strategy as opposed to tillage (Menalled et al., 2021). There can be several downsides to seeding soybean at higher rates, including increased seed costs, soybean lodging and an increased risk of disease (Liebert and Ryan, 2017; Lee et al., 2005; Cooper, 1971)

Mowing between crop rows has been used as a mechanical weed management tool by farmers; however, research on this practice is lacking (Abdulai and Clark, 2018; Donald, 2000). Inter-row mowers have individual mower units that are positioned between crop rows and directly cut weeds close to the soil surface. Donald (2000) suggested that inter-row mowing can reduce soil erosion by not disturbing the soil surface and covering the soil surface with residue from cut weeds. Early work by Donald (2001, 2000) in soybean demonstrated that the combination of inter-row mowing and herbicides that were band-applied at planting could manage annual broadleaf weeds and increase yields compared to a weedy check. Field trials in

no-till soybean without herbicides found that inter-row mowing with a cereal rye cover crop reduced weed biomass when compared to traditional tillage and cultivation and that mowing generally controlled broadleaf weeds better than grass weeds (Abdulai and Clark, 2018). Previous research has also reported that monocot species recover quicker than dicot species after mowing because monocot growing points, or meristems, are underground or right at the soil surface, and thus are not damaged by mowing (Thompson, 2005; Donald, 2000). Researchers found that mowing twice during the critical period of weed control, the period of early crop growth where weed competition can cause yield loss, substantially decreased weed biomass and prevented yield loss (Donald, 2000; Zimdahl, 1980). The critical period of weed control for soybean is between growth stages V2 to V4, however the period may vary based on location and soil type (Eyherabide and Cendoya, 2002). Management decisions, such as crop fertilization rates and early crop planting could influence timing of mowing, as soybean canopy closure limits the ability to mow between rows (Donald, 2000).

Perennial weeds may be more difficult to manage with mowing compared to annual species because many perennials quickly regrow by way of resources in storage organs. Farmers can manage perennial weeds by exhausting nutrient stores through repeated mowing, which forces weeds to allocate resources toward foliar regrowth rather than toward resource competition, storage organs, or seed production (Mohler et al., 2021). Inter-row mowers have recently become commercially available with the advent of the Row-Shaver (Row Shaver Systems, LLC Great Bend, KS) and the IRM-X4 Inter-Row Mower (R-Tech Industries Ltd., Homewood, MB).

Another physical weed management tactic is electric weed control, a method patented in the late 1800's (Opp & Opp, 1952). Some field trials were performed in the 1970's, however,

farmer adoption and research on electric weed control has only recently become a subject of interest (Vingneault and Benoit, 2001; Diprose et al., 1985; Rasmusson et al., 1980). Increased electric weed control use is likely due to the increase in herbicide resistant weeds (Heap, 2023) and the development of new electrical weeding machines (Bloomer et al., 2022; Lehnhoff et al., 2022; Lati et al., 2021). When electricity is directed at a plant, the increase in temperature causes water molecules inside the plant vasculature to vibrate with a high intensity that causes the cell walls to burst (Lati et al., 2021; Vingneault and Benoit, 2001). The destruction of plant cells leads to disruption of nutrient and water pathways and ultimate plant death. Several studies have documented effective electric suppression of weeds in laboratory settings (Bloomer et al., 2022; Lehnhoff et al., 2022; Lati et al., 2021; Sahin and Yainkilic, 2017). However, high cost, energy needs, and safety of the operator can limit in-field experiments using electricity (Lehnhoff et al., 2022; Rask and Kristofferson, 2007; Bond and Grundy, 2001). Several studies in tilled systems have been successful, reporting high rates of weed necrosis when high voltage (< 13kV) was applied to weeds in later growth stages for several seconds (Schreier et al., 2022; Diprose et al., 1985). Electric weed control studies display varied results with weed control in later growth stages, as weed response to electricity depends on weed morphology, age, and lignin content (Vingneault and Benoit, 2001). Weeds with a higher water content tend to be more susceptible to electricity and weeds with woody stems less susceptible (Moore et al., 2023; Schreier et al., 2022). In addition, grass weed species tend to display less signs of damage, likely because of the physiology of the plants (Schreier et al., 2022).

Integrated weed management (IWM) is a systematic, proactive approach of using multiple weed management strategies that can reduce the negative impacts of weeds while preserving ecological benefits of a cropping system (Riemens et al., 2021; Storkey and Neve,

2018). IWM seeks to manage weed communities in a way that will reduce selection for dominant weed species that may become resistant to a singular weed management tactic (Riemens et al., 2021; Liebman and Gallandt, 1997). Using a variety of weed management strategies also decreases risk, for if one tactic fails, others may be able to fill gaps in weed management (Benaragama and Shirtliffe, 2013; Liebman et al., 2001; Liebman and Gallant, 1997). An idea that stems from IWM is the many little hammers approach, where effective weed control can be achieved when combining several weed management tactics that may not be fully effective on their own (MacLaren et al., 2020; Liebman and Gallant, 1997). One can observe synergistic interactions when using IWM tactics, where a result is observed from combining tactics that could not have been predicted from the tactics performance in isolation (Liebman and Gallant, 1997, Swanton and Murphy, 1996).

Planting soybean at a high seeding rate, inter-row mowing, and weed electrocution are weed management tactics that are compatible with cover crop based organic no-till systems, for they create little disturbance of the cereal rye mulch. The tactics target the cropping system across space and time, with the high seeding rate targeting within row weeds at planting, the inter-row mower managing between row weeds in the middle of the season and weed electrocution controlling weeds that grow above the soybean canopy later in the season. As far as the authors are aware, no other studies have tested these tactics in an organic no-till system as part of an IWM program at the time of publication. To this end, an experiment was conducted in a cover crop based, organic no-till soybean system to determine if three weed management tactics (high soybean seeding rate, inter-row mowing, and weed electrocution) used independently and in combination would affect weed biomass, weed community structure, and soybean yield. We hypothesized that the combination of all three tactics would result in the

lowest weed biomass and greatest soybean yield. Costs of weed management tactics were assessed to estimate their impact on profitability.

MATERIALS AND METHODS

Study site and experimental design

The experiment was established at the Cornell University Musgrave Research Farm in Aurora, NY (42.73, -76.66) from 2020 to 2022. The soil in the fields used for this experiment was a Honeoye – Lima silt loam. Soil conditions and field history can be found in Table 1. The experiment was conducted in five fields with different cereal rye mulch levels ranging from 0 to over 9000 kg ha^{-1}. All fields were managed without the use of herbicides to simulate the constraints imposed under organic systems. Two fields without cereal rye were left in a bare winter fallow until soybean planting and were used to represent a scenario with insufficient mulch for weed suppression. Cereal rye cultivar 'Aroostook' was planted in field 1a and cereal rye cultivar 'ND Gardner' was planted in fields 1b and 2a (Albert Lea Seed; Albert Lea, MN, USA; Table 1). Before cereal rye planting in the fall, all fields were moldboard plowed, followed by a disk and rolling harrow, and lastly a cultimulcher. Cereal rye was planted on 29 September 2020 and 13 October 2021 using a John Deere 1590 no-till drill at 168 kg (3 million) pure live seeds ha^{-1} with 19 cm row spacing. Fields 1a and 1b received 1000 lb product/acre of '5-4-3' Kreher's fertilizer at cereal rye planting. Fertility was only applied if a) crops were harvested or removed from a field after the most recent fertility application or b) there was not a history of legumes present before establishing the cereal rye.

Cereal rye was terminated with a roller-crimper at anthesis on 8 June 2021 and 3 June 2022 with a water-filled I&J crop roller weighing approximately 1195 kg (I&J Manufacturing; Gordonville, PA, USA). Soybean was planted with a 4-row (76-cm width) John Deere 1755 planter (John Deere, Moline, IL, USA) as part of single pass operation at rolling in fields with

cereal rye (fields 1a, 1b, and 2a) (Table 1). The planter was modified for cover crop-based organic no-till planting, with hydraulic downforce, double disc openers before the planting tube, a seed-firmer behind the seed tube, and cast-iron notched closing wheels (Ryan et al., 2021). Before soybean planting, fields without cereal rye (field 1c and 2b) were disked and cultimulched, but no secondary cultivation (i.e., tine weeding, rotary hoeing, or inter-row cultivation) was used after soybean planting (Table 1). The baseline soybean seeding rate was 432,000 pure live seeds ha^{-1}. A spatially balanced randomized complete block design was used with four blocks in all five fields.

Table 1: Field specifications, history, experiment operations, and sampling events of 'Soybean Weed Integrated Management' (SWIM) 2021 & 2022. RM = relative maturity. Summer annuals = black bean, corn, soybean, sunflower, and sorghum. Cereal rye planting, soybean planting, inter-row mowing, and weed electrocution are field operations, soybean and weed biomass, and yield harvest are sampling events.

	Field				
	1a	**1b**	**1c**	**2a**	**2b**
Organic matter	3.18	3.86	3.35	2.90	2.83
pH	7.90	7.40	7.50	7.15	7.12
Cereal rye variety	Aroostook	ND Gardner	-	ND Gardner	-
Soybean variety	Viking 01517, RM 2.5- 2.6	Viking 1A1029, RM 1.7	Viking 1A1029, RM 1.7	Viking 1A1029, RM 1.7	Viking 1A1029, RM 1.7
Plot size	3m x 27m	3m x 27m	3m x 27m	3m x 5m	3m x 27m
Previous year crop	Spring oats – Cereal rye	Summer fallow (conv) - Cereal rye (org)	Cereal rye + Hairy vetch – Summer annuals – Winter fallow	Red clover – Cereal rye	Red clover – Winter fallow
Cereal rye planting	29-Sep-2020	29-Sep-2020	-	2-Oct-2021	-
Soybean planting	8-Jun-2021	8-Jun-2021	16-Jun-2021	3-Jun-2022	3-Jun-2022
Inter-row mower					
Pass 1	7-Jul-2021	7-Jul-2021	27-Jul-2021	14-Jul-2022	14-Jul-2022
Pass 2	10-Aug-2021	-	9-Aug-2021	2-Aug-2022	29-Jul-2022
Weed Zapper					
Pass 1	4-Aug-2021	6-Aug-2021	4-Aug-2021	12-Aug-2022	12-Aug-2022
Pass 2	16-Aug-2021	-	16-Aug-2021	-	-
Soybean and weed biomass	19-Aug-2021	19-Aug-2021	23-Aug-2021 - 24-Aug-2021	25-Aug-2022	25-Aug-2022
Yield	19-Oct-2021	12-Oct-2021	12-Oct-2021	14-Oct-2022	14-Oct-2022

Treatments

Nine experimental treatments were compared: 1) Untreated control (CO), 2) High soybean seeding rate (SR), 3) Inter-row mower (IM), 4) Weed Zapper (WZ), 5) SR x IM 6) SR x WZ, 7) IM x WZ, 8) SR x IM x WZ, and 9) Weed free (WF). The high seeding rate (SR) and all treatment combinations with SR were seeded at 680,000 pure live seeds ha^{-1}, which was 45% higher than the baseline seeding rate of 432,000 pure live seeds ha^{-1} that was used in all other treatments. The baseline seeding rate is closer to rates used in tillage based organic production (370,500 seeds ha^{-1}), however, the baseline rate may be considered a high rate compared to recommended seeding rates for conventional production (296,000-345,000 seeds ha^{-1}) (Cox et al., 2019; Rees, 2019; Conley and Santini, 2007; Delate et al., 2003). The baseline seeding rate was chosen because it is slightly below what is recommended for organic no-till, feed-grade soybean (530,000 pure live seeds ha^{-1}) (Menalled et al., 2021). The high soybean seeding rate (680,000 pure live seeds ha^{-1}) was chosen to be slightly above the organic no-till recommended rate, while minimizing risk of soybean lodging and disease (Mohler et al., 2021; Cooper, 1971).

