ELECTRICAL WEED CONTROL IN INTEGRATED WEED MANAGEMENT: IMPACTS ON VEGETABLE PRODUCTION, WEED SEED GERMINATION, AND SOIL MICROBIAL COMMUNITIES

By

Christopher G. Galbraith

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ABSTRACT

Electrical weeding is an emerging practice for late-season weed control in vegetable production. However, little scientific research has been conducted directly evaluating the performance of electrical weeding and its effects on the agroecosystem. The objectives of the research program were to investigate electrical weeding in terms of 1) weed control, 2) crop injury, 3) economic viability, as well as its effects on 4) weed seed germination and 5) rhizosphere microbial communities. Field trials at Hart, MI in 2021 and 2022 investigated these research objectives in conventional carrot and organic green bean production systems. Late-season weed control methods, including one hand-weeding event (HW), one electrical weeder pass (1P), two electrical weeder passes performed consecutively [2P(ST)], one pass followed by one pass after a 14-day interval [2P(14d)], two passes followed by one pass after a 14-day interval (3P), and no late-season control (NLC), were evaluated in both carrot and beans. Early-season weed control methods [low, medium, and intensive herbicide programs, weed-free, and no early-season control (NEC)] were included in the carrot trials. Increasing passes above 2P(ST) did not provide higher control of redroot pigweed (*Amaranthus retroflexus*) in carrot, while 3P did have higher weed control in green beans. Electrical weeding did not cause any internal damage to carrot root tissue or have an effect on carrot root length. Electrical weeding did not lead to a difference in carrot or green bean yield. Hand weeding had a significantly higher cost acre^{-1} than all electrical treatments due to the greater amount of time required. Electrical weeding was found to significantly reduce redroot pigweed seed germination in 2021, though germination did not differ between varying number of passes. Electrical weeding did not generally lead to differences in inorganic N (NH_4^+ and NO_3^-) or microbial biomass C and N that would indicate changes in rhizosphere N cycling dynamics or population size.

This thesis is dedicated to all of the Michigan growers and ranchers whose work stands to benefit from Michigan State University's land-grant mission to provide teaching, research, and extension.

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1P	1 electrical weeder pass
2P(ST)	2 electrical weeder passes applied at the same time
2P(14d)	1 electrical weeder pass followed by another after a 14-day interval
3P	3 electrical weeder passes (2 followed by 1 after a 14-day interval)
DAIT	days after initial electrical weeding treatment (#1)
DAFT	days after final electrical weeding treatment (#2)
EW#1	1st (initial) electrical weeder treatment
EW#2	2nd (final) electrical weeder treatment
HW	1 hand weeding event
MBC	microbial biomass carbon
MBN	microbial biomass nitrogen
NEC	no early-season control
NLC	no late-season control

CHAPTER I: Weed Control Efficacy, Crop Injury, and Economics of Electrical Weeding in Carrot and Green Bean Production

Abstract

Electrical weeding is an emerging practice for late-season weed control that is being adopted in numerous agricultural industries, including Michigan vegetable production. The objectives of the research program were to investigate electrical weeding in terms of 1) weed control, 2) crop injury, and 3) economic viability. Field trials at Hart, MI in 2021 and 2022 explored these objectives in conventional carrot and organic green bean production systems. Late-season practices including one hand-weeding event (HW), one electrical weeder pass (1P), two electrical weeder passes performed consecutively [2P(ST)], one pass followed by one pass after a 14-day interval [2P(14d)], two passes followed by one pass after a 14-day interval (3P), and no late-season control (NLC) were evaluated in both carrot and beans. Early-season weed control methods [low, medium, and intensive herbicide programs, weed-free, and no early-season control (NEC)] were also included in the carrot trials in order to produce different weed densities within which to assess the performance of the late-season practices. In 2022, redroot pigweed (*Amaranthus retroflexus*) control tended to be higher for treatments that caused initially lower weed densities. Increasing passes above 2P(ST) did not lead to higher control of redroot pigweed in carrot, while 3P did have higher weed control in green beans. Electrical weeding was not found to cause any internal damage to carrot root tissue and did not have any effect on mean carrot root length. Electrical weeding did not lead to a difference in carrot or green bean yield. Hand weeding had a significantly higher cost acre^{-1} than all electrical treatments in both years due to the greater amount of time required.

Introduction

As a subsector of the vegetable industry, carrot (*Daucus carota)* and snap bean (*Phaseolus vulgaris)* production serve as important contributors to the economy of Michigan and the U.S., providing a source of livelihood for family farms and agricultural employees across the country. Nationwide, the combined production value of these two crops is worth close to $1 billion as of 2020 (National Agricultural Statistics Service, 2020). Recent commodity surveys show that carrots and snap beans generated $14.5 million and $21.5 million, respectively, for Michigan's economy in 2018 (National Agricultural Statistics Service, 2018). Weeds pose a serious threat to the profitability and sustainability of vegetable enterprises due to increased resource competition with crops, harboring of detrimental pest species, and complications with harvest and other management operations. While a slow germination/emergence rate renders carrots particularly susceptible to weed competition (Swanton et al., 2010), establishment and productivity of snap beans and other vegetable crops can also be greatly compromised by high weed pressure. Late-season escaped weeds reduce yield potential and, if allowed to reach reproductive maturity, cause management problems in future years due to replenishment of the weed seedbank. Heavy reliance on chemical weed control, coupled with the slowdown of new site of action discoveries, has led to the selection of resistant biotypes that require alternative means of control (Duke, 2012; Qu et al., 2021). The increasing prevalence of herbicide resistant weed species exemplifies the mounting challenges growers face in improving or maintaining yield in the face of dwindling weed control options.

A foundational principle of integrated weed management (IWM) is that all weed control methods contain their own inherent trade-offs, indicating that a combination of practices might be optimal depending on contextual environmental and economic conditions (Swanton et al., 2008). Herbicide usage is the prevailing weed control method that has contributed to the high level of productivity that characterizes modern agriculture. Despite its applicability, there is concern over a number of adverse consequences that can result from overuse of certain herbicides, including human health risks (Sabarwal et al., 2018), selection of herbicide-resistant weed communities (Heap, 2014), and environmental toxification, specifically in aquatic ecosystems (de Souza et al., 2020; Marin-Morales et al., 2013). Moreover, effective herbicide solutions are notoriously limited for vegetable producers as compared to the products available for more widely grown commodity field crops. Organic production, a market that is seeing increasing consumer demand, is heavily reliant on alternative control methods such as mechanical cultivation and flame-weeding, which carry their own limitations and externalities. Frequent soil disturbance through the use of tillage for weed control may deplete soil organic matter, increase erosion (Mohler, 2001), bring buried weed seeds to the surface, and is generally constrained to certain weed sizes/locations in the growing environment. Flame weeding is fuel-intensive and also has a low selectivity that limits its range of use due to risk of crop damage (Datta and Knezevic, 2013). Additional options, such as synthetic/living mulches, weed seed harvest and destruction, and a host of other cultural practices also have a place in an IWM program, but likewise come with their own costs and constraints.

Late-season weed management options for control of escaped or herbicide resistant weeds are relatively limited for vegetable and field crop growers, despite their importance for reducing weed seedbank inputs and impediments to crop harvest (Swanton et al., 2009). Among the few options for eliminating or mitigating the effects of escaped weeds are hand weeding, targeted destruction of seedheads through harvest weed seed control methods, or mowing (Hill et al., 2016). Hand weeding, while effective, can be prohibitively expensive to implement based on its high acre^{-1} labor and time requirements (de Boer et al., 2019). Clipping of weed seedheads and flowers above the crop canopy using a modified swather or flail mower has been shown to reduce weed populations and, at some sites, increase lentil (*Lens culinaris*) yield in both the year of and year after clipping was performed (Prairie Agricultural Machinery Institute, 2003). Weed wipers, which treat weeds utilizing an applicator made out of an absorbent material like rope wick or sponge saturated with herbicide, provide another low-cost option for managing above canopy weeds (Wills and McWhorter, 1981). While this method allows for application of non-selective herbicides in a way that minimizes drift (Farr et al., 2022), post-emergence options labeled for and effective against large weeds still remain limited. As well, this practice may be unproductive depending on the herbicide resistance status of the weed populations and is not a viable option for organic producers.

A relatively new technology for late season weed management that is gaining progressively greater traction in the vegetable grower community is electrical weed control. This method involves terminating weeds through contact with a tractor-mounted, high-voltage electrode that is charged via a power take-off driven generator/transformer system. Upon contact, current is conducted through the weed as it returns back to the transformer through the soil and a grounding device, completing the circuit (Vigneault and Benoit, 2001). The heat energy accumulated from the electrical resistance of the plant causes vaporization of cellular fluids that builds internal pressure, eventually bursting cell walls and causing systemic tissue death (Diprose et al*.,* 1980; Vigneault and Benoit, 2001). Following treatment, plants that received a lethal amount of energy through sufficient contact time will gradually desiccate and break down in the field, roughly following a four-stage process observed by Martens and Vigoureux (1983). During and immediately after treatment, a plant will release a burst of steam and undergo a loss of turgor pressure leading to wilting (1), which is followed by central stem desiccation (2), progressive die-off of smaller leaves/branches (3), and ultimately full plant necrosis (4).

Electrical weeding equipment has historically utilized two distinct methods of treatment: continuous contact and spark discharge (Diprose et al*.,* 1984). Continuous contact, which operates by direct contact of the plant with the electrode to facilitate conduction of current through the weed/soil environment, is the mechanism that has by far dominated most formal studies and been integrated into modern commercial systems, such as the Weed Zapper$^{\text{TM}}$ and the XPower brand of electrical weeders released by AgXtend. Spark discharge departs from this technique in that no direct contact is required; weeds are instead electrocuted via a spark pulse produced by a charged energy storage capacitor connected to either individual or sets of electrodes (Bayev and Savchuk, 1974). While the spark discharge method is generally more energy efficient, continuous contact-based equipment has been primarily adopted due to lower up-front investment and relative operational/mechanical simplicity (Diprose et al*.,*1984). Spark discharge may hold promise in coming years for application in crop thinning or precision spot weeding as innovation in technological design advances.

Effective electrical weeding rests on an understanding of the factors that lead to the desired level of lethal plant damage that has been characterized in the literature. Variables that dictate the degree of weed mortality can be broadly classed into two categories: operational and environmental. Operational variables include voltage, tractor RPM/horsepower, generator power output, and duration of weed-electrode contact time, which is itself determined by tractor speed, electrode height, number of passes, and directionality (Vigneault and Benoit, 2001; Vigneault et al., 1990). Environmental variables include weed density, plant/soil moisture, field evenness, and plant morphology (Vigneault and Benoit, 2001). Morphological structure of different weed species can dramatically influence the amount of electrical resistance, which determines current flow through the plant and thus the extent of critical, systemic damage. This results in certain weed types being less susceptible to electrical weeding due to the presence of larger root systems or specialized root structures, such as rhizomes or tubers (Vigneault and Benoit, 2001). Aboveground phenotypes that reduce control efficacy include high number of stems per plant that may shield other parts of the weed or nearby weeds from direct electrode contact (Vigneault and Benoit, 2001, Diprose et al., 1985). Plant biochemical composition that includes a high proportion of typically recalcitrant polymers such as lignin may also increase resistance, accounting for the observed higher resilience of woody species to electrical treatment (Dykes, 1977). The concept of a minimum lethal threshold energy (LTE), or quantity of energy measured in kJ plant^{-1} that is needed to reach the inflection point where the plant's electrical resistance is overcome and plant death occurs, varies based on structural differences and species composition (Vigneault et al., 1990). Greenhouse trials have corroborated that increasing voltage reduces the amount of contact time required to reach the minimum LTE (Diprose et al., 1978). Required LTE for controlling mature common lambsquarters (*Chenopodium album*) and field mustard (*Brassica campestris*) in field conditions is estimated to be an average of 1.71 kJ plant^{-1} at an operating voltage of 12 to 14.4 kV (Vigneault et al*.,* 1990), which resembles the voltage levels found in modern, commercial electrical weeders being built for large-scale agriculture. This implies as a benchmark an average of 0.4 seconds of contact time required for control of members of these species; however, LTE can shift based on population and individual variability, even if other operational and environmental variables are controlled. One of the few recent studies investigating electrical weeding as a rescue treatment in soybean (*Glycine max*) found variation in weed architecture, specifically higher number of axillary shoots in species like waterhemp (*Amaranthus tuberculatus*), can cause shielding of inner stems that reduced overall plant mortality (Schreier et al., 2022). Schreier et al. (2022) also observed lower control in grass species, especially at earlier growth stages. The heterogeneity in weed populations necessitates adapting electrical weeding parameters and approaches to specific field conditions as part of an overall IWM program.

