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The Electric Spatula: Killing Weeds with Pulsed Microshocks from a Flat-Plate Electrode

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Abstract: Seeking an easy-to-deploy, energy-efficient, non-herbicide weed control method, we tested a flat-plate electrode to apply pulsed electric microshocks (PMS) to a grass and four broadleaf weed species. The method can be deployed via a hand-held unit or as part of a fully automated system to control escape weeds in field crops. The effectiveness of the treatments and the relative energy discharges when applying similar electric doses to the plant leaves or to the plant when pressed to the soil with a flat-plate electrode were compared. The method killed only half of the treated *Lolium multiflorum* "Winter Star" plants, well below our target rate, but significantly reduced growth rates and indicated that effective treatment of <1.0 MJ ha^{-1} for treating five plants m^{-2} is possible. *Polygonum aviculare* L., *Amaranthus powellii* S. Wats., *Amaranthus deflexus*, and *Solanum nitidibaccatum* Bitter plants were successfully controlled, with the energy required to kill 100% of seedlings varying from 0.1 to 0.9 MJ ha^{-1}, indicating that broadleaf weeds are more susceptible. This easily met our target effectiveness and efficiency goals. The discharged energy increased when the electrode pressed the plant to a dry soil surface rather than to the leaves only and increased further when the electrode pressed the plant to a wet soil surface.

Keywords: nonchemical weed control; site-specific weed management; electric weeding; robotic weeding; electric shocks; applied energy; grass weeds; broadleaf weeds

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1. Introduction

For decades, herbicides have provided easy-to-use, cost-effective weed management, but now, consumer preference for chemical-free food [1–3], awareness of environmental impacts [4,5], increasing regulations restricting agrichemical use [6,7], and the increasing prevalence of herbicide resistance [8–10] are forcing changes to weed management strategies [11]. The emergence of agritechnologies incorporating automation, machine vision, and artificial intelligence [12–15] and the development of new techniques for weed destruction [11,16,17] offer alternatives that minimise or avoid the requirement for herbicides and avoid soil disturbance and can work effectively in high crop or crop-residue conditions. Our focus has been on electric weeding, which we have previously discussed [11,18]. Slavin et al. [19] provided a thorough review of the methods and equipment commercially available in 2023.

According to the evaluation criteria for autonomous weeding in sugarbeet of Nørremark et al. [20], the target weed control efficiency should be >90%, and the energy demand should be <2 kJ m^{-1} of a 50 cm wide row, which equates to 40.2 MJ ha^{-1}. This is about twice the 19 MJ ha^{-1} (380 J plant^{-1}) energy estimate assuming five plants m^{-2} of Coleman et al. [21], a density considered reasonable for post-weeding escapes [22,23]. Most commercially available electric weeding equipment uses continuous contact alternating current (AC), operating at 5–15 kV and 0.5–2 amps [24]. Energy levels of 4 kJ–111 kJ plant^{-1} were reported using continuous contact in greenhouse conditions [25]. To reach the target of Nørremark et al. [20], this would allow for only one weed every 2–55 m of row length.

The amount of energy required for effective control is related to plant size. Lati et al. [16] showed that as little as 9 J killed very small (size not stated) *Trifolium pratense* plants using 2.2 kV AC shocks two weeks after seed sowing (WAS). However, at 4 WAS, 180 J was required to achieve a 95% biomass reduction. Baev and Yudaev [26] stated that the effect on vegetation of any damaging factors is related to the energy involved. Working with weed stem fragments in vitro, they showed that pulsed direct current (DC) was more than five times more energy-efficient than sinusoidal AC in creating intracellular plant tissue damage. Harvey et al. [27] suggested an exponential relationship, and thus the highest energy efficiency would be achieved by treating weeds when small and young.

We identified electric weeding with pulsed electric microshocks (PMS) as a very low-energy option requiring a fraction of the energy of any other system. We demonstrated in greenhouse trials that a minimal amount of electrical energy was sufficient to control small, non-tillering grass and broadleaf weed seedlings up to 15 cm in height using a precisely placed point electrode [18]. At 5 J plant^{-1}, our system treating five plants m^{-2} would require 0.25 MJ ha^{-1} plus transport and actuation energy to control a range of non-tillering grasses. A simple flat electrode plate applied to plants was thought to be more practically realistic for field deployment as a simple hand-held weeding system, on low-energy autonomous field robots, or for application by high-efficiency strip-weeders. It would simplify application, particularly to effect control of very small weed seedlings. Even with a ten-fold increase in energy, our system's energy requirement would be an order of magnitude lower than that of other reported systems. Human safety needs to be considered when deploying high-voltage equipment, but we noted that commercially available high-voltage weeding systems use far higher energy than our PMS system. As described in Bloomer et al. [11], regulations do not specifically address systems such as ours, which approximates the risks associated with electric fence energisers.

Here, we report results from greenhouse trials using PMS applied with a flat plate to a grass, *Lolium multiflorum* "Winter Star", and four different species of broadleaf weed seedlings, *Polygonum aviculare* L. (wireweed), *Amaranthus powellii* S. Wats. (redroot), *Amaranthus deflexus* L. (prostrate amaranth), and *Solanum nitidibaccatum* Bitter (hairy nightshade). The objectives of this study were to determine whether a flat plate used in a practical way for paddock treatment could apply a threshold "dose" of voltage and energy to achieve >90% mortality, to assess energy expenditure, and to compare relative responses of different species. Two electrode placements were tested: the plate pressed against the plant only with a 3 cm separation from the soil surface and the plate pressing the plant onto the soil with the soil surface either wet or dry. The effectiveness in terms of plant death or biomass reduction and energy consumption are reported.

2. Materials and Methods

A custom-built PMS device that produced multiple DC pulses of up to 4.5 kV was developed by Weda Tech (Hastings, New Zealand). The device was controlled using custom software running on a laptop, with the discharge voltage, pulse duration, pulse period, and number of pulses able to be programmed. To improve accuracy and ensure full capacitor recharge, a 50 ms interval was maintained between pulses. A PicoScope 2000 series oscilloscope was coupled with a Pico TA044 high-voltage differential probe connected to the positive and earth electrodes to monitor the applied doses. Pulse data were automatically recorded and logged in csv files.

In all trials, the growing medium was silt loam soil sieved to 5 mm. Plants were grown in 450 mL polythene bags, placed in a greenhouse, and hand-watered as required. Temperature and humidity were logged and showed no values considered likely to cause any negative effects. Bags were arranged in blocks and randomised within each block. Each trial had six replicates.

Six certified *L. multiflorum* "Winter Star" seeds were sown in each bag, and 12–14 days after emergence, the seedlings were thinned to three plants per bag, aiming to keep all plants within a similar size profile, typically with three or four leaves. The *P. aviculare*, *A. powellii*, *A. deflexus,* and *S. nitidibaccatum* seedlings were collected from fallowed cropping areas, transplanted one per bag, and allowed to establish for 16–21 days before treatment.

The voltage was set between 3.0 and 4.5 kV, the pulse length was between 25 and 5000 µs, and the number of pulses was selected to adjust the total energy potentially delivered by each treatment. A 5 mm diameter aluminium earth electrode was inserted into the soil at the base of the plastic bag being treated (Figure 1). The positive electrode was a flat aluminium plate with dimensions of 75 mm × 100 mm (similar in shape and size to a kitchen spatula) and was pressed fully to the soil surface or only to the leaves. For "leaf" treatments, the plate was set on a plastic spacer placed on the soil to maintain a gap of approximately 30 mm above the soil surface. For "soil" treatments, the plant and plate were pressed to the soil. During the application of PMS, each pulse was measured; the voltage, current, pulse duration, and pulse period were logged, and the resistance and discharged energy were calculated.