The inter-row mower (IM), (IRM X4, R-Tech Industries Ltd., Homewood, MB), has five individual mower units that mow between soybean rows (Figure 1). The IM mower was attached to the front of a John Deere 5100R tractor with a 3-point hitch. Each mower unit was powered with a hydraulic motor system that spins four swing blades attached to a central disc at 1800 rpm. The individual mower units have shields to protect crops from the blades that are narrow at the top and extend outward at the bottom to a width of 56 cm. Cutting height is adjustable, ranging from 5-18 cm above the soil surface. The inter-row mower was used twice each year when weeds were at least 15 cm above the cereal rye mulch and before the soybean canopy formed. Transport to experimental fields and precipitation events delayed inter-row mower

operations and sampling events in 2021. In 2021, mowing occurred on 20 (1a, 1b) and 27 (1c) July for the first pass and 9 (1c) and 10 (1a) August for the second pass (Table 2). Field 1b did not receive a second pass in 2021 because there were almost no weed species growing through the mulch to be targeted by the inter-row mower. In 2022, the first mowing occurred on 14 July and the second mowing occurred on 29 (2b) July and 2 (2a) August (Table 2). The tractor traveled at 2.7 km per hour for all passes.

Figure 1: The inter-row mower used in this experiment, attached to a John Deere 5100R tractor with a 3-point hitch. The mower is powered with a hydraulic system and was custom made by IRM X4, R-Tech Industries Ltd. in Homewood, MB.

The weed electrocution treatment was applied using a rear-mounted generator that delivered electricity to weed plants through a front-mounted copper boom (6R30 Weed Zapper, Old School Manufacturing, LLC, Sedalia, MO) (Figure 2). The machine is commercially available and used by farmers in the United States. The generator can produce up to 200,000 W of electricity and 225-275 A. Both units were attached to a John Deere 5100R tractor using a front and rear 3-point hitch. The boom was trimmed to a 3-meter length for compatibility with

width of experimental plots. The generator has a power take off (PTO) shaft that is attached to the tractor and approximately 7500 W of tractor power is needed for every 30 cm of electrified boom width. The copper boom was positioned above the soybean canopy using a hydraulic top-link control to target weeds that grow higher than the crop canopy. In this experiment, the 'broadleaf' setting was used for all passes, which is the recommended setting for the first pass and for all weeds that are knee-height or taller. The tractor traveled at a speed of 2.7 km per hour and boom height was adjusted during treatment application to contact weeds of different heights. In 2021, electric weed control treatments occurred on 4 (1a, 1c) and 6 (1b) August for the first pass and 16 August for the second pass (Table 2). Field 1b did not receive a second pass in 2021 because there were almost no weed species growing through the mulch to be targeted by the Weed Zapper. In 2022, electric weed control treatments occurred on 12 August. No second pass was performed in 2022 in any fields because heavy rainfall precluded timely weed electrocution operations and subsequent soybean canopy closure risked excessive soybean damage from Weed Zapper operations.

For the weed free (WF) treatment, a 3 m x 4.5 m microplot was randomly established within each WF plot at soybean planting and was hand-weeded on a weekly basis until soybean canopy closure. All data collected in the WF treatment were collected from within the microplot area.

Figure 2: The model 6R30 Weed Zapper used in this experiment. The generator is attached to the back of a John Deere 5100R tractor with a 3-point hitch. The 4.6 m electric copper boom is attached to the front of the tractor with a 3-point hitch. The Weed Zapper was purchased from Old School Manufacturing, LLC in Sedalia, MO.

Data collection

Aboveground cereal rye and weed biomass were sampled at the block level (n = 4) on 4 June 2021 and 31 May 2022, prior to terminating cereal rye with a roller-crimper. Samples were taken to characterize fields before treatment implementation. One 0.76 cm x 0.66 cm quadrat was randomly placed encompassing four cereal rye rows in each block. All stems rooted in the quadrat were clipped at soil level and separated by species. All samples were dried at 55^0C for 7-10 days, and their dry weight was recorded for analysis.

Aboveground soybean and weed biomass were sampled at the plot level on 19 August (1a, 1b), 23 August (blocks 1-2, 1b) and 24 August (blocks 3-4, 1b) in 2021 (Table 1). In 2022, biomass was sampled on 25 August. In 2021, biomass was sampled 9-14 days after the last mowing event and 3-8 days after the last weed electrocution event. In 2022, biomass was sampled 23-27 days after the last mowing event and 13 days after weed electrocution (Table 1).

Minimum plot size was 3 m x 15 m (Table 1) and weed coverage and soybean stands were consistent within each plot. One 0.76 cm x 0.66 cm quadrat was randomly placed over either the 2nd or 3rd soybean row of the four rows established by the planter for each plot. In all samples, the edge of the quadrat was flush against the soybean row and the space between rows 2 and 3 was always included in the quadrat. Within each quadrat, soybean plants with pods were clipped at the soil surface and counted. Within the same quadrat, weed biomass was clipped and separated by species. Sampled were placed in separate bags and dried at 55 ºC for at least 10 days. Rows 1 and 4 were avoided during sampling to reduce edge effects.

Specific guidelines were followed when sampling weed biomass in any treatment that included the Weed Zapper. Any weed that had a main stem that was still green (live tissue) and was flowering or producing seed after electrocution was collected for total weed biomass, even if that weed had originally been electrocuted. These specifications were chosen because a green stem and active seed production indicates active competition with the crop that could impact yield. All soybean and weed biomass samples were oven dried at 55ºC for 7-10 days and weighed.

Soybeans were sampled to quantify yield on 12 (1b, 1c) and 19 (1a) October 2021 and 14 October 2022 approximately 5 days after 95% of pods were brown and dry with no green or yellow leaf matter left on plants (Table 1). Two 1-m row lengths were randomly sampled one from row 2 and the other from row 3. Soybean plants from both rows were clipped at the soil surface and placed in a single canvas bag. Samples were dried at 55 ºC for 10 days and then threshed with the Wintersteiger LD 350 (Wintersteiger Inc., Salt Lake City, UT) to separate seeds from pods. Seeds were weighed immediately after threshing. Yield was adjusted to 13% moisture after weighing.

Statistical analysis

All statistical analyses were carried out using R software version 4.1.2. (R Core Team 2022). Soybean density, weed biomass, soybean yield, weed species richness, and Pielou's evenness were described each with separate linear mixed effects models (Bates et al., 2015). Weed biomass was analyzed for total, monocot, dicot, annual, and perennial biomass data, which was classified using the TRY plant trait database (Kattge et al., 2020). All response variables were analyzed with separate linear mixed models that included treatment as a fixed effect (n = 9) and field (n = 4) and block nested within field (n = 16) as random effects. The weed free treatment was removed from each analysis apart from soybean yield because weed biomass was less than 5 g m^{-2} in all plots and would result in almost no variance. The model residuals for all weed biomass variables (total, monocot, dicot, annual, perennial) violated the assumption of homogeneity of variance. All weed biomass models were log (x + 1) transformed to correct for assumptions of normality and homogeneity of variance and to account for zeros in the data. After confirming model fit, fixed effects were assessed with a type III analysis of variance (ANOVA) test. Treatment levels were compared with least-squares means comparisons using the Fisher LSD method (Lenth, 2022). However, arithmetic means from untransformed data and standard errors are used for presentation in graphics and text. Package ggplot2 was used for all graphics (Wickham, 2016).

Dominant weed species in each treatment were determined using untransformed weed-by-species biomass data. For each field, the four blocks were pooled and the average weed biomass for each species in each treatment was found. The average individual species biomass was divided by the average total weed biomass for each treatment. The result was a number that

indicates the percent biomass of a particular species in each treatment. The weed species that made up the top 70% of the average total weed biomass were recorded (Table 2).

Species richness and Pielou's evenness indices were calculated with the 'vegan' package (Oksanen et al., 2022) to investigate weed community diversity by treatment. Species richness (S) represents the number of unique species in a given community and Pielou's evenness (*J*) is an indicator of biodiversity that accounts for the relative species abundance in each weed community (Pielou, 1966). Species richness was calculated as the number of weed species per $0.5m^2$ quadrat in each plot. Pileous Evenness (*J*) was calculated from biomass data as:

$$J = H'/\ln(S) \qquad \text{[Equation 1]}$$

where S is the total number of species in the treatment and *H'* is Shannon's diversity index value. Species evenness is constrained between 0 and 1, with 0 being no evenness, (all biomass is from a single species), and 1 being complete evenness, (all species having the same biomass in a community) (Pyron, 2010).

RESULTS AND DISCUSSION

Temperature was similar during both site years; however, precipitation was above the 30-year average for most of the growing season in 2021 and below the 30-year average in 2022 (Figure 3). Cereal rye biomass averaged 7913 ± 426.6 kg ha^{-1} in field 1a, 10165 ± 440.4 kg ha^{-1} in field 1b, and 7255 ± 349.8 kg ha^{-1} in field 2a. Fields 1a and 2a produced cereal rye close to the recommended biomass for adequate weed suppression (8000 kg ha^{-1}), and field 1b produced high levels of cereal rye biomass, resulting in a high level of weed suppression (Silva and Delate, 2017; Mirsky et al., 2013).

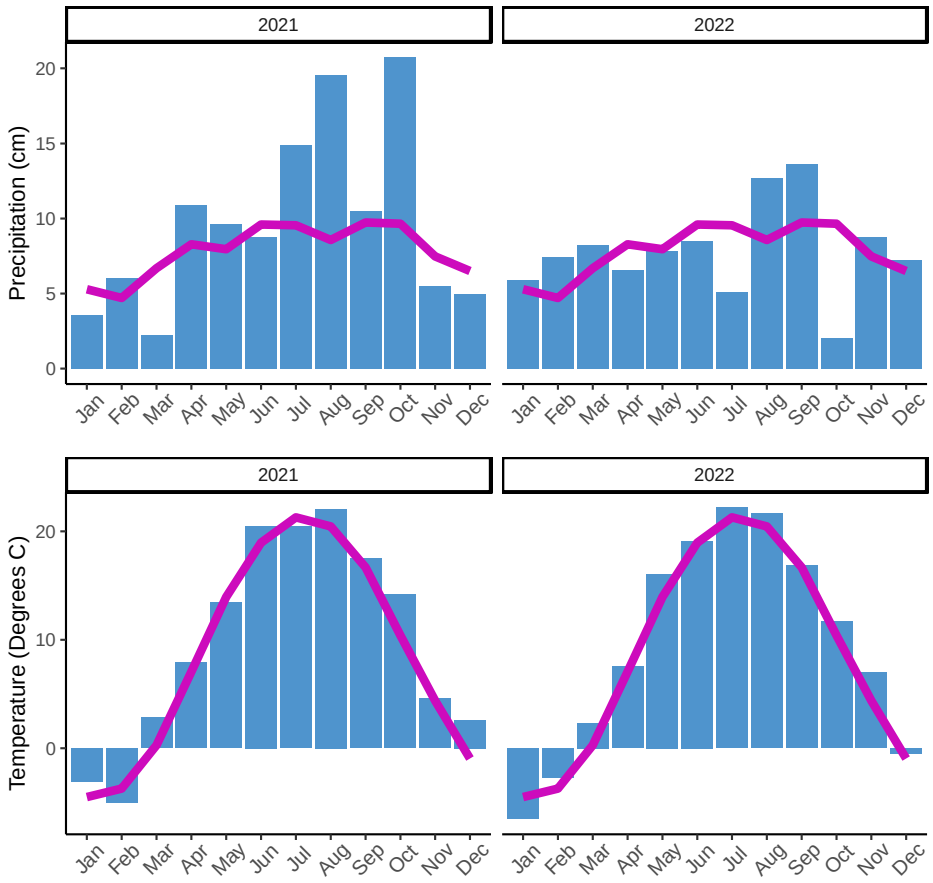

Figure 3: Monthly temperature (^{O}C) and precipitation (cm) in Aurora, NY in 2021 and 2022. Pink lines indicate 30-year average.

