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Sub-second low-energy electrical application effectively controls small but not established plants of scentless mayweed (*Tripleurospermum inodorum*), wild oat (*Avena fatua*) and couch grass (*Elymus repens*)

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Abstract

For electrical weed control to become an efficient complement to herbicides and tillage, treatment times and energy use must be reduced. Four pot experiments were conducted, testing different voltage levels (5–20 kilovolts) and exposure times (0.2–13.5 s) to find the most efficient combination for weed control. Experiments tested (1) seedlings of the annual dicotyledon *Tripleurospermum inodorum* and the annual grass *Avena fatua*, treated at 18 and 14 days after sowing, respectively; (2) adult *T. inodorum* and *A. fatua* plants, treated at 6 weeks after sowing; (3) established plants of the perennial grass *Elymus repens*, cut 34 days after emergence and treated 14 days after the cut; (4) *E. repens* plants treated 17 days after planting. Five kilovolts was equally or more effective than higher voltage levels regardless of plant size. Five kilovolts for 0.2 s resulted in 100% mortality of *T. inodorum* seedlings and >99% reduction of *A. fatua* seedling shoot biomass. Five kilovolts for >1.5 s reduced the aboveground biomass of adult *T. inodorum* plants by >80%, compared to control. Five kilovolts for 4.5 s reduced the vegetative biomass of adult *A. fatua* plants by 47%, compared to control. Five kilovolts for 0.2 s killed the shoots of small *E. repens* plants, reducing shoot and rhizome biomass by 75% and 28%, respectively, compared to control. No treatment significantly reduced the established *E. repens* plants. In conclusion, 5 kilovolts for 0.2 s effectively kills small annual weeds and forces *E. repens* to resprout, but established plants need longer exposure times.

KEYWORDS

electrocution, electrophysical, electro-weeding, *Elytrigia repens*, integrated pest management, integrated weed management, microshocks, regenerative agriculture

1 | INTRODUCTION

In agricultural systems, weed management is necessary to avoid yield losses (Oerke, 2006). However, there is increasing concern over agriculture's overreliance on herbicides and tillage to control weeds. For herbicides, this is due to concerns over environmental persistence, groundwater pollution, effects on non-target organisms and residues in food (Van Bruggen et al., 2018). Moreover, there are concerns that the ever-increasing proliferation of herbicide-resistant weeds will eventually render chemical weed control impotent (Peterson et al., 2018). For tillage, the concerns instead centre around the fact that high tillage intensities can have detrimental effects on many aspects of soil health, for example, reduce soil organic carbon and microbial activity (Nunes et al., 2020). Tillage can also increase the risk of soil erosion and nutrient leaching by removing the protective vegetation cover from the soil (Klik & Rosner, 2020). Moreover, tillage is energy-and time-consuming.

Electricity has long been considered a promising weed control method since it is one of the few non-chemical methods that can kill both aboveground and belowground biomass without disturbing the soil (Wei et al., 2010). Thus, electricity can control not only annual weeds, but potentially also perennial weeds such as *Elymus repens* (L.) Gould (couch grass), *Cirsium arvense* L. (creeping thistle) and *Rumex* spp. (docks), which can survive disturbance by resprouting from their underground organs, such as rhizomes and taproots (Ringselle et al., 2020). Moreover, electricity can also be used for other purposes such as terminating leys and cover crops and desiccating potato plants (Klauk et al., 2023). Historically, the main obstacles to electrical weed control have been (a) the high energy use (and associated risk of fire), (b) the risk of electrocuting the operator and (c) the relatively long treatment time and consequently low capacity compared to herbicides and tillage. With increasing concerns over the negative effects of herbicides and tillage, there has been renewed interest in electrical weeding, and there are now several commercial products. For example, the Zasso XPower series including the XP300, Thor, XPS and others; the NUCROP; the RootWave Pro; and RootWave Top Fruit (Slaven et al., 2023), and the Weed Zapper (Schreier et al., 2022).

The commercial machines have been evaluated in their ability to control many different annual weeds (e.g., Koch et al., 2020; Schreier et al., 2022; Tatnell et al., 2020) and perennial weeds, such as *Taraxacum officinale* (L.) Weber ex F.H. Wigg. (dandelion), *C. arvense* (Tatnell et al., 2020), *Cyperus esculentus* L. (yellow nutsedge) (Feys et al., 2023) and *Rumex* spp. (Tatnell, 2022). In general, they show that electricity can effectively kill the shoots of annual and perennial weeds, but that multiple treatments or integrated strategies are needed to exhaust the underground storage organs of perennial weeds. There is also a great deal of selectivity between different plant species and plant sizes, but more research is needed on how electrical weed control efficacy is affected by species-specific plant morphological and anatomical traits and what the long-term effects are on plants that are not fully killed by the electrocution (Schreier et al., 2022; Slaven et al., 2023). Most studies that have looked at the effect of electrical weed control on non-target organisms, such as earthworms and other soil organisms, have found a lower impact than tillage, though application method matters (per plant applications likely carry far lower risk than over-the-surface applications) (Slaven et al., 2023; Tatnell et al., 2020). However, while the more modern solutions have a reduced (albeit not eliminated) risk to the operator, they still struggle with the risk of sparks causing fire, high energy requirements and slow treatment speeds.

