Impact of Electrocution on Weed Control and Weed Seed Viability in Soybean

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By

Haylee Elizabeth Schreier

Dr. Kevin Bradley, Thesis Supervisor

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The undersigned, appointed by the dean of the Graduate School,

have examined the Thesis entitled

Impact of Electrocution on Weed Control and Weed Seed Viability in Soybean

Presented by Haylee Elizabeth Schreier

A candidate for the degree of

Master of Science

And hereby certify that, in their opinion it is worthy of acceptance.

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Dr. Kevin Bradley

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Mr. Gregory Luce

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Dr. Christine Spinka

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Abstract

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integrated program could eliminate late-season herbicide-resistant weed escapes in soybean, and reduce the number and viability of weed seed that return to the soil seedbank.

CHAPTER I

LITERATURE REVIEW

Justification

Among all crop pests, weeds have the potential to cause the most yield loss, which results in a threat to agricultural production and food security (Oerke 2006). Herbicides have been relied on for weed control in modern agriculture due to their efficacy, as well as the lack of alternative weed management tools. Another factor that causes a greater reliance on herbicides is the need for conservation-tillage practices. Conservation-tillage is beneficial tool for soil health that several farmers have adopted, but this creates a greater need for the use of herbicides for weed control (DeVore et al. 2013). However, because of continued herbicide use, herbicide-resistant weeds are becoming more prevalent and chemical control options are becoming more limited. Currently, there are a total of 509 unique cases of herbicide resistance globally and weeds have evolved resistance to 21 of the 31 known herbicide sites of action (Heap 2021). Compounding this problem is the fact that there has been a substantial decline in the discovery of new herbicide modes of action in the past several decades (Pallett 2016). This situation has created a greater need for non-conventional methods of weed management such as weed electrocution, weed seed destruction, bioherbicides, and precision herbicide application and/or tillage (Bajwa et al. 2015; Coleman et al. 2019). Little research has been done on weed electrocution, but it was previously shown to be effective in specialty crops like sugar beet (*Beta vulgaris* L.). Therefore, there is the potential that electrocution could prove to be a successful method of eliminating weed escapes in other crops where a height differential exists between the weed and crop canopy, such as soybean (*Glycine max* (L.) Merr.).

Integrated Weed Management (IWM)

Herbicides are the most common tool used for weed control in current soybean production systems, but the increase in herbicide-resistant weeds has led to a need for a more integrated approach to weed management. IWM can be defined as a holistic approach that integrates different methods of weed control to provide the crop with the greatest advantage over the weed species (Harker and O'Donovan 2013). An effective IWM approach includes a variety of chemical, biological, cultural, and physical weed management tools. Most IWM systems do not include all of these tools, but many include chemical and physical or chemical and cultural management techniques. Many of our conventional agricultural production fields in the U.S. still only include chemical methods of control (Harker and O'Donovan 2013). Based off 2020 USDA survey data, 94% of U.S. soybean acres are herbicide-tolerant, indicating that 94% likely use herbicides for the control of weeds (USDA ERS 2020). Alternative weed management tools such as weed electrocution may not completely replace chemical weed control in these environments, but an IWM approach that considers all available methods of weed management will likely be more sustainable in the long run.

History of Weed Electrocution

The concept of weed electrocution dates back to the 1970s using a machine manufactured by Lasco for the control of weeds in a variety of settings (Diprose et al. 1980). Previous researchers reported that electrocution of weeds can be done either through spark discharge or continuous contact, and several factors can contribute to its effectiveness (Rask and Kristoffersen 2007; Wei et al. 2010). Spark discharge is the process of placing electrodes within 1 to 2 cm of the plant to cause electricity to pass through the plant, whereas the continuous contact method involves an electrode that contacts the plant and causes a current to flow for the amount of time contacted (Diprose and Benson 1984). Spark discharge utilizes higher voltages between 25 and 60 kV for short periods of time, while continuous contact uses lower voltages between 6 and 25 kV (Diprose and Benson 1984).

Some of the first reported research on weed electrocution involved annual wild beets (*Beta maritima*) that were infesting sugar beets. This research was conducted in 1978 and 1979 to test the effects of different voltages and the duration of electricity to control bolting of the sugar beet crop (Diprose et al. 1980). In the laboratory, annual beets were treated with a maximum current of 5 kV root mean squared (rms). Results indicated that damage occurred more rapidly at higher voltages and should be conducted in excess of 5 kV for effective control of sugar beet bolts without excessively long treatment times (Diprose et al. 1980). In a field study with a mobile generating unit, treatments at 4, 6, and 8 kV were effective regardless of contact time while 3 kV was only effective if contact time was greater than 5 seconds (Diprose et al. 1980). This work progressed into a tractor-driven system that covered six crop rows. The tractor stopped to apply voltages between 4 and 8.4 kV rms for a range of time from 4.3 to 21.8 seconds. Results from this field study followed a similar trend as the laboratory study which showed the higher the treatment voltage, the less time required to control the plants. A further experiment with the tractor-driven system was done with a constant output of 8.4 kV rms, where forty-eight sugar beet rows were treated with a tractor speed of 1.6 km/h. Of the beets that were treated, 75% were controlled successfully due to their inability to produce seed (Diprose et al. 1980). The physiological mechanism of weed control due to electrocution was hypothesized as thermal, as the "passage of the electric current rapidly heats up the tissue, bursts the cells and boils the water" (Diprose et al. 1980). These experiments laid the foundation for the potential of weed electrocution as an alternative weed management tool in other cropping systems.

An effective weed management system prevents weeds from setting seed and returning more seed to the soil seedbank. Therefore, the timing of treatments is very important in determining success. In the annual weed beet studies, the idea was to use the machine in June or July when there was a small amount of viable seed present on the weeds and electrocuting the weed would prevent any further seed formation (Diprose et al. 1980). Schwartz-Lazaro et al. (2020) determined seed shatter rates of several broadleaf weed species commonly encountered in soybean production and found that less than ten percent of their seeds had shattered by the time of soybean harvest. However, seed shatter occurred sooner for grass species, and at varying rates among the different species and geographies. Waterhemp, for example, retained 98 to 100% of seeds by the time of soybean harvest (Schwartz-Lazaro et al. 2020). Even if weeds are electrocuted before seed shatter, there is a question of whether or not electrocuted seed will be viable following electrocution. Diprose et al. (1985) found that electrocution reduced the number of viable annual beet seeds by 83% and reduced embryo viability by as much as 92% compared to the non-treated control. In a more recent study with a newer, commercially-available implement referred to as The Weed Zapper, Peters (2020) found that electrocuted waterhemp [*Amaranthus tuberculatus* (Moq.)] seed germination was 5% compared to 67% germination of non-treated seed. The Weed Zapper generates 200,000 watts of electricity compared to the 50,000 watts that were generated by equipment used in the 1970s and 1980s.

Energy Requirements Needed to Injure Weeds

Although weed electrocution can be effective, there can be disadvantages. Because of the high amount of voltage required for weed electrocution, there is a high energy requirement. Diprose and Benson (1984) reported that using electrical weeding with continuous contact can require a range of voltages between 6 and 25 kV. From this, the associated energy cost is estimated at an average of 19 MJ ha^{-1} for continuous contact and 14.5 MJ ha^{-1} for spark discharge (Coleman et al. 2019). Coleman et al. (2019) proposed that the total energy estimation can be given by the equation $E_{total} = E_{direct} + E_{indirect}$, where E_{direct} is the energy that is directly applied for weed control and $E_{indirect}$ is energy that is indirectly associated with weed control. The direct energy requirement can further be calculated as $E_{direct} = E_{draft} + E_{PTO} + E_{elec} + E_{chem}$, where the mechanical energy source is due to draft force (E_{draft}) and through the power takeoff (E_{PTO}) and the thermal energy source is either electrical (E_{elec}) or chemical (E_{chem}) (Coleman et al. 2019). Indirect energy is also important to consider, and it can be estimated by adding the energy required to move consumables and equipment around the field (Coleman et al. 2019). Another important factor when estimating energy requirements is the weed density of the area being treated, as the energy cost associated with site-specific treatment is directly proportional to the number of weeds present (Coleman et al. 2019). Therefore, a high weed density can be very energy costly. Because of the high amount of energy required by weed electrocution, it can also lead to high financial costs and dangers to operators as well as any personnel nearby (Korres et al. 2019; Wei et al. 2010). Thus far, these factors have resulted in a low adoption rate of weed electrocution in most conventional agriculture systems today (Korres et al. 2019).