Soybean density

Soybean density was quantified after treatments were imposed to 1) confirm that the high soybean seeding rate treatment was successful in achieving a higher soybean density, and 2) to determine if soybean density was affected by inter-row mowing or weed electrocution. As intended, soybean density was higher in treatments that included the high seeding rate ($P < 0.0001$) (Figure 4). The baseline seeding rate (432,000 pure live seeds ha^{-1}) resulted in 30.8 plants m^{-2} (308,000 plants ha^{-1}) and the high seeding rate (680,000 pure live seeds ha^{-1}) resulted in 46.0 plants m^{-2} (460,000 plants ha^{-1}). Soybean densities were slightly lower than expected, with 71% percent plant emergence for the baseline rate and 68% plant emergence for the high seeding rate. Lower percent emergence could have been the result of inadequate seed placement through cereal rye mulch, inconsistent seeding depth, low soil moisture impacting germination in 2022 or intraspecific competition between soybean plants (resulting in self-thinning) (Klimek-Kopyra et al., 2021; Liebert and Ryan, 2017; Mirsky et al., 2013; Fehr et al., 1973). Other soybean seeding rate experiments for organic no-till soybean systems have reported similar percent emergence of plant populations at high seeding rates (Menalled et al., 2021; Liebert and Ryan, 2017). Inter-row mowing and electrical weeding did not impact soybean density (Figure 4). Furthermore, increasing the seeding rate did not lead to increased injury to the crop from physical weed control operations.

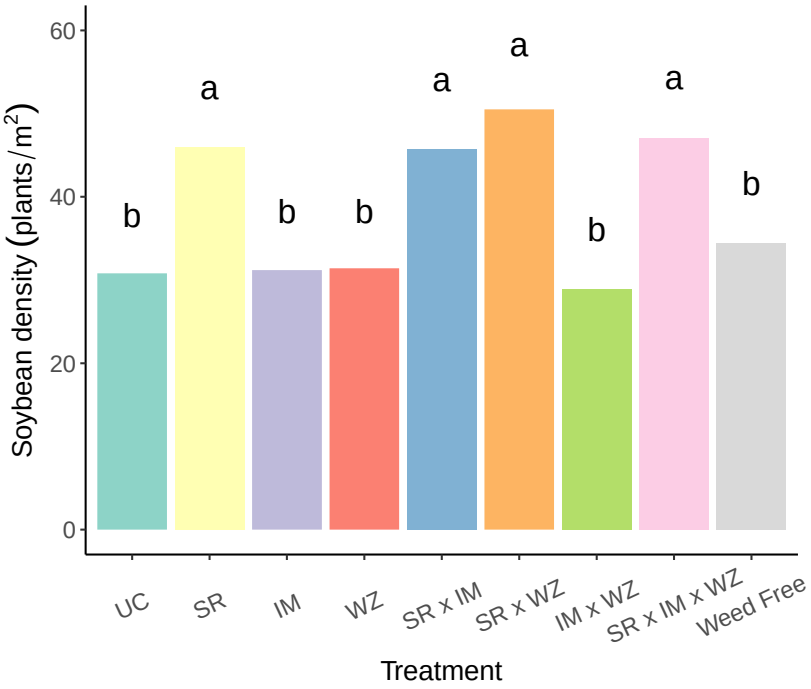

Figure 4: Soybean density (plants/m^2) in August after all weed management treatments were applied. Data were pooled across all site years. Similar letters above bars indicate no significant difference ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

Weed biomass

Weed biomass in untreated control plots ranged from 4 g m^{-2} (Field 1b) to 284 g m^{-2} (Field 1c) and weed biomass was different between treatments ($P < 0.0001$). The high seeding rate alone treatment did not decrease weed biomass (Figure 5). Although increasing crop seeding rate can be an effective cultural weed management practice, as increased soybean densities lead to increased soybean leaf cover (Yelverton and Coble, 1991) and light competition with weeds within the crop row (Mohler et al., 2021; Liebman et al., 2001), the effect largely depends on the baseline rate. This is because crop-weed competition relationships are hyperbolic such that the greatest decrease in weed biomass (y-axis) occurs with an initial increase in seeding density (x-axis). As seeding rate increases, the proportional reduction in weed biomass decreases (i.e.,

diminishing returns on the investment in higher seed density). Thus, the baseline seeding rate may have already been providing a high level of weed suppression; however, this cannot be tested because a treatment without soybean allowing for maximum weed growth was not included in the experiment.

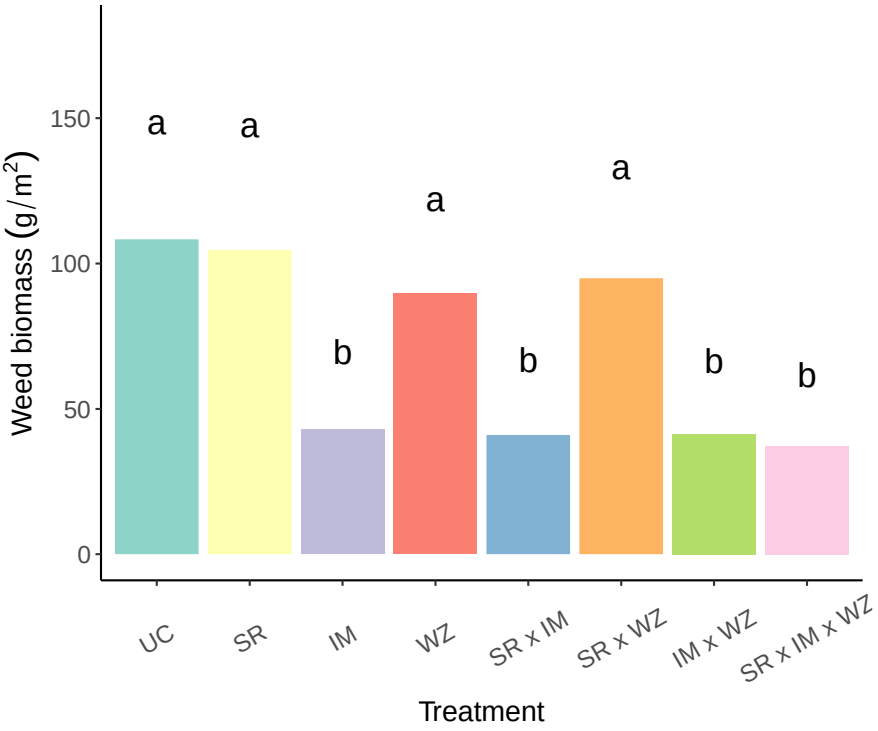

Figure 5: Weed biomass (g/m^2) in each weed management treatment pooled across all site years. Biomass was sampled in mid-August after all management tactics had been applied. Similar letters above bars indicate no significant difference ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

When used in isolation, the inter-row mower reduced weed biomass by 60% compared to the untreated control (Figure 5). In both years of the experiment, mowing occurred twice during the critical period of weed control, when weeds were exerting high levels of competition with soybean (V2 to V4) (Eyherabide and Cendoya, 2002; Liebman et al., 2001) (Table 2). After the

first mowing event, weeds likely put their energy towards foliar regrowth, which was then mowed again. The second mowing likely limited the ability of the weeds to capture acquire resources and produce more biomass (Mohler et al., 2021). The inter-row mower directly reduced the biomass of weeds within the 56 cm width of each individual mowing unit, a space that was 74% of the 76 cm between row space. Research has demonstrated that weeds that grow farthest from the soybean canopy tend to produce the highest biomass because they are not shaded by the soybean crop until late in the season and can reach soil nutrients that may not be as accessible to the crop (Mohler et al., 2021; Korres et al., 2019; Barnes et al., 2018; Monks and Oliver, 1998). In this experiment, weeds that grew in the space between rows had the highest likelihood of producing the most biomass (Korres et al., 2019; Yelverton and Coble, 1991). The inter-row mower was able to remove a large proportion of these weeds in the area between rows, which could explain the substantial reductions in weed biomass after inter-row mowing compared to other treatment plots where inter-row mowing did not occur. Competitive or late-emerging weed species produced some regrowth after the second mowing event, which contributed to the weed biomass present in the inter-row mowing treatments. In addition, the inter-row mower chopped the cereal rye mulch during operations in fields with high cereal rye biomass. The cut mulch did not impede inter-row mower operations but did lead to increased cereal rye reseeding in mowed treatments in September and October.

When used in isolation, the Weed Zapper did not reduce weed biomass compared to the untreated control (Figure 5). The Weed Zapper requires a large height differential (>30 cm) between the top of the soybean canopy and the top of a weed to effectively electrocute the weed (Schreier et al., 2022; Vigneault and Benoît, 2001). In both years, visual observations indicated that few weeds grew at least 30 cm above the soybean canopy before canopy closure. Several

weeds reached heights greater than or equal to 30 cm above the canopy only after the canopy closed, when the Weed Zapper could no longer travel through the field without damaging soybeans. Cereal rye mulch can delay weed seed germination because the mulch reduces soil temperature and creates an additional barrier a germinated seed must penetrate, which could also explain the delay in competitive weeds breaching the canopy (Mohler et al., 2021; Mirsky et al., 2011; Mischler et al., 2010; Teasdale and Mohler, 2000). In addition, cereal rye mulch has been shown to suppress small-seeded weed species (Menalled at al., 2022), and many competitive, fast-growing weed species have small seeds (Mohler et al., 2021). Therefore, the cereal rye may have selected for a weed community where the majority of weed species present did not grow faster than soybean. In regions that have higher populations of tall weed species that grow faster than the crop, such as *Ambrosia trifida* (L.) or *Amaranthus* spp., the Weed Zapper would likely be more effective.

No support was observed for the hypothesis that combinations of tactics would improve weed management. When additional tactics were added to inter-row mowing, weed biomass was not reduced further compared to when the inter-row mower was used alone (60% compared to the untreated control) (Figure 5). Success of multi-tactic weed management has varied in no-till systems. Snyder et al. (2016), found that an IWM program with delayed cover crop termination, herbicide banding, and high-residue cultivation did not reduce weed biomass or increase soybean yield compared to a continuous tillage and full herbicide use program. However, Ryan et al. (2011b) reported that combining the cultural practices of increased cereal rye biomass and high soybean planting density in organic no-till systems reduced weed biomass compared to standard practices of no mulch and conventional seeding rates. It is likely that the method of weed

management (i.e., mechanical, chemical, or cultural practices), as well as the weed communities in a particular site-year can influence results of multi-tactic management.

Weed community

Weed management treatments did not differ in species richness. However, treatments differed slightly in species evenness based on biomass of weeds sampled ($P < 0.05$). The treatment that combined all three weed management tactics had a higher species evenness than the untreated control (Figure 6). The combination of all three practices had an evenness of 0.74 and the untreated control had an evenness of 0.63. This observation of a more even weed community emerging after multiple weed management tactics are used is supported by previous work that demonstrated continuous implementation of integrated weed management can shift community emergence patterns and promote higher weed biodiversity (Cordeau et al., 2022; Cardinale et al., 2012). A combination of practices can place a range of stressors on dominant weed species but not on less competitive species, fostering diverse weed communities that are limited in abundance, do not threaten yields, and may promote resilience to pests and pathogens (Cordeau et al., 2022; MacLaren et al., 2020; Storkey and Neve, 2018). Comparable work has found that diverse cropping systems with varied disturbance regimes can promote richer weed communities while preserving crop profitability and environmental health (Liebman et al., 2021; Murphy et al., 2006).