As noted, electrical weed control has a limited research history that lends a sense of importance to current academic programs exploring key questions around the many new electrical weeding technologies coming to market. Earliest recorded use of electricity for controlling weeds was the invention of steam-powered devices to clean up railroad tracks in the late 19th century (Scheible, 1895). Research began in the Soviet Union in the 1970s, where spark discharge systems were tested in beet (*Beta vulgaris*) and sunflower (*Helianthus annuus*; Diprose et al., 1984). Diprose *et al.* conducted the bulk of the earlier studies in the 1980s, experimenting with an early electrical weeding system in control of bolting sugar beet, as well as the problem weeds common lambsquarters and wild oat (*Avena fatua*) (Diprose and Benson, 1984). Around the same time came the release of the first commercial electrical weeding equipment, the Lasco Electric Discharge System (EDS) Lightning Weeder, which prompted two notable studies in the Midwest assessing the new implement in sugar beet production. Researchers at North Dakota State University compared the ownership and operating expenses of electrical weeding to herbicide usage via a recirculating sprayer or roller applicator (i.e., weed wiper) in controlling escaped weeds. Their experiment concluded that the Lasco EDS was competitive with the tested herbicide methods at a farm scale of 250 acres and actually more cost-effective at > 350 acres (Kaufmann and Schaffner, 1982). Weed scientists at University of Nebraska carried out a groundbreaking experiment that looked at the relationship between number of treatments passes and weed mortality of common lambsquarters, kochia (*Kochia scoparia*), and redroot pigweed (*Amaranthus retroflexus*), finding that effectiveness of additional treatment passes was contingent on patterns of weed emergence and weed-crop height differential (Wilson and Anderson, 1981). Overall, the introduction of the Lasco EDS Lightning Weeder left a relatively small ripple in the field of weed control at a time when U.S. and world herbicide usage had been steadily intensifying (Osteen and Fernandez-Cornejo, 2016). Research and innovation in this area became relatively sparse in the ensuing decades, leaving a fundamental shortage of data and knowledge regarding the extent of the equipment's potential for both weed control and accidental crop injury in the numerous low-canopy crops that are amenable to electrical treatment. Electrical weeding at earlier soybean reproductive stages was found to significantly reduce yield by up to 26%; however, this experiment simulated conditions of constant electrode contact with the crop which would likely not occur in real-world cropping scenarios (Schreier et al., 2022). It is thus important to discern the level of ambient crop injury resulting from electrical weeding treatments that mimic actual use cases across various farming systems and weed communities to determine crop safety. With the resulting proliferation of herbicide-resistant weed populations, cultural movement toward ecologically safe farming practices, and ongoing technological transformation of agriculture that is leading to greater adoption of electrical weeding, gaining a more refined understanding of the safety and efficacy of this new management practice is imperative.

The cost of hand weeding poses an economic burden on vegetable and specialty crop growers who are driven to produce within a domain of limited options for removing escaped weeds before the plants contribute to the weed seed bank, disrupt harvest operations, or degrade quality of the final crop. Demand for reliable labor has outstripped domestic supply, forcing growers to increasingly depend on the H-2A Temporary Agricultural Program for bringing in seasonal migrant workers to accomplish hand-weeding and other necessary tasks such as harvest and processing (Wu and Guan, 2016). While this program provides a source of income and opportunity for families from less affluent nations and the level of worker productivity is generally satisfactory for growers, the labor performed is notorious for being physically demanding, monotonous, and at times dangerous (Williams and Escalante, 2019). Wages and housing/transportation expenses for H-2A guest workers can cost growers a substantially higher amount per person than hiring local employees at or close to the U.S. federal minimum wage, but this outsourcing of labor is often required if growers are to find and retain a reliable workforce throughout the season. Therefore, mechanization of late-season weed control has the opportunity to greatly reduce the onerous costs of hand weeding many vegetable growers incur on a yearly basis.

Due to the recency of electrical weeding as a serious weed control implement, the precise cost-benefit comparison between electrical weeding and hand weeding has not been clearly articulated in the weed science or agricultural economics literature. It has been estimated to take around 10 to 21.6 hours for a single skilled worker to hand weed one acre, depending on the level of escaped weed pressure and the field’s early-season herbicide program (Carvalledo et al., 2013). Even at the gradual tractor speeds necessary for treatment (1.5 to 6 mph per manufacturer guidelines), electrical weeding seems highly promising for saving time and labor. It is important to consider then how these savings relate to any tradeoffs in efficiency between electrical and hand weeding, initial investment and ownership costs of the electrical weeder, and the extent of labor and time reduction when assessed against the variables contributing to the partial budget analysis.

Adhering to the principles of IWM demand a careful analysis of the potential pitfalls of electrical weeding in addition to its favorable aspects. The drawbacks of electrical weeding include a possibility of reduced farm profitability as a result of incorporating a new weed control practice which could entail a heightened risk of crop injury, variable efficacy for different weed species/growth stages, and prohibitively expensive operating and initial investment costs. The current research seeks to address these concerns by evaluating the performance of electrical weeding within a context of variation in number of electrical weed passes/application timings and weed density. As well, assessing and comparing the economic viability of this new technology against alternative late-season control practices (namely, hand weeding) is an integral part determining the legitimacy of this new equipment and whether or not its performance justifies adoption by farms and other agribusinesses. The overall objectives of the research in conventional carrot and organic green bean production are to 1) evaluate the weed control efficacy of electrical weeding, 2) determine its risk of crop injury and impact on crop yield/quality, and 3) compare the level of financial risk/reward associated with using electrical weed control over the alternative solution of hand weeding and discern the primary criteria impacting financial viability when utilizing this equipment. Developing a basic scientific understanding of the operational and economic practicality of electrical weed control is essential for growers to optimize the use of this equipment in their production systems and for researchers and engineers to explore better ways of applying electricity to control weeds in the agroecosystem.

Materials and Methods

Site Description/Experimental Design

Field trials were carried out at Oomen Farms in Hart, MI during the summer of 2021 and 2022. Two separate trials were conducted in each field season: one in carrots (cultivar Canberra in 2021 and Belgrado in 2022) grown in a conventional production system and the other in green beans *(*cultivar High Style) grown in an organic production system. In 2021, the soil type for the carrot field location (43.84°N 86.36°W) was a Pipestone fine sand [6.4 pH and 4.4% organic matter (OM)] with 0-4 percent slopes, while for the green bean field location (43.85°N 86.34°W) the soil was a Covert sand (7.6 pH and 2.5% OM) with 0-6 percent slopes. In 2022, the carrot field location (43.71°N 86.20°W) soil type was a Benona sand (5.7 pH and 1.8% OM) with 0-6 percent slopes and the green bean field location (43.68°N 85.98°W) was a Covert sand (6.5 pH and 3.5% OM) with 0-4 percent slopes [soil series data sourced from Soil Survey Geographic (SSURGO) Database].

For the carrot trial, the experiment was structured as a spit-plot design with four replications. The main plot factor was late-season weed control methods and included: 1) one hand-weeding event (HW), 2) one electrical weeder pass (1P), 3) two electrical weeder passes performed consecutively [2P(ST)], 4) one pass followed by one pass after a 14-day interval [2P(14d)], 5) two passes followed by one pass after a 14-day interval (3P), and 6) no late-season control (NLC). Within each main-plot variable, the sub-plot factor tested different early-season weed control methods in order to produce different weed densities with which to test the late-season weed control methods. These consisted of 1) one application of postemergent herbicide linuron (Lorox; Dupont, Wilmington, DE; "Low" early-season control;), 2) two applications of linuron ("Medium" early-season control), 3) two applications of linuron and one application of the preemergent herbicide pendimethalin (Prowl H_2O; BASF Ag Products, Ludwigshafen, Germany; “Intensive” early-season control), 4) a weed-free control and 5) no early-season control (NEC). Each sub-plot early-season weed control treatment was tested on individual 6-ft x 35-ft beds, comprising five beds per main plot with three carrot rows per bed. Each sub-plot was further divided into two sections: a front section to use for collecting in-field data such as weed control ratings, weed counts, and crop yield at harvest, and a back section from which soil and seed samples were collected without compromising in-field data through sampling disturbance.

Initial applications of pendimethalin were performed in early May using a CO_2 pressurized backpack sprayer at a rate of 1.9 lb ai acre^{-1} in 2021 and 0.95 lb acre^{-1} in 2022. The first application of linuron was performed 3-4 weeks after the preemergent at a rate of 1 lb ai acre^{-1}. The final linuron application was applied 3 weeks afterwards at 1 lb acre^{-1}. Weed counts and timed hand weeding treatments were performed 4-6 weeks after the final herbicide application. The first electrical weeding treatment took place 1 week after weed counts in 2021 and 3 weeks after weed counts in 2022. Environmental parameters such as percent cloud cover, relative humidity and soil moisture/temperature were recorded at the time of application for every treatment in both trials during the 2022 season. Volumetric water content (VWC) was measured at the time of the first electrical treatment in 2021 and both electrical treatments in 2022 using a Field Scout time-domain reflectometer 300 soil moisture meter (Spectrum Technologies, Aurora, IL) with both short (1 inch) and long (7.6 inch) measurement rods.

For the green bean trial, the experiment was structured as a randomized complete block design with four replications. Treatments were identical to the late-season weed control methods used in the carrot trial. Each treatment plot consisted of 12 rows of beans, with each row being 30 ft in length. Volumetric water content readings were also taken during one of the electrical treatments in 2021 and during both in 2022. Dates of key field operations for both the carrot and green bean trials in both years are provided in Table 1.1. Standard cultural practices for growing carrots (conventional production) and green beans (organic production), including insect and disease management, fertilization, and irrigation, were performed by the grower. In the green bean trials, cultivation was performed 3-4 times to manage early-season weeds.

Weed Control

The electrical weeding equipment used for the trials was the Annihilator 12R30 manufactured by the Weed Zapper™ (Old School Manufacturing, LLC., Sedalia, MO) and owned/operated by the growers at Oomen Farms. An operating speed of 1-2 mph at 230 horsepower was maintained for all treatments in both trials. Electrical treatment was timed for when a substantial proportion of the weeds were at least 4-6 inches taller than the crop, per manufacturer recommendations (Old School Manufacturing, LLC., 2020). In both carrot trials, redroot pigweed had formed mature seedheads, with seeds close to a dark brown color, by the time electrical weeding was performed. Above-canopy weeds were generally large, with few weeds observed growing below the crop canopy, leading to repeat electrocution of the same plants at EW#1 and #2. In green beans, common lambsquarters and redroot pigweed were beginning seed formation by the time electrical weeding was performed. In these trials, more weeds were growing below the crop canopy, leading to new plants being electrocuted at EW#2 as they emerged above the canopy. Weed density and species composition of the weed communities were determined prior to late-season weed control treatments by performing two weed counts per treatment using two 5-ft x 2-ft quadrats. Weeds were categorized as either above or below the crop canopy (i.e. within or beneath the treatment zone) and the number of individuals of each species recorded. Visually assessed weed control ratings on a scale of 0-

100% were taken at about 7 days following each treatment (days after late-season weed control treatment; DAT) in 2021 and at about 7 and 14 DAT in 2021.

Crop Injury

Crop injury ratings were also taken on a 0-100% scale at about 7 DAT in 2021 and 7 and 14 DAT in 2022. Yield data (topped carrot root weight and harvested green bean pod/plant biomass weight) was collected from a 5-ft section from 3 rows per plot in carrot and a 10-ft section from 4 rows per plot in green beans. A sample of 10 carrots were randomly selected from each treatment during yield data collection to assess the impact of electrical weeding on root quality (root length and internal root injury). Each carrot root was subjected to visual assessment for internal damage to determine potential injury from electrical weeding by slicing individual roots into cross-sections which were then inspected for presence of burnt ground or vascular tissue. In 2022, this root sampling and inspection was also performed no more than 3 days after both electrical weeding treatments in carrot to monitor any immediate damage to the carrot roots.

Economic Viability

An economic assessment was carried out to compare the cost-effectiveness of electrical weeding to the primary alternative method of hand-weeding. Hand-weeding sessions and electrical weeding sessions were timed to the nearest second and recorded for use in calculations. Hand weeding was performed without the use of any cultivation tools and time required to gather and pile uprooted weeds was also included in the recorded final time. Research and consultation with the grower/owner of the electrical weeding equipment was used to gather information necessary for calculating ownership and operating expenses.

For use in this case study, an average diesel fuel price of $2.94/gallon was calculated from historical U.S. prices from 2016-2021 (U.S. Energy Information Administration, 2022). In the moderate weed densities observed in our experimental plots, it was estimated that fuel usage for operating the electrical weeder would require about 5 gallons per hour (Oomen Farms, personal communication). An hourly wage of $23 per hour was set as the compensation per laborer engaging in hand weeding based on the typical cost of H-2A labor for the grower-collaborator (Oomen Farms, personal communication). An hourly wage of $23 per hour was also assigned as compensation for the electrical weeder operator. The cost of operating expenses was then determined using the following equation:

$$E_{op} = (f(v) * t) + (l * t)$$

where E_{op} is operating expenses acre^{-1}, f is diesel fuel price per gallon, v is volume of fuel used per hour (gallons), t is electrical weeding time required acre^{-1} (hours) and l is the hourly labor price.

Ownership costs were calculated to provide a more comprehensive picture of cost acre^{-1} for electrical weeding. The manufacturer's price for a new 12R30 Weed Annihilator electrical weeder ($71,500, as of 2022) was used as the purchase price in estimating the cost of ownership. As well, estimates of an annual usage of 60 hours per year and an equipment lifespan of 15 years were used (Oomen Farms, personal communication). Annual maintenance costs and resale/salvage value were held at $0.00 due to uncertainty around realistic values. The cost of ownership expenses was then determined using the following equation:

$$E_{ow} = \frac{(e_p + e_m - e_r)/e_l}{a}$$

Where E_{ow} is the ownership expenses acre^{-1}, e_p is the equipment purchase price, e_m is the total maintenance costs for entire equipment lifespan, e_r is the resale/salvage value, e_l is the equipment lifespan, and a is the number of acres treated per year. Operating and ownership expenses were then summed to find total cost acre^{-1}.

Data Analysis

All data was subjected to ANOVA using SAS 9.4 (SAS 9.4, SAS Institute Inc., Cary, NC) PROC GLIMMIX and means separation using Fisher's Protected LSD test (P ≤0.05). All data were checked for normality and homogeneity of variance before statistical analysis by plotting residuals. Data was analyzed by year for both crops due to the variability in data collection timings and presence of different weed species. In the data from the carrot trial, early-season weed control methods, late-season weed control methods, and their interaction were considered fixed effects and replication as a random effect. In the data from the green bean trial, late-season weed control methods was considered a fixed effect and replication as a random effect.

Results and Discussion

Carrot

Weed density and control

The major weed species for the carrot trial in 2021 and 2022 was redroot pigweed. Other weeds that were reported included witchgrass *(Panicum capillare*), common lambsquarters, tumble pigweed (*Amaranthus albus*), and eastern black nightshade (*Solanum ptychanthum*) in 2021 and large crabgrass (*Digitaria sanguinalis*) in 2022. Overall lighter weed pressure (both above and below canopy) was observed in 2022 as compared to 2021 (Table 1.2). The reduced weed density in 2022 can be attributed to partial overlap of the grower's sprayer band onto non-treated experimental plots and general inter-field variation.