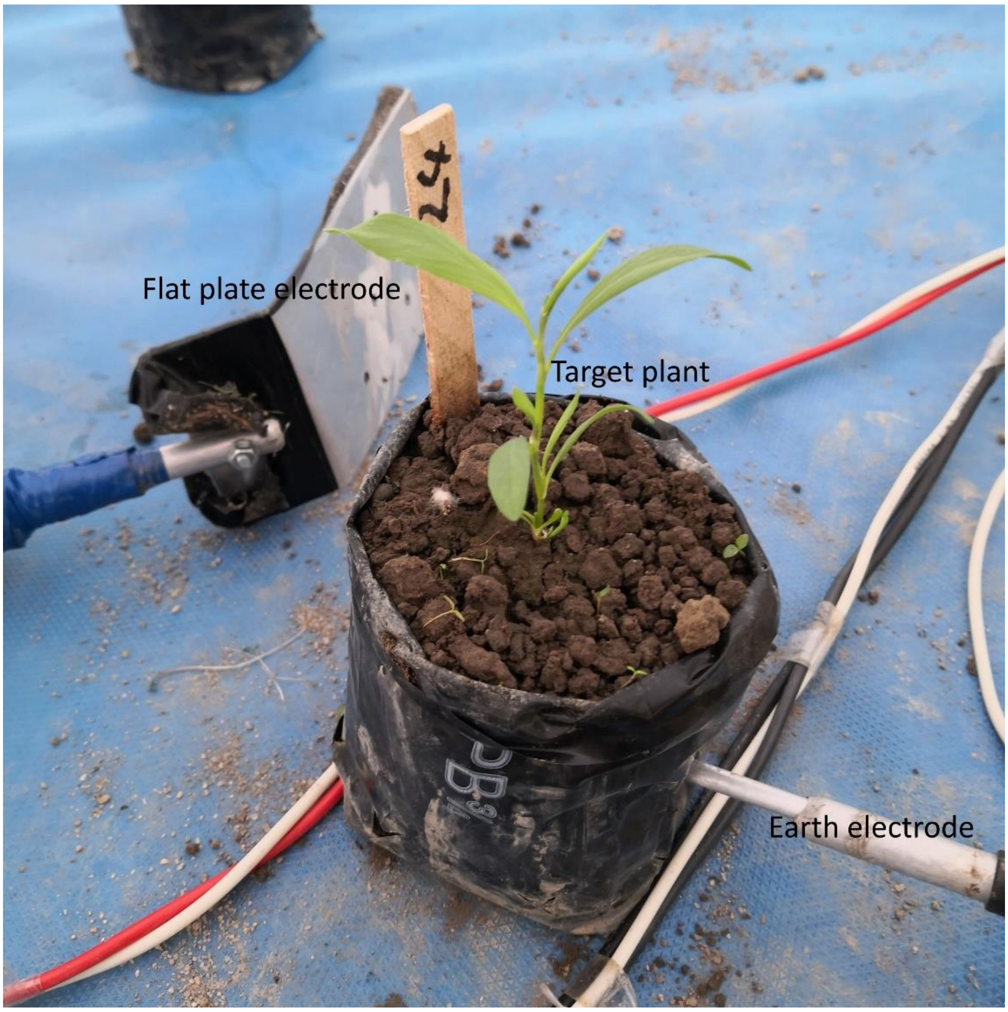

Figure 1. Application method showing the earth electrode inserted horizontally into the base of the bag and the flat plate electrode ready to be pressed against the weed (*Polygonum aviculare*).

One or two days prior to treatment, the top of the soil in "dry" treatments was cultivated 1–2 cm deep to encourage a layer of dry soil peds at the surface. As *Lolium multiflorum* had three plants in each bag, the plate electrode was pressed to all plants in each bag at once so that the dose was shared among the three plants. A range of treatments were applied, with various combinations of voltage, pulse length, pulse number, electrode placement, and soil surface moisture status compared against the controls, which were pressed but not shocked. The minimum voltage was 3 kV, and the maximum was 4.5 kV (Table 1).

Table 1. Trial summary table showing trial number, weed species, plant size, and treatments applied.

Trial	Species	Mean Size	Treatments
1	*L. multiflorum*	1.63 tillers, 3.65 leaves, longest leaf 141 mm	Control plus nine treatments: 3 kV; 100 µs pulses; 50, 100, and 200 pulses applied to the leaves only or leaves pressed to a dry or wet soil surface
2	*L. multiflorum*	1.91 tillers, 4.05 leaves, longest leaf 197 mm	Control plus 10 treatments: 100 × 200, 200 × 200, and 200 × 400 µs pulses at 3.5 kV applied to leaves only or leaves pressed to a dry soil surface; 100 × 100, 200, or 400 µs 4.5 kV pulses or 50 × 100 µs 4.5 kV pulses pressed to a dry soil surface
3	*P. aviculare*	42 mm stem length, 1.0 mm stem basal diameter, 12.2 leaves	Control plus 10 treatments: 3.0 and 4.5 kV, pulse lengths 50–200 µs, 100–400 pulses, plate pressed to soil. One treatment of 4.5 kV 200 × 200 µs pulses was applied to the leaf only
4	*A. powellii*	34.3 mm stem length, 1.6 mm stem basal diameter, 8.5 leaves, 3.5 side shoots	Control plus eight treatments with the electrode on leaves only or on leaves pressed to soil; 4.5 kV; 100 or 200 µs pulse length; 50, 100, and 200 pulses. 1 treatment with 10 × 1000 µs pulses
5	*A. powellii*	64.3 mm stem length, 1.8 mm stem basal diameter, 9.8 leaves, 5.8 side shoots	Control plus 8 treatments: 4.5 kV, 25 and 50 × 100 µs pulses with electrode on leaves only or on leaves pressed to dry soil; 5 × 250, 500, or 1000 µs pulses or 1 × 5000 µs pulse pressed to dry soil
6	*A. deflexus*	40.1 mm stem length, 1.4 mm stem basal diameter, 7.2 leaves, 4.6 side shoots	Control plus one treatment at 4.5 kV with 50 × 100 µs pulses applied to leaves pressed to a dry soil surface
7	*S. nitidibaccatum*	63.0 mm stem length, 2.9 mm stem basal diameter, 27 leaves, 3.5 side shoots	Control plus eight treatments at 3.18 and 4.50 kV, 25 and 50 × 100 µs pulses with electrode on leaves only or on leaves pressed to dry soil and 1 × 5000 µs pulse at 3.18 kV to leaves pressed to dry soil

Prior to treatment, *L. multiflorum* plants were visually assessed, the number of green leaves and tillers were counted, and the length of the longest leaf of each plant was measured. Following treatment, measurements were repeated, and plant deaths were recorded 10 days after treatment (DAT). Severely shrivelled or dead parts of the leaf were discounted. Surviving plants were measured and harvested, and their fresh mass was determined. Plants from each bag were aggregated, oven-dried at 62 °C for 3 days, and reweighed. The mean plant dry weight was determined for the surviving plants in each bag.

Prior to treatment, the *P. aviculare*, *A. powellii*, *A. deflexus*, and *S. nitidibaccatum* plants were measured and graded by size before being sorted into equivalent groups for treatment. They were monitored for 24 days post-treatment, at which time final measurements were made, including survival (dead or alive), days to death, stem length, stem basal diameter, fresh mass of green tissue, and subsequent dry mass after oven drying at 62 °C for 3 days. All the plants that were not obviously dead were classified as alive. Dead plants had no green mass and were recorded as 0 g.

Data were statistically analysed using SPSS Version 28.0.1.0 (142). Where biomass differences are reported, the default for statistical comparisons of groups was the independent samples Kruskal–Wallis one-way ANOVA (k samples) because almost all cases failed the ANOVA homogeneity of variance using Levene's test. Homogenous subsets were determined from post hoc analyses using all pairwise multiple comparisons. Following the recommendations of Armstrong [28] and Perneger [29], no multiple test (e.g., Bonferroni) corrections were applied. For *L. multiflorum*, biomass data were analysed with each bag of three grasses representing one replicate (n = 6), a sample size satisfactory for Kruskal–Wallis [30].

The dichotomous result "dead" or "not dead" at the end of each experiment was analysed using binary logistic regression. *Polygonum aviculare, A. powellii*, and *S. nitidibaccatum* modelling included set voltage, electrode placement, set energy, energy applied, leaf number, shoot number, and stem diameter. Those parameters that did not add to the model were discarded.

3. Results

Throughout all trials, no control plants died, and all grew healthily.

3.1. *Lolium Multiflorum*

When 3.0 kV multiple pulse treatments were applied to *L. multiflorum* (Trial 1), only three of 180 plants died. However, the Kruskal–Wallis test showed there were significant differences in the final plant dry mass at 10 DAT (H (9) = 31.64, $p < 0.001$), with the two higher-dose treatments (100 × 100 µs pulses and 200 × 100 µs pulses) that pressed the plants to dry soil being the most effective (Figure 2).