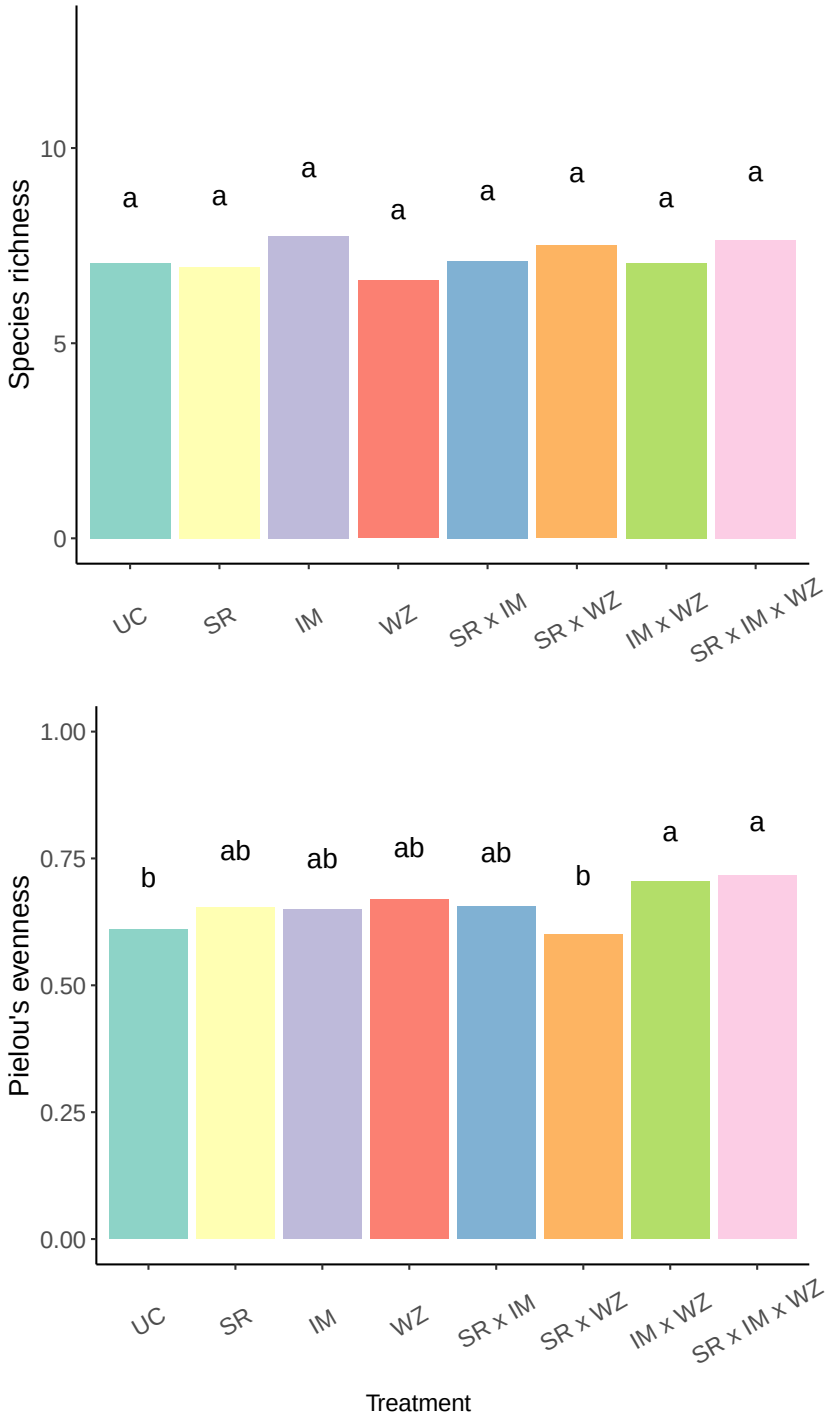

Figure 6: Diversity indices of weed communities for all treatments. Weed by species biomass was pooled across fields. Similar letters above bars indicate no significant difference using separate Fisher LSD tests ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

Functional groups

Weed biomass data were split into monocot and dicot species to understand which functional traits were targeted by the inter-row mower. Treatment differences were observed for dicot biomass ($P < 0.0001$). Like results for total weed biomass, all treatments that included the inter-row mower had lower biomass than the untreated control (Figure 7). Monocot weed biomass did not differ among treatments (Figure 7). The weed community was dominated by dicot weeds, as mean dicot weed biomass was approximately 85 g m^{-2} and monocot biomass 24 g m^{-2} in untreated control treatments. Monocots present in the experiment included *Setaria faberi* R.A.W. Herrm. and *Setaria pumila* (Poir.) Roem. & Schult., which emerge after dominant dicot weeds, such as *Ambrosia artemisiifolia* L. and *Chenopodium album* L. (Mohler et al., 2021). The delayed emergence suggests some monocots may have escaped management. In addition, *S. faberi* and *S. pumila* can regrow after mowing (Abdulai and Clark, 2018; Martin, 2018; Donald, 2000). Moreover, the inter-row mower substantially reduced dicot weed biomass because of their dominance in the weed community, earlier emergence time, and lack of underground growing points to allow for regrowth (Mohler et al., 2021; Everman et al., 2008). The experimental inter-row mowing results align with those of Abdulai and Clark (2018), who found that an inter-row mower was more effective at managing dicot broadleaf weeds than monocot grasses in organic, no-till planted soybean. Mowing also has the potential to produce other beneficial effects, such as the restructuring of the soil microbial community, which may encourage increased soil organic matter (SOM) decomposition (Xia et al., 2019; Guo et al., 2018). When plant species are defoliated, they increase root respiration and microbial activity, which in turn can increase soil carbon cycling (Guo et al., 2018).

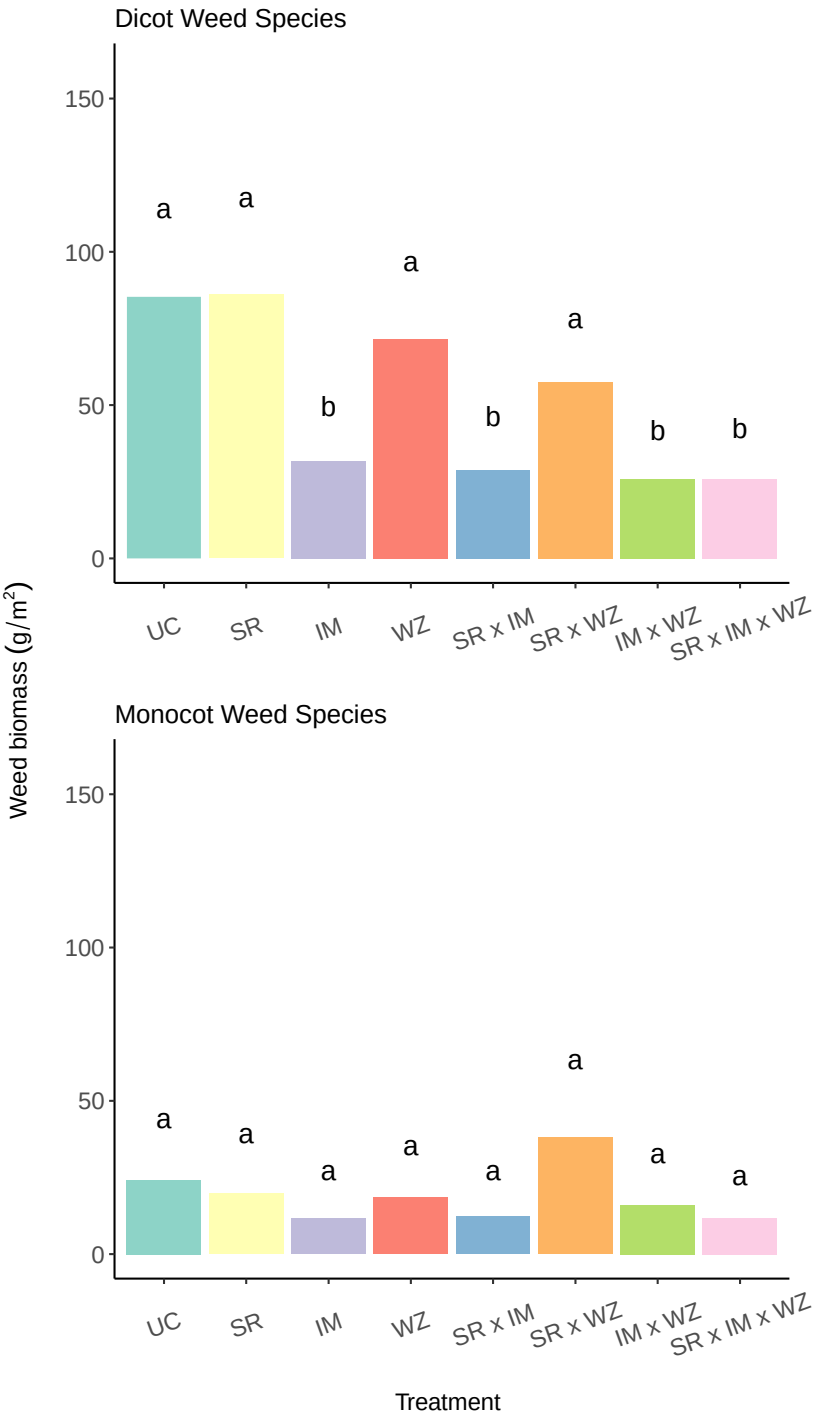

Figure 7: Dicot and monocot weed biomass (g m^{-2}) in each weed management treatment pooled across fields. Similar letters above bars indicate no significant difference using separate Fisher LSD tests ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper

Weed biomass data were also split into annual and perennial species to describe differential responses to the inter-row mower. Treatment differences were observed for annual weed biomass ($P < 0.0001$), but no differences were observed between treatments for perennial weed biomass (Figure 8). Treatments that included the inter-row mower reduced annual weed biomass compared to the untreated control (Figure 8). Annual weed species dominated the weed community, with annual biomass at 92 g m^{-2} and perennial biomass at 17 g m^{-2} in untreated control treatments. These findings correlate with Donald (2000), who reported that annual species were managed with inter-row mowing, but it was more difficult to manage perennial species because of their underground storage organs that provide energy for quick foliar regrowth after defoliation (Mohler et al., 2021; Donald et al., 2007; Liebman et al., 2001). Mowing can be an effective perennial weed management strategy if the practice is performed multiple times within a season to deplete storage organ resources (Mohler et al., 2021; Sheley et al., 2003; Liebman et al., 2001). Moreover, the results of this experiment demonstrate that in organic reduced-tillage systems, inter-row mowing during the critical period of weed control can be an effective tactic for reducing annual dicot weed biomass.

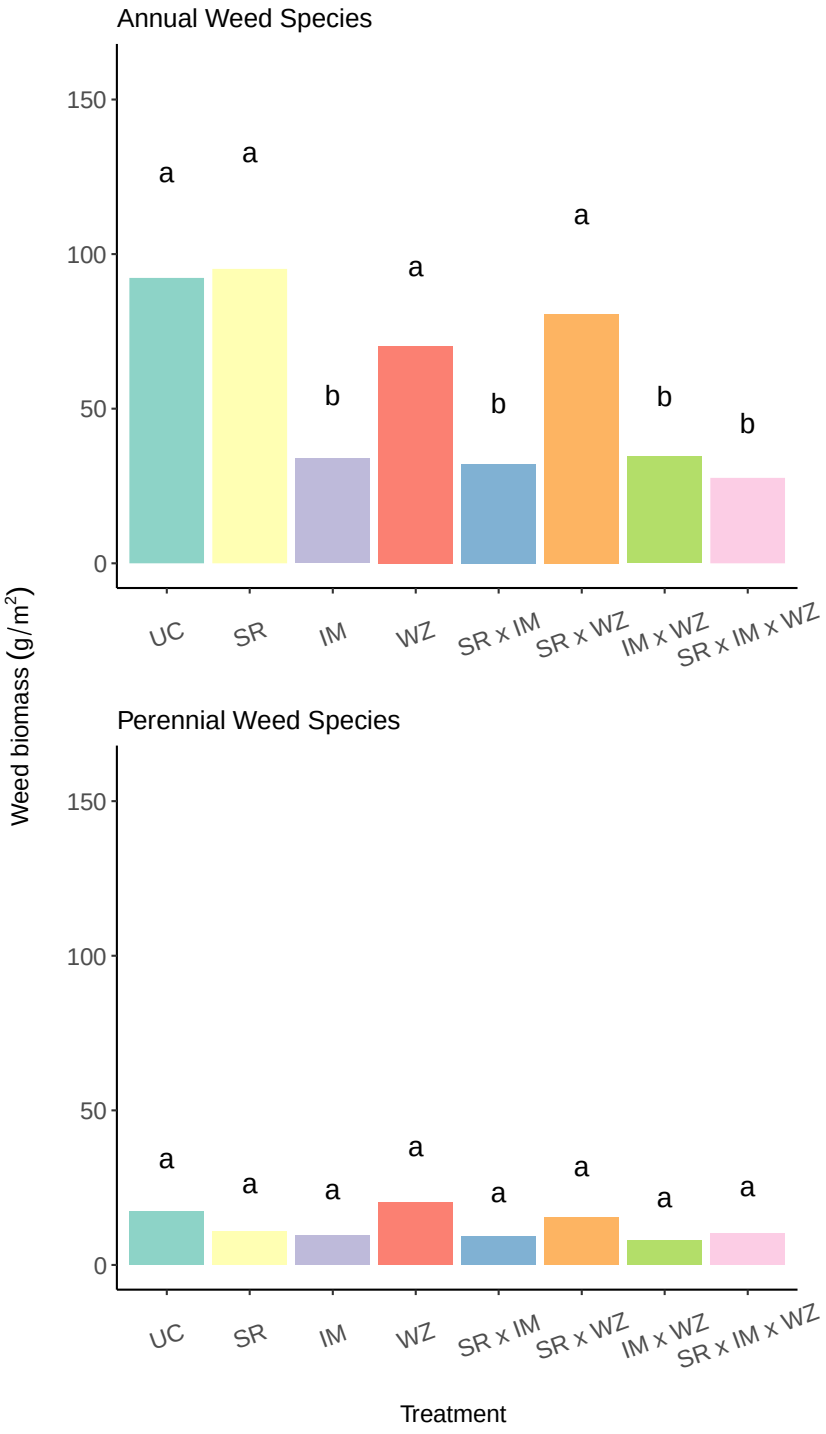

Figure 8: Annual and perennial weed biomass (g/m^2) in each weed management treatment pooled across all fields. Similar letters above bars indicate no significant difference using separate Fisher LSD tests ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