The main goal of using different herbicide program intensities was to produce various levels of weed density during the later growing season within which to evaluate electrical weeding. There was a decreasing trend observed for above-canopy redroot pigweed density with increasing number of herbicide applications during both years (Table 1.2). However, this trend showed a significant difference in above-canopy redroot pigweed density between only the NEC (19,602 plants acre^{-1}) and intensive (10,527 plants acre^{-1}) herbicide programs in 2021 ($P = 0.0003$) and between the medium (1,543 plants acre^{-1}) and intensive (545 plants acre^{-1}) herbicide programs and NEC (3,721 plants acre^{-1}) in 2022 ($P < 0.0001$). In terms of all other weeds, the herbicide treatments provided significant control in both years as compared to the NEC, though there was no difference between the various herbicide programs. Redroot pigweed density was observed to be the same with respect to all the late-season weed control treatments except 2P(ST) during both years. In 2021, 2P(ST) had a significantly higher above-canopy redroot pigweed density ($P = 0.0004$) than all other late-season weed control methods, but conversely had the lowest in 2022 (Table 1.2; $P = 0.0401$).

In 2021 at 8 DAIT, HW, 2P(ST), and 3P provided a similar level of redroot pigweed control but exhibited greater control than 1P and 2P(14d), which were similar to each other (Figure 1.1). This shows the equivalence of HW and 2P(ST), with the other relationships observed showing expected results for this earlier time point. At this timing, 3P and 2P(ST) had actually received the same number of electrical passes; likewise, with 1P and 2P(14d) at this first time point. For 22 DAIT (10 DAFT), when all electrical weeding passes had been performed, these equivalencies are for the most part conserved except that 2P(14d) was not found to be significantly different from 3P or 2P(ST). With respect to early-season weed control methods, all treatments provided lower control than the weed-free plot at 8 DAIT; however, by 22 DAIT all treatments were equivalent in control except the medium herbicide program, which was the lowest at 67% (Figure 1.2).

In 2022, 2P(ST) actually provided better extended redroot pigweed control than 3P and was comparable to HW (Figure 1.3). The long-term control of 2P(14d) resembled 2P(ST), as mean redroot pigweed control was similar at 17 DAFT. The treatment 3P actually resembled 1P in terms of providing lower control throughout the season. Redroot pigweed control was reported ≥ 85% from all the late-season weed control treatments at 17 DAFT. Based on these observations, the inclusion of a 14-day does not appear to lead to significantly greater weed control in conventional carrots due to initial control of redroot pigweed escapes at 2P(ST) or 1P, leading to repeat electrocution of desiccated above-canopy redroot pigweed at 14 days that provides little additional weed control.

With respect to early-season weed control methods, the weed-free treatment had generally higher redroot pigweed control than other herbicide treatments, being most similar to the intensive herbicide program (Figure 1.4). The medium herbicide program provided the lowest control at 17 DAIT, where it was equivalent to the NEC, which had among the lowest control throughout the entire rating period. However, at 7 and 17 DAFT, the efficacy of the medium herbicide program increased to the same level as for the intensive herbicide program, while redroot pigweed control for the low herbicide program became similar to the NEC. This pattern indicating that electrical weeding treatments with lower weed densities (weed-free or intensive herbicide programs) results in greater control may be a result of increased electrode contact with and energy delivered to individual weeds due to lower incidence of weeds shielding each other from contact and less diminished performance coming from multiple weeds contacting the electrode at one time. While more weeds may incur some damage at high densities, damage per plant is reduced and therefore more plants recover, leading to less long-term control for plots with higher weed densities.

In sum, there was little difference reported in redroot pigweed control with respect to early-season weed control methods after performing the various late-season weed control methods in 2021. However, in 2022, redroot pigweed control tended to be higher for treatments that caused initially lower weed densities (weed-free and intensive herbicide program). Lower control is generally observed at higher weed densities, though increasing number of passes can compensate by increasing control in denser weed infestations (Vigneault and Benoit, 2001). Based on the weed control results from the carrot trial, increasing passes above 2P(ST) does not appear to provide better control; indeed, 3P showed lower control than 2P(ST) in 2022, though this is likely due to the higher above-canopy redroot pigweed density for 3P (Table 1.2). Hand weeding and 2P(ST) gave similar redroot pigweed control for both years. All late-season weed control methods showed ≥ 70% control across the rating period for both years.

Crop injury

In 2021 at 8 and 22 DAIT, 2P(ST) had the highest level of in-season injury at 8.3 and 9%, respectively (Table 1.3). At both 8 DAIT and 22 DAIT, the in-season injury for 3P was not significantly different from 2P(ST), the treatment with the highest injury. The treatments 1P and 2P(14d) showed comparable injury to HW at both times. The injury from HW was not found to be significantly different from the NLC at 22 DAIT, which had 0% injury. For early-season weed control methods at 22 DAIT, the low (7.3%) and intensive (6.7%) herbicide program was correlated with the highest crop injury, while the weed-free (3.1%) and NEC (3.8%) treatments had lower injury.

In 2022, increasing passes above 2P(ST) did not lead to significantly higher injury. HW typically showed lower injury than most electrical treatments, apart from 1P which was similar at all rating dates. There was no difference in crop injury reported between different early-season weed control treatments in 2022. Finally, the injury observed did not exceed 10% for any of the treatments in either year, indicating that the level of crop damage that was observed tended to be fairly negligible.

Root quality and yield

There was no evidence of internal damage from the electrical weeder in carrot root samples collected at harvest in 2021 (data not presented). Likewise, carrot root samples collected within 3 days of electrical weeding were not found to have any internal damage in 2022 (data not presented). Cavitation of vascular tissue in roots collected at harvest in 2022 was observed (ranging from about 1.1 to 3.3% of roots sampled); however, number of damaged roots in all treatments was not found to be significantly different from NLC indicating that these hollow roots are likely the result of other abiotic or biotic factors.

The 2P(ST) treatment was the only late-season control method that was found to have a significantly different carrot length, which was lower than other treatments in 2021 (Table 1.4). Carrot length for 2P(ST) was lower than both 1P, 3P, and HW, with an average length similar to the NLC. As mentioned, the plots that received 2P(ST) were found to have an unusually high redroot pigweed density [up to 4x the density of the other treatments (Table 1.2)], which is likely responsible for this reduction in length rather than any damage caused by the electrical weeder. There were no differences in carrot length for any of the early or late-season weed control methods in 2022.

None of the late-season weed control methods led to a carrot yield difference in 2021, except for 2P(ST) in carrot which showed a slightly reduced yield (Table 1.4). Again, the initially high redroot pigweed density for this treatment is likely responsible for the reduced yield. In 2022, all electrical treatments were found to have lower carrot yields than the NLC and HW, except for

2P(ST). This is likely a result of the 2P(ST) replications being localized on the same side of the field as the NLC: a portion of the field that showed evidence of overlap with the grower's spray band and thus received greater control and had the lowest above-canopy redroot pigweed density (Table 1.2) early in the season. As yield in the HW treatment also had a similar yield to 2P(ST) and NLC, it suggests that hand weeding can indeed lead to a yield increase by the end of the season, which was an effect not observed in 2021. Hand weeding has been observed to lead to increases in carrot yield and root length but generally when performed much earlier in the season, such as at 30 days after planting (Chaitanya et al., 2014) as compared to 83 days after planting for the 2022 carrot trial.

There is a trend observed in carrot yields with respect to early-season weed control methods in 2021, where the highest yields were observed from the weed-free treatment followed by low, medium, and intensive herbicide programs and with the lowest from the NEC treatment. These observations relate to the fact that the critical weed free period in carrot (0-930 growing degree days for carrots planted in late April, or approximately from planting to 12 leaf stage) outlined by Swanton et al. (2010) had already passed, leading to no yield difference from late-season control practices but higher yields corresponding roughly to lower weed densities for early-season control practices in 2021. No statistically significant yield difference for early-season weed control methods was reported in 2022.

Green Beans

Weed density and control

The major weed species for the green bean trial were common lambsquarters and redroot pigweed in 2021 and redroot pigweed in 2022. Above and below-canopy common lambsquarters and redroot pigweed densities ranged from 28,314 to 78,408 plants acre^{-1} and 6,534 to 58,806 plants acre^{-1}, respectively, in 2021. Above-canopy redroot pigweed ranged from 39,204 to 54,450 plants acre^{-1} and below-canopy redroot pigweed ranged from 2,178 to 23,598 plants acre^{-1} in 2022. Above and below-canopy common lambsquarters density ranged from 0 to 10,890 plants acre^{-1} in 2022, showing the contrast in dominant species between the two years.

In 2021, at 3 DAIT there was significantly higher common lambsquarters control in the plots where two passes had been applied than where only one pass had been applied (Figure 1.5). By 7 DAFT, 3P and 2P(14d) had the best control apart from the consistent and full control provided by HW. Redroot pigweed control showed a very similar trend in 2021, despite the lower weed density (Figure 1.6). In 2022, there was no difference between 1P or 2P(ST) at 6 DAIT for redroot pigweed control, but the same trend of 3P and 2P(14d) giving superior control compared with other electrical treatments following EW#2 was observed (Figure 1.7). This was not observed in carrot, where increasing passes above 2P(ST) did not lead to any better control of redroot pigweed (Figures 1.1 and 1.3). Compared to the carrot trial, there were a greater amount of weeds observed under the crop canopy at the time of EW#1 in green beans in both years. By EW#2, these below canopy weeds had emerged above the green beans and were electrocuted, resulting in improved weed control for 3P or 2P(14d). Similarly, Schreier et al., (2022) observed that electrical weeding efficacy was enhanced at later weed growth stages, mostly as a consequence of more weeds at a sufficient height to be contacted by the electrode. Farr et al. (2022) also observed that variation in weed-crop height and patterns of above-canopy weed emergence affected outcomes when applying dicamba using a roller wiper. As a general rule, the larger the plant is the greater the resistance to electrical conduction it has, though variation in resistivity of plant tissue also influences current flow (Diprose and Benson, 1984). Thus, it requires balance in timing electrical weeding for when after an optimal proportion of weeds have emerged above the crop canopy yet not before above-canopy weeds reach a size where mortality from electrocution is compromised. Indeed, even fully desiccated weeds remaining in the fields can interfere with operations by obstructing harvesters if they became large enough prior to lethal electrical treatment (Oomen Farms, personal communication).

Crop injury

In 2021, injury for all late-season weed control methods was higher than HW at 3 and 7 DAIT, but became similar to or even lower than HW at 7 DAFT (Table 1.5). At 3 DAIT, injury from electrical weeding was the most severe, ranging from about 15-19%. This higher electrical weeding injury in green beans compared with the carrot trials (1-9% in-season injury throughout both 2021 and 2022; Table 1.3) likely relates to the dynamics of the organic production system, where a higher proportion of weeds were growing at or about the same height as the crop. This not only decreased weed control more on average compared with the conventional carrot trial as more weeds were growing below the treatment zone, but increased crop injury as the electrode contacted more green bean foliage due to the insufficient height differential that would normally allow for a buffer between the electrode's path and the crop canopy. The level of crop injury was not found to significantly change with greater number of electrical weeder passes or inclusion of a 14 day interval for 3 DAIT, 7 DAIT, or 7 DAFT. In 2022, there was no significant difference in green bean injury between any of the late-season weed control treatments and the 0% injury observed in NLC, indicative of a safe height differential between the treated redroot pigweed and the crop foliage.

There was no significant difference in green bean yield reported between any of the late-season weed control methods in 2021 or 2022 (Table 1.6). Schreier et al. (2022) did observe yield reduction when applying electrical treatment during early reproductive stages (R1 – R3) in soybean; however, this was when purposefully applying constant electrode contact to the crop and therefore represents an extreme amount of electrode contact time with crop foliage compared with the green bean trials. In terms of plant biomass, 2P(ST) was lower than every other treatment except NLC in 2021 while, in 2022, there were no differences in biomass reported.

Carrot and Green Bean Economic Viability

For the carrot and green bean trials in both years, HW required a significantly greater amount of time acre^{-1} and had a higher cost acre^{-1} than all electrical treatments (Table 1.7). There were no significant differences in time acre^{-1} or cost acre^{-1} between different number of electrical weeder passes. The 2021 carrot trial had the greatest time requirement for HW (1779.5 minutes acre^{-1}) and, consequently, the highest cost acre^{-1} ($682.03). The range of time/cost acre^{-1} observed relates to the differences in weed pressure, with fields that had higher weed competition requiring longer hand weeding and electrical weeding times.

Averaged across both years, mean HW time in carrot was found to be 1,114.4 minutes acre^{-1} (18.6 hours) for one worker. In green bean, mean HW time was 1,223.3 minutes (20.4 hours). Hand weeding time has been shown to vary dramatically due to variation in weed pressure; Forcella et al. (2015) described a range of 2 to 34.4 hours acre^{-1} required for an individual hand weeding in cucurbits, depending on early-season cultural weed control methods. This contrast in weeding time reflects the weed pressure characterizing the two production systems, with the conventional carrot fields requiring about 54% of the HW time required for organic green beans. Greater variation in weeding time was observed in the carrot trials (7.5 to 29.7 hours acre^{-1}) compared with the green bean trials, which were consistently high (17.5 to 23.3 hours acre^{-1}).

Mean 1P weeding time for the carrot and green bean trials was 11.3 and 8.23 minutes acre $^{-1}$, respectively. This higher time requirement for carrot reflects the greater variance in tractor speed for the 2021 carrot trial (1 to 2 mph) before speed was increased to and held consistent at 2 mph for all following trials in carrot and green bean. This slower tractor speed, as well as the overall higher weed density in the 2021 carrot trial (Table 1.2), is reflected in the higher time acre^{-1} requirement for all electrical weeding treatments in 2021 compared to 2022. Higher weed density in carrot 2021 led to a 296% increase in HW time from carrot 2022 compared with only a 62.8% increase for 1P weeding time from 2022 to 2021, much of which is likely due to the slower tractor speeds in 2021. For green bean, the percentage increase from 2022 (lighter weed density) to 2021 (heavier weed density) for HW compared to 1P was not as extreme (32.8% and 22.4% increase, respectively) due to similar weed densities between years, as well as smaller weeds in the green bean fields that would have made hand weeding easier and quicker than for the large redroot pigweed escapes in the carrot trials.