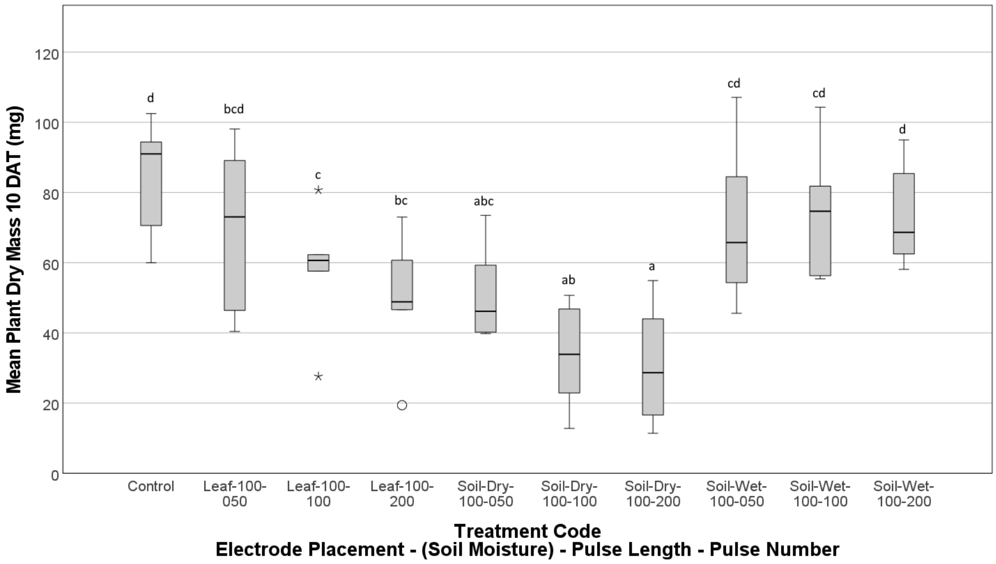

Figure 2. Simple box plot of mean *L. multiflorum* plant dry mass per bag 10 days after treatment by treatment applied, with treatments varying by placement of the electrode (electrode contact), the electric pulse length, and the number of pulses applied in the treatment. Asterisks indicate extreme outliers, and the circle indicates a mild outlier. Plots sharing the same letters are not significantly different.

Doubling the number of pulses doubled the amount of energy discharged. Excluding the untreated controls, the energy discharged under each treatment was compared using the Kruskal–Wallis test, which showed that there were significant differences (H (8) = 49.713, $p < 0.001$). Treatments were categorised into homogeneous subsets based on an asymptotic significance level of $p = 0.05$. The same doses applied to dry soil discharged more energy than those applied to leaves only but fell into the same homogenous subsets. Applications to wet soil resulted in up to five times more energy being discharged than the same dose applied to leaves only, such that the lowest dose in the wet soil treatment discharged the same energy as the highest leaf or dry soil dose (Figure 3).

On the basis of these results, a second *L. multiflorum* trial (Trial 2) was conducted at two higher voltages, 3.5 and 4.5 kV. The leaf versus dry soil surface application comparisons continued, but the wet soil treatments were dropped. Of 192 plants treated in Trial 2, only 34 died. The most effective leaf-applied 3.5 kV treatment with 200 × 400 µs pulses killed 44% of plants treated at an average of 69 J per application or 23 J plant^{-1}. The most effective treatment was the 4.5 kV treatment with 100 × 400 µs pulses pressed to the soil, which killed half the plants at an average of 102 J or 34 J plant^{-1}. The lowest-dose leaf treatment (3.5 kV, 100 × 200 µs pulses), the lowest-dose 3.5 kV soil-applied treatment (100 × 200 µs pulses), and the lowest two 4.5 kV soil-applied treatments (50 × 100 µs pulses and 100 × 100 µs pulses) were ineffective, with no plants dying (Figure 4). The Kruskal–Wallis test showed there were significant differences in the plant death rate by 14 DAT (H (10) = 35.3, $p < 0.001$), with all treatments that resulted in any deaths being significantly different to the control, as assessed by homogeneous subsets based on an asymptotic significance level of 0.05.

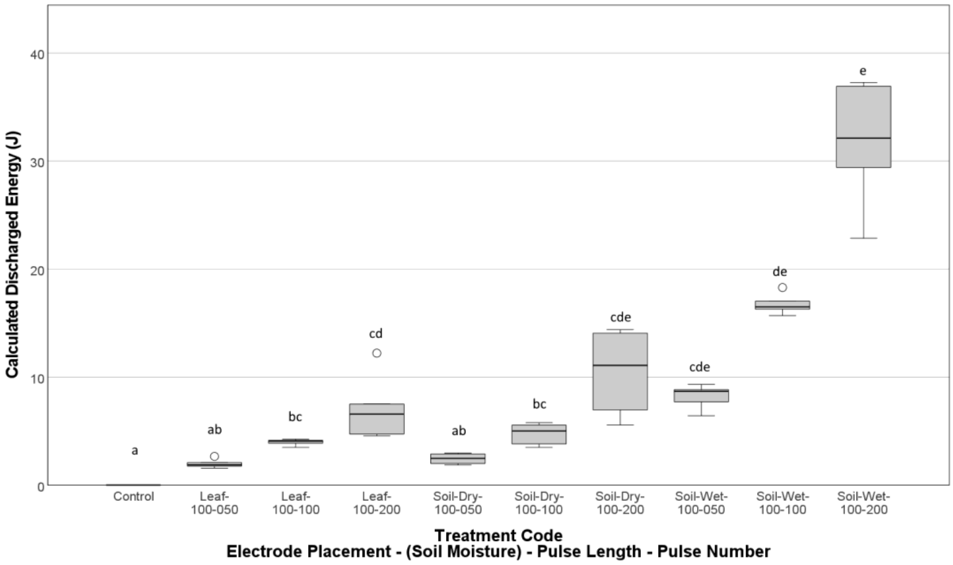

Figure 3. Simple boxplot of calculated discharged energy (J) by treatment when multiple DC electric pulses of varying pulse lengths were applied to sets of three *L. multiflorum* seedlings in bags with a flat-plate electrode pressed to the leaves only or plants pressed to the soil with either a dry or wet soil surface. Mild outliers are indicated by small circles. Plots sharing the same letters are not significantly different.

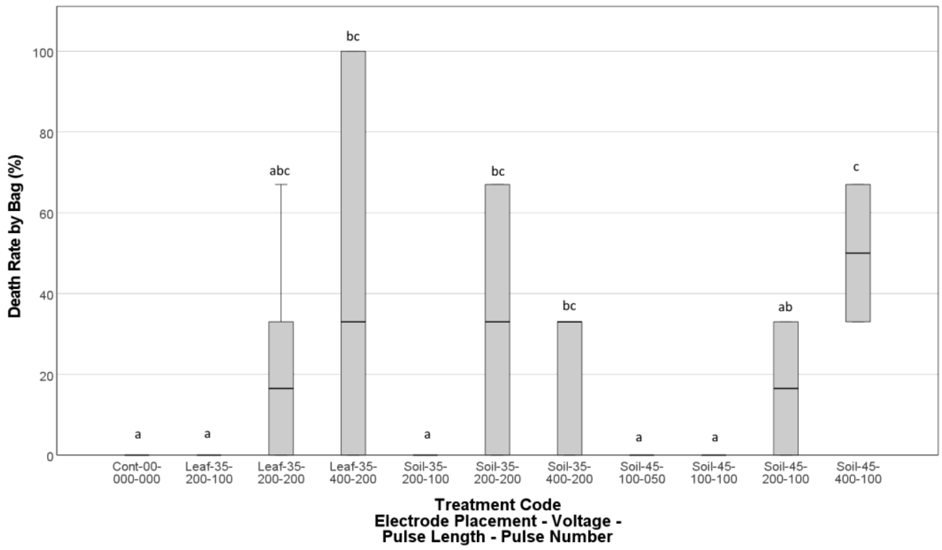

Figure 4. Simple box plot of *L. multiflorum* final death rate per bag when treated with pulsed microshocks at a range of voltages, pulse lengths, and number of pulses, which were applied to leaves only or to leaves pressed to the soil. Plots sharing the same letters are not significantly different.

The Kruskal–Wallis test showed that there were significant differences in the final plant dry mass (Figure 5) at 14 DAT (H (10) = 40.9, $p < 0.001$). The leaf-applied treatment at 3.5 kV with 100 × 200 µs pulses and the soil-applied treatments at 4.5 kV with 50 × 100 µs pulses and 100 × 100 µs pulses were not significantly different to the control. The soil-applied treatment at 3.5 kV with 100 × 200 µs pulses and the treatment at 4.5 kV with 100 × 100 µs pulses did not result in any plant deaths, but the dry mass of plants from these treatments at 14 DAT were significantly different to the control.