In recent years, there have been multiple controlled studies looking at the potential of low-energy electrical methods for controlling weeds (e.g., Bloomer et al., 2022, 2023; Lati et al., 2021; Matsuda et al., 2023). By using a low voltage and aiming to reduce the exposure time by targeting seedlings rather than adult plants, these studies have shown that it is possible to perform effective electrical weeding with a fraction of the energy used by the commercial electrical weeders. However, more studies with different combinations of voltage and exposure time are needed to find the best balance between efficacy and treatment time, and energy use for weed species with different traits. Specifically, there is a lack of data on how effective sub-second electrical applications are at controlling weeds and how low-energy weed control affects perennial weeds and their belowground organs.

The goal of the current study was to determine which voltage and exposure time combination most efficiently controls both annual and perennial weeds of different sizes. A series of pot experiments were conducted where a low-energy electrical method was used at different voltage levels and exposure times against seedlings and adult plants of the annual dicotyledon weed *Tripleurospermum inodorum* (L.) Sch.Bip. (scentless mayweed) and the annual grass weed *Avena fatua* L. (wild oat), as well as small and established plants of the perennial grass weed *E. repens*. The tested hypotheses were that the low-energy electrical control would: (1) kill seedlings of the annual weeds *T. inodorum* and *A. fatua*, (2) significantly reduce the biomass of adult *T. inodorum* and *A. fatua* plants, (3) significantly reduce both the shoot biomass and rhizome biomass of small and established plants of the perennial weed *E. repens* and (4) that the efficacy would increase with increasing voltage and exposure time.

2 | MATERIALS AND METHODS

2.1 | Electrical equipment

The equipment used in the experiments was a lab version of the technology developed by one of the co-authors, M. Stankovic (patent number SE540099). The lab equipment has two electrodes for applying the treatments to plants and for grounding. The application part of the electrodes consists of metal rods which are placed at or near the target; and it does not damage the plant through heating or by being attached. It has a high frequency (22 000 Hz) of direct current (DC) applied as multiple pulses. The device is capable of a range of voltage applications and has a timer to allow for precise and sub-second applications. The maximum output of the equipment is 300 W, measured with a multimetre (EX520 by Extech, NH, USA) and a high voltage probe (TT-HVP40 by Testec, Dreieich, Germany). Thus, the prototype can account for the possibility that in certain conditions (weather, humidity, etc.), weeds may draw more current, temporarily increasing consumption at a given moment (seconds or milliseconds). Amperes (A) were measured at 5–20 kilovolts (kV) with a current clamp (TM501A by Tektronix, Beaverton, OR, USA) and an oscilloscope (54603B by Hewlett Packard, Palo Alto, CA, USA), with the A and resulting Watt (W) measured as follows: 0.83 mA at

20 kV = 16.6 W; 1.2 mA at 15 kV = 18 W; 1.6 mA at 10 kV = 16 W; 2 mA at 5 kV = 10 W. Thus, for example, a 5 kV treatment for 0.2 s would use 10 W × 0.2 s = 2 J, depending on how treatment conditions affect the resistance. The higher A at a lower kilovolts is because at a lower voltage there are fewer windings in the transformer and the resistance is lower, making the current higher compared to higher voltages.

2.2 | Experimental setups

Four experiments using the low-energy weed control method were conducted to test different voltages and exposure times against seedlings (Expt 1) and adult plants (Expt 2) of *A. fatua* and *T. inodorum*; and against established plants (Expt 3) and small plants (Expt 4) of the perennial grass weed *E. repens*.

2.2.1 | Experiment 1: Seedlings of annual weeds

Seeds of *A. fatua* and *T. inodorum* were sown on 2 March 2017, in 0.5 L square plastic pots (9 × 9 × 9 cm), each filled with a fertilised peat substrate (Hasselfors Garden S-jord, which has 125 g N, 65 g P and 140 g K per m^3). The pots were placed in a greenhouse with a temperature regime of 18°C during daytime (16 h) and 10°C during night (8 h). Artificial light irradiation of 200 μmol s^{-1} m^{-2} 50 cm above the table was supplied during daytime with 400 W lamps (Koninklijke Philips N.V, the Netherlands). After emergence, seedlings were thinned, leaving one seedling in each pot. Water with Wallco nutrient solution (51-10-43 NPK + micro [Cederroth International AB, Sweden]) was added as needed.

Electrical treatments were conducted 14 days after sowing for *A. fatua* seedlings, when they were at stage 12 according to Zadok's scale (Zadoks et al., 1974); and 18 days after sowing for *T. inodorum* seedlings, when they had reached four to six true leaves. At treatment, one electrode of the device was placed in contact with the soil and the other placed in contact with the seedling's hypocotyl or coleoptile. This treatment was chosen because it was considered likely to cause more damage than applying the treatment to plant leaves