Mean HW cost acre^{-1} was \$427.07 for carrot and \$473.44 for green bean. In contrast, 1P electrical weeding cost acre^{-1} was \$20.69 for carrot and \$16.10 in green bean. Redroot pigweed/common lambsquarters control was reported at or close to 100% for HW for both trials in both years (Figures 1.1, 1.3, 1.5-1.7) and HW seemed to be correlated with an increased carrot yield in 2022 (Table 1.4). In addition, HW had among the lowest carrot injury in both years (Table 1.3) and includes control of below-canopy weeds as well as removal of all uprooted weeds from the field. This more thorough control of weeds at various sizes could have the additional financial advantage of preventing weed residues from degrading the final quality of the crop or impeding harvest efficiency. However, the significantly higher cost acre^{-1} for hand weeding compared to 1P electrical weeding (19.6- and 28.4-fold increase in carrot and green bean, respectively) indicates that alternative late-season control options can be more cost-effective and have the potential to reduce annual costs involved with manual weeding considerably.

Conclusions

In conclusion, use of a 14-day interval appeared to lead to greater control in the organic green bean production system as compared to the conventional carrot system. This likely relates to the higher density of weeds growing at- or below-canopy in the organic system, where electrocution after the 14-day interval allows for treatment of weeds that had newly emerged above the crop canopy. In the carrot trial, there were fewer below canopy weeds due to stronger early-season control. This led to the same weeds being electrocuted at each timing, limiting utility of the 14-day interval. This finding indicates that number of passes and their timing can be adapted based on the relative height and density of weeds to optimize control while minimizing unnecessary passes over the field. Weed control was lower overall in the organic green bean system due to the higher below-canopy weed density. Evidence from the carrot trial supports the assertion that electrical weeding has lower performance in higher weed densities.

Electrical weeding can lead to higher in-season crop injury than hand weeding but was not found to cause any internal damage to carrot root tissue. Crop injury was higher overall in the organic green bean system due to greater number of weeds growing at- or below-canopy, which required more aggressive electrical treatment in order to get sufficient control which resulted in more electrode contact time with the crop foliage. There was no significant increase in carrot or green bean yield from electrical weeding in either year. Hand weeding only appeared to be correlated with a yield increase in 2022. This indicates that primary advantage of electrical weeding as a form of late-season control is not to increase yield in the current crop, but to control escaped weeds before they develop or disperse seed in order to decrease weed pressure in later years.

Hand weeding was found to have a higher time and cost acre^{-1} than electrical weeding in carrots and green beans in both years. There was found to be no difference in time/cost acre^{-1} between different number of electrical weeder passes. While hand weeding possesses key benefits over electrical weeding as a late-season weed control method, its substantially higher time and cost requirements may compromise these additional advantages depending on a farm's financial and operational context.

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APPENDIX

Table 1.1. Key dates for field operations and data collection for carrot and green bean trials in 2021 and 2022 at Hart, MI.

Activity	Carrot		Green Bean	
	2021	2022	2021	2022
Crop planted	20 April	28 April	9 July	11 July
PRE application[a]	6 May	10 May	-	-
POST #1 application[b]	27 May	1 June	-	-
POST #2 application[c]	16 June	21 June	-	-
Hand weeding treatment	30 July	20 July	23 Aug	23 Aug
Weed counts taken	30 July	20 July	23 Aug	23 Aug
Electrical weeding treatment #1	5 Aug	12 Aug	20 Aug	23 Aug
Weed control/crop injury rating #1	13 Aug	18 Aug	23 Aug	29 Aug
Electrical weeding treatment #2	17 Aug	26 Aug	27 Aug	31 Aug
Weed control/crop injury rating #2	27 Aug	29 Aug	27 Aug	6 Sept
Weed control/crop injury rating #3	-	2 Sept	2 Sept	-
Weed control/crop injury rating #4	-	12 Sept	-	-
Harvest – yield data collected	19/22 Oct	3/4 Oct	9 Sept	8 Sept

[a] PRE = 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

[b] POST #1 = 1 application of linuron (1 lb ai acre^{-1})

[c] POST #2 = 1 application of linuron (1 lb ai acre^{-1})

Table 1.2. Weed densities measured one and three weeks before performing electrical weeding in 2021 and 2022 carrot trials, respectively, at Hart, MI.

	Redroot pigweed				All other weeds[e]			
Dependent Variables[a]	Above[b]		Below[c]		Above[b]		Below[c]	
	2021	2022	2021	2022	2021	2022	2021	2022
Early-Season Weed Control Methods[d]				Plants acre $^{-1}$				
No Early-Season Control	19602 a	3721 a	454	454	12977 a	1180 a	57449 a	10073 a
Low	12161 ab	2723 ab	635	272	2178 b	363 b	5536 b	2087 b
Medium	15700 ab	1543 bc	1361	817	2087 b	0 b	454 b	635 b
Intensive	10527 b	545 c	1089	545	272 b	91 b	544 b	1180 b
Weed-free	272 c	181 c	635	272	0 b	0 b	272 b	635 b
Late-Season Weed Control Methods								
No Late-Season Control	11217 b	1198 ab	1089	218	3703	545	7405	2614 bc
1 Hand Weeding	11217 b	2505 a	1307	871	2287	327	7950	4683 a
1 Pass Electrical Weeding	4356 b	2396 a	327	109	2831	545	11870	2505 bc
2 Pass Electrical Weeding (Same	25592 a	545 b	1198	436	3703	109	15355	1198 c
2 Pass Electrical Weeding (14-day	8820 b	1307 ab	218	871	5445	218	18186	3267 ab
2 Pass followed by 1 Pass (14-day	8712 b	2505 a	871	327	3049	218	16335	3267 ab
Early-Season Weed Control Methods (P-Value)	0.0003	<.0001	0.3847	0.4016	<.0001	<.0001	<.0001	<.0001
Late-Season Weed Control Methods (P-Value)	0.0004	0.0401	0.2638	0.1233	0.1669	0.5436	0.166	0.027
Late-Season × Early-Season (P-Value)	0.7712	0.295	0.3318	0.0728	0.3281	0.9062	0.3337	0.0774

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Represents above the crop canopy.

[c] Represents below the crop canopy.

Table 1.2. (cont'd)

[d] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

[e] All other weeds include: 2021 – lambsquarters (*Chenopodium album*), witchgrass (*Panicum capillare*), tumble pigweed (*Amaranthus albus*), eastern black nightshade (*Solanum ptychanthum*), purslane (*Portulaca oleracea*), yellow rocket (*Barbarea vulgaris*), and maple (*Acer* spp.)

2022 - Large crabgrass (*Digitaria sanguinalis*), eastern black nightshade, virginia creeper (*Parthenocissus quinquefolia*), purslane, field pansy (*Viola arvensis*), clover (*Trifolium* spp.), and maple.

Table 1.3. Impact of early- and late-season weed control methods on carrot injury in 2021 and 2022 at Hart, MI.

	2021		2022			
Dependent Variables[a]	8 DAIT[b]	22 DAIT	6 DAIT	17 DAIT	7 DAFT[c]	17 DAFT
	% injury					
Early-Season Weed Control Methods[d]						
No Early-Season Control	4.6	3.8 c	1.8	2.1	1.7	1.4
Low	5.8	7.3 a	6	3.3	3	3.8
Medium	3.3	4 bc	3.2	2.2	1.5	0.8
Intensive	6.1	6.7 ab	5.2	2.9	1.8	1.8
Weed-free	3.5	3.1 c	3.2	2	1.3	1.5
Late-Season Weed Control Methods						
No Late-Season Control	0 c	0 d	0 b	0 c	0 c	0 b
1 Hand Weeding	4.8 b	3 cd	0.8 b	0.7 bc	1.5 bc	0.9 b
1 Pass Electrical Weeding	4 b	5.3 bc	3.6 ab	2.6 ab	1 bc	1.9 ab
2 Pass Electrical Weeding (Same Time)	8.3 a	9 a	7 a	3.9 a	2.9 ab	3.2 a
2 Pass Electrical Weeding (14-day interval)	4.3 b	5.8 bc	5 a	3.1 a	1.9 abc	1.7 ab
2 Pass followed by 1 Pass (14-day interval)	6.8 ab	6.8 ab	6.8 a	4.7 a	4 a	3.6 a
Early-Season Weed Control Methods (P-Value)	0.1168	0.0093	0.194	0.7126	0.4398	0.0754
Late-Season Weed Control Methods (P-Value)	<.0001	<.0001	0.0028	0.001	0.0067	0.0234
Late-Season × Early-Season (P-Value)	0.035	0.4566	0.7701	0.6249	0.9012	0.9047

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] DAIT = Days after initial treatment (Electrical Weeding #1).

[c] DAFT = Days after final treatment (Electrical Weeding #2).

[d] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

Table 1.4. Impact of early- and late-season weed control methods on carrot yield and length in 2021 and 2022 at Hart, MI.

Dependent Variables[a]	Carrot Yield 2021	Carrot Yield 2022	Carrot Length 2021	Carrot Length 2022
	tons/acre		inches	
Early-Season Weed Control Methods[b]				
No Early-Season Control	14 c	35.5	6.4 c	9.8
Low	18.7 b	37.6	6.8 ab	9.7
Medium	19.2 b	37.5	6.7 abc	9.5
Intensive	19.2 b	37.2	6.6 bc	9.9
Weed-free	22.9 a	39.0	6.9 a	9.7
Late-Season Weed Control Methods				
No Late-Season Control	19.7 a	41.5 a	6.5 bc	9.8
1 Hand Weeding	19.7 a	39.9 a	7.1 a	9.6
1 Pass Electrical Weeding	18.5 ab	34.3 b	6.8 ab	9.4
2 Pass Electrical Weeding (Same Time)	16.2 b	40.7 a	6.3 c	9.9
2 Pass Electrical Weeding (14-day interval)	19 a	32.9 b	6.6 abc	9.6
2 Pass followed by 1 Pass (14-day interval)	20.6 a	34.9 b	7 a	10
Early-Season Weed Control Methods (P-Value)	<.0001	0.5975	0.0221	0.5938
Late-Season Weed Control Methods (P-Value)	0.0483	0.0004	0.0112	0.2017
Late-Season × Early-Season (P-Value)	0.6343	0.9932	0.2913	0.9065

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

Table 1.5. Impact of late-season weed control methods on green bean injury in 2021 and 2022 at Hart, MI.

	2021			2022	
Late-Season Weed Control Methods[a]	3 DAIT[b]	7 DAIT	7 DAFT[c]	6 DAIT	6 DAFT
	------------------------------% injury ---------------				
No Late-Season Control	0 b	0 b	0 c	0	0
1 Hand Weeding	0 b	0 b	10 a	3.8	0.8
1 Pass Electrical Weeding	16.3 a	10 a	5 b	6.3	0.8
2 Pass Electrical Weeding (Same Time)	18.8 a	8.8 a	7.5 ab	5	4.3
2 Pass Electrical Weeding (14-day interval)	18.8 a	10 a	5 b	3.8	0
2 Pass followed by 1 Pass (14-day interval)	15 a	10 a	7.5 ab	2.5	1.8
P-Value	<.0001	0.0002	<.0001	0.1504	0.3306

[a] Means within columns for treatments that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] DAIT = Days after initial treatment (Electrical Weeding #1).

[c] DAFT = Days after final treatment (Electrical Weeding #2).

Table 1.6. Impact of late-season weed control methods on green bean yield and plant biomass in 2021 and 2022 at Hart, MI.

	Bean Yield		Plant Biomass	
Late-Season Weed Control Methods[a]	2021	2022	2021	2022
	bushels/acre		tons/acre	
No Late-Season Control	278.0	346.0	3.1 bc	4.9
1 Hand Weeding	389.5	401.6	3.9 ab	5.9
1 Pass Electrical Weeding	398.8	333.1	3.9 ab	4.7
2 Pass Electrical Weeding (Same Time)	255.2	284.9	2.7 c	4.3
2 Pass Electrical Weeding (14-day interval)	424.1	259.1	4.2 a	3.9
2 Pass followed by 1 Pass (14-day interval)	360.9	328.4	3.8 ab	4.5
P-Value	0.0575	0.0569	0.0166	0.2870

[a] Means within columns for treatments that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

Table 1.7. Time and cost acre^{-1} for electrical weeding and hand weeding in carrot and green bean in 2021 and 2022 at Hart, MI.

	Minutes required acre^{-1}				Total cost acre^{-1} (USD)			
	Carrot		Green		Carrot		Green Bean	
Late-Season Weed Control Methods[a]	2021	2022	2021	2022	2021	2022	2021	2022
1 Hand Weeding[b]	1779.5 a	449.3	1395.48 a	1051.1 a	$682.03 a	$172.10 a	$534.93 a	$402.94 a
1 Pass Electrical Weeding	14 b	8.6 b	9.06 b	7.4 b	$22.40 b	$18.98 b	$17.69 b	$14.51 b
2 Pass Electrical Weeding (Same Time)	33 b	17.3 b	20.05 b	15.6 b	$34.40 b	$24.42 b	$39.15 b	$30.38 b
2 Pass Electrical Weeding (14-day interval)	26.3 b	17.7 b	19.26 b	17.3 b	$30.10 b	$24.74 b	$37.60 b	$33.75 b
2 Pass followed by 1 Pass (14-day interval)	39.3 b	26.7 b	27.49 b	25.8 b	$38.40 b	$30.39 b	$53.66 b	$50.29 b
P-Value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

[a]Means within columns for treatments that are followed by the same letter are not significantly different using Fisher's Protected LSD

(α=0.05).

[b]Estimated time required reflects one laborer for hand weeding.