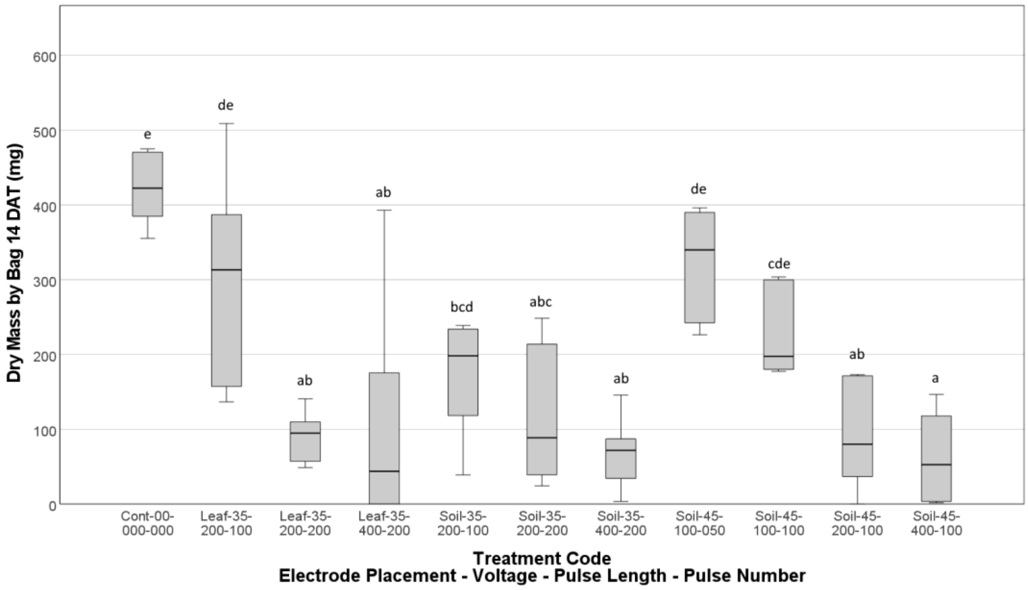

Figure 5. Simple box plot of *L. multiflorum* plant dry mass by bag (mg) measured 14 days after treatments were applied to leaves only or to leaves pressed to the soil with pulsed microshocks at 3.5 or 4.5 kV with different pulse lengths and a different number of pulses applied to plants. Plots sharing the same letters are not significantly different.

Plotting the final plant dry mass against the energy discharged by treatments indicates a point at which plants reach zero dry mass, i.e., will be killed. Figure 6 shows collected data and a linear trend line, with the individual 90% confidence lines fitted.

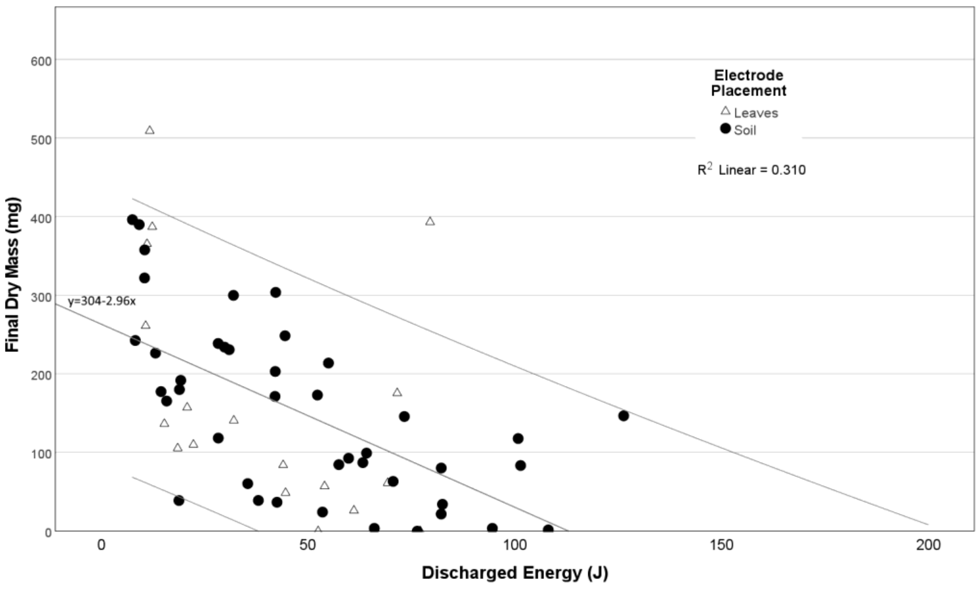

Figure 6. Scatter plot of *L. multiflorum* plant dry mass (mg) by discharged energy (J) by electrode placement with overall linear fit line bounded by 90% individual confidence levels.

A review of the energy discharged by treatment showed predictable increases as the voltage, length of pulses, or number of pulses increased (Figure 7). At 3.5 kV, the energy discharge rate was 51% higher for the soil contact compared with leaf-only contact. The energy discharge rate of soil contact was 93% higher at 4.5 kV than at 3.5 kV.

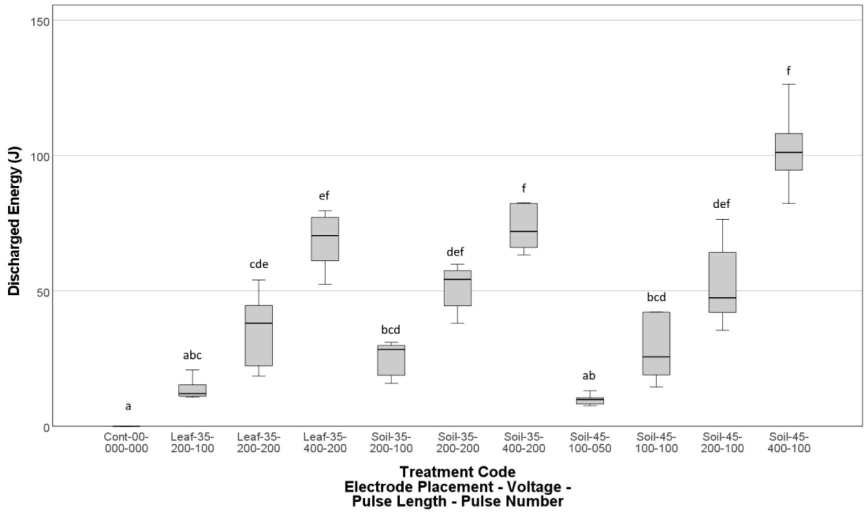

Figure 7. Simple box plot of discharged energy (J) applied to *L. multiflorum* by treatments at 3.5 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied to plants. Plots sharing the same letters are not significantly different.

3.2. *Broadleaf Weeds*

Treatments for *P. aviculare* applied both 3.0 kV and 4.5 kV doses to plants pressed to the soil surface, with pulse length and number aiming to double and redouble energy applying between 15 and 120 J. However, machine firmware limited the possible number of pulses, and the maximum was reduced to 81 J. An additional treatment applied 4.5 kV doses with the flat electrode pressed to the leaves only. Pressing the plant to the soil surface without applying electric shocks did not kill any plants.

The leaf-applied 4.5 kV treatment killed all plants (Figure 8) despite the discharged energy being far less than that for the soil treatments (Figure 9).

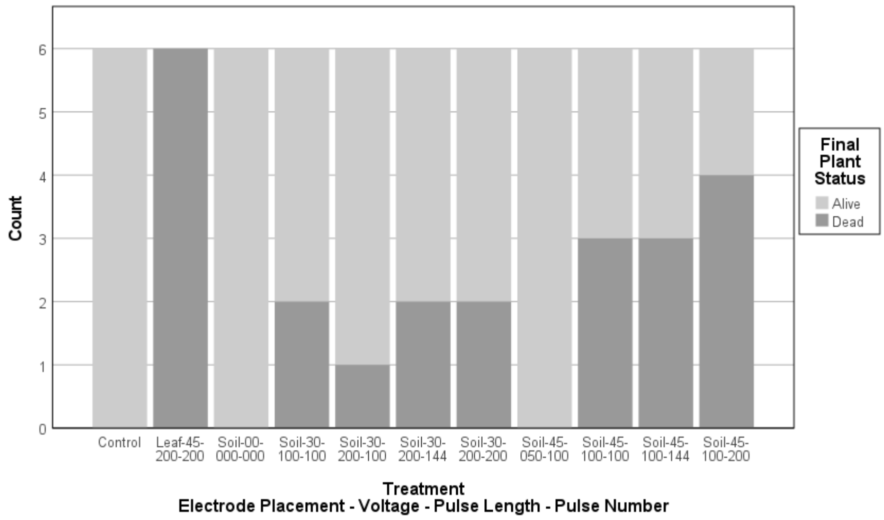

Figure 8. Stacked histogram count of treatment by final status of *P. aviculare* plants that were subjected to treatments at 3.0 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied with the electrode pressed to the leaves only or to the leaves pressed against the soil.