Dominant weed species

The dominant weed species in each weed management treatment were determined to investigate the potential for weed species selection by tactics. The dominance table was separated by site year to obtain a higher resolution of each individual weed community (Table 3). Annual dicot species that are competitive in soybean cropping systems, such as *C. album* and *A. artemisiifolia,* were present in the untreated control treatment and the high seeding rate treatment. In four out of five fields, the individual inter-row mower treatment reduced upright annual dicot species in favor of prostrate growth forms or monocots, such as *Sonchus arvensis* L. and *Medicago lupulina* L. A weed species that can be dominant in organic, no-till systems, *A. artemisiifolia* (Mirsky et al., 2011; Cowbrough et al., 2003), was not present in most Weed Zapper treatments, which suggests electric management may have controlled this fast-growing, competitive species. Schreier et al., 2022 found similar results, with >80% control of *A. artemisiifolia* at flowering or beyond. In two combinations of tactics with the inter-row mower (SR x IM and IM x WZ), annual dicot dominance was reduced in favor of monocot or perennial species, such as *S. pumila, Setaria italica* (L.) P. Beauv., and *S. arvensis*. Dominance of monocots and perennials in the IM treatments aligns with the decrease in annual dicots post inter-row mowing (Figures 7, 8). The dominant species for the SR x IM x WZ treatment was *A. artemisiifolia* in three of the five fields. Yet, in the fields where *A. artemisiifolia* was present, the weed species made up less than 30% of the total biomass in the three-tactic treatment, whereas the species made up higher percentages of the total biomass in the untreated control treatments. Therefore, species dominance was reduced when using three weed management tactics, which is supported by species evenness results.

Table 2: Percent biomass of dominant weed species in all treatments, split by field and averaged across all blocks. '%B' indicates percent biomass and 'B' indicates biomass (g m^{-2}). 'Total' indicates the sum of '%B' and 'B' of individual species in each treatment. Weed species are in EPPO codes. Only weed species that make up at least 70% of the average total weed biomass per treatment are reported. UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

	Field														
	1a			1b			1c			2a			2b		
Treatment		% B	B		% B	B		% B	B		% B	B		% B	B
UC	AMBEL	39%	20	AMBEL	60%	7	AMBEL	27%	39	AMBEL	45%	8	CHEAL	33%	19
	SONAR	43%	22	ANGAR	16%	2	POLPE	18%	26	MEDLU	22%	4	HIBTR	32%	18
							POAAN	11%	16	TRFPR	12%	2	AMBEL	9%	5
							SETPU	11%	15						
							SETIT	7%	10						
Total		**82%**	**42**		**76%**	**9**		**74%**	**106**		**79%**	**14**		**74%**	**42**
SR	AMBEL	46%	19	SINAR	21%	3	AMBEL	31%	48	AMBEL	30%	6	HIBTR	47%	21
	SONAR	24%	10	ARISE	15%	2	POLPE	21%	32	MEDLU	26%	5	CHEAL	31%	14
				PLAMA	12%	2	SETIT	18%	28	SETFA	14%	3			
				AMBEL	11%	2									
				MEDLU	11%	2									
Total		**70%**	**29**		**70%**	**10**		**70%**	**108**		**70%**	**14**		**78%**	**35**
IM	SONAR	45%	9	MEDLU	27%	2	AMBEL	38%	21	SECCE	19%	1	HIBTR	49%	12
	TAROF	29%	6	STEME	20%	1	POLPE	19%	11	AMBEL	18%	1	PANCA	16%	4
				CERVU	14%	1	SETIT	16%	9	SETPU	11%	1	CHEAL	8%	2
				SETPU	12%	1				TRFCA	10%	1			
										TRFPR	10%	1			
										MEDLU	9%	1			
Total		**74%**	**15**		**72%**	**5**		**73%**	**41**		**77%**	**4**		**73%**	**18**
WZ	AMBEL	31%	18	SETPU	40%	3	POLPE	24%	22	MEDLU	27%	23	HIBTR	47%	23
	SONAR	27%	16	SETFA	16%	1	AMBEL	18%	17	SETPU	27%	23	SETFA	26%	13
	MEDSA	26%	15	AMBEL	11%	1	VICVI	17%	15	AMBEL	25%	21			
				ANGAR	11%	1	CHEAL	14%	13						
Total		**84%**	**49**		**78%**	**5**		**73%**	**67**		**79%**	**67**		**73%**	**36**
SR x IM	SONAR	61%	12	POLCO	42%	3	SETIT	26%	9	SETPU	31%	2	HIBTR	28%	11
	AMBEL	18%	3	TAROF	22%	1	SETPU	16%	6	AMBEL	19%	1	AMBEL	22%	9
				SETFA	14%	1	AMBEL	14%	5	TRFPR	13%	1	CHEAL	13%	5
							POLPE	9%	3	SECCE	11%	1	PANCA	11%	5
							CHEAL	9%	3						
Total		**79%**	**15**		**78%**	**5**		**75%**	**26**		**74%**	**5**		**74%**	**30**
SR x WZ	AMBEL	40%	18	AMBEL	48%	4	SETIT	36%	33	AMBEL	34%	8	SETVI	47%	133
	SONAR	28%	13	MEDLU	24%	2	POLPE	15%	14	SETPU	24%	6	HIBTR	28%	79
	TRFPR	13%	6				CHEAL	14%	13	MEDLU	16%	4			
							SETFA	13%	12						
Total		**81%**	**37**		**72%**	**6**		**78%**	**73**		**74%**	**18**		**75%**	**212**
IM x WZ	SONAR	34%	8	CC.RYE	24%	3	SETIT	29%	12	SETPU	27%	1	HIBTR	37%	12
	SETFA	19%	4	MEDLU	18%	2	SETPU	17%	7	SECCE	20%	1	CHEAL	22%	7
	TAROF	16%	4	AMBEL	15%	2	POLPE	17%	7	MEDLU	13%	1	AMBEL	17%	5
	AMBEL	10%	2	SETPU	11%	1	AMBEL	13%	5	AMBEL	7%	0			
				TAROF	7%	1									
Total		**79%**	**18**		**75%**	**9**		**76%**	**31**		**67%**	**4**		**76%**	**24**
SR x IM x WZ	AMBEL	20%	5	TAROF	27%	1	SETIT	21%	7	AMBEL	29%	3	AMBEL	26%	5
	SONAR	19%	5	CC.RYE	21%	1	SETPU	20%	7	SETPU	18%	2	HIBTR	20%	4
	TAROF	18%	5	SETPU	20%	1	POLPE	18%	6	MEDLU	15%	2	CHEAL	18%	3
	TRFPR	13%	3	ACCVI	13%	1	AMBEL	12%	4	SECCE	9%	1	SETFA	10%	2
		71%	**18**		**81%**	**4**		**70%**	**24**		**71%**	**8**		**74%**	**14**

Soybean yield

Soybean yield varied between treatments ($P < 0.0001$) (Figure 9). The inter-row mower (IM) alone produced a yield of 2639 kg ha^{-1}, which was greater than the untreated control (2314 kg ha^{-1}) (Figure 9). All combinations of tactics with the IM treatment also produced yields greater than the untreated control (Figure 9). The weed free treatment produced the highest yield of 3419 kg ha^{-1}. In the United States, the average yield for soybean in 2022 was 3300 kg ha^{-1}, therefore the weed free treatment produced yields comparable to the national average (USDA-NASS, 2022). The high yield of the weed free treatment sets a benchmark for future work and indicates additional weed management strategies could be integrated into an organic no-till planted soybean system.

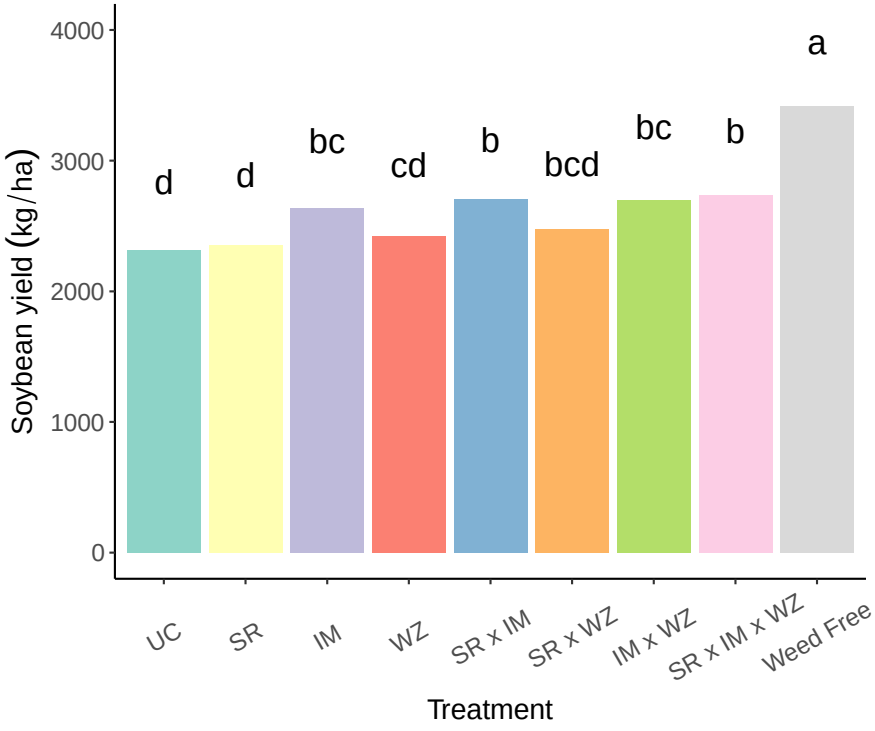

Figure 9: Soybean yield (kg/ha) from each weed management treatment pooled across fields. Yield is dry weight corrected to 13% moisture. Similar letters above bars indicate no significant difference ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

The high seeding rate (SR) alone treatment did not increase soybean yield compared to the untreated control treatment (Figure 9). High seeding rates led to higher plant densities (Figure 4), and studies have reported that yield will increase asymptotically with increasing soybean densities (Menalled et al., 2021; Liebert and Ryan, 2017). Crop yield will reach a plateau at high plant densities, a concept also referred to as 'the law of constant final yield' (Liebman et al., 2001; Ball et al., 2000). The yield plateau can be attributed to intraspecific competition between soybean plants and reduced light use efficiency when plants are at a higher density (Corassa et al., 2018; Luca and Hungría, 2014). High planting rates can also lead to soybean lodging, which can reduce soybean yield, however little soybean lodging was observed in this experiment. It is likely that the baseline seeding rate of 432,000 pure live seeds ha^{-1} and the high seeding rate of 680,000 pure live seeds ha^{-1} produced similar yields as a result of the upper yield limit at high plant populations (Menalled et al., 2021; Liebert and Ryan; 2017; DeBruin and Pedersen, 2008).