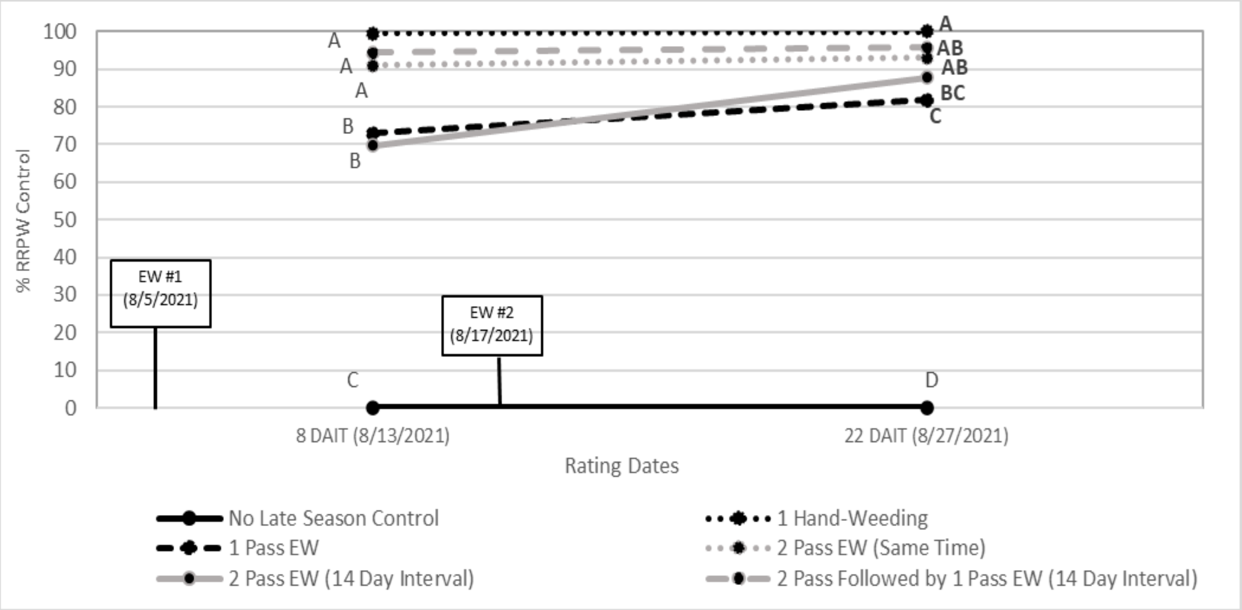

Figure 1.1. Impact of late-season weed control methods on redroot pigweed (RRPW) control in carrots in 2021 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1).

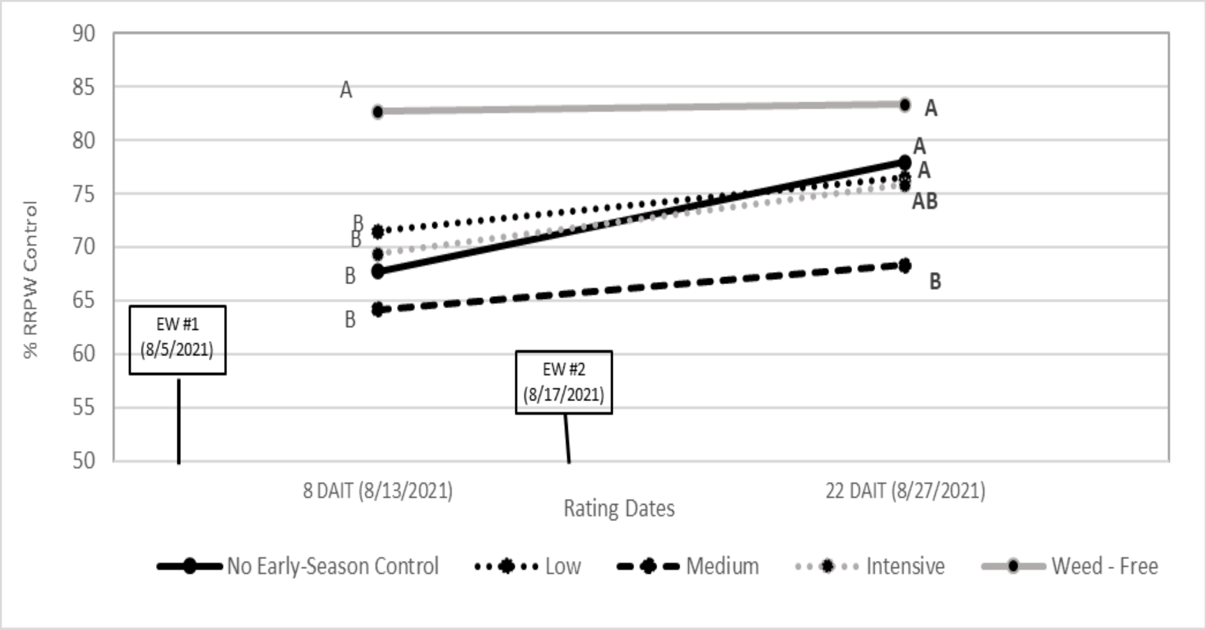

Figure 1.2. Impact of early-season weed control methods on redroot pigweed (RRPW) control evaluated at various timings after application of late-season weed control methods in carrots in 2021 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fischer's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1). Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

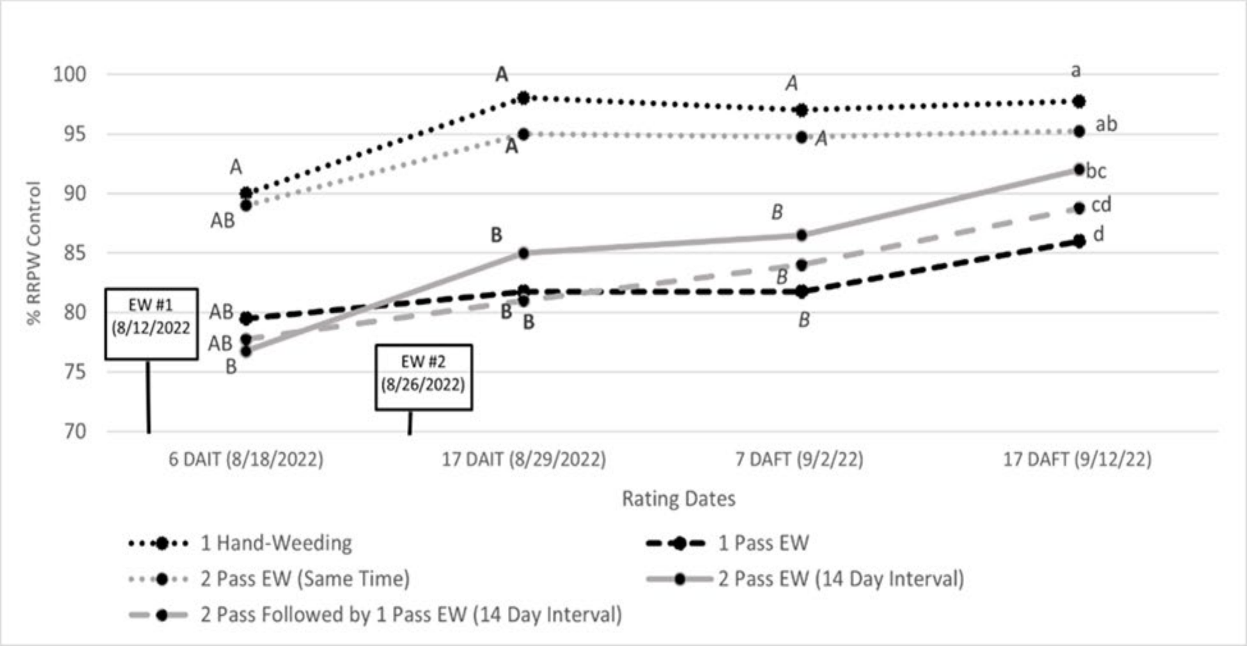

Figure 1.3. Impact of late-season weed control methods on redroot pigweed (RRPW) control in carrots in 2022 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1) and DAFT = Days after final treatment (Electrical Weeding #2).

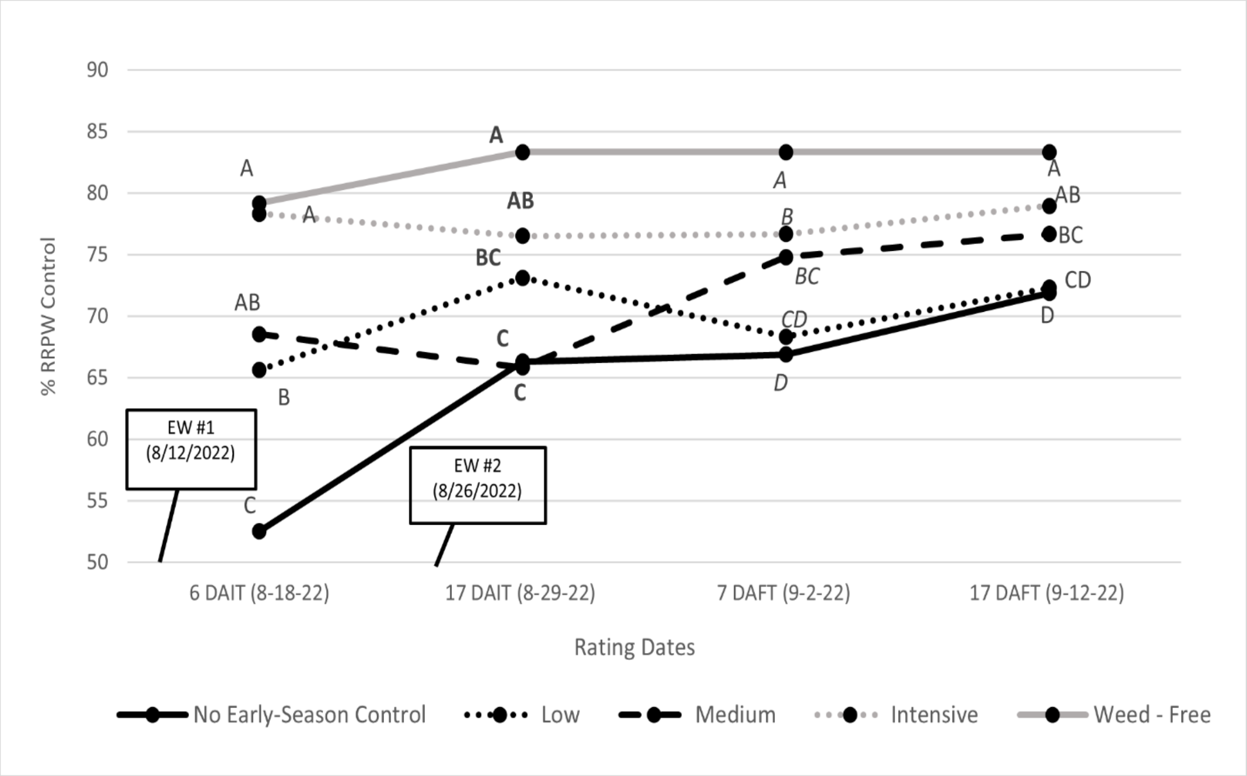

Figure 1.4. Impact of early-season weed control methods on redroot pigweed (RRPW) control evaluated at various timings after application of late-season weed control methods in carrots in 2022 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1) and DAFT = Days after final treatment (Electrical Weeding #2). Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

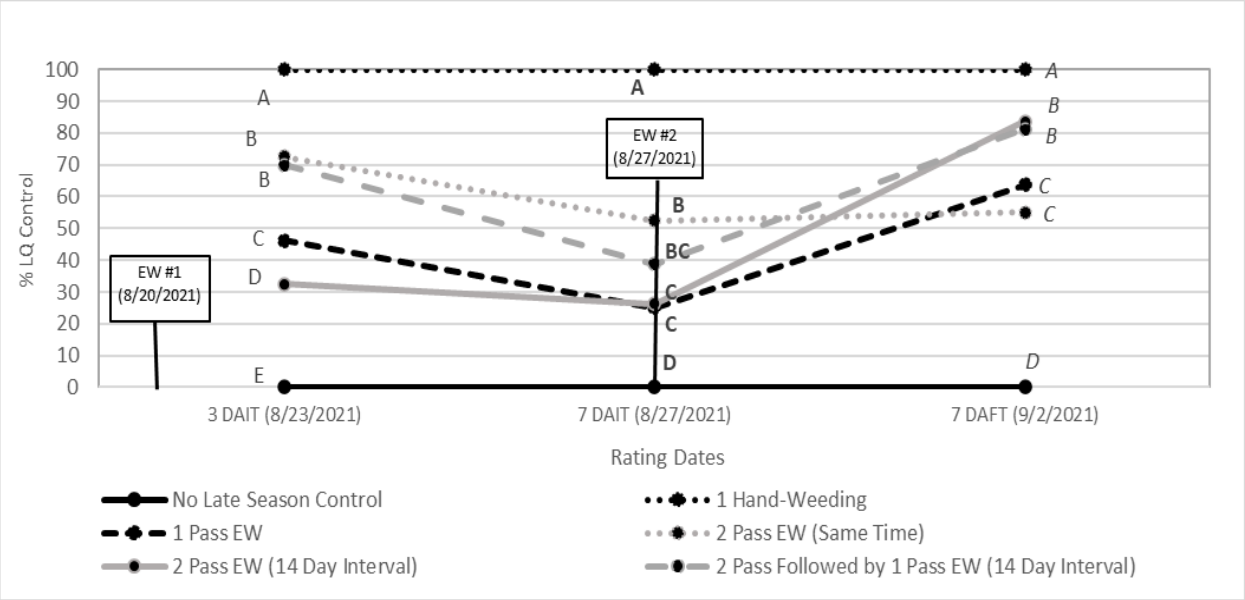

Figure 1.5. Impact of late-season weed control methods on common lambsquarters (LQ) control in green beans in 2021 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1) and DAFT = Days after final treatment (Electrical Weeding #2).