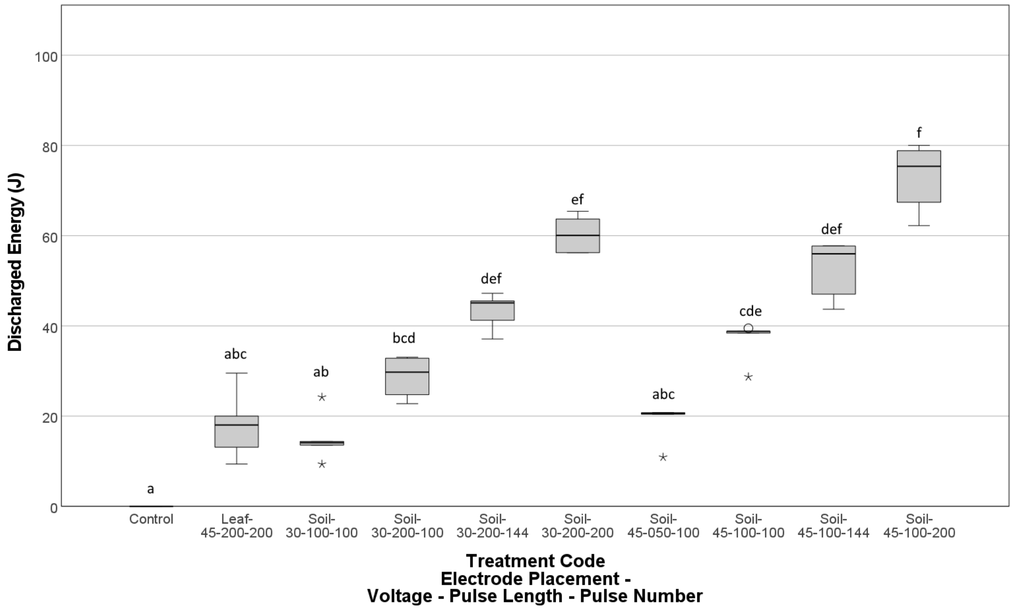

Figure 9. Simple box plot of discharged energy (J) applied to *P. aviculare* by treatments at 3.0 kV and 4.5 kV at different electric pulse lengths and a different number of pulses applied with the electrode pressed to the leaves only or to the leaves pressed against the soil. Extreme outliers are indicated by stars. A mild outlier is indicated by a small circle. Plots sharing the same letters are not significantly different.

The average energy discharge was 17.9 J plant^{-1}, equivalent to 0.895 MJ ha^{-1} if treating five plants m^{-2}. With the plate electrode pressing plants to the soil surface, about one-third of *P. aviculare* weed seedlings were killed by the 3.0 kV treatments, with no greater effect as the energy increased. The 4.5 kV treatments did show an increase in effectiveness with increasing energy, although no soil-applied treatments were fully effective. The most effective was the strongest 4.5 kV treatment that applied 200 × 100 µs pulses, with a kill rate of 66%. The same patterns were shown in the final dry mass measurements (Figure 10). The Kruskal–Wallis test showed that there were significant differences in final dry mass (H (10) = 32.29, $p < 0.001$) but only between the control and leaf-applied 4.5 kV, 200 × 200 µs pulses ($p = 0.001$), control and soil-applied 4.5 kV, 200 × 100 µs pulses ($p = 0.006$), and control and soil-applied 4.5 kV, 144 × 100 µs pulses ($p = 0.032$).

A logistic regression was performed to ascertain the effects of treatment on the likelihood that plants would be killed. The logistic regression model was statistically significant, $\chi^2(10) = 32.733$, $p < 0.011$. The model explained 53.9% (Nagelkerke R^2) of the variance in the outcome and correctly classified 77.3% of the cases. A second regression was performed using set voltage, discharged energy, stem length, stem diameter, leaf number, soil or leaf contact, and pulse length on the likelihood that plants would be killed. The logistic regression model was statistically significant, $\chi 2(8) = 23.351$, $p < 0.003$. The model explained 43.8% (Nagelkerke R^2) of the variance in the outcome and correctly classified 76.7% of cases. Hosmer and Lemesow also indicated good fit $\chi 2(8) = 5.213$, $p < 0.735$. However, no variables were independently significant. When the leaf application treatment was removed from the analysis, the model was not statistically significant, $\chi 2(5) = 6.716$, $p = 0.243$. The model explained 16.4% (Nagelkerke R^2) of the variance in the outcome but correctly classified 74.1% of the cases.

The measured discharged energy when the plate electrode was pressed to the soil was very close to the values estimated in earlier trials, with the overall $R^2 = 0.956$. The mean resistance with the plate pressed to the soil surface was 5430 Ω. When the plate was rested on the leaves with no soil contact, the resistance was 9.3 times higher, at 50,400 Ω. This led to the current being only 13.7% and the average discharged energy being 20% of the equivalent for soil contact.

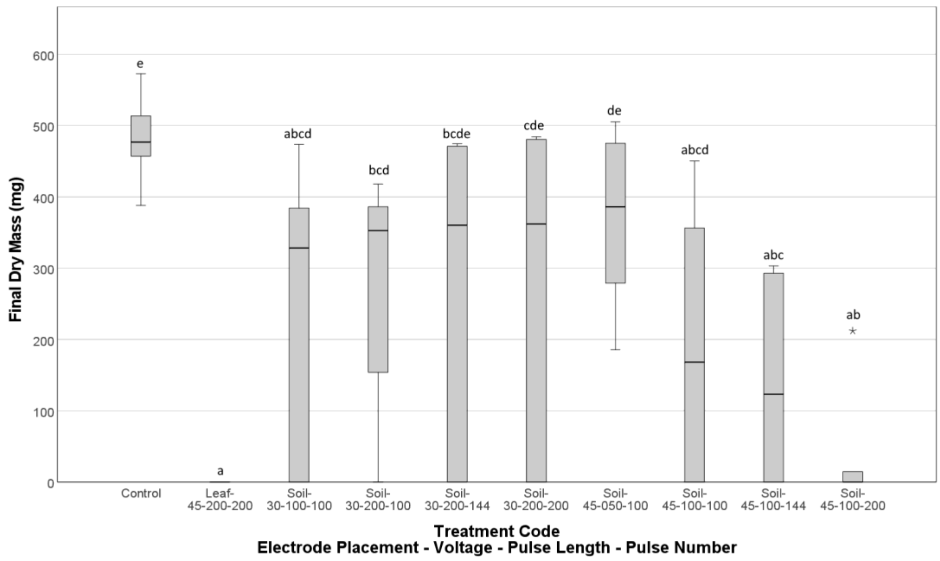

Figure 10. Simple boxplot of *P. aviculare* final dry mass following application of treatments at 3.0 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied with the electrode pressed to the leaves only or to the leaves pressed against the soil. An extreme outlier is indicated by the star. Plots sharing the same letters are not significantly different.

Two trials applied treatments to *A. powellii* seedlings. The first trial (Trial 4) used 4.5 kV treatments applying 50 or 100 pulses of 100 µs duration or 100 or 200 pulses of 200 µs duration with the flat plate electrode either on the leaves only or pressed to the soil. An additional treatment applied 10 × 1000 µs pulses to plants pressed to the soil. All but one of the treated plants died within 7 days, and the last outlier died after 23 days. Even the weakest 4.5 kV treatment with 50 × 100 µs pulses applied to the soil killed all plants. A dose of 3 J applied to the leaves only or 5 J applied to plants pressed to dry soil was sufficient to kill all plants. A Kruskal–Wallis test was completed with the "Life Days" of the surviving plants set to 25, the end of observations when survivors were completely healthy and growing. All treatments were significantly different to the control plants (H (9) = 29.89, $p < 0.001$). The soil-applied 4.5 kV, 100 × 100 µs treatment, which died faster, was different to the leaf-applied 4.5 kV, 50 × 100 µs pulse treatment, which lasted longer.