Summary and Objectives

The increase in the number of herbicide-resistant weed populations throughout U.S. agricultural production systems emphasizes the need for new alternative weed management tools. Collectively, the limited amount of information available on the subject of weed electrocution indicates that the effectiveness of this practice can be dependent on several factors including amount of voltage, contact time with voltage, plant species, plant morphology, plant age, amount of wood fibers within the plant, and number of passes with the implement (Diprose et al. 1980; Diprose et al. 1985; Rask and Krisstofferson, 2007). Since several factors can lead to increased or decreased efficacy of the implement, more research is needed to determine if weed electrocution can be used as a practical and effective weed management tool for farmers. As mentioned previously, no single method of weed control is best, but an integration of methods is ideal. Experiments on weed electrocution were done in the 1970s and 1980s in sugar beets; however, since then no research has been published concerning the effectiveness of weed electrocution within soybean. Therefore, the objectives for this research are to: 1) determine the efficacy of weed electrocution on problematic weed species at different growth stages, different tractor speeds, and in a 1- or 2-pass system, 2) investigate the viability of weed seeds following electrocution, and 3) evaluate the effects of electrocution on soybean injury and yield at different soybean growth stages.

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CHAPTER II

IMPACT OF ELECTROCUTION ON WEED CONTROL AND WEED SEED VIABILITY IN SOYBEAN

Haylee Schreier, Mandy Bish, and Kevin Bradley

Abstract

Field experiments were conducted in 2020 and 2021 to test the effectiveness of electrocution on several weeds commonly encountered in Missouri soybean production using an implement known as The Weed Zapper™. The first set of experiments targeted individual weed species. Weeds examined were waterhemp, cocklebur, giant and common ragweed, horseweed, giant and yellow foxtail, and barnyardgrass. Each species was electrocuted when plants reached average heights and/or growth stages of 30 cm, 60 cm, flowering, pollination, and seed set. Each electrocution treatment took place either once or sequentially, and at two different tractor speeds. Growth stage at the time of electrocution had a significant effect on weed control, with greater control achieved when electrocution occurred at later growth stages. Pearson correlation coefficients indicated that control of weed species was most related to plant height and amount of plant moisture at the time of electrocution. When plants contained seed at the time of electrocution, viability was reduced from 54 to 80% among the species evaluated. A separate experiment was conducted to determine the effects of electrocution on waterhemp escapes in soybean, and to determine potential soybean injury and yield loss. Electrocution timings took place throughout reproductive soybean growth stages. Yield of soybean electrocuted at the R4 and R6 growth stages were similar to the non-treated control, but soybean yield was reduced by 11 to 26% following electrocution at all

other timings. However, the visual injury and yield loss observed in these experiments likely represents a worst-case scenario as growers that have a clear height differential between waterhemp and the soybean canopy would not need to maintain contact with the soybean canopy. Overall, results from these experiments indicate that electrocution as part of an integrated program could eliminate late-season herbicide-resistant weed escapes in soybean, and reduce the number and viability of weed seed that return to the soil seedbank.

Introduction

The predominance of herbicide-resistant weeds continues to threaten U.S. corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean (*Glycine max* (L.) Merr.) production by reducing the number of effective chemical weed control options (Norsworthy et al. 2012). Herbicides have been the main method of weed control in these crops for decades, and as a result, the discovery of herbicide-resistant weeds dates back to the 1950s (Heap 2022). There are currently 509 unique cases of herbicide resistance across the globe, consisting of 266 weed species (Heap 2022). Historically, farmers have relied on new herbicide chemistries to deal with herbicide resistance (Heap and Duke 2018). However, there have been no new herbicide mode of action discoveries in the last 20 years (Duke 2012). The compounding problems of herbicide resistance in weeds along with a lack of new effective herbicide modes of action has resulted in a greater need for a more diversified approach to weed management, including non-conventional methods of weed control (Norsworthy et al. 2012; Bajwa et al. 2015). In one review of the subject, Bajwa et al. (2015) described several non-conventional methods of weed control including weed electrocution, weed seed destruction, bioherbicides, and precision-based tools. The authors speculated that electrocution may have practical implications in weed management. However, little research has been conducted on weed electrocution.

The idea of weed electrocution emerged in the 1970s using a machine manufactured by Lasco for the control of weeds in a variety of settings (Diprose et al. 1980). The majority of previously-published research on weed electrocution was conducted to control annual weed beets within sugar beets and to control the bolting of the sugar beet crop. Diprose et al. (1980) conducted laboratory and field research to look at the effectiveness of electrocution on annual weed beets infesting the sugar beet crop and found that effective control of sugar beet bolts required in excess of 5 kilovolts (kV) in order to avoid excessively long treatment times (Diprose et al. 1980). One field study that contained a mobile generating unit found that the treatments of 4, 6, and 8 kV were effective regardless of contact time while 3 kV was only effective at contact times greater than 5 seconds (Diprose et al. 1980). The successes of the mobile generating unit progressed into a tractor-driven electrocution system that stopped to apply voltages between 4 and 8.4 kV for a range of time from 4.3 to 21.8 seconds. Results from this experiment followed a similar trend as the laboratory study which showed the higher the treatment voltage, the less time required to injure plants (Diprose et al. 1980). A second experiment with a tractor-driven system was conducted with a constant voltage output of 8.4 kV and a tractor speed of 1.6 km/h. Seventy-five percent of the treated weed beets in this trial were successfully controlled (Diprose et al. 1980). This research supports the potential of electrocution to be a successful method of eliminating weed escapes in other crops where a height differential exists between the weed and crop canopy, such as soybean.

Diprose and Benson (1984) described the energy costs required for two types of electrical weeding; continuous contact and spark discharge. Continuous contact requires a range of voltages from 6 to 25 kV while spark discharge utilizes higher voltages between 25 and 60 kV (Diprose and Benson 1984). The associated energy costs were estimated at 19 MJ ha^{-1} and 14.5 MJ ha^{-1} for continuous contact and spark discharge, respectively. Coleman et al. (2019) also demonstrated that the energy cost associated with site-specific treatment is directly proportional to the number of weeds present. Therefore, an area with high weed densities can be very energy costly. Because of the high amount of energy required by weed electrocution, it can also lead to high financial costs and dangers to operators or nearby personnel (Korres et al. 2019; Wei et al. 2010). Thus far, these factors have likely contributed to the relatively low adoption rate of weed electrocution in most conventional agriculture systems (Korres et al. 2019).

As the number of herbicide-resistant weed populations throughout U.S. agriculture continues to increase, the need for alternative methods of weed control becomes more dire. Few studies have been conducted on weed electrocution to determine its effectiveness and practicality in a major agricultural crop like soybean. Although weed electrocution may never completely replace chemical control options, it could be used in an integrated approach to help combat herbicide-resistant weeds (Harker and O'Donovan 2013). The limited amount of information available on weed electrocution has shown that the amount of voltage, contact time with voltage, plant species, plant morphology, plant age, amount of wood fibers within the plants, and number of electrocution passes are all factors that have been found to influence control (Diprose et al. 1980; Diprose et al. 1985; Rask and Kristofferson 2007).

The objectives of this research were to: 1) determine the efficacy of weed electrocution on problematic weed species at different growth stages, different tractor speeds, and with either a single or sequential electrocution pass; 2) investigate the viability of weed seeds following electrocution; and 3) determine the effects of electrocution on soybean injury and yield at different soybean growth stages.