When used alone, the inter-row mower produced yields greater than the untreated control, but not different from any of the combined weed management treatments (Figure 9). The use of the inter-row mower during the critical period of weed control, as well as the machine's ability to reduce biomass of competitive weeds present in organic no-till systems, namely *A. artemisiifolia* (Table 2) (Mirsky et al., 2011; Cowbrough et al., 2003), likely contributed to the increased yield. The ability of the inter-row mower to increase soybean yield on its own suggests that a higher seeding rate and weed electrocution may not be needed as weed management tactics in this experimental system. However, the inter-row mower did not produce yields comparable to the weed free treatment (Figure 9), which is likely because weeds that were not controlled by the inter-row mower competed with soybean. Regrowth of some weed species after inter-row

mowing may have further contributed to the decreased yields in IM treatments compared to the weed free treatment. Future work could combine weed management tactics that were not tested in this experiment with the inter-row mower to achieve soybean yields closer to the weed free treatment.

The treatment with the inter-row mower and the Weed Zapper (IM x WZ), did not produce soybean yields greater than the untreated control (Figure 9). The inter-row mower removed weeds growing between rows during the critical period of weed control, however, weeds were present within the soybean row that were not cut by the mower and did not grow high enough to be targeted by the Weed Zapper. These weeds that grew within the row may have competed with soybean plants and decreased yield in the IM x WZ treatment (Donald, 2000; Willard et al., 1994). All other combinations of weed management tactics produced greater yields than the untreated control (Figure 9), which suggests that these tactics could work well as an integrated weed management strategy for organic no-till soybean. However, given that the inter-row mower alone increased yields compared to the untreated control, a farmer should consider whether profits would outweigh the cost of using additional weed management practices. Cost of weed management machines, organic premiums for food-grade vs. feed-grade, ease of harvest, and effects on weed seed production could all play into this decision.

CONSIDERATIONS

Several outcomes beyond weed biomass and soybean yield may be useful to consider when assessing the value of the tactics tested. Integrated weed management (IWM) can reduce the likelihood that a dominant weed species will become resistant to a particular tactic because varied stresses across time and space will target differential weed species traits (Storkey and Neve, 2018; Liebman and Gallandt., 1997). This statement is supported by the species evenness result in this experiment, where species evenness was highest in the treatment with three weed management tactics compared to the untreated control (Figure 6). Thus, there was no single dominant species that emerged after three weed management tactics were used. Although this research was focused on organic production, these results are applicable to farmers who have weed species that are difficult to control and are resistant to herbicides.

The inter-row mower could lead to additional benefits besides reducing weed biomass and increasing yield. The elimination of weed biomass between soybean rows could have lasting effects by reducing weed seed production of dominant species (Appendix 2), which could reduce the soil weed seed bank the following year. Reduction of the weed seed bank is an important principle of ecological weed management (Menalled, 2008; Gallandt et al., 1999). The inter-row mower could also facilitate soybean harvest by reducing interference with harvesting operations. The timing of mowing is also an important consideration, for in both years of this experiment, the first mowing event occurred during the critical period of weed control, yet in 2022 the second mowing event was likely outside of the range (Table 1) (Keramati et al., 2008; Zimdahl, 1980). Therefore, mowing may only need to occur once in systems with a weed suppressive cover crop

mulch, rather than twice, as suggested by Donald et al (2001). Mowing only once would save farmers fuel and labor.

Although weed electrocution did not prevent weed-crop competition and yield loss (Figure 9), the tactic may still be valuable for the long-term reduction of weed populations. Electric weed control can reduce weed seed production (see Appendix 2) and viability of dominant weed species (Moore et al., 2023; Schreier et al., 2022). Moore et al. (2023) reported that weed seed production of *Amaranthus palmeri* S. Watson was reduced by 70% and 93% when electricity was applied 0 and 2 weeks after first visible inflorescence, respectively. In addition, Schreier et al. (2022) conducted an experiment with the same Weed Zapper model used in this experiment and reported up to 80% reduction in weed seed viability in *A. artemisiifolia* and up to 60% reduction in viability in *Setaria* spp., both of which are competitive weed species that are commonly found in organic systems in the Northeast (Brown et al., 2022). Reducing weed seed production and viability is critical for decreasing the weed seed bank, which could lead to the long-term reduction of weed biomass and increased crop yields. Weed electrocution could also reduce weed biomass between crop rows if the machine controls a high number of fast-growing weeds. Like the inter-row mower, this could increase ease of crop harvest. Therefore, the Weed Zapper has the potential to be a valuable medium- to long-term management tool in fields with heavy infestations of weeds that grow faster than the crop.

As cost is one of the largest barriers to IWM adoption, the impact of equipment on profitability is an important factor when deciding what tools to integrate into an IWM strategy. The inter-row mower used in this experiment was purchased for $34,750, had five mower row units on 76 cm spacing, and was attached to a John Deere 5100R tractor with a category II 3-point hitch. A Weed Zapper can cost up to $88,500, depending on generator wattage, tractor

model, and length of boom. The unit purchased for this experiment was $69,000 and is one of the smallest models, with a 110,000+ watt generator and a 4.6 m boom that was powered by a John Deere 5100R tractor. In addition, around the time of this publication, the baseline seeding rate would cost approximately $216 ha^{-1} to seed while the high seeding rate would cost approximate $349 ha^{-1} to seed. Thus, a farmer must decide if the weed management tactics used will increase yields enough to outweigh management costs.

CONCLUSIONS

In this study, three weed management tactics were implemented alone and in combination in organic no-till planted soybean: a high soybean seeding rate, inter-row mowing, and weed electrocution. All treatments that included the inter-row mower reduced weed biomass by 60% compared to the untreated control ($P < 0.0001$) (Figure 5). The inter-row mower targeted annual dicot weeds, which dominated the weed community in this experiment (Figures 7, 8). Although the combination of all three tactics did not result in the largest reduction of weed biomass, as hypothesized, the SR x IM x WZ treatment led to the highest weed species evenness (Figure 6). All treatments with the inter-row mower produced yields greater than the untreated control, indicating that the inter-row mower may be an effective tool for managing weeds and increasing yields in organic no-till planted soybean. Although multi-tactic management did not improve weed suppression or soybean yield beyond what was achieved with inter-row mowing in this research, results may vary depending on weed species present, their growth rate relative to the crop, and their susceptibility to shading. In spite of the weed suppression provided by the inter-row mower, yields were still considerably lower than the weed free treatment. The high soybean yield in the weed free treatment suggests that additional weed management tactics could be integrated into an organic no-till system in combination with the inter-row mower to achieve higher yields. In addition to testing the effect of the weed management tactics used in this experiment across different environmental conditions and with different crop cultivars, future research should evaluate the effects of tactics on other metrics including crop harvestability, grain quality, and weed seed production.

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EPILOGUE

In the prologue, I suggested that an integrated weed management strategy had the potential to manage weeds and increase biodiversity in soybean cropping systems. In the experiment described in chapter 1, we hypothesized that combining three weed management tactics; a high soybean seeding rate, inter-row mowing, and weed electrocution, would result in reduced weed biomass and increased soybean yield compared to the untreated control. The inter-row mower reduced weed biomass by 60% compared to the untreated control (Figure 5), likely because of the ability of the mower to manage a high proportion (74%) of the between row space, including weeds that were farther away from the crop that may have higher biomass (Korres et al., 2019). Although no benefit of multi-tactic management was observed for weed biomass or soybean yields, the combination of the three tactics did produce greater species evenness compared to the untreated control (Figure 6).

The high seeding rate (680,000 pure live seeds ha^{-1}) did not suppress weed biomass compared to the baseline seeding rate (432,000 pure live seeds ha^{-1}) (Figure 5). Although increasing crop seeding rate can be an effective cultural weed management practice, the effect largely depends on the baseline rate. If the baseline rate is already high, a farmer might be faced with diminishing returns if they continue to plant at higher densities. In this experiment, the baseline rate, which is high compared to conventional production, may have already been providing a considerable level of weed suppression.

Weed biomass sampling was challenging to implement because optimal sampling methodology in the inter-row and Weed Zapper treatments was unknown. Compared to other weed control methods that completely terminate weeds, these treatments results in weed plants

that were partially terminated. In the case with the inter-row mower, it was not clear if weed biomass below the height of the mower should be sampled. Thus, for all treatments besides treatments that included the inter-row mower, weed biomass was clipped 5 cm above the soil surface and separated by species. For treatments that included the inter-row mower, weed biomass was clipped at the height of mowing, approximately 10 cm above the soil surface, and separated by species. In year 2, all weed biomass that grew between 5cm and 10cm above the soil surface was sampled to ensure that sampling weeds at mower height in inter-row mowing treatments did not bias results. The resulting supplemental weed biomass was only present in 14% of the inter-row mower treatments and no supplemental biomass was more than 0.3% of the total weed biomass in the inter-row mower treatments. Therefore, we conclude the sampling method did not bias results.

Multiple challenges were encountered when using the Weed Zapper that could explain the lack of weed control. Many weeds did not fully die after contact with the copper boom, either because they were not hit with enough voltage to cause complete plant death, or they did not conduct electricity well (Vigneault and Benoît, 2001; Schreier et al., 2022). On several occasions the Weed Zapper generator powered off because the ampere threshold (when ~66% of the boom is contacted by weeds) was reached on the copper boom or the speed sensors sensed too slow of a ground speed because of bumps or short plot sizes. The sampling methods used in the experiment could also have contributed to high levels of weed biomass in Weed Zapper treatments. We considered weeds that had been electrocuted to be “not controlled” if they were less than 50% necrotic and contained reproductive parts at sampling. Weeds that were not controlled were collected for weed biomass. However, as visual observations suggested, it may take up to a week for a weed to become fully necrotic after electrocution. Therefore, the weeds

sampled for weed biomass may have become necrotic over the preceding days, and thus would not have been sampled if sampling occurred a few days later. Waiting a few more days to sample could have decreased the amount of weed biomass collected in the WZ plots, although this would have been beneficial primarily in the first year of the experiment, when weed biomass was sampled 3-7 days after weed electrocution occurred. In the second year, weed biomass was sampled 14 days after electrocution and visual observations suggested that few weeds were fully controlled by the Weed Zapper. In future work, I would recommend sampling at least a week after weed electrocution. If a weed was still alive and producing seeds a week after electrocution, samplers could confidently say that the weed recovered, was not managed, and could be sampled for weed biomass.

Weather impacted field operations in both years of the experiment. In 2021, the bare soil field was planted late because rain events prevented the tractor from entering the field. The Weed Zapper was also difficult to set up in year one and many technical problems (i.e., slow speeds, rocky terrain, contacting too many plants at once) caused the machine to shut off while in the middle of several plots and not electrocute weeds that were above the soybean canopy. If not for these issues, the Weed Zapper may have contacted more weeds, which could have decreased weed biomass in WZ plots. The machine also could have been used earlier in the bare soil field in 2021, which would have prevented weed biomass sampling from happening so soon after weed electrocution. In 2022, repeated rainfall prohibited the Weed Zapper from entering a third field with cereal rye cover crop before soybean canopy closure. Therefore, previously collected samples from the third field could not be used in the data analysis. If the third field was included in the analysis, the data would have increased in resolution and may have revealed differing

trends, particularly in the yield data, where yields were not different across many of the multi-tactic treatments (Figure 9).