The second trial (Trial 5) repeated the 4.5 kV voltage level, applying 25 or 50 × 100 µs pulses with the flat-plate electrode either on the leaves only or pressed to the soil, and 5 × 250 µs, 500 µs, or 1000 µs pulses pressed to the soil. An additional 3.0 kV treatment applied a single 5000 µs pulse pressed to the soil. Some leaf-treated plants and 35 of 36 soil-treated plants died (Figure 11). The surviving soil-treated plant had received the lowest measured energy discharged (1.13 J) of any soil-treated plants, a level similar to leaf-treated plants that did not die. All plants receiving more than 3 J treatments died. A logistic regression was performed to ascertain the effects of treatment on the likelihood that plants would be killed. The logistic regression model was statistically significant, $\chi^2(5) = 27.425$, $p < 0.001$. The model explained 58.4% (Nagelkerke R^2) of the variance in the outcome and correctly classified 85.2% of the cases.

Electrical measurements showed significant differences when the same dose was applied with the plate electrode pressed to the soil surface, discharging at least twice as much energy (Figure 12), e.g., 4.5 kV, 25 × 100 µs pulses ($p = 0.012$) and 4.5 kV, 50 × 100 µs pulses ($p = 0.032$).

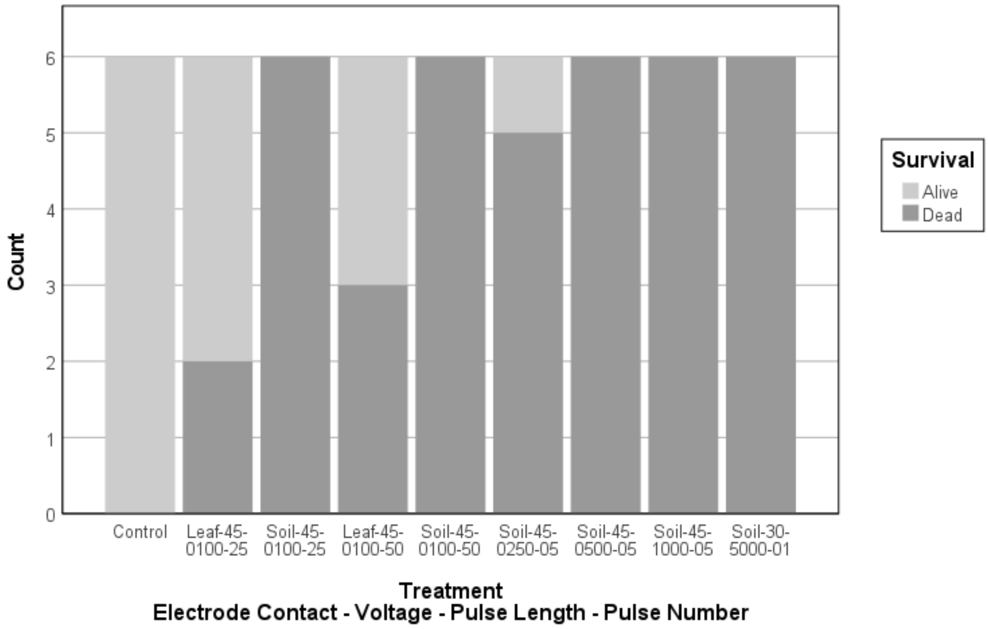

Figure 11. Stacked histogram count of treatment by survival of *A. powellii* following application of treatments at 4.5 kV with different electric pulse lengths and a different number of pulses applied with the electrode pressed to the leaves only or to the leaves pressed against the soil.

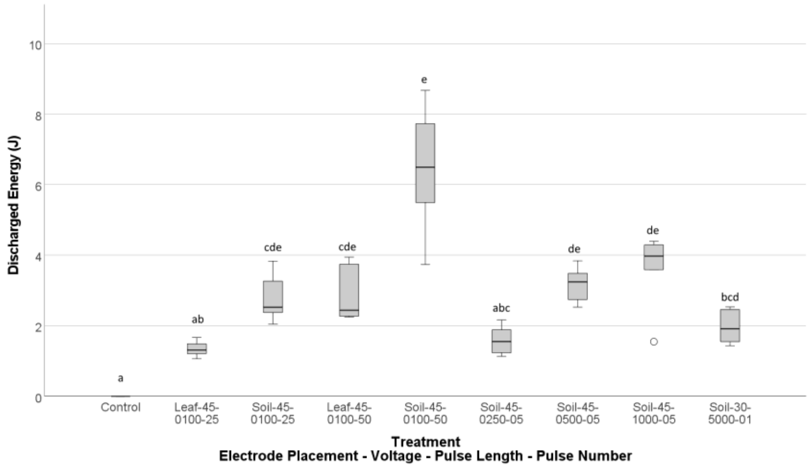

Figure 12. Clustered boxplot of measured energy (J) discharged when *A. powellii* were subjected to treatments at 3.0 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied to plants with the electrode pressed to the leaves only or to the leaves pressed against the soil. A mild outlier is indicated by the small circle. Plots sharing the same letters are not significantly different.

A Kruskal–Wallis test was completed with the longevity of the surviving plants set to 28 days, the end of observations when survivors were completely healthy and growing (Figure 13). It showed that there was a significant effect of treatments (H (8) = 25.269, $p < 0.001$). Unadjusted significant differences were found between the untreated control and all soil-applied treatments but not with the leaf-applied treatments. There were significant differences in longevity between the lower energy leaf treatment at 4.5 kV with 25 × 100 µs pulses and soil treatments at 4.5 kV with 5 × 500 µs pulses, 4.5 kV with 5 × 1000 µs pulses, 4.5 kV with 50 × 100 µs pulses, and 3.0 kV with 1 × 5000 µs pulse but not at 4.5 kV with 5 × 250 µs pulses or 4.5 kV with 5 × 500 µs pulses. The higher-energy leaf treatment at 4.5 kV with 50 × 100 µs pulses was significantly different to the soil treatment at 4.5 kV with 5 × 1000 µs pulses but not to other treatments. The more sensitive

Jonckheere–Terpstra test also indicated a significant difference between the control and the stronger leaf treatment at 4.5 kV with 50 × 100 μs pulses.

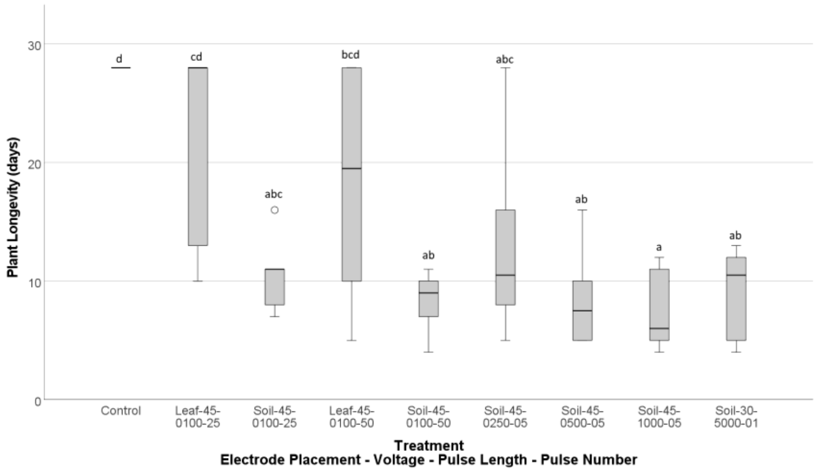

Figure 13. Simple boxplot of plant longevity when *A. powellii* were subjected to treatments at 3.0 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied to plants with the electrode pressed to the leaves only or to the leaves pressed against the soil. Plant assessment stopped 28 days after treatment. A mild outlier is indicated by the small circle. Plots sharing the same letters are not significantly different.

Final plant dry mass measurements included dead tissues so that dead plants would have a positive recorded weight, reflecting any growth at treatment plus additional biomass accumulation before death (Figure 14). A Kruskal–Wallis test showed significant effects of treatment (H (8) = 19.915, $p < 0.011$). Unadjusted significant differences were found between the untreated control and all treatments except the lowest-energy leaf-applied treatment at 4.5 kV with 25 × 100 μs pulses. The lower-energy leaf treatment at 4.5 kV with 25 × 100 μs pulses was significantly different to the soil treatments at 4.5 kV with 50 × 100 μs pulses and 4.5 kV with 5 × 1000 μs pulses.