Materials and Methods

Equipment and Site Description

All electrocution treatments were conducted with the Weed Zapper™ 6R30 unit (Old School Manufacturing LLC, Sedalia, MO). This implement consisted of a PTO-driven

110,000-watt generator attached to a 125-horsepower tractor, with a 3 m copper boom in the front that was capable of being raised or lowered depending on weed size. The generator produces from 225 to 275 amps, and it is advertised that approximately 7 to 20 amps and 15,000 volts actually reach the plants contacted (B Kroeger, personal communication; Anonymous 2021). With the PTO engaged and the unit turned on, the copper boom will send an electric current through any plant that comes into contact with it. All experiments were conducted in 2020 and 2021 at the Bradford Research Center near Columbia, Missouri. The soil type of the locations where all the field trials were located is a Mexico silt loam with 2.2 to 2.5% organic matter and a pH ranging from 6.7 to 7.4.

Individual Weed Experiments

To determine the efficacy of electrocution on individual weed species, separate locations were chosen that had previously contained dense, natural infestations of waterhemp [(*Amaranthus tuberculatas* (Moq.)], common cocklebur (*Xanthium strumarium* L.), giant ragweed (*Ambrosia trifida* L.), common ragweed (*Ambrosia artemisiifolia* L.), horseweed (*Erigeron canadensis* L.), giant foxtail (*Setaria faberi* Herrm.), yellow foxtail [(*Setaria pumila* (Poir.)], and barnyardgrass (*Echinochloa crus-galli* L.). No crops were planted in these locations during the course of these experiments. Approximately one week prior to electrocution, all broadleaf species were treated with clethodim to eliminate grass species and achieve a pure stand of the desired broadleaf weeds. All grass species were treated with dicamba to eliminate broadleaf species and achieve a pure stand of the desired grass. Herbicide treatments were applied with a 3-m wide boom using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 138 kPa. Clethodim applications were applied with XR 8002 nozzles (TeeJet®, Spraying Systems Co., Wheaton, IL), while dicamba applications were made with TTI 11002 nozzles. Table 1 provides a list of all herbicide treatments and adjuvants.

Each weed species was treated with electrocution once plants reached average heights and/or growth stages of 30 cm, 60 cm, flowering, pollination, and seed set. Table 2 shows the dates of electrocution for each species in each year. The electrocution boom was maintained at a height of approximately 30 cm above the soil surface. Treatments consisted of two different tractor speeds, 3.2 or 6.4 km hr^{-1}, and were applied either singly or in a sequential 2-pass system spaced approximately one week following the first pass. A non-treated control was included for comparison. Treatments were arranged in a randomized complete block design with 4 replications. Individual plots were 3 by 15 m.

Prior to each application, ten plants of each of the target weed species were collected by cutting plants at the soil surface, weighing each plant immediately, and then drying plants in a forced-air oven at 37 C. Dry weights were recorded every 48 hours until the weights stopped decreasing between measurements. Moisture content was then determined using the equation: [(fresh weight – dry weight)/fresh weight * 100]. Soil moisture was also determined prior to each electrocution treatment by taking two soil moisture measurements in each plot using a FieldScout TDR 350 soil moisture probe (Spectrum Technologies, Inc., Aurora, IL). Lastly, average plant density per m^{-2} and height of plants were determined at the time of each electrocution application in at least one plot per replication. Following application, visual control ratings were taken at 3 and 42 days after treatment (DAT) on a scale of 0 to 100%, where 0 was equivalent to no injury and 100 was equivalent to complete control of the plant. Following the last application, recovered plants were determined by counting recovered plants within a 1-m^2 quadrat in each plot. Plants were deemed recovered if they had green tissue and a clear ability to regrow and/or produce seed following electrocution.

Seed Viability Testing

Following the last electrocution timing, seedheads that were present at electrocution were collected within a 1-m^2 quadrat in each plot, placed in paper bags, and stored until further analysis. Seed were gleaned from seedheads and then the resulting samples of seed were weighed. The number of seed in a 0.05 g subsample of seed from each sample of yellow foxtail, barnyardgrass, common ragweed, and waterhemp were counted to extrapolate the total number of seed in each sample similar to Schwartz et al. (2016). A 1 g subsample of seed from the giant ragweed samples and 2 g sample of seed from the cocklebur samples were counted and extrapolated in the same manner. Horseweed seed were not tested due to size and the inability to slice embryos. Seed were then stored in labeled paper bags until viability screening. Subsamples of seed from each weed species were then tested for viability following procedures from the Tetrazolium Testing Handbook (Peters 2000; Miller 2010). Twenty-five seed (twenty-five burs for cocklebur) from each sample were preconditioned on water-saturated filter paper (Whatman No. 2, Fisher Scientific, Hanover Park, IL) in a 10-cm petri dish and soaked overnight to allow seedcoats to soften. Petri dishes were prepared with filter paper saturated with a 0.5 or 1% tetrazolium (2,3,5-triphenyl tetrazolium chloride; MP Biomedicals, LLC, Solon, OH) solution, depending on the species (Peters 2000; Miller 2010). Seeds were then cut in half to expose the embryos and placed embryo-down onto the filter paper. Petri dishes were wrapped with foil and stored in darkness to prevent degradation of the tetrazolium solution (Miller 2010). Once seeds had incubated on the solution for the prescribed time, they were evaluated under a dissecting microscope. Seeds with a red-stained embryo were considered viable while seeds that did not have a red-stained embryo or did not have an embryo inside the seedcoat were considered non-viable.

Statistical Analysis

Visual rating, seed viability, and recovered plant data were analyzed using the PROC GLIMMIX procedure in SAS (SAS 9.4, SAS® Institute Inc. Cary, NC). Means were separated using Fishers Protected Least Significant Difference (LSD) at $P \leq 0.05$. Fixed effects were growth stage, speed of the implement, and number of passes with the implement, while year and plot were random effects. Years were chosen as random effects in the model so that conclusions could be made across a range of environments (Blouin et al. 2011; Carmer et al. 1989). Pearson's correlation coefficients were generated in SAS using the PROC CORR procedure to assess potential relationships between soil moisture, plant moisture, plant density, and plant height with visual weed control.

Soybean Experiment

Glufosinate and 2, 4-D-resistant soybean ('MorSoy 3859E'and 'Pioneer 38T05E' in 2020 and 2021, respectively) were planted in rows spaced 76 cm apart at an approximate density of 350,000 seeds ha^{-1} on June 2 and June 4 in 2020 and 2021, respectively. The trial area was prepared by discing followed by a single pass with a field cultivator. In both years the trial was placed in an area that had previously contained dense infestations of waterhemp. Electrocution treatments took place at a constant speed of 4.8 km hr^{-1} with single passes at the R1, R2, R3, R4, R5 and R6 stages of soybean growth and sequential passes at the R1 followed by R3 and R1 followed by R5 growth stages. Table 3 presents the dates that each electrocution treatment took place. The electrocution boom maintained contact with the top 2 to 8 cm of soybean foliage approximately 75% of the time in order to evaluate soybean injury and yield loss that could occur if soybean were electrocuted. Half of the plots were maintained weed-free by applying 2,4-D choline plus glufosinate approximately 4 weeks after planting (Table 1) in order to determine the effects of electrocution on soybean injury and yield without the interference of weeds. The remaining half of the plots were designed to simulate a weed escape scenario in soybean, and received a treatment of clethodim to control grass species and create a purer stand of waterhemp. All herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 138 kPa. The 2,4-D choline and glufosinate treatment was applied with AIXR 11002 nozzles while the clethodim treatment was applied with XR 8002 nozzles. Non-electrocuted, weed-free and weed escape controls were included for comparison. All treatments were arranged in a randomized complete block design with 6 replications and individual plots were 3 by 18 m.

Plant and soil moisture measurements were conducted in the same manner as described previously. Average soybean and waterhemp density and heights were recorded at each application. Following application, visual waterhemp control ratings were taken at 7 and 42 DAT on a scale of 0 to 100%, where 0% was equivalent to no injury and 100% was equivalent to complete control of the plant. Visual estimates of soybean injury were also assessed at the same timings as the waterhemp control ratings, using a scale of 0% to 100%, where 0% represented no injury and 100% represented complete plant death. Soybean yield was collected by harvesting the two innermost soybean rows within each plot using a small-plot combine (Massey Ferguson, 8XP Kincaid®, Haven, KS) equipped with a Harvest Master H2 Single Grain Gauge® (Juniper Systems, Logan, UT), and moisture was adjusted to 13%.