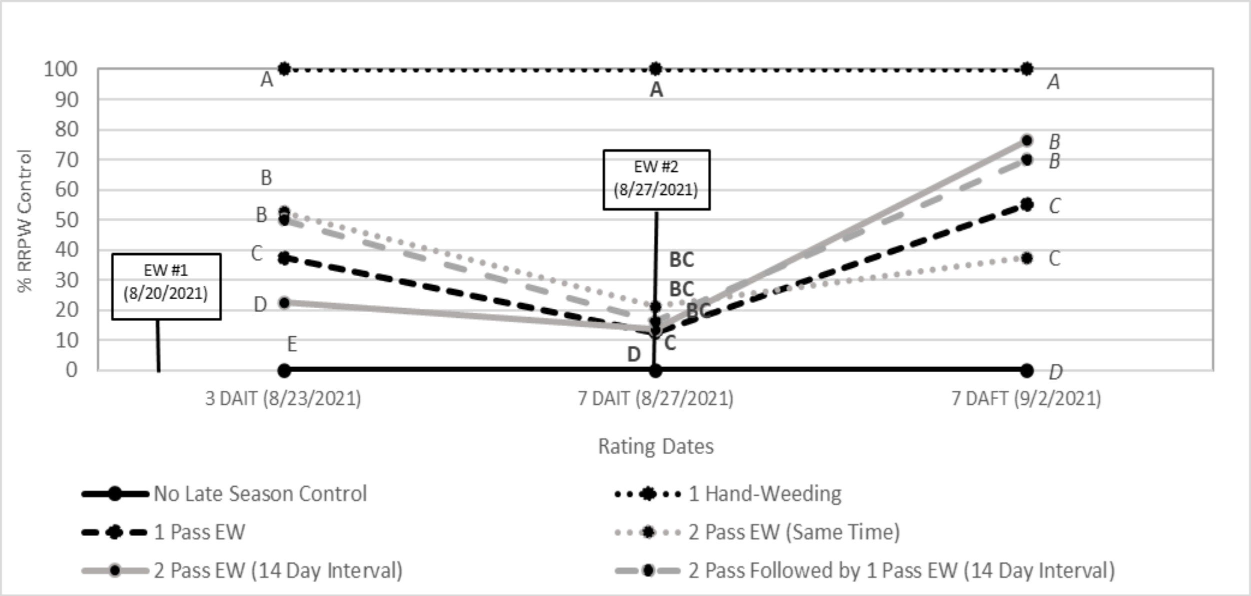

Figure 1.6. Impact of late-season weed control methods on redroot pigweed (RRPW) control in green beans in 2021 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1) and DAFT = Days after final treatment (Electrical Weeding #2).

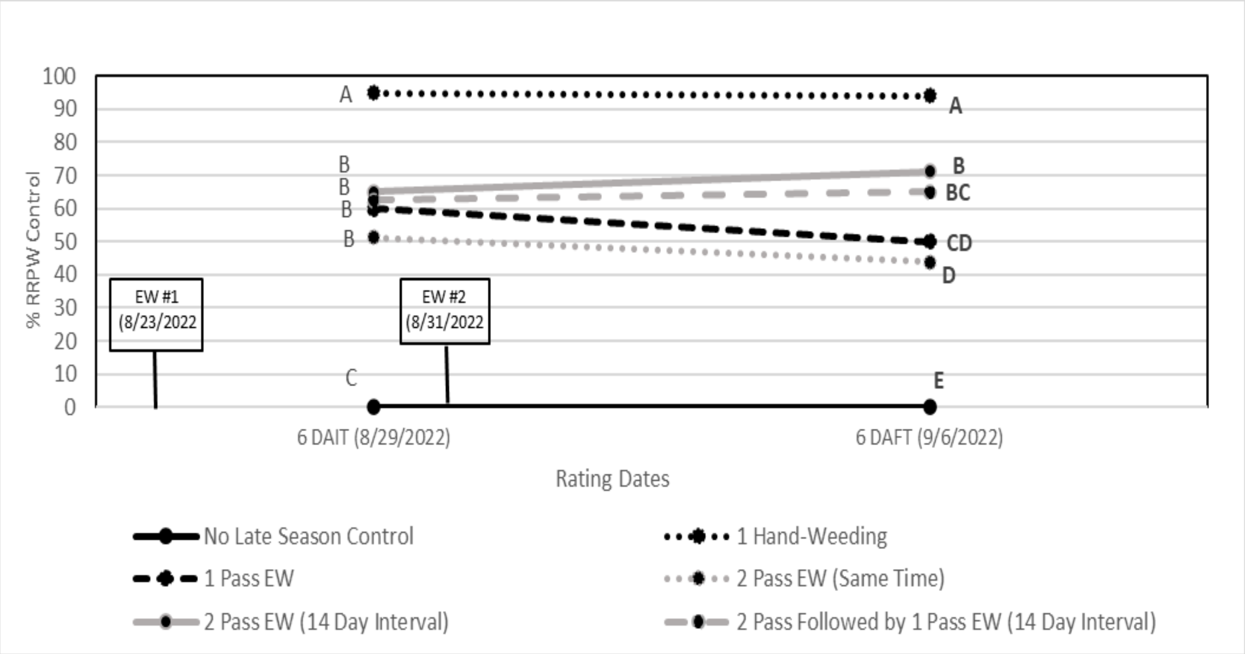

Figure 1.7. Impact of late-season weed control methods on redroot pigweed (RRPW) control in green beans in 2022 at Hart, MI. Means for treatments within the same time-point that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05). DAIT = Days after initial treatment (Electrical Weeding #1) and DAFT = Days after final treatment (Electrical Weeding #2).

CHAPTER II: Effects of Electrical Weed Control on Weed Seed Germination and Rhizosphere Microbial Communities in Carrot

Abstract

Electrical weeding's potential as a tool for integrated weed management relies on evidence of both its performance in controlling the weed seed bank and lack of damage to essential agroecosystem processes and communities. The efficacy of electrical weed control in killing seeds from mature weeds as a long-term management strategy, as well as the equipment's effects on rhizosphere microbial communities, were evaluated through field trials at Hart, MI in 2021 and 2022 in conventional carrot production. Late-season weed control methods that were tested included one hand-weeding event (HW), one electrical weeder pass (1P), two electrical weeder passes performed consecutively [2P(ST)], one pass followed by one pass after a 14-day interval [2P(14d)], two passes followed by one pass after a 14-day interval (3P), and no late-season control (NLC). Early-season weed control methods [low, medium, and intensive herbicide programs, weed-free, and no early-season control (NEC)] were also included in order to produce different weed densities within which to assess the performance of the late-season weed control methods. Electrical weeding was found to significantly reduce redroot pigweed seed germination in 2021 only, though germination did not differ between early- or late-season weed control methods in either year. For the most part, early- and late-season weed control practices did not lead to any difference in soil ammonium (NH_4^+) or soil nitrate (NO_3^-) concentrations that would indicate changes in nitrogen (N) cycling dynamics in the rhizosphere. Microbial biomass C was higher after 1P than for NLC in 2021, indicating an increase in population size following electrical weeding. Apart from this, there were no differences in microbial biomass C or N for any of the early- or late-season weed control methods in either year.

Introduction

Skillful management of natural systems to produce food, fuel, and fiber to fulfill human needs has been the central objective of civilization since its inception. Technological advancement has shifted prioritization from mitigating sheer material scarcity in the short term to managing our agroecosystems to remain productive and renewable for the long term, in order to ensure future generations access to similar resources and ecosystem services that humanity benefits from today. The compounding of knowledge and innovation that generates breakthroughs in agronomic practices also requires an awareness of possible unanticipated outcomes emerging from their implementation. Electrical weeding presents an example of a technology with the potential to greatly improve current cropping systems through reducing weed seed germination while also posing a potential risk to associated ecological processes; namely, activity of rhizosphere microbial communities. The potential of electrical weeding as a long-term management strategy to reduce the weed seed bank is compromised if it is found to be damaging to biological soil health; likewise, the benign effects of the electrical current on root zone microbe populations are inconsequential if the practice has no durable place in an effective integrated weed management plan. It is then important to address the two concerns in tandem, given the essential need to skillfully change environmental processes in a way that meets human goals while ensuring the tools we use do not unnecessarily afflict other life-preserving components of the managed system.

Weeds that survive to reach reproductive maturity and succeed in setting/dispersing viable seed maintain and modify weed seedbank levels within an agroecosystem. The accumulation of annual weed seed in the soil serves as the reservoir from which new seedlings are recruited to form seasonal weed communities, presenting a prolonged management concern for growers

(Buhler et al., 1997). Attempts to model these community dynamics have indicated that long-term control of summer annuals and biennials can be effectively catalyzed by strategic efforts to both deplete the ambient seedbank and reduce influxes of new seed from maternal weeds (Davis, 2006). Interventions that prevent replenishment of and/or actively diminish the current seed bank take on even greater importance when attempting to control the spread of herbicide-resistant weed biotypes (Norsworthy et al., 2018). The potential benefits of enforcing a choke point at this stage in the weed proliferation cycle has influenced the use of traditional integrated weed management practices like cover cropping (Mennan et al., 2020), leveraging intercrop allelopathy (Scavo et al., 2019), stale seed bed techniques (Caldwell and Mohler, 2001) and altering field conditions to favor natural weed seed predators (Menalled et al., 2007). Furthermore, sharpened focus on targeting the weed seed bank has motivated the development of numerous new methods and technological solutions, such as harvest weed seed control (Shergill et al., 2020), deactivation of weed seeds using ultra-high frequency microwaves (Menges and Wayland, 1974; Brodie et al., 2018), anaerobic soil disinfestation (Khadka et al., 2021), steam weeding (van Loenen et al., 2003), and many more.

Electrical weeding is earning recognition as a practical method for controlling herbicide resistant and escaped weeds in conventional fields, as well as an addition to the limited weed management options for organic production. This could prove a major boon for reducing weed pressure in subsequent seasons through elimination of mature weeds prior to seed production and/or dispersal. An electrical weeder with 8.4 kV output was shown to prevent seed set in bolting sugar beets, even in plants that had survived treatment due to reduced duration of electrode contact time (Diprose et al., 1980). However, it is not yet known what effect the high-voltage electrical current has on mature weed seeds and if they are still able to germinate in the soil after death of the treated parent plant. Electricity of varying sub-electrothermal voltage/current levels has been shown to elicit a number of phenotypic responses in plants, including increases in growth rate, pigment concentrations, and secondary metabolite production (Dannehl, 2018). Experimentation has discerned an optimal range for stimulating germination of tomato seed through alternating current electrical field exposure of roughly 4-12 kV cm^{-1} to isolated seed samples for 30-45 seconds, with higher voltage/exposure regimes causing declines in germination rates (Moon and Chung, 2000), though some evidence exists for enhanced germination at much lower voltage levels in other crops (Li et al. 2019; Rifna et al., 2019). Pulsed electric fields (6-15 kV) applied directly to isolated yellow nutsedge (*Cyperus esculentus*) seed samples via spark discharge showed a reduction in germination rates at similar durations as a result of suspected seed embryo damage (Bokka et al., 2009). This dissimilitude in effects indicates that a) method of electrical application may influence the degree of damage/hormetic response and b) morphological traits influencing ohmic resistance may extend to seed-scale characteristics, such as presence of a protective coat, dormancy mechanisms, and other seed defense adaptations (Bokka et al., 2009). Tetrazolium testing conducted on seeds collected from weeds electrocuted at various growth stages has determined that electrical weeding can reduce seed viability by up to 80% for several major weed species in the Midwest (Schreier et al., 2022). A recent trial at North Dakota State University is also testing seed viability and seedling emergence using samples from electrically treated kochia and waterhemp, but as of this writing no results or preliminary findings have been published (Peters et al., 2020).

Given both the growing interest in finding new methods of depleting the weed seed bank and the sparse state of research looking into electricity's effects on weed seed germination reduction, an investigation into electrical weeding's potential in this domain is warranted. Given the diverse reproductive phenology present in weed communities containing multiple species, field and weather conditions that influence application schedules, and the competing priorities for growers' attention throughout the season, electrical weeding may be applied at non-optimal timings where many weeds have already developed fully mature seedheads. While the benefit of electrical weed control in eradicating escaped weeds before they develop mature seed is evident, the ability of the equipment to render seed non-germinable after it has matured remains in question. If seed from treated plants is still able to germinate, there may be little benefit in electrocuting late-season weeds as yield loss has already occurred due to competition from the maternal plant and the seed is still added to the existing seedbank to contribute to severity of weed pressure in the following seasons. Thus, the research program set out to investigate the efficacy of electrical weeding as a tool for reducing the weed seed bank through reducing germination in seeds from electrocuted weeds.

The role of rhizosphere microbial populations in influencing crop health has gained greater appreciation as our understanding of biological soil health has progressed. The soil sub-habitat known as the rhizosphere, or root zone, can be characterized by the astonishing complexity of bacteria, archaea, viruses, fungi, oomycetes, nematodes, protozoa, and other microfauna that occupy the area immediately surrounding plant roots (Mendes et al., 2013). This diversity of soil microbial life is generally categorized into functional groups based on their metabolic pathways and is linked to the overall level of ecosystem resilience (Torsvik and Øvreås, 2002). Rhizosphere microbial communities exist in dynamic feedback cycles influenced by root exudates and other rhizodeposits that support, inhibit, and otherwise shape these populations through the vast array of nutrients, signaling compounds, and toxins released (Berendsen et al., 2012). The dense network of interactions and microbial diversity in the rhizosphere has direct and indirect effects on crop productivity through enhancement of both plant growth and soil quality. Plants regulate root zone community structure by secreting compounds that encourage successful competition of plant-growth promoting rhizobacteria that form close symbiotic relationships with roots by suppressing plant pathogens and increasing availability of nutrients for root uptake (Hassan et al., 2019). The intricate food webs of the rhizosphere microbiome drives cycling of nutrients into plant-available forms through decomposition of soil organic matter, nitrogen fixation, nitrification, denitrification, and other processes, all of which may be co-mediated by plant root exudation through a series of symbiotic relationships (Zhang et al., 2017). Maintenance of large, diverse, and active rhizosphere microbial communities is thus critically important for sustaining soil health and yield potential proceeding into the future.