In 2022, I performed additional work to study weed cover and weed seed production post-treatment application that was not detailed in my thesis chapter (Appendix II & III). Weed cover increased from August to October in all fields, likely because of weed regrowth post-mowing and late emerging weed species (Figure 2.1A). Visually, weed cover was lower in the cover crop field, likely because of increased weed suppression from the cereal rye mulch (Menalled et al., 2021; Ryan et al., 2021; Mirsky et al., 2013; Davis, 2010; Mischler et al., 2010). I also measured seed production of dominant weed species in control plots and compared weed seed production of each treatment to the untreated control (Table 3.1A). The inter-row mower reduced seed production for 3 of the 5 dominant weed species in the bare soil field ($P < 0.05$) (*A. artemisiifolia*, *Hibiscus trionum* L., and *C. album*). We also found that the combination of the high seeding rate and the inter-row mower reduced *A. artemisiifolia* seed production compared to the untreated control and the combination of all three tactics reduced *H. trionum* seed production compared to the untreated control ($P < 0.05$) (Table 3.1A). These data were collected only once for each field, which may not be comprise enough samples to make accurate conclusions. Therefore, additional work should be completed focusing on weed seed production after use of the inter-row mower or the Weed Zapper. Knowledge of how management techniques impact specific weed species is valuable for reducing the weed seedbank, especially in fields where herbicide use is restricted or there is a large population of herbicide resistant weeds.

I completed several trait-based multivariate analyses to study how weed management tactics influenced weed community composition. I conducted a permutational analysis of variance (PERMANOVA) to investigate if there were differences in weed community structure

among any of the nine treatments. I found no differences in structure among weed communities. I also conducted a non-metric multidimensional scaling (NMDS) analysis. The purpose of the NMDS was to visualize any pairwise dissimilarity among weed communities in different treatments when plotted in low-dimensional space. Almost all weed communities were ordinated close to each other, which indicated each treatment contained similar weed species. Lastly, I ran a functional diversity analysis using several traits mined from TRY plant database, including plant height, seed weight, Raunkier growth form, division, specific leaf area (SLA), and life history (Kattge et al., 2020). I did not find any differences among treatments in any of the functional diversity indices.

I did not report any results from my multivariate analysis in my manuscript because there was no indication that weed management tactics selected for specific species traits. However, I hypothesize that if this experiment was repeated over multiple years in the same agricultural fields, weed species trait selections might emerge. Such patterns can be observed in other longitudinal integrated weed management studies, such as those from Cordeau et al. (2022) and Adeux et al. (2019). If this experiment was repeated over many years, each weed management tactic may select for specific weed species traits (Cordeau et al., 2022; Benaragama and Shirtliffe, 2013; Liebman and Gallandt, 1997). The high seeding rate may select for weeds with increased leaf area (SLA) and those that can reach greater heights, traits that would allow weeds to penetrate the soybean canopy and absorb a higher proportion of light. Weeds that emerge early and set seed before canopy closure may also be selected for by a higher seeding rate, for such species would have an increased proportion of resources to compete with soybean in early growth stages (Menalled et al., 2022; Zimdahl, 1980).

This experiment indicated that the inter-row mower can target annual broadleaf weeds. The inter-row mower was used in mid-July after most weed species had emerged, therefore early emerging weeds were mowed whereas later emerging weeds may have evaded mowing and then set seed. Previous research indicates perennial weeds with deep vegetative reproductive organs (geophytes) are more likely to survive mowing because of their ability to direct carbohydrate reserves towards taproots or rhizomes, allowing for regrowth (Mohler et al., 2021; Liebman et al., 2001; Aldrich and Kremer, 1997). Weed species that have rosette-forming or prostrate growth forms may also avoid defoliation by mowing, as they grow close to the soil surface. Therefore, if a multi-year IWM experiment was conducted, mowing may select for late emerging, low growing perennial species. Lastly, the Weed Zapper has been documented to reduce weed species that emerge early in the season and grow faster than the crop (Moore et al., 2023; Schreier et al., 2022). In addition, weeds with a high SLA are likely to be controlled by weed electrocution, increased area of contact with the electric boom can lead to a larger electric current sent through the plant (Vigneault and Benoît, 2001). Therefore, the Weed Zapper may select for short, grass-like species with low SLA over a multi-year experiment.

If I had the opportunity to perform the experiment again, I would change several aspects of the experimental design. I would establish fields with low levels of cereal rye biomass instead of the no-till fields with bare soil that were used in this experiment. A field with low levels of mulch would more effectively simulate the reality that farmers could face if they had a poor stand of cereal rye mulch compared to a bare soil field with no tillage, which is an unlikely scenario for many farmers. To expand on this idea, I could envision an experiment where fields were planted with a range of cereal rye mulch seeding rates. This would establish a range of mulch biomass and provide information pertaining to the effectiveness of weed management

treatments in different levels of cereal rye mulch. If fields were kept in the same location every year, a long-term experiment could determine the weed community that emerges as a result of different management practices and levels of mulch. I would also measure the average height of dominant weed species at time of inter-row mowing and Weed Zapping if I were to perform the experiment again. This information could have been useful to report in the manuscript and would inform future operators of the machines. I would also consider taking two samples per plot when sampling weed biomass. In both years, the weed community in each plot was variable across space. Taking two 0.5 m^2 samples would have provided greater resolution into how the management tactics may have impacted functional weed traits.

None of the weed management techniques used in this experiment significantly reduced perennial weed biomass (Figure 8). Perennial weeds may not have been present at a high enough abundance to detect differences. Even so, previous research suggests that perennial weeds can be difficult to manage with inter-row mowing (Donald et al., 2001) and weed electrocution (Diprose et al., 1984) because of their ability to regrow from storage organs and their persistence year-round (Mohler et al., 2021; Håkansson, 1982). Therefore, weed management tools that can control perennial weeds are needed for organic no-till systems (Mirsky et al., 2013). High residue (HR) cultivation could be a rescue tool if a farmer is faced with a high population of deep-rooted perennials. However, HR cultivation is not compatible with the cover-crop based system, for the practice disrupts the protective layer of cereal rye mulch (Keene and Curran, 2016). Consequently, a management gap exists for perennial weeds in organic, no-till planted soybean.

Additional weed management strategies could be added to an organic no-till system. Abrasive weeding, or shooting small, sand-like objects at weeds at a high speed, could be a

candidate for early season weed management in row crops, as studies have documented effective management when weeds are less than 4 cm tall (Carlson et al., 2018). Abrasive weeding is also an economical alternative when a lack of labor for hand weeding exists in organic systems (Wortman et al., 2020). Another promising tool is an inter-row mower called the Row Shaver, which is being produced for commercial sales in the United States. The Row Shaver machine has five swing blades that can be adapted to mow 50-to-91 cm rows in soybean, corn, sorghum, and cotton systems (Row Shaver Systems, 2023). In addition, precision weed management for organic systems has become a promising subject of research and development (Monteiro & Santos, 2022, Westwood et al., 2018). There are several new precision tools that could be used in an organic, no-till system. One tool is Carbon Robotics' LaserWeeder, which uses artificial intelligence to distinguish weeds from crops and thermal energy from lasers to destroy weeds at their meristem (Carbon Robotics, 2023). Naïo technologies has also created a semi-autonomous mechanical weeder called Orio, which can be altered for wide or narrow rows and uses non-intensive cultivation techniques (Naïo Technologies, 2023). Both precision management tools are expensive and only cover 1-2 acres per hour, therefore a farm should have the economic justification and physical infrastructure to use the machine.

Organic, cover-crop based reduced till systems offer multiple benefits. When soil is minimally disturbed and covered by cover crop mulch, soil erosion is reduced, soil health is improved, and labor and fuel costs decrease (Wells et al., 2014; Ryan, 2010). High levels of cover crop mulch can suppress weeds (Silva and Delate 2017; Ryan et al., 2011; Davis, 2010), however, if weed suppression by the mulch is not sufficient, additional weed management tactics are needed in the system. Additional tactics can be implemented as part of an integrated weed management (IWM) framework, where multiple strategies are used holistically to manage weeds

across time and space with the broad goal of preventing crop yield loss while conserving weed biodiversity (Riemens et al., 2021; Liebman and Gallandt, 1997). A promising weed management practice that can be used in organic no-till soybean systems is inter-row mowing, which reduced weed biomass and increased soybean yield in this experiment (Figures 5, 9). My results suggest that the Weed Zapper may be more valuable when used in disturbed fields with weed species that grow faster than the crop. Both the inter-row mower and the Weed Zapper have the potential to provide additional benefits, including weed seed reduction and increasing harvest efficiency. Overall, this experiment offers an alternative to solely using tillage or herbicides to manage weeds. We described a multi-tactic weed management program implemented in a cover crop based organic no-till system that targets weeds across time and space and encourages the reduction of practices that could harm the agricultural environment.

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APPENDIX I

SYNERGISTIC INTERACTIONS OF WEED MANAGEMENT TACTICS

The “many little hammers” approach to weed management is the practice of using several weed management tactics, which may not be fully effective on their own, in combination to manage weeds in a cropping system (MacLaren et al., 2020; Liebman and Gallant, 1997). Using multiple tactics presents an opportunity for synergism between tactics, which can be defined as an unprecedented result when tactics are combined that could not have been predicted from the tactics performance in isolation (Liebman and Gallant, 1997). Understanding the interactions that could occur between weed management tactics is critical as a farmer integrates new tools into their practice that may target different weed species traits (Benaragama and Shirtliffe, 2021; Rasmussen et al., 2004). Synergistic interactions were tested for between the three weed management practices used in this experiment for total weed biomass and soybean yield.

Several studies report increased weed suppression using the ‘many little hammers’ approach in organic systems (Brown and Gallandt, 2018; Benaragama and Shirtliffe 2013; Ryan et al., 2011; Anderson, 2003). Benaragama and Shirtliffe (2013) found that combining a competitive soybean crop genotype, increased seeding rate, and post-emergence harrowing decreased weed biomass by 71% compared to standard practices. Brown and Gallandt (2018) reported that using several stacked inter-row cultivation tools in a corn system reduced weed biomass up to 50% more than using a single tactic and that there was a synergistic interaction among tools. Research in corn and sunflower systems found that the combination of three cultural weed management practices – narrow row spacing, increased seeding rate, and delayed planting – reduced weed biomass up to 90% compared to a tillage-based systems after 3 years of

weed seed rain to soil (Anderson, 2003). Notably, Ryan et al., 2011 found a synergistic interaction between high cereal rye biomass and high soybean density in an organic no-till planted soybean system, a result that could have implications for this organic no-till experiment.

Using data from the experiment reported in Chapter 1, I conducted a formal test for synergy between the three tactics that were evaluated: high seeding rate, inter-row mower, and Weed Zapper. For this analysis, treatments were coded as dummy variables (Slinker 1998). Two linear mixed models, one for weed biomass and one for soybean yield were fit with the log of weed biomass and the log of soybean yield as response variables, explained by coded dummy treatment variables (Slinker 1998). Response variables were log transformed to describe their effects on weed suppression and soybean yield on a multiplicative scale (Knol et al., 2007). After confirming model fit, fixed effects were assessed with a type III analysis of variance (ANOVA) test. Interactions in the log-transformed dummy variable models indicate that treatment effects differed when applied alone or in combination with other treatments. Analysis was performed using R software version 4.1.2. (R Core Team 2022).

To find the expected observed weed biomass or soybean yield for each multi-tactic treatment we used the formula:

$$\exp(ß_0 + ß_n) \qquad \text{[Equation 2]}$$

where $ß_0$ is the coefficient for the untreated control treatment and $ß_n$ is the sum of all regression coefficients for tactics included in the treatment. For example, to calculate observed weed biomass for treatment IM + WZ, we added the coefficients for $ß_0$, IM, WZ, and IM + WZ and took the exponent of the sum. To find the percent change from the untreated control (for the individual tactic treatments) or the percent change from the expected result based on individual tactic efficacy (for the multi-tactic treatments, calculated with Equation 4) we used the formula:

$$100\ (e^{ß_n} - 1) \qquad \text{[Equation 3]}$$

where $ß_n$ is the specific treatment coefficient given by the regression. For the multiple tactic treatments, the expected weed biomass or soybean yield was calculated based on individual tactic efficacy with the formula:

$$(ß_0)[1 - (\%\triangle)][1 - (\%\triangle)] \qquad \text{[Equation 4]}$$

where $ß_0$ is the coefficient for the untreated control treatment and $\%\triangle$ is the percent change from the untreated control for the individual tactic treatments included in the multi-tactic treatments. For the multi-tactic treatments, the p-value of the ANOVA table indicated if the observed weed biomass or soybean yield (Equation 2) was significantly different from the expected result based on individual tactic efficacy (Equation 4).