Visual waterhemp control, visual soybean injury, and soybean yield data were analyzed using the PROC GLIMMIX procedure in SAS. Means were separated using Fishers Protected Least Significant Difference (LSD) at $P \leq 0.05$. Fixed effects were soybean growth stage and initial weed presence, while year and plot were random effects. Years were chosen as random effects in the model so that conclusions could be made across a range of environments (Blouin et al. 2011; Carmer et al. 1989). The relationship between visual waterhemp control and height differences between waterhemp and the soybean canopy at application was analyzed in SAS using the Pearson PROC CORR procedure.

Results and Discussion

Individual Weed Experiments

Growth stage at the time of electrocution had a significant effect on weed control of all species at both the 3 and 42 DAT ratings ($P<0.001$; Table 4). Additionally, the number of passes was a significant factor in the level of control observed for at least one rating timing for all species besides yellow foxtail (Table 4). The average control of weeds other than yellow foxtail was from 4 to 15% higher with two passes compared to one (Table 5). These results are consistent with Diprose et al. (1985) who reported higher weed beet control following two passes with electrocution compared to one. Speed was significant only for the 3 DAT rating for giant foxtail ($P<0.05$; Table 4) and for 3 and 42 DAT ratings for giant ragweed ($P<0.001$; Table 4). There were interactions between growth stage and number of passes for barnyardgrass, cocklebur, giant foxtail, giant ragweed, and horseweed. A growth stage by speed interaction was observed for giant ragweed. However, no other significant interactions were discovered.

The visual injury symptoms observed following electrocution included severe necrosis and an immediate wilting phenotype. Cross sections of the apical and basal portions of electrocuted stems revealed that browning or necrosis of cells was observed as soon as 3 hours after treatment (HAT) and typically became more prominent by 24 HAT (Figure 1). In general, vascular tissues seemed to stay intact with no cell lysis evident. Necrosis observed in the apical and basal portions of the stems provides support that the electrical signal is likely moving through the vascular tissues, but more research should be conducted to confirm this possibility.

In most cases, there seemed to be a slight decline in control observed by 42 DAT due to some recovery from electrocuted plants or as a result of newly emerging plants. Overall, there was a trend towards greater weed control when electrocution occurred in the later growth stages (Figure 2), which is most likely due to a greater number of weeds being contacted by the electrocution boom when weeds were taller. Several weed species were controlled similarly when electrocution occurred in later growth stages. However, when the level of control was averaged across all growth stages, the order of control from greatest to least was giant ragweed > common ragweed > waterhemp > horseweed > cocklebur > giant foxtail > barnyardgrass > yellow foxtail. Grass species typically had slightly lower visual control compared to broadleaf species, which is likely due to differences in physiology of the plants.

Although minimal, there were barnyardgrass, giant and yellow foxtail, and waterhemp plants that survived electrocution treatments (Figure 3). For the grass weed species, there were more plants that recovered following electrocution at the earlier growth stage timings. For waterhemp, the number of recovered plants never exceeded 1.6 plants/m^2 and more plants recovered following electrocution at pollination and flowering compared to the other growth stages. It is possible that the survival of some waterhemp plants may be due to only parts of the plant getting electrocuted and the tendency of waterhemp to compensate growth at the axillary buds when a loss of apical dominance occurs (Horak and Loughin 2000; Mager et al. 2006). Similar responses can exist following a failed herbicide application. For example, Haarmann et al. (2020) found that waterhemp plants produced 1.7 to 7.9 new branches upon recovery from a failed application of glufosinate. Diprose et al. (1980) also observed that weed beet that survived applications of electrocution contained multi-branched stems with only one or two branches that had been contacted by the electrode. The number of passes was also a significant factor for recovered waterhemp. On average, 1.4 waterhemp plants/m^2 recovered following 1 pass of electrocution, while 0.68 plants/m^2 recovered following sequential passes (data not shown).

Pearson correlation coefficients indicated that the control of all weed species 3 and 42 DAT was related to the plant height and amount of plant moisture present at the time of electrocution (Table 6). When considering all broadleaf weeds alone, there were also significant correlations among plant moisture, height, and control while for grass species, visual control and plant moisture, density, and height were significantly correlated (Table 6). The strongest correlation observed was for the effect of plant height on grass weed species control. Coefficients were 0.70 and 0.76 at 3 and 42 DAT, respectively, indicating that higher control was achieved as plant height increased. Similar positive coefficients were produced for relationships between plant height and control when comparisons were made on broadleaf weeds alone or all species combined. These results emphasize the importance of plant height on the success of weed electrocution. Among all species where plant moisture was significant, correlation coefficients were negative, indicating that higher plant moisture led to lower control. There was also a significant positive correlation between grass weed control and plant density, but it is difficult to speculate why greater control of these species would occur when present at higher densities.

Late-season electrocution reduced weed seed viability from 54 to 80% when compared to the non-treated control of each species (Figure 4). Common ragweed had the highest percentage of non-viable seeds (80%), while giant foxtail was lowest (54%). Waterhemp, the most common and troublesome weed found in soybean in the U.S. (VanWychen 2019), had a 59% reduction in weed seed viability. Diprose et al. (1985) also reported that weed beet seed viability was reduced by 83% compared to the non-treated control. Collectively, these results indicate that electrocution can serve as an effective method of reducing the number of viable seed that are returned to the soil seedbank.

Soybean Experiment

Soybean injury in response to weed electrocution at various growth stages ranged from 11 to 25% 7 DAT but declined to 5 to 17% by 42 DAT (Table 7). There was not a significant interaction between soybean growth stage at the time of treatment and the weed-free versus weed escape treatment (P=0.96), therefore soybean yield was combined across the weed-free and weed escape treatments (Figure 5). Yield losses ranged from 11 to 26% compared to the non-treated control (Figure 5). The lowest yield loss came from the R1 followed by R3 treatment, which also had the highest visual soybean injury (Figure 5; Table 7). Yield of soybean electrocuted at the R4 and R6 growth stages were not different from the non-treated control, however soybean yields were lower than the non-treated control following application at all other growth stages. Based on the results of this research alone it is difficult to identify a specific growth stage to avoid when electrocuting, but our results suggest that too much contact of the electrocution boom with the soybean canopy in later growth stages will likely cause yield loss. It is important to re-iterate that in this research, soybean injury and yield loss occurred due to purposely contacting soybean plants with the electrocution boom. However, under normal circumstances where a height differential exists between the weed escapes and the upper portions of the soybean canopy, contact of the soybean foliage would not need to occur.

Control of waterhemp escapes ranged from 55 to 97% 7 DAT and from 51 to 93% 42 DAT (Table 7). Sequential electrocution treatments did not provide higher waterhemp control than any of the single application treatments. Highest waterhemp control was achieved when electrocution treatments took place at the R5 and R6 stages of soybean growth, most likely due to a greater proportion of waterhemp plants above the soybean canopy. To further explore this possibility, waterhemp control in relation to the difference in height between waterhemp and soybean at the time of treatment was determined. The scatter plot and best-fit line in Figure 6 suggest higher waterhemp control was achieved when there was a greater height differential between the weed and soybean canopy. Pearson correlation coefficients for this relationship were 0.91 ($P<0.001$) and 0.89 ($P<0.001$) for the 7 and 42 DAT ratings, respectively and corroborate that observation. These results are in agreement with those from the individual weed experiment with waterhemp. Diprose et al. (1980) also reported that most of surviving weed beet plants were below the crop canopy.