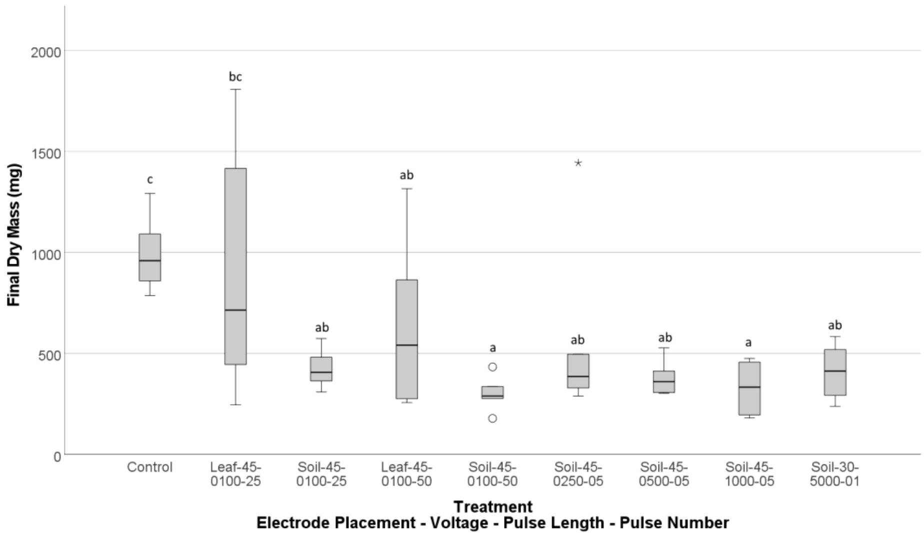

Figure 14. Simple boxplot of *A. powellii* final plant dry mass when plants were subjected to treatments at 3.0 kV and 4.5 kV with different electric pulse lengths and a different number of pulses applied to plants with the electrode pressed to the leaves only or to the leaves pressed against the soil. An extreme outlier is indicated by the star. Mild outliers are indicated by the small circles. Plots sharing the same letters are not significantly different.

The third associated trial (Trial 6) using the slightly smaller *A. deflexus* applied 50 × 100 µs pulses at 3.0 kV with the flat-plate electrode pressed onto the plant and soil surface. All treated plants and no control plants died. The energy discharged averaged 1.64 J and was not significantly different to the same voltage single 5000 µs pulses applied to *A. powellii* in the same soil type and bags, which averaged 2.46 J (ANOVA $p = 0.369$).

Trial 7 with *S. nitidibaccatum* applied four increasing energy treatments with the electrode pressed to leaves only and with the electrode pressing plants to the soil surface. Energy levels were based on changing voltage and pulse number. The voltages used were 4.500 kV and 3.182 kV, which, in theory, has half the energy. Either 25 or 50 × 100 µs pulses were applied. A ninth treatment applied a single 5000 µs pulse to the leaves only at 3.182 kV, theoretically the same energy as the 50 × 100 µs pulses.

When electrical doses were applied with the electrode pressed to the plant leaves only, 18 of 24 plants died. All but one of the plants treated with 4.5 kV died. Only two of the 24 plants given the same doses died when the electrode pressed the plant against the soil surface. None of the plants treated with a single long pulse died. The surviving 4.5 kV leaf-treated plant received the lowest discharge of the treatment (3.6 J compared with the 5.5 J treatment average). All plants receiving leaf-contact applications with a discharge greater than 3.6 J died. The energy discharges for the two soil-pressed plants that died were 9.9 J and 19.9 J.

A Kruskal–Wallis test showed significant effects of treatment on the final dry mass (H (9) = 21.497, $p = 0.011$). However, only two 4.5 kV leaf-applied treatments, 4.5 kV with 25 × 100 µs pulses ($p = 0.014$) and 4.5 kV with 50 × 100 µs pulses ($p = 0.002$), were significantly different to the control. The was no significant biomass difference between the control and treatments with the electrode pressing the plant to the soil.

Higher energy doses gave higher measured energy discharges in all equivalent cases (Figure 15). At 3.182 kV, the treatments applied with plants pressed to the soil discharged 226% more energy than the same dose applied to the plant leaves only. At 4.5 kV, the soil discharges were 145% higher than the leaf discharges. Only one pairing of treatments that were expected to have the same discharge, leaf-applied and soil-applied 3.18 kV with 50 × 100 µs pulse doses, showed the possibility of a significant difference when analysed independently (Sig. = 0.017), but when the Bonferroni correction was applied, the difference was insignificant (Adj. Sig. = 0.776) (Table 2). The leaf-applied 4.5 kV with 50 × 100 µs pulses treatment killed all plants with an average energy discharge of 12.5 J plant^{-1}, equating to 0.625 MJ ha^{-1} at five plants m^{-2}.

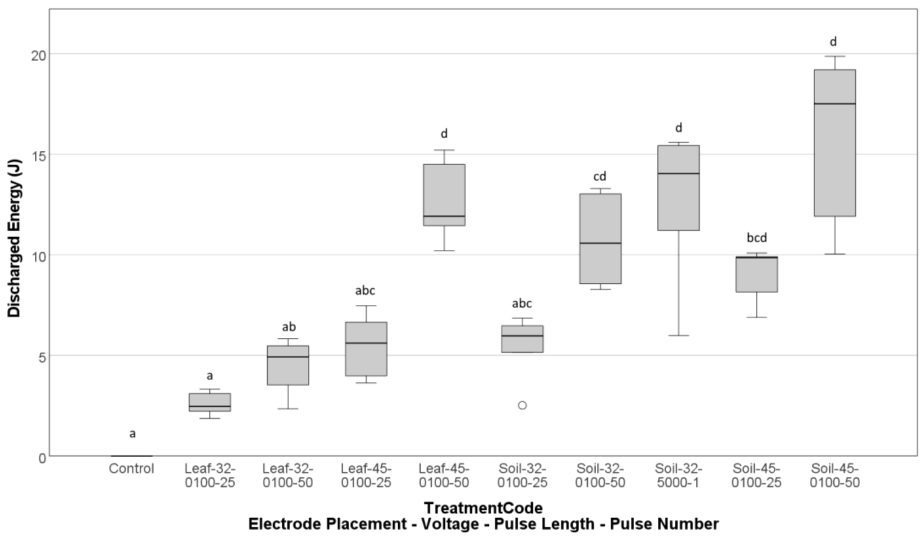

Figure 15. Clustered boxplot of discharged energy (J) by dose applied by electrode placement when PMS was applied to *S. nitidibaccatum*. A mild outlier is indicated by the small circle. Plots sharing the same letters are not significantly different.

Table 2. Comparison of selected electrical dose applications showing mean discharged energy, difference between treatment pairs and Kruskal–Wallis pairwise comparisons of selected treatments with (Adj.Sig.) and without Bonferroni corrections (Sig.).

Treatments		Mean Value			Pairwise Comparisons of Treatments				
Treatment 1	**Treatment 2**	**Treat 1**	**Treat 2**	**Difference**	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
Leaf-32-0100-25	Soil-32-0100-25	2.573	5.491	2.134	−12.333	10.078	−1.224	0.221	1.000
Leaf-32-0100-50	Soil-32-0100-50	4.505	10.720	2.380	−24.000	10.078	−2.381	0.017	0.776
Leaf-45-0100-25	Soil-45-0100-25	5.493	9.127	1.662	−12.667	10.078	−1.257	0.209	1.000
Leaf-45-0100-50	Soil-45-0100-50	12.535	16.010	1.277	−5.500	10.078	−0.546	0.585	1.000
Leaf-32-0100-50	Leaf-45-0100-25	4.505	5.493	1.219	4.505	5.493	1.219	0.620	1.000
Soil-32-0100-50	Soil-45-0100-25	10.720	9.127	0.851	10.720	9.127	0.851	0.530	1.000
Soil-32-0100-50	Soil-32-5000-01	10.720	12.717	1.186	−5.167	10.078	−0.513	0.608	1.000
Soil-45-0100-25	Soil-32-5000-01	9.127	12.717	1.393	11.500	10.078	1.141	0.254	1.000

The energy discharge of energy equivalent pairs with different voltage balanced by the number of pulses, 3.18 kV with 5 × 100 µs pulses and 4.5 kV with 25 × 100 µs pulse doses, were 21.9% higher and 14.9% lower in the cases of leaf and soil applications, respectively.