A formal test for synergistic interactions between treatments demonstrated that the effect of combining the three weed management tactics could be predicted from their performance in isolation for both weed biomass and soybean yield (Table 1.1A). While the combination of weed management tactics did not improve their efficacy in this experiment, it also did not compromise the tactics ability to suppress weeds. The consistent ability of weed management tactics to suppress weeds when used in combination supports a multi-tactic approach to weed management. Using several methods to manage weeds furthers the development of the integrated weed management approach and could contribute to the reduction of dominant weed species while preserving weed community diversity (Riemens et al., 2021; Storkey and Neve, 2018; Liebman et al., 2001).

Table 1.1A: Results from linear mixed-effect models testing synergistic interactions between weed management tactics for weed biomass and soybean yield. Observed weed biomass or soybean yield was calculated with [Equation 2]; the percent change from the untreated control (individual tactics) or percent change from expected result (multi-tactic treatments) was calculated with [Equation 3]; and the expected weed biomass or soybean yield for multi-tactic treatments was calculated with [Equation 4]. P-values indicate differences between observed biomass and the untreated control for individual tactics and differences between observed biomass and expected biomass (based on individual tactic efficacy) for the multi-tactic treatments.

	Weed biomass				**Soybean yield**			
Treatment	Observed biomass $g\ m^{-2}$	Expected biomass $g\ m^{-2}$	Observed change %	P-value	Observed biomass $kg\ ha^{-1}$	Expected biomass $kg\ ha^{-1}$	Observed change %	P-value
Control	82.4				2159.4			
SR	84.2		2.2	0.9361	2197.0		1.7	0.7604
IM	42.4		-48.7	0.0139 *	2501.8		15.9	0.0102 *
WZ	85.2		3.3	0.9036	2244.8		4.0	0.4930
SR x IM	36.6	43.2	-15.4	0.6591	2639.0	2545.3	3.7	0.6514
SR x WZ	92.8	87	6.7	0.8659	2368.6	2283.9	3.7	0.6490
IM x WZ	48.4	43.6	10.9	0.7849	2536.9	2600.7	-2.5	0.7560
SR x IM x WZ	41.4	44.6	-7.3	0.8879	2628.1	2775.3	-5.3	0.6300

APPENDIX II

VISUAL ESTIMATES OF WEED COVER

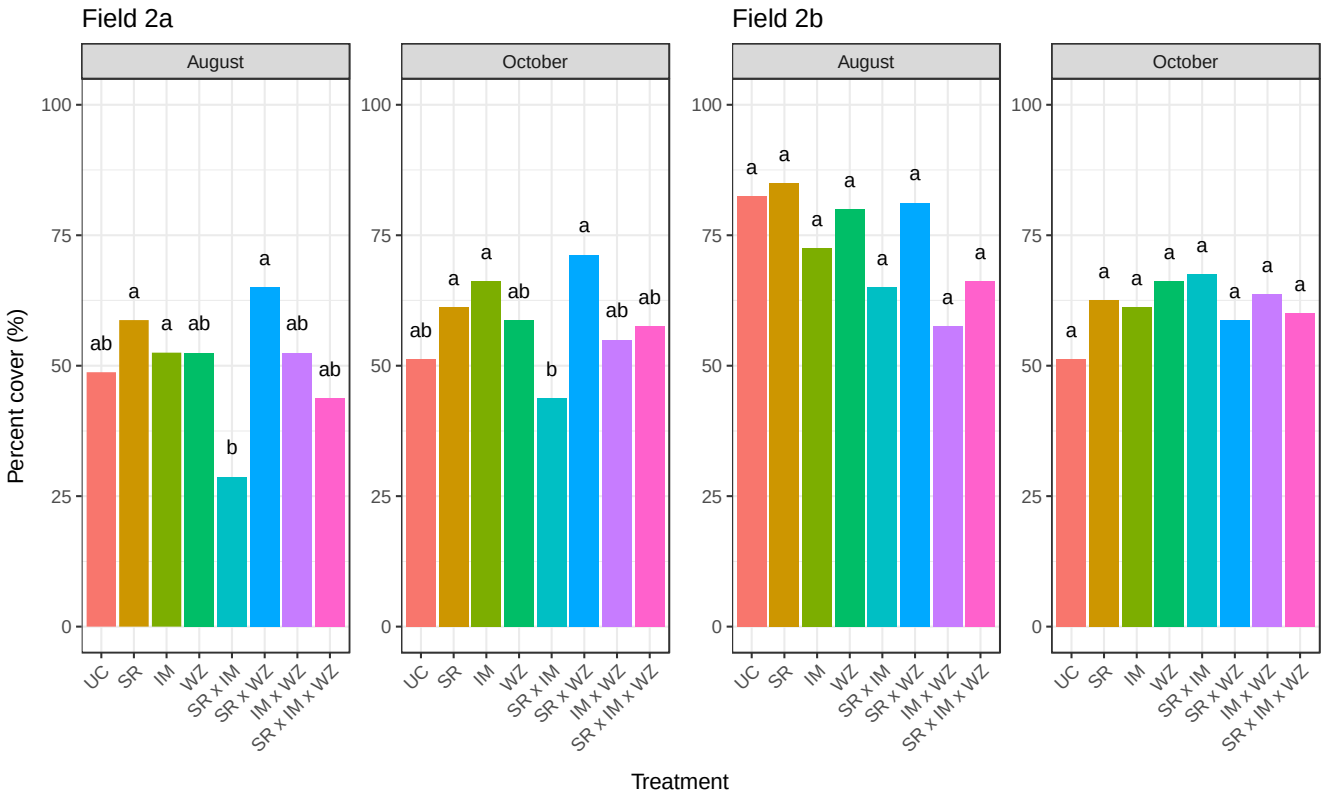
Inter-row mowing and weed electrocution are weed management practices that have not been widely studied in field crop production. To better understand tactic efficacy, weed canopy cover was visually estimated within each plot for both fields in 2022. Visual estimates were used to discern 1) the ability of weeds to regrow after inter-row mowing or weed electrocution and 2) the effect of control tactics on crop harvestability. Two visual estimates were completed, the first shortly after all tactics were implemented on 26 August 2022 and the second on 30 September (blocks 1-3, 2a and 2b) and 6 October (block 4, 2a and 2b) 2022 before theoretical yield harvest. Estimates were completed between the center two rows within a 9 m space in all plots (avoiding plot edges). The percentage of soil area covered by weeds that had live tissue was recorded, with 0% being no live tissue and 100% completely covered with live tissue. Live tissue was specified because there were some weeds that were electrocuted and were necrotic but still standing. Dominant weed species that made up at least 50% of the live tissue were recorded along with the percent cover they occupied.

Weed cover was analyzed using R software version 4.1.2. (R Core Team 2022). Weed cover data was separated by field and each field was described with a linear mixed effect model with treatment as a fixed effect and block as a random effect. Fields were not pooled for analysis because of lack of site years. The models were logit transformed and adjusted by 0.025 to encourage linearity in the percentage data. Linear model assumptions were assessed by visually checking residuals for homogeneity of residual variance and normality. After confirming model fit, fixed effects were assessed with a type III analysis of variance (ANOVA) test. Treatment

levels were compared with least-squares means comparisons using the Fisher LSD method. All transformed means were back-transformed for presentation in the text, table, and graphics.

Treatments differed in the cover crop field in both August and October ($P < 0.001$) (Figure 2.1A). In both August and October, the high seeding rate and the inter-row mower (SR x IM) treatment visually reduced weed cover compared to the combination of the high seeding rate and the weed zapper treatment (SR x WZ), the individual high seeding rate treatment (SR), and the individual inter-row mower treatment (IM). However, the SR x IM treatment did not differ from the untreated control. There were no differences in visual estimates of weed cover across treatments for either month in the bare soil field (Figure 2.1A).

Figure 2.1A: Visual estimates of weed cover (%) in fields 2a and 2b in August and October 2022. Similar letters above bars indicate no significant difference using separate Fisher LSD tests ($P > 0.05$). Error bars are standard errors and treatments are abbreviated: UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.



APPENDIX III

SEED PRODUCTION OF DOMINANT WEED SPECIES

Reducing seed production through weed management is critical to reduce weed pressure overtime. To this end, the weed seed production of dominant weed species in all treatment plots were compared to seed production of dominant species in untreated control plots to understand how weed management tactics influenced the seed production. On 30 September 2022 the biomass of any weed species producing seeds were sampled in all untreated control plots. A 0.76 cm x 0.66 cm quadrat was randomly placed covering the space between soybean rows 2 and 3. Weeds were clipped at soil level, separated by species, placed in separate paper bags, and dried at 55 ^{o}C for 7-10 days. Individual weed species were threshed and weed seeds were weighed and recorded. Total seed weight was then divided by the average weight of a single seed for each weed species to find the total seed production by each dominant weed species. In each block, seed production for dominant species in each treatment was visually analyzed and compared to the total seed production of the untreated control with percentage bins; 0-20, 21-40, 41-60, 61-80, and 81-100.

All statistical analyses were carried out using R software version 4.1.2. (R Core Team 2022). Each dominant weed species in each of the two fields was analyzed with a separate linear mixed effect model that included treatment as a fixed effect (n = 9) and block (n = 4) as a random effect. All models were logit transformed and adjusted by 0.025 to encourage linearity in the percentage data. The weed free treatment was removed from each analysis because there were no dominant species producing weeds in the weed free treatment. After confirming model fit, fixed effects were assessed with a type III analysis of variance (ANOVA) test. Treatment

levels were compared with least-squares means comparisons using the Fisher LSD method (Lenth, 2022). All transformed means were back-transformed for presentation in the text and table.

Seed production varied across weed species and fields. The inter-row mower reduced weed seed production for three of the five dominant weed species (*A. artemisiifolia*, *C. album*, and *H. trionum*) in the bare soil field compared to the untreated control treatment (Table 3.1A). The combination of all three tactics also reduced seed production of *H. trionum* in the bare soil field. In the cover crop field, the combination of the high seeding rate and the inter-row mower treatment reduced *A. artemisiifolia* seed production compared to the untreated control treatment (Table 3.1A). In both fields, no treatments reduced *S. pumila* seed production compared to the untreated control.

Table 3.1A: Weed seed production of dominant weed species (per m^2) in bare soil and cover cropped fields. Seeds from dominant weed species in the untreated control were collected and threshed to obtain baseline seed production. Percent seed production of dominant weed species in all other treatments were rated compared to the untreated control and adjusted to quantify seed production compared to the untreated control. Weed species are displayed in EPPO codes. Letters indicate significant differences using separate Fisher LSD tests for each weed species ($P < 0.05$). UC = Untreated control, SR = Seeding rate, IM = Inter-row mower, WZ = Weed Zapper.

	Field 2a		**Field 2b**				
Treatment	**AMBEL**	**SETPU**	**AMBEL**	**CHEAL**	**HIBTR**	**PANCA**	**SETPU**
UC	16908 a	36874 a	2856 ab	49914 a	16736 a	257760 a	530 a
SR	8454 a	18437 a	3570 a	22461 ab	7113 abc	31700 ab	239 a
IM	4649 ab	12906 a	284 b	9982 b	4602 bc	27737 ab	172 a
WZ	5706 ab	16593 a	856 ab	16222 ab	8368 a	29718 ab	185 a
SR x IM	845 b	12445 a	856 ab	16222 ab	6276 abc	31700 ab	132 a
SR x WZ	4438 ab	17515 a	1142 ab	18717 ab	7531 ab	7925 b	225 a
IM x WZ	3381 ab	13828 a	856 ab	18717 ab	5857 abc	25756 ab	159 a
SR x IM x WZ	3804 ab	10140 a	1142 ab	13726 ab	4184 c	19812 ab	92 a

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