In conclusion, in order to achieve maximum efficacy, electrocution applications should take place when weed species are at least 60 cm tall and/or when weeds escape above the soybean canopy. A second sequential electrocution pass approximately one week following the first did not always improve weed control, especially when a soybean crop was present. This lends support for the importance of a height differential between the weed and the soybean canopy. Although most weeds were completely controlled following electrocution, giant foxtail, yellow foxtail, barnyardgrass, and waterhemp had some surviving plants. Overall, results from these experiments indicate that using weed electrocution in an integrated approach can help combat herbicide-resistant weeds and is best fit to serve as a late season rescue treatment that can offer both weed control as well as reduction of viable weed seed return to the soil seedbank. Future research with weed electrocution should explore factors that have an effect on plant survival as well as physiological differences that may affect efficacy among species.

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Table 1. Sources and rates of herbicides and adjuvants used in the experiments.

Experiment	Active ingredient /type of adjuvant	Trade name	Rate	Manufacturer	Address
Individual weed/soybean	Clethodim[a]	Select Max®	0.14 kg ai ha^{-1}	Valent	San Ramon, California
Individual weed	Dicamba[b]	Xtendimax®	0.56 kg ae ha^{-1}	Bayer	St. Louis, Missouri
Soybean	2,4-D choline[c]	Enlist one®	0.8 kg ae ha^{-1}	Corteva	Indianapolis, Indiana
Soybean	Glufosinate[c]	Liberty® 280 SL	0.66 kg ai ha^{-1}	BASF	Raleigh, North Carolina
Individual weed/soybean	Non-ionic surfactant	Astute	0.25% vol/vol	MFA	Columbia, Missouri
Individual weed	Water conditioning agent	Class Act Ridion	1% vol/vol	Winfield United	St. Paul, Minnesota
Individual weed	Volatility reducing agent	Vapor Grip	1% vol/vol	Bayer	St. Louis, Missouri
Individual weed	Drift reduction agent	Interlock	0.5% vol/vol	Winfield United	St. Paul, Minnesota
Soybean	Ammonium sulfate	Amsol	2.5% vol/vol	Winfield United	St. Paul, Minnesota

[a] Applied with non-ionic surfactant
[b] Applied with water conditioning agent, volatility reducing agent, and drift reduction agent
[c] Applied with ammonium sulfate

Table 2. Dates of electrocution and average densities of weed species at the time of electrocution in 2020 and 2021.

Growth stage	Barnyard-grass		Cocklebur		Common ragweed		Giant foxtail		Giant ragweed		Horseweed		Waterhemp		Yellow foxtail	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
30 cm	7/9 (10)[c]	7/14 (12)	7/17 (4)	8/5 (18)	6/23 (54)	6/4 (22)	7/9 (164)	7/14 (308)	6/23 (54)	6/4 (60)	--[b]	6/1 (75)	7/17 (64)	8/5 (74)	7/9 (4)	7/14 (1)
2nd pass[a]	7/16 (10)	7/22 (12)	7/24 (4)	8/12 (18)	6/30 (54)	6/11 (22)	7/16 (164)	7/22 (308)	6/30 (54)	6/11 (60)	--	6/8 (75)	7/24 (64)	8/12 (74)	7/16 (4)	7/22 (1)
60 cm	--	7/28 (12)	7/28 (4)	8/15 (12)	7/8 (63)	6/23 (31)	--	7/28 (370)	7/8 (38)	6/23 (75)	6/25 (6)	7/7 (65)	7/28 (40)	8/15 (122)	--	7/28 (14)
2nd pass	--	8/3 (12)	8/5 (4)	8/22 (12)	7/15 (63)	7/6 (31)	--	8/3 (370)	7/15 (38)	7/6 (75)	7/2 (6)	7/22 (65)	8/5 (40)	8/22 (122)	--	8/3 (14)
Flowering	7/29 (14)	8/3 (10)	8/6 (4)	8/18 (8)	8/5 (30)	8/2 (20)	7/29 (124)	8/3 (298)	8/5 (18)	8/2 (69)	7/17 (6)	7/23 (49)	8/6 (48)	8/18 (64)	7/29 (0.2)	8/3 (16)
2nd pass	8/5 (14)	8/11 (10)	8/17 (4)	8/25 (8)	8/14 (30)	8/9 (20)	8/5 (124)	8/11 (298)	8/14 (18)	8/9 (69)	7/24 (6)	7/30 (49)	8/17 (48)	8/25 (64)	8/5 (0.2)	8/11 (16)
Pollination	8/20 (16)	8/11 (12)	8/19 (4)	8/20 (8)	8/20 (45)	8/16 (20)	8/20 (72)	8/11 (808)	8/20 (58)	8/16 (41)	8/5 (5)	8/11 (30)	8/19 (64)	8/20 (56)	8/20 (0.4)	8/11 (92)
2nd pass	8/26 (16)	8/18 (12)	8/26 (4)	8/29 (8)	8/26 (45)	8/24 (20)	8/26 (72)	8/18 (808)	8/26 (58)	8/24 (41)	8/13 (5)	8/19 (30)	8/26 (64)	8/29 (56)	8/26 (0.4)	8/18 (92)
Seed set	9/8 (20)	8/26 (16)	9/8 (6)	9/16 (12)	8/27 (18)	9/10 (18)	9/8 (130)	8/26 (378)	8/27 (63)	9/10 (37)	8/20 (3)	8/26 (79)	9/8 (60)	9/16 (58)	9/8 (1.6)	8/26 (76)
2nd pass	9/16 (20)	9/1 (16)	9/17 (6)	9/24 (12)	9/4 (18)	9/17 (18)	9/16 (130)	9/1 (378)	9/4 (63)	9/17 (37)	8/26 (3)	9/1 (79)	9/17 (60)	9/24 (58)	9/16 (1.6)	9/1 (76)

[a] Indicates the second pass of electrocution that occurred to plots within the same growth stage as the previous row.
[b] Dashes indicate electrocution timings that did not occur due to unfavorable soil conditions or because the 60 cm and flowering growth stages occurred at the same time.
[c] Values within parentheses are the average density of the weed species per m^2 at the time of treatment.

Table 3. Dates of electrocution treatments and the associated soybean growth stages in 2020 and 2021.

Soybean growth stage	Year	
	2020	2021
R1	7/21	7/23
R2	7/29	7/28
R3	8/6	7/30
R4	8/17	8/2
R5	8/20	8/5
R6	8/27	8/20

Table 4. Summary of effects for visual control of barnyardgrass, cocklebur, common ragweed, giant foxtail, giant ragweed, horseweed, waterhemp, and yellow foxtail at 3 and 42 days after treatment (DAT)[a].

Effect	Barnyard-grass		Cocklebur		Common ragweed		Giant foxtail		Giant ragweed		Horseweed		Waterhemp		Yellow foxtail	
	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT
Growth stage	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Pass	***	NS	***	***	NS	***	***	*	***	***	***	***	***	***	NS	NS
Speed	NS	NS	NS	NS	NS	NS	*	NS	***	***	NS	NS	NS	NS	NS	NS
Growth stage x pass	***	NS	***	*	NS	NS	*	NS	**	**	***	***	NS	NS	NS	NS
Growth stage x speed	NS	NS	NS	NS	NS	NS	NS	NS	***	***	NS	NS	NS	NS	NS	NS
Pass x speed	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Growth stage x pass x speed	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] *, **, and *** indicates significant differences at ∝=0.05, 0.01, and 0.001, respectively. NS indicates no significant differences at ∝=0.05.

Table 5. Visual control of various weed species at 3 and 42 days after treatment (DAT) following 1 or 2 passes of electrocution[a].

	Barnyard-grass		Cocklebur		Common ragweed		Giant foxtail		Giant ragweed		Horseweed		Waterhemp		Yellow foxtail	
Number of passes	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT	3 DAT	42 DAT
1	68 B	54[b]	68 B	65 b	87	80 b	71 B	61 b	89 B	82 b	75 B	71 b	83 B	76 b	38	39
2	74 A	57	83 A	74 a	91	85 a	79 A	66 a	93 A	88 a	83 A	80 a	88 A	82 a	41	39

[a] Means followed by the same letter within a column are not different, ∝=0.05.

[b] Means within the same column that are not followed by a letter are not significant, ∝=0.05.