With the benefits of having robust rhizosphere communities well established, it is then problematic that the effects of electrical weeding on these soil microbial populations have not been sufficiently characterized in the scientific literature. It remains unknown what effect the electrical current has on root zone microbial communities as the flow of charged electrons leaves the roots, passes back through the soil, and returns to its source. Research suggests that soil microbial population composition is generally stable in the face of infrequent disturbance events due to a combination of resistance, resilience, and functional redundancy (Allison and Martiny, 2008). Soil microorganisms have shown diverse responses to disturbance events resulting from weed control efforts, with observed positive, negative, and neutral reactions to herbicide applications (Lupawayi et al., 2010) and negligible decreases in topsoil microbial biomass from flame-weeding, even at extreme heat intensities far above what is used in common practice (Rahkonnen et al., 1999). Early research has confirmed bactericidal properties of high-voltage discharges in aqueous mediums via electrohydraulic shock waves (Palaniappan et al., 1990). More recently, pulsed electric fields ranging from 10 to 80+ kV have been used to disinfect wastewater, contaminated surfaces, and certain food products by causing microbial lysis via electroporation (Castro et al., 1993; Kumar et al., 2015, Narsetti et al., 2006). Recent work on the effects of lightning strikes on soil microbiology suggests that natural lightning may mediate genetic transformation in soil populations by inducing active gene transfer in "lightning-competent" microorganisms (Cérémonie et al., 2004).

Considering the resilience of soil microbes and varied responses to non-tillage-based weed management techniques, it remains an open question whether intense electrical disturbance events in the upper soil layers could shape microbial communities in unpredictable ways. While one can conjecture based off related papers, the absence of peer-reviewed research examining the repercussions of high-voltage current coursing through the soil habitat as part of the electrical weeding process warrants direct research on the topic. Electrical weeding is being propelled, in part, by the modern renaissance in sustainable, resource-efficient agriculture, where the implement is being upheld as an ecologically benign method of weed control due to qualities such as a lack of soil disturbance and absence of harmful residues left in the environment. A survey of the minimal body of literature around electrical weeding does not immediately support an ecologically benign representation in full, with the blank spaces in our model of the impacts of the applied electricity as it moves through the agroecosystem presupposing a number of possible externalities. Increased popularity of electrical weed control in the absence of this understanding indicates a need for further research to cover key gaps in our knowledge. The research objectives were to 1) determine if electrical weeding affects germinability of seeds from treated weeds, and 2) investigate the impact of electrical weeding on rhizosphere soil microbial communities by looking at (a) inorganic N concentrations as an indicator of net N mineralization rates, and (b) microbial biomass C and N as an indicator of population size. The uncertainties regarding the effects of electrical weeding on the rhizosphere microbiome and on weed seed germinability for economically important species are important to investigate in order to create a clearer picture of the impact of this new technology on agroecological processes that have serious implications for a farm's economic and environmental viability.

Materials and Methods

Site Description/Experimental Design

In 2021, the soil type for the carrot field location (43.84°N 86.36°W) was a Pipestone fine sand [6.4 pH and 4.4% organic matter (OM)] with 0-4 percent slopes. In 2022, the carrot field location (43.71°N 86.20°W) soil type was a Benona sand (5.7 pH and 1.8% OM) with 0-6 percent slopes. The carrot cultivars grown were Canberra in 2021 and Belgrado in 2022. The experiment was structured as a spit-plot design with four replications. The main plot factor was late-season weed control methods and included: 1) one hand-weeding event (HW), 2) one electrical weeder pass (1P), 3) two electrical weeder passes performed consecutively [2P(ST)], 4) one pass followed by one pass after a 14-day interval [2P(14d)], 5) two passes followed by one pass after a 14-day interval (3P), and 6) no late-season control (NLC). Within each main-plot variable, the sub-plot factor tested different early-season weed control methods in order to produce different weed densities with which to test the late-season weed control methods. These consisted of 1) one application of the postemergent herbicide linuron (Lorox; Dupont, Wilmington, DE; "Low" early-season control;), 2) two applications of linuron ("Medium" early-season control), 3) two applications of linuron and one application of the preemergent herbicide pendimethalin (Prowl H_2O; BASF Ag Products, Ludwigshafen, Germany; "Intensive" early-season control), 4) a weed-free control and 5) no early-season control (NEC). Each sub-plot early-season weed control treatment was tested on individual 6-ft x 35-ft beds, comprising 5 beds per main plot with 3 carrot rows per bed. Each sub-plot was further divided into two sections: a front section to use for collecting in-field data such as weed control ratings, weed counts, and crop yield at harvest, and a back section from which soil and seed samples were collected without compromising in-field data through sampling disturbance.

Initial applications of pendimethalin were performed in early May using a CO_2 pressurized backpack sprayer at a rate of 1.9 lb ai acre^{-1} in 2021 and 0.95 lb acre^{-1} in 2022. The first application of linuron was performed 3-4 weeks after the preemergent at a rate of 1 lb ai acre^{-1}. The final linuron application was applied 3 weeks afterwards at 1 lb acre^{-1}. Weed counts and timed hand weeding treatments were performed 4-6 weeks after the final herbicide application. The first electrical weeding treatment took place 1 week after weed counts in 2021 and 3 weeks after weed counts in 2022. Environmental parameters such as percent cloud cover, relative humidity and soil moisture/temperature were recorded at the time of application for every treatment in both trials during the 2022 season. Volumetric water content (VWC) was measured at the time of the first electrical treatment in 2021 and both electrical treatments in 2022 using a Field Scout time-domain reflectometer 300 soil moisture meter (Spectrum Technologies, Aurora, IL) with both short (1 inch) and long (7.6 inch) measurement rods.

The electrical weeding equipment used for the trials was the Annihilator 12R30 manufactured by the Weed Zapper™ (Old School Manufacturing, LLC., Sedalia, MO) and owned/operated by the growers at Oomen Farms. An operating speed of 1-2 mph at 230 horsepower was maintained for all treatments in both trials. By the time electrical weeding was performed, redroot pigweed had formed mature seedheads as evidenced by the presence of seeds that were dark brown in color.

Weed Seed Germination

Seedheads were collected from electrocuted weeds immediately following each electrical treatment for the carrot trials in 2021 and 2022. For each trial, up to 20 seedheads per plot were collected from treated weeds of the predominant weed species occurring in the field, which was found to be redroot pigweed in both years. Seedheads were then dried down in the greenhouse prior to separation. Once dry, the seedheads were manually threshed and broken up before being winnowed using a combination of sieving (4mm mesh size) and air column separation using a seed blower (Seedburo Equipment Co., Des Plaines, IL). The seeds were refrigerated at 4 C before being systematically tested for germinability.

Germination tests were carried out in a Conviron CMP 3244 controlled growth chamber (Conviron, Pembina, North Dakota) using a protocol similar to Guo and Al-Khatib, 2003. Weed seeds were arranged in a 5 by 5 matrix (four plates per treatment) in petri dishes lined with filter paper that was moistened with 2 mL deionized water (DI H_2O). The plates were sealed and placed in the growth chambers and germinated seedlings (radicle > 1 mm) were enumerated and removed using forceps every 3 days for a 12-day period, with filter paper rehydrated as needed during every check. Day/night growth chamber parameters for redroot pigweed were 35/30 C with a 14:10 hour light regime.

Rhizosphere Microbial Communities

Root zone soil samples were collected from the carrot trial for both years. Samples were taken at a depth of ~3 inches from the root zone of electrocuted weeds within each treatment immediately following EW#1 and #2. Bulk soil samples from the NLC plots were pulled at random areas from the sampling section due to lack of treated weeds. The soil samples were sieved to a particle size of 2 mm and stored at 4 C prior to analysis.

Within 4 weeks of sampling for both the EW#1 and #2 samples, 10 g (± .02g) subsamples of field moist soil were weighed to attain fresh weight (m_w) before being dried at 100 C. After at least three days, the subsamples were re-weighed to attain the dry weight (m_d) and gravimetric soil moisture content (θ) was calculated using the following formula:

$$\theta = \frac{m_w - m_d}{m_d}$$

Changes in microbial biomass were measured using the chloroform fumigation extraction method outlined in Vance et al. (1987). To determine the amount of C contained within microbial biomass, 8 g soil sub-samples were fumigated by adding 2 mL $CHCl_3$ (chloroform) stabilized with non-polar hydrocarbons and left to incubate for 24 hours. Another unfumigated 8g sub-sample underwent C extraction by addition of 40 mL of 0.5M K_2SO_4 and agitation using an orbital shaker at 200 RPM for 1 hour. The extracts were filtered out and stored at -20 C until analysis. Following incubation, the fumigated samples were vented for 2 hours and extracted/stored using the same protocol. Extract sub-samples were analyzed for total organic carbon (TOC) and total nitrogen (TN) using a Shimadzu TOC-V analyzer (Shimadzu Scientific Instruments, Kyoto, Japan). The analyzer utilizes the high temperature oxidation combustion method of measuring carbon concentrations in aqueous solutions, where the extract sample is injected onto a 720 C catalyst that combusts organic forms of carbon, converting them to CO_2 which is quantified using a non-dispersive infrared sensor. TN is measured by exposing the sample to ozone, which reacts with nitrogen monoxide (NO) to make NO_2, which is in turn quantified via a chemiluminescence gas analyzer (TOC-V analyzer protocol information provided by Ecosystem and Soil Ecology Laboratory at University of Toledo, personal communication).

The mass of extractable C from the soil samples was calculated using the following formula:

$$C = \frac{ec * (v_e + (m_w - m_d))}{m_d}$$

Where C is extractable carbon in a sample in μg g soil^{-1}, ec is total organic carbon in the sample in ppm-C (corrected for blanks and dilution factor) , v_e is the volume of 0.5M K_2SO_4 extractant in mL used, m_w is the mass of wet soil in g used, and m_d is the mass of dry soil in g used. Microbial biomass C (*MBC*) was then found using the following equation:

$$MBC = C_f - C_u$$

Where C_f is the amount of extractable carbon in fumigated samples and C_u is the amount of extractable carbon in unfumigated samples. Similar equations were used for calculating microbial biomass N (MBN) from the soil samples.

Short-term changes in root zone inorganic N concentrations were measured using an inorganic N extraction procedure adapted from Mulvaney (1996). A volume of 50 mL 1M KCl was added to flasks containing 10 g soil before being agitated on orbital shaker at 200 RPM for 30 minutes. The extracts were then filtered out and stored at -20 C prior to analysis. Samples were analyzed for ammonium (NH_4^+) and nitrate (NO_3^-) using a Lachat 8500 Quikchem flow injection analyzer (Hach Company, Loveland, CO). The Lachat 8500 uses a dual-line system to measure ammonium and nitrate separately. For measuring nitrate, the extract is passed through a cadmium column that reduces nitrate to nitrite, which goes on to react with the reagents sulfanilamide and N-1-napthyl-ethylenediamine to produce a pink color which can be quantified by its absorbance at 520 nm via an integrated colorimeter (Huffman and Barbarick, 1981).

Ammonium is measured by mixing the extract with salicylate ($C_7H_6O_3$) in a bleach solution, yielding a deep green color that is read using a colorimeter at 660 nm (Nelson, 1983).

Data Analysis

All data was subjected to ANOVA using SAS 9.4 (SAS 9.4, SAS Institute Inc., Cary, NC) PROC GLIMMIX and means separation using Fisher's Protected LSD ($P \leq 0.05$). All data was checked for normality and homogeneity of variance before statistical analysis by plotting residuals. Data was analyzed by year for carrot due to the variability in the data collection timings. Late-season weed control practices, early-season control practices, and their interaction were considered fixed effects and replication as a random effect.

Results and Discussion

Weed Seed Germination

In 2021, electrical weeding was found to significantly reduce redroot pigweed seed germination by 10-14% compared with NLC (Table 2.2). There was not found to be any significant difference in redroot pigweed germination reduction between different number of electrical weeder passes or variation in timing. Redroot pigweed seed samples from 2P(14d) and 3P were also collected in 2021, with germination rates of 77.7 and 77.1%, respectively. However, values were not included in Table 2.2 due to collection of these samples immediately following EW#2: a time-point when there were no NLC samples collected.

In 2022, there were no differences in redroot pigweed seed germination between NLC and electrical weeding treatments. As well, there was no difference between early-season control methods in either year, indicating that varying weed densities do not have an impact on germination reduction from electrical weeding. Overall redroot pigweed germination was far lower in 2022 (21.3 to 52.4%) than in 2021 (80.7 to 94.7%). Seeds from 2021 were stored at 4 C prior to testing, while seeds from 2022 were subject to germination testing immediately following seedhead processing. Prechilling of redroot pigweed seeds at temperatures of $\leq$ 20 C favors higher germination due to modulation of far-red light absorbing phytochromes (Taylorson and Hendricks, 1969). The lack of cold stratification treatment prior to testing likely accounts for the lower germination percentage observed in 2022. Schreier et al. (2022) found substantially higher reductions in seed viability following two electrical weeder passes, with 54 to 80% non-viable seed depending on the weed species. Determining viability of 2022 seed samples using tetrazolium (TZ) testing may have provided evidence of electrical damage that was concealed by seed dormancy in NLC when performing germination testing only. While overall redroot pigweed germination rates were high in 2021, TZ testing also could have been used to indicate which proportion of ungerminated seed were non-viable as opposed to still dormant.

The mechanism by which germination is inhibited is essential to consider in order to adjust equipment or operating procedures so as to maximize damage to weed seeds. Peters et al. (2020) speculated that the transformation of electrical energy into heat due to the resistance of the seed would cause protein denaturation from the extreme temperatures. Electrical treatment may prevent further development of the seed embryo from the time of electrocution, of which one pass is sufficient to deliver the energy needed to destroy the embryo. This would explain why, in 2021, increasing number of passes did not lead to greater germination reduction while the NLC seeds, which went on to complete their development, had a higher germination rate. Hill et al. (2016) found that timing of late-season weed control was linked to the number of viable seed produced and that the optimal treatment timing varied between species. Termination of maternal weeds prior to seed maturation (before or shortly after beginning of the flowering period) was found to drastically lower number of viable seed produced compared to when the plant had already set mature seed (Hill et al., 2016).