4. Discussion

The objectives of this study were to determine whether a flat plate used in a practical, 'paddock-treatment' way could apply a threshold dose of voltage and energy to weed seedlings to achieve >90% mortality, to assess energy expenditure, and to compare relative responses of different species. Two electrode placements were tested: the plate pressed against the plant only with a 3 cm separation from the soil surface and the plate pressing the plant onto the soil, with the soil surface either wet or dry. As in our earlier trials [18], we again found that different species had different sensitivities to PMS, a result similar to the findings of Lati et al. [16], who tested seedlings of analogous species: *Lolium rigidum*, *Sorghum halepense*, *Amaranthus retroflexus*, and *Portulaca oleracea*.

The flat plate method failed to adequately control tillering *L. multiflorum* plants, with the best treatment killing only half the treated plants, much less than the target rate of 90% control. However, the flat plate treatment with PMS had a limiting effect on growth and significantly reduced growth rates. A linear trend line with individual 90% confidence lines fitted to the trial data suggested that complete control of *L. multiflorum* can be achieved at about 200 J. While the trial treated three plants with each application, this does not imply that the per-plant dose may be 70 J, because much of the energy is directly lost to the soil. However, if successfully treating an average of three plants per application was achieved, it does indicate an energy requirement of under 1.0 MJ ha^{-1} if treating five plants m^{-2}.

While monitoring plants post-treatment, we observed that if any tillers emerged, the plant recovered. However, the subsequent growth delay may allow crop plants growing alongside treated grass weeds to develop unimpeded. We previously suggested that insufficient energy reached the meristems of *L. multiflorum* at or below ground level within the stem sheath, enabling newly developing tillers to survive [18]. This was also postulated by Lati et al. [16] who reported an 85% biomass reduction when *L. rigidum* plants were treated 2 weeks after sowing. They do not provide information on plant size at treatment or whether any plants died. Our earlier work treated younger *L. multiflorum* plants that, in most cases, were not tillering and found that 3 kV was more effective than 6 kV when a point electrode was applied to the leaves [18]. The trials reported here used 3.0, 3.5, and 4.5 kV treatments and did not show conclusive evidence that voltage is a key determinant of the plant death rate or post-treatment biomass.

Treating broadleaf weed seedlings was effective, and all trials showed that PMS could achieve the target >90% kill rate at <2 MJ ha^{-1}. Different broadleaf species of approximately similar sizes require different doses to achieve the target kill rate with, in decreasing energy order, *P. aviculare* > *S. nitidibaccatum* > *A. powellii* > *A. deflexus*. A single leaf-applied treatment killed all *P. aviculare* weeds with 17.9 J plant^{-1}, equivalent to 0.895 MJ ha^{-1} if treating five plants m^{-2}. While not tested, the data for soil-applied PMS suggest that the 90% target could be achieved by increasing the pulse length to 200 µs, the same as the leaf treatment, but the energy discharge would be far greater.

Treatments applied only to the leaves of *S. nitidibaccatum* were more effective than the same doses applied to leaves pressed to the soil. The most effective treatment was leaf-applied and killed all plants, with an average energy discharge of 12.5 J plant^{-1}, equating to 0.625 MJ ha^{-1}. When treated with half the dose, 83% of plants were killed. Only one plant died when these doses were applied with the electrode pressing the plant to the soil. Our earlier point-electrode trials [18] showed PMS to be less effective when treating the related species *Solanum nigrum*, with no treatment killing all plants. These are fleshy species with the ability to regenerate roots from aerial stem tissues. We observed that plants that successfully established new roots in the soil were able to recover, although their growth was delayed. Similarly, Lati et al. [16] noted biomass reduction of the fleshy *Portulaca oleracea* but did not report deaths.

Treatments applying only 3 J to *A. powellii* plants by leaf contact only or 5 J to plants pressed to the soil were fully effective in Trial 4, with a kill rate of 100%. In Trial 5, treatments applied to plants pressed to the soil killed all plants with an average of 2.76 J plant^{-1}, equivalent to 0.138 MJ ha^{-1}. The same applications to leaves only discharged 1.34 J plant^{-1}. All plants receiving more than 3 J died. Although slightly smaller when treated, the closely related *A. deflexus* seedlings all died when they received treatment with the flat plate electrode pressed onto the plant and the soil surface and discharged energy of an average of 1.64 J plant^{-1}, equivalent to 0.082 MJ ha^{-1}.

Electrical weeding technology typically uses very high electrical current treatments and attributes control to resistive heating, causing cell damage, boiling, and disruption [19,31–33]. These methods are characterised by a rapid impact on plants, with steam or flames often reported. Our very low-energy treatments do not exhibit the same instantaneous effects, often taking several days or more for symptoms to become apparent. While we have not determined a mechanism for death, there is no obvious evidence of cellular boiling, and the applied energy seems inadequate to severely raise tissue temperatures. Lehnhoff et al. [34] noted that 'mechanisms by which plants die by an electric current are not well understood'. Their work applied relatively low currents to large plants and trees for a very long duration and effected control. This leads us to ponder whether some other plant response is triggered by the treatments, eventually leading to plant death.

We note that our use of a flat plate electrode generated an electrostatic field between the plate and the ground, which may have affected the plant's cells and membranes [35–39]. The application of an external electric field can control the elongation of shoots and roots [40], and even sub-lethal electric currents can act as abiotic elicitors that increase the production of secondary plant metabolites [41] as for a disease response. The role of secondary metabolites in programmed cell death is variously reported [42–44], suggesting that this is an area in which further research is warranted.

Our goal is a weeding system that can selectively remove weeds from field crops without a negative impact on crop plants. Our flat plate electrode is narrower than vegetable and arable crop row spacings and could be drawn between them, and in a robotic deployment, it could apply PMS only where weeds are present. We did not find evidence of significant damage to soil microbiota in the literature dealing with high-energy electric weeding, and we postulate that our very low-energy system is unlikely to have significant adverse effects. We have observed earthworms coming to the surface and moving away from treatment sites when we have applied repeated doses in our trial work. The flat plate electrode system would be less suited to intra-row weeding of very high-population crops that have close interplant spacings. We have yet to test for negative effects on adjacent crop plants but note that the much higher-powered systems for vineyard and orchard strip-weeding by Zasso [45] and others have shown no impacts on adjacent plants and leave a well-defined edge between treated and untreated sward zones.

5. Conclusions

These experiments used a flat-plate electrode to apply PMS to a range of species, using different voltages, pulse lengths, and pulse numbers to plants grown in bags in a greenhouse. They further demonstrate the potential of PMS as an ultra-low-energy treatment method for controlling small non-tillering grasses and a range of broadleaf weed species at the seedling stage. Very short, high-voltage DC treatments require far less energy than alternative weed control options, including currently available electrical weeding systems, and we achieved better control using less time and energy than other low-energy electrical weed treatment methods that have been reported. In these trials, our method killed only half of the treated *L. multiflorum* "Winter Star" plants, well below our target rate, but it significantly reduced growth rates and indicated that an effective treatment of <1.0 MJ ha^{-1} for treating five plants m^{-2} is possible. *Polygonum aviculare*, *A. powellii*, *A. deflexus*, and *S. nitidibaccatum* plants were successfully controlled using from 0.1 to 0.9 MJ ha^{-1}, indicating that broadleaf weeds are more susceptible than grasses, although different species require different doses. This result easily met our target effectiveness and efficiency goals. Although broadleaf weeds appear easier to kill than grasses, fleshy broadleaf species with the ability to produce aerial roots may be more difficult to control. Treatment is more energy-efficient when the electrode is separated from direct ground contact. The application with the plate electrode pressing on a wet soil surface used far more energy than that on a dry soil surface. Given the overall extremely low energy use, there is a practical opportunity for increasing doses to effect better seedling kill rates.

While these trials were conducted in a laboratory setting, with precise field application, the results should be replicable, and this is the subject of our ongoing research. The ability to apply PMS using a flat-plate electrode pressed to the plant leaves or plants and soil removes the issue of the very precise targeting required when using a point electrode. Coupled with the small energy requirement, this makes the system suitable for incorporation in a mobile hand-held weeding tool or individually or in groups in a precision robotic system to control herbicide-resistant weed seedlings that have escaped chemical or other control methods. Voltages have been kept below 10 kV, and the energy released by the equipment is low. In general, these would place the equipment used within the criteria acceptable for electric fence energisers [46,47].

Further research is needed to test the effectiveness of the flat-plate PMS system in the field. Among the issues to resolve are the optimum distance of the target plant and the treatment electrode from the earth electrode; the effect of soil conditions on weed control, including soil density, moisture level, and soil type; and whether target plants become more tolerant to electric treatment in an outdoor environment. Some of this research is currently underway.

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Conflicts of Interest: The authors declare no conflict of interest.

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