Table 6. Pearson correlation coefficients and their significance for visual control, soil moisture, plant moisture, plant density, and plant height at 3 and 42 days after treatment (DAT) for all weed species combined, broadleaf weed species only, and grass weed species only.

Variable	Pearson correlation coefficient	P > F
All species combined		
Soil moisture vs. 3 DAT weed control	-0.03	0.6239
Plant moisture vs. 3 DAT weed control	**-0.26**	**< 0.001**
Plant density vs. 3 DAT weed control	0.05	0.4209
Plant height vs. 3 DAT weed control	**0.54**	**< 0.001**
Soil moisture vs. 42 DAT weed control	0.00	0.9615
Plant moisture vs. 42 DAT weed control	**-0.33**	**< 0.001**
Plant density vs. 42 DAT weed control	0.06	0.2855
Plant height vs. 42 DAT weed control	**0.57**	**< 0.001**
Broadleaf weed species		
Soil moisture vs. 3 DAT weed control	-0.06	0.4101
Plant moisture vs. 3 DAT weed control	**-0.19**	**0.0069**
Plant density vs. 3 DAT weed control	-0.01	0.8506
Plant height vs. 3 DAT weed control	**0.49**	**< 0.001**
Soil moisture vs. 42 DAT weed control	-0.08	0.2810
Plant moisture vs. 42 DAT weed control	**-0.19**	**0.0098**
Plant density vs. 42 DAT weed control	-0.06	0.3809
Plant height vs. 42 DAT weed control	**0.55**	**< 0.001**
Grass weed species		
Soil moisture vs. 3 DAT weed control	0.06	0.5240
Plant moisture vs. 3 DAT weed control	**-0.31**	**0.0016**
Plant density vs. 3 DAT weed control	**0.21**	**0.0284**
Plant height vs. 3 DAT weed control	**0.70**	**< 0.001**
Soil moisture vs. 42 DAT weed control	0.09	0.3745
Plant moisture vs. 42 DAT weed control	**-0.32**	**0.0008**
Plant density vs. 42 DAT weed control	**0.20**	**0.0404**
Plant height vs. 42 DAT weed control	**0.76**	**< 0.001**

Table 7. Soybean injury and waterhemp control 7 and 42 days after treatment (DAT) following electrocution at different soybean growth stages.

Soybean growth stage at time of treatment	Soybean injury[a]		Waterhemp control[a]	
	7 DAT	42 DAT	7 DAT	42 DAT
R1	11 d	5 d	55 c	54 bc
R2	12 cd	5 d	56 c	51 c
R3	16 bc	10 bc	61 bc	55 bc
R4	14 bcd	8 cd	71 bc	65 bc
R5	13 bcd	9 bcd	82 ab	77 ab
R6	17 b	17 a	97 a	93 a
R1/R3	25 a	14 ab	61 bc	55 bc
R1/R5	14 bcd	11 bc	63 bc	58 bc

[a]Values followed by the same letter within a column are not different, $\propto$=0.05.

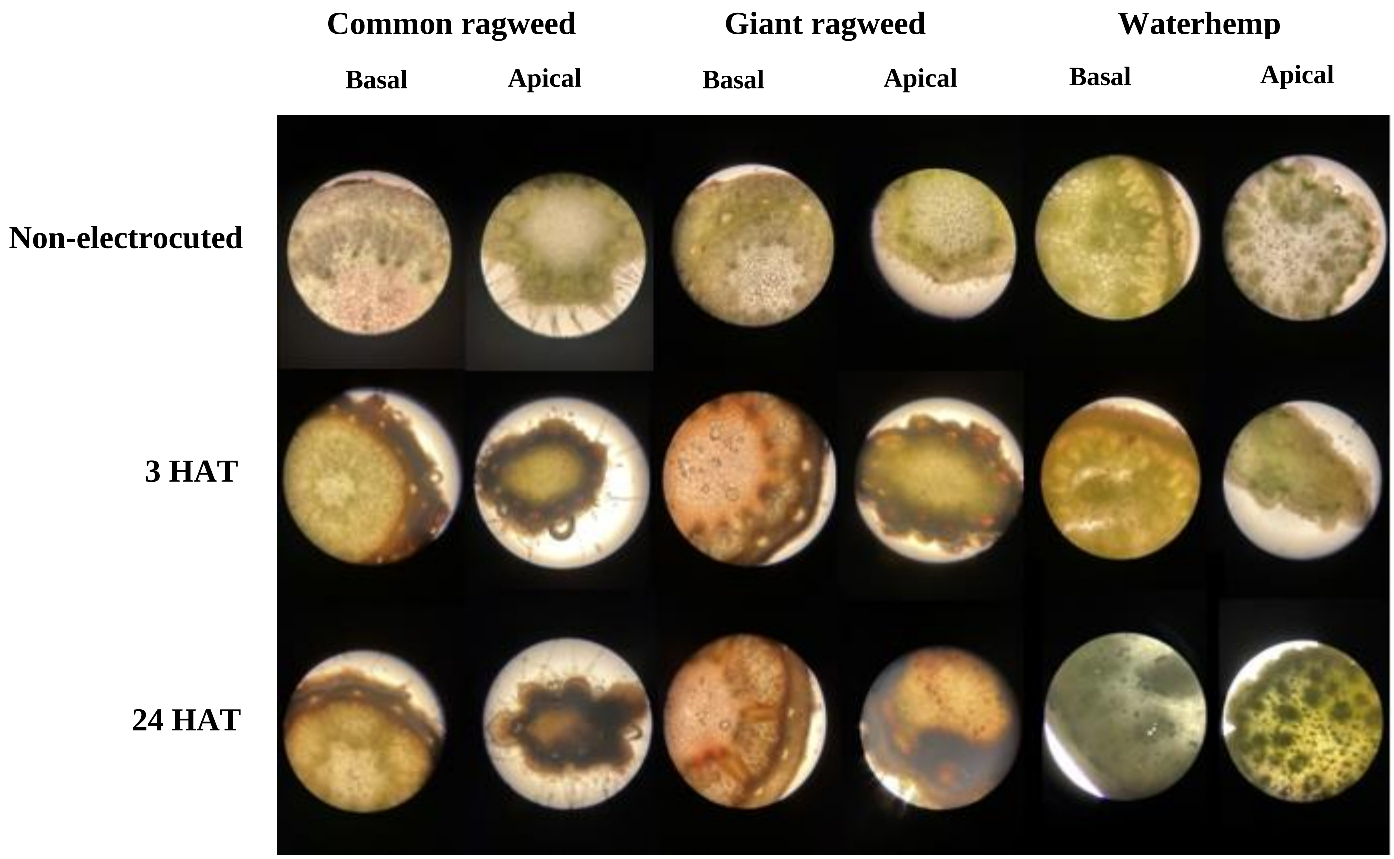

Figure 1. Common ragweed, giant ragweed, and waterhemp apical and basal stem cross sections from non-electrocuted plants, plants from 3 hours after treatment (HAT), and plants from 24 HAT.

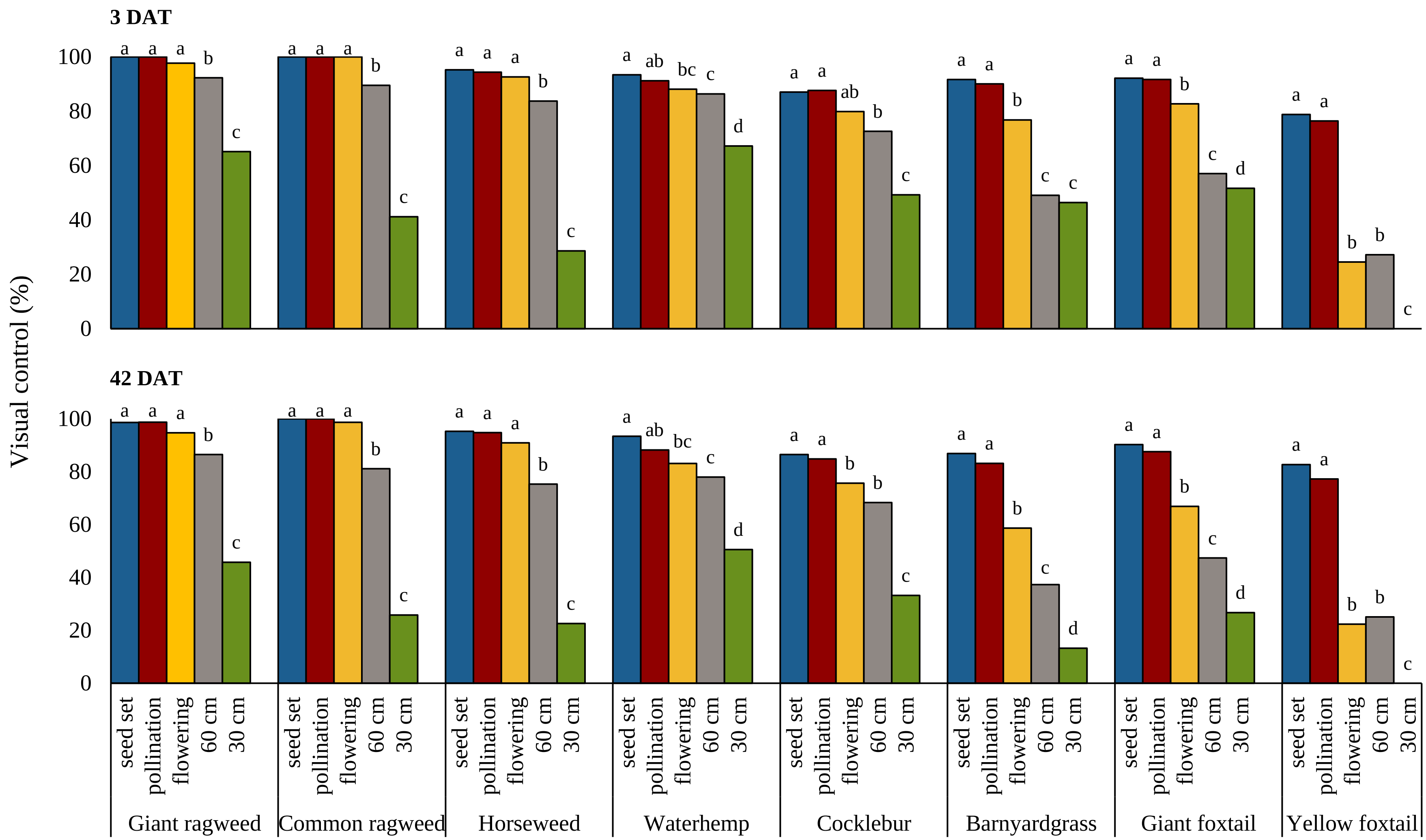

Figure 2. Visual control of various weed species 3 and 42 days after treatment (DAT) at various growth stages. Bars followed by the same letter within a given species and graph are not different, ∝=0.05.

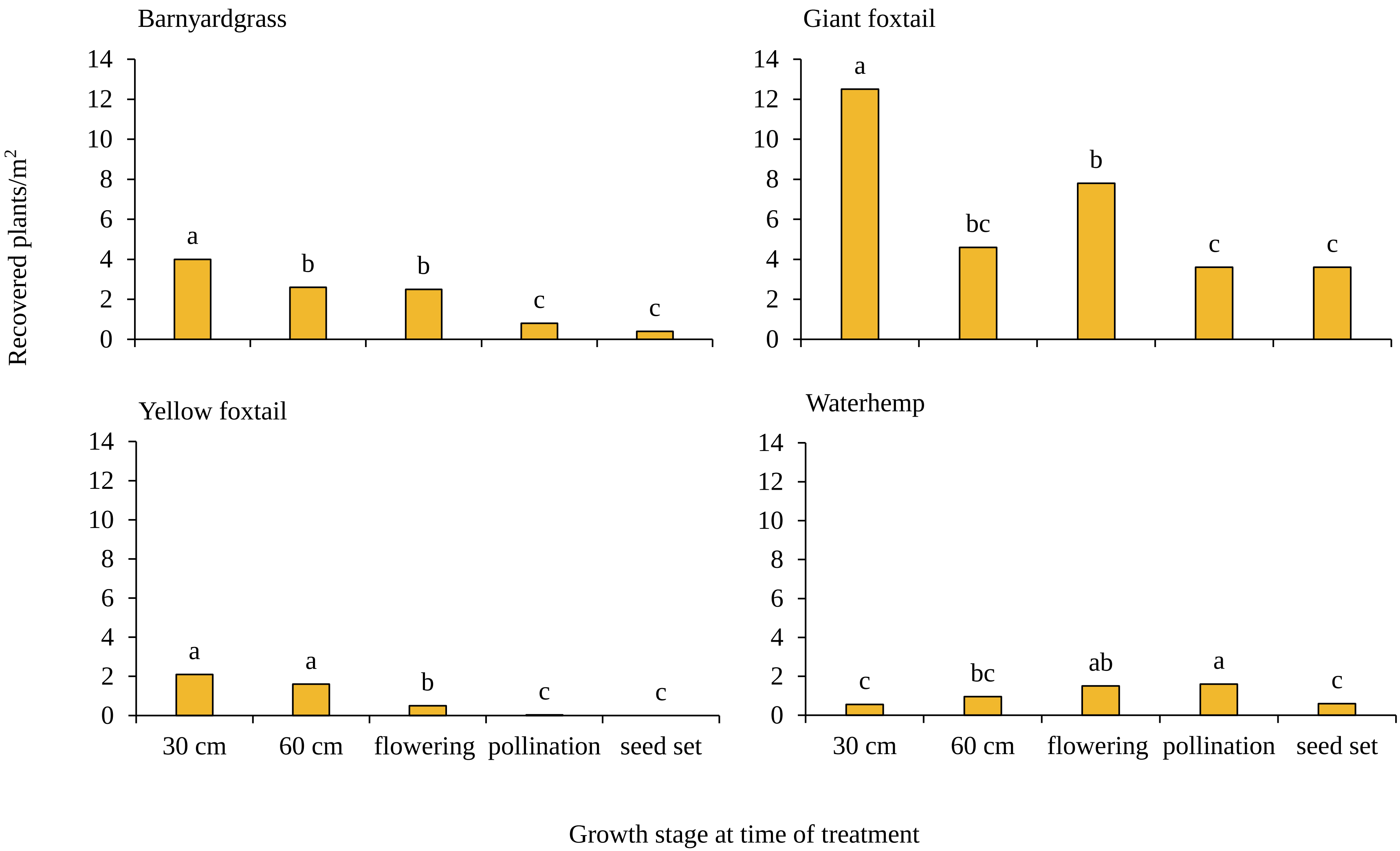

Figure 3. The average number of barnyardgrass, giant and yellow foxtail, and waterhemp plants per m^2 that recovered following electrocution at different growth stages. Bars followed by the same letter within a species are not different, ∝=0.05.

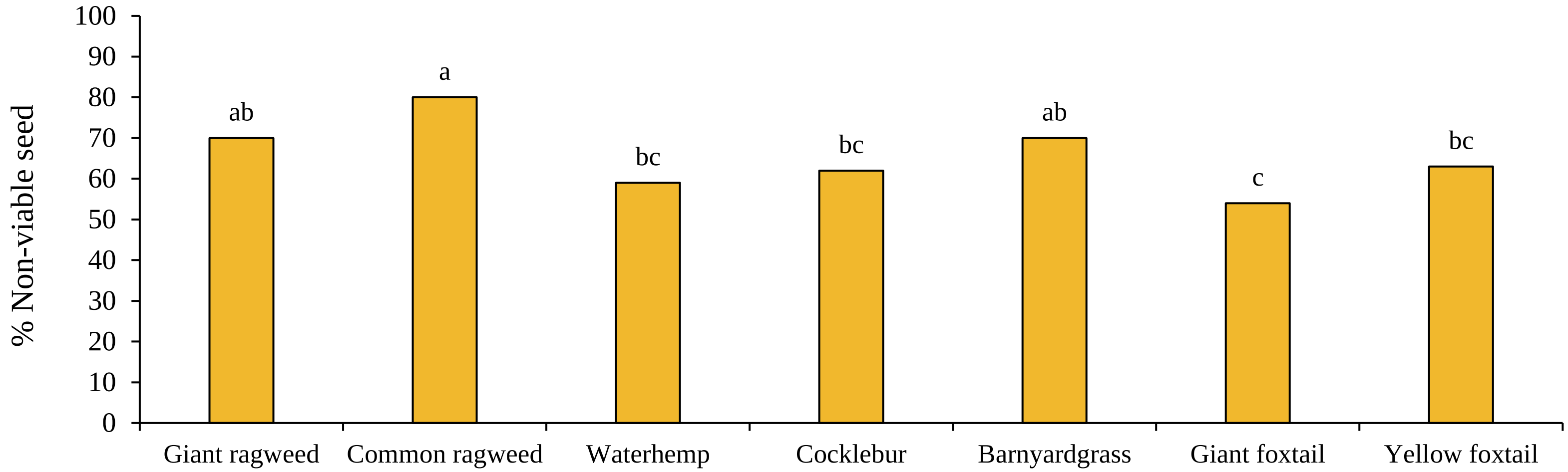

Figure 4. Viability of weed seeds following electrocution. Viability was determined in comparison to the non-treated control of each species. Bars followed by the same letter are not different, ∝=0.05.

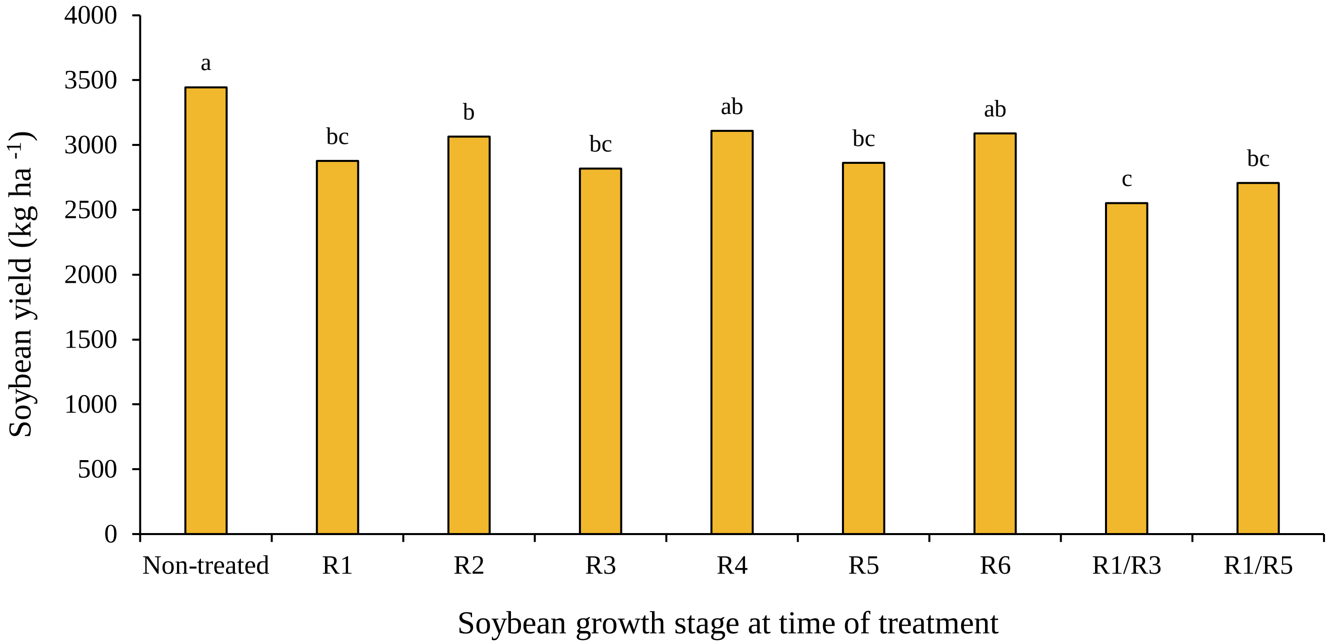

Figure 5. Soybean yield following electrocution at different growth stages. Bars followed by the same letter are not different, ∝=0.05.

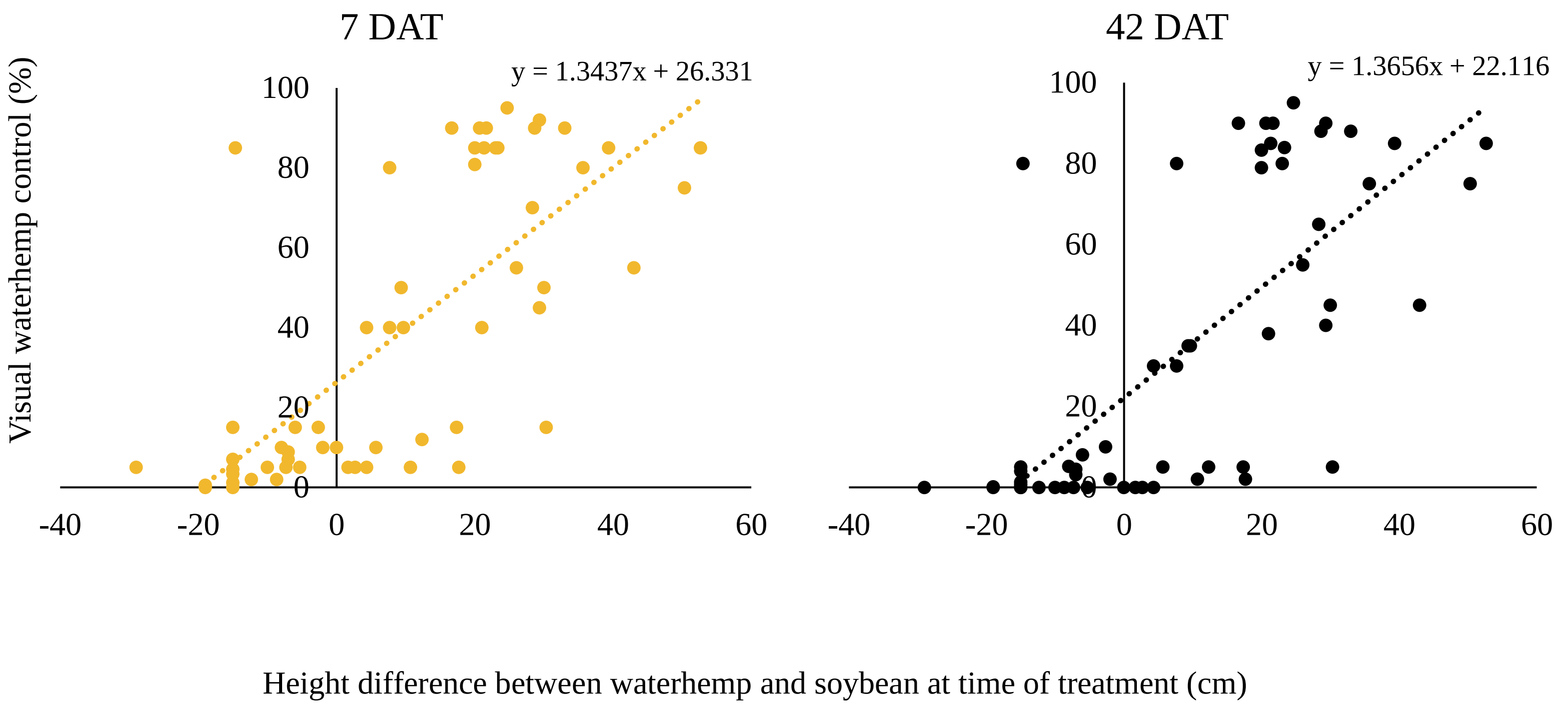

Figure 6. Waterhemp control at 7 and 42 days after treatment (DAT) in relation to the difference in height between waterhemp and soybean at the time of electrocution.