Further work could investigate electrocution of weeds at different stages of seed development, to determine if electricity is merely hampering further development of the seed prior to dispersal or if it can actually destroy the embryo of fully mature seed. The latter would have implications for using electricity to target weed seeds post-dispersal and could encourage studies looking at electrical weeding's effects on germination/viability of ambient seed within the soil. It is important to note that the scope of our results is constrained by redroot pigweed being the sole species that was sufficiently abundant and at reproductive maturity by the time electrical weeding was performed. While ideal timing for electrical treatment would target weeds before they develop mature seed, the diverse and asynchronous phenology within weed communities can result in tradeoffs regarding the amount of weeds emerging above the crop canopy and the size/seed formation of established weeds. As electrical control of escaped weeds is generally performed in mid-to late-summer, further germination reduction research efforts should be focused on highly competitive, early-emerging summer annuals like marestail (*Erigeron canadensis*), common lambsquarters, and common ragweed (*Ambrosia artemisiifolia*). Conducting post-electrocution seed germinability testing on many of the economically important weed species across different regions will be needed to legitimately ascertain the usefulness of electrical weeding on this front and guide IWM planning and extension recommendations.

Rhizosphere Microbial Communities

Soil inorganic N

In 2021 and 2022, there were no significant differences in NH_4^+ concentrations in the rhizosphere immediately after 1P or 2P(ST) compared with NLC (Tables 2.3 and 2.4). In 2022, there was no difference between NLC and 2P(14d) and 3P (Table 2.5). Early-season herbicide programs also showed no significant difference in NH_4^+ concentrations between treatments.

There was no difference in NO_3^- concentrations in the rhizosphere immediately after 1P or 2P(ST) compared with NLC in 2021 (Table 2.3). In 2022, however, significantly higher NO_3^- levels were found after 1P at EW#1 (Table 2.4), while there was no difference between 3P, 2P(14d), and NLC for EW#2 (Table 2.5). Similar to NH_4^+, there was no difference in NO_3^- between early-season herbicide programs. This lack of significant differences in soil inorganic N levels seems to indicate that generally there is no impact of the electrical current on root zone N dynamics.

While the data suggests that N cycling dynamics are not affected by electrical weed control, it should be noted that variability in field conditions could potentially conceal any real effects on the rhizosphere communities. N mineralization and transformation rates can vary based on multiple environmental factors such as soil moisture, temperature, and aeration. Greater soil water content has been shown to lead to higher N mineralization rates at various temperature regimes (Knoepp and Swank, 2002). Hydration of A horizon soils can trigger increased breakdown of dead microbial biomass that built up during periods of low moisture (Borken and Matzner, 2009). Other integral N cycling processes like nitrification can also be inhibited in dry soil conditions (Stark and Firestone, 1995). At the time of the first electrical treatment in 2021, mean VWC (averaged across readings from 1- and 7.6-inch measurement rods) was 12.38% (moisture data not shown). For sandier soils, VWC can range from 7% at permanent wilting point to 20% at field capacity (Datta et al., 2017). The textural class for the carrot field in 2021 was characterized as a sandy clay loam, suggesting that soil moisture was nearing the low end at the time of electrical weeding, which could have inhibited a flush of N mineralization from occurring even if the electrical current did damage rhizosphere microbiota. In the 2022 carrot field, which was classified as a sandy loam, average VWC was 5.93% at EW#1 and 12.32% at EW#2. The abnormally low VWC at EW#1 was correlated with lower NO_3^- levels (0.7 to 1.5 ppm g dry soil^{-1}) and NH_4^+ levels (0.09 to 0.1 ppm g dry soil^{-1}) compared to levels in the same field under conditions of higher VWC at EW#2 (4.4 to 5.5 ppm g dry soil^{-1} for NO_3^+ and 0.4 to 0.7 ppm g dry soil^{-1} for NH_4^+). This potentially supports the relationship between root zone soil moisture and mineralization/nitrification rates, though other factors could also contribute to these observations. Performing electrical treatment in and analyzing rhizosphere soils from conditions of greater VWC are needed to assess if differences in inorganic N between treatments are more evident at higher soil moisture regimes.

Based on the multiple factors affecting N mineralization rates in the soil, using inorganic N levels as an indicator of N mineralization comes with its limitations and is not in itself a clear determinant of electrical weeding's effects. As well, sampling root zone soils immediately after electrical weeding may not allow adequate time for decomposition and N cycling to reach measurable levels where differences would present themselves. Sampling at regular intervals in the hours/days following electrical weeding could be used to determine differing trends in decomposition over time that could give a more comprehensive picture of how N cycling rates in the rhizosphere change as a result of exposure to the electrical current.

Microbial biomass C/N

In 2021, there were no differences in MBN between treatments. However, MBC for 1P was significantly higher than NLC (Table 2.3), implying that electrical weeding does not decrease the microbe population size but actually may accord a slight enhancing effect given the optimal amount of electrical treatment. Hormesis is a positive response elicited by an organism upon exposure to low levels of an environmental stressor that may be lethal in higher quantities and has been observed at multiple scales of biological complexity (Erofeeva, 2022). Most of the hormetic agents known to affect microbial function have been xenobiotic chemicals such as certain pesticides (Agathokleous et al., 2021) and little research seems to have been done directly assessing the potential of electricity in stimulating rhizosphere microbiota. Other explanations could be that stress from electrical damage to the plant triggers a release of root exudates or other rhizodeposits, providing organic C sources to the microbial populations which results in a net increase in MBC. Similarly, even damage to a portion of the microbe population would release labile forms of C that could be taken up by other microbes, potentially leading to the higher MBC after electrical weeding. Finally, variable rates of C cycling in soil samples while undergoing fumigation and incubation could explain the higher MBC observed in 1P.

There were no differences in MBC or MBN between late-season weed control practices reported in 2022 (Tables 2.4 and 2.5). As well, no effect was observed for different early-season practices in either year, indicating number of weeds contacting the electrode does not impact MBC/MBN. As the higher MBC for 1P was not replicated in the second year, it appears likely that rhizosphere MBC is not substantially affected by electrical weeding. This is similar to results from Wick et al., (2010), who concluded that application of 1.4 V cm^{-1} direct current electrical fields did not impair soil microbial function, as measured by changes in community composition via phospholipid fatty acid profiling. However, this may be a relatively weak voltage compared to what would be affecting the root zone in an electrical weeding field scenario. Voltage drop from the $\leq$ 15 kV transformer output used in electrical weeding depends on the load resistance created by the number/types of weeds in simultaneous contact with the electrode, as well as the resistivity of the soil (Vigneault and Benoit, 2001). By determining soil resistivity at root zone depth using the Wenner four-probe method (Ünal et al., 2020), ascertaining the level of electrical current in the soil (Mohamed et al., 2021), and performing electrical weeding in controlled conditions where the number of weeds being treated at once and their relative resistivity values are known, voltage levels in the rhizosphere could be approximated so as to gain an understanding of the magnitude of electrical force the microbial communities are being exposed to.

Conclusions

Based on these studies, electrical weeding appears to show promise for decreasing weed seed bank inputs by reducing germination of seeds from treated weeds. While observed germination reduction was relatively minor, the exponential proliferation of highly fecund weeds means that even incremental progress in managing weed bank replenishment can have outsized benefits on weed management in later seasons. Determining the mechanism of germination inhibition/seed destruction, as well as expanding research to investigate electrical weeding's effects on seeds from different weed species, is important for understanding the full potential of this equipment in integrated weed management.

There is little to no evidence that electrical weeding is having any negative effect on rhizosphere microbial populations by looking at microbial biomass C and N, as well as when looking at inorganic N as an indicator of N cycling dynamics. Increased MBC for 1P over NLC in 2021 may suggest that the impact of electricity can increase population size through greater organic sources released into the rhizosphere upon plant death or hormetic stimulation of microbial communities; however, this could also be an artifact of differential rates of C cycling in the soil samples during lab work. Further research looking at delayed changes in root zone MBC/MBN and inorganic N over time, as well as expanding to investigate changes in functional diversity in the rhizosphere, could be useful in developing a clearer picture of electrical weeding's impact on soil microbial communities.

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APPENDIX

Table 2.1. Key dates for field operations and data collection for carrot in 2021 and 2022 at Hart, MI.

Activity	2021	2022
Crop planted	20 April	28 April
PRE application[a]	6 May	10 May
POST #1 application[b]	27 May	1 June
POST #2 application[c]	16 June	21 June
Hand Weeding Treatment	30 July	20 July
Electrical Weeding Treatment #1	5 Aug	12 Aug
Weed seed sample collection #1	5 Aug	12 Aug
Rhizosphere soil sample collection #1	5 Aug	12 Aug
Electrical Weeding Treatment #2	17 Aug	26 Aug
Weed seed sample collection #2	17 Aug	26 Aug
Rhizosphere soil sample collection #2	17 Aug	26 Aug

[a] PRE = 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

[b] POST #1 = 1 application of linuron (1 lb ai acre^{-1})

[c] POST #2 = 1 application of linuron (1 lb ai acre^{-1})

Table 2.2. Impacts of early- and late-season practices on redroot pigweed seed germination in carrot in 2021 and 2022 at Hart, MI.

Dependent variables[a]	2021	2022	
		EW#1	EW#2
	--------% germination-----		
Early-Season Weed Control Methods[b]			
No Early-Season Control	82.1	33.5	26.4
Low	84.5	41.3	25.2
Medium	84.4	44.7	27.7
Intensive	83.4	35.0	21.3
Late-Season Weed Control Methods			
No Late-Season Control	94.7 a	38.7	29.4
1 Pass Electrical Weeding	85.3 b	34.2	-
2 Pass Electrical Weeding (Same Time)	80.7 b	52.4	-
2 Pass Electrical Weeding (14-day interval)	-	-	23.7
2 Pass followed by 1 Pass (14-day interval)	-	-	26.0
Early-Season Weed Control Methods (P-Value)	0.8689	0.435	0.8869
Late-Season Weed Control Methods (P-Value)	0.0010	0.3148	0.6812
Late-Season × Early-Season (P-value)	0.4652	0.0245	0.8984

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

Table 2.3. Impacts of early- and late-season weed control methods on soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and inorganic nitrogen levels in carrot in 2021 at Hart, MI.

Dependent variables	MBC[a]	MBN	NO_3^-	NH_4^+
	$\mu g\ g\ dry\ soil^{-1}$			
Early-Season Weed Control Methods[b]				
No Early-Season Control	69.9	7.6	4.4	0.09
Low	67.6	5.8	4.8	0.10
Medium	86.2	9.5	4.9	0.11
Intensive	82.6	9.5	5.1	0.09
Late-Season Weed Control Methods				
No Late-Season Control	65.7 b	7	4.6	0.10
1 Pass Electrical Weeding	87 a	8.3	5.2	0.10
2 Pass Electrical Weeding (Same Time)	77.1 ab	9.1	4.7	0.11
Early-Season Weed Control Methods (P-Value)	0.1300	0.2050	0.4528	0.4307
Late-Season Weed Control Methods (P-Value)	0.0383	0.4011	0.3293	0.3506
Late-Season × Early-Season (P-value)	0.8900	0.7044	0.3718	0.2434

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Low = 1 application of linuron (1 lb ai $acre^{-1}$); Medium = 2 applications of linuron (1 lb ai $acre^{-1}$); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai $acre^{-1}$ in 2021 and 0.95 lb ai $acre^{-1}$ in 2022).

Table 2.4. Impacts of early- and late-season weed control methods on soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and inorganic nitrogen levels following Electrical Weeding #1 in carrot in 2022 at Hart, MI.

Dependent variables[a]	MBC[a]	MBN	NO_3^-	NH_4^+
	μg g dry soil^{-1}			
Early-Season Weed Control Methods[b]				
No Early-Season Control	102.3	6.7	1.0	0.10
Low	101.4	7.3	0.9	0.10
Medium	109.8	7.4	0.9	0.09
Intensive	91.3	6.4	1.3	0.10
Late-Season Weed Control Methods				
No Late-Season Control	104.7	7.2	0.7 b	0.10
1 Pass Electrical Weeding	96.0	6.2	1.5 a	0.10
2 Pass Electrical Weeding (Same Time)	102.7	7.5	0.7 b	0.09
Early-Season Weed Control Methods (P-Value)	0.3556	0.7838	0.4747	0.3229
Late-Season Weed Control Methods (P-Value)	0.5889	0.4148	0.0060	0.2711
Late-Season × Early-Season (P-value)	0.9115	0.2760	0.5512	0.8250

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).

Table 2.5. Impacts of early- and late-season weed control methods on soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and inorganic nitrogen levels following Electrical Weeding #2 in carrot in 2022 at Hart, MI.

Dependent variables[a]	MBC	MBN	NO_3^-	NH_4^+
	μg g dry soil^{-1}			
Early-Season Weed Control Methods[b]				
No Early-Season Control	72.2	6.4	5.0	0.9
Low	68.7	4.9	5.0	0.4
Medium	74.5	5.6	5.1	0.7
Intensive	66.7	4.7	5.1	0.3
Late-Season Weed Control Methods				
No Late-Season Control	68.7	6.1	5.5	0.7
2 Pass Electrical Weeding (14-day interval)	68.5	4.7	4.4	0.6
2 Pass followed by 1 Pass (14-day interval)	74.4	5.5	5.3	0.4
Early-Season Weed Control Methods (P-Value)	0.6082	0.6321	0.994	0.2640
Late-Season Weed Control Methods (P-Value)	0.4709	0.4950	0.1262	0.5311
Late-Season × Early-Season (P-value)	0.5800	0.7807	0.2051	0.1138

[a] Means within columns for dependent variables that are followed by the same letter are not significantly different using Fisher's Protected LSD (α=0.05).

[b] Low = 1 application of linuron (1 lb ai acre^{-1}); Medium = 2 applications of linuron (1 lb ai acre^{-1}); Intensive = 2 applications of linuron + 1 application of pendimethalin (1.9 lb ai acre^{-1} in 2021 and 0.95 lb ai acre^{-1} in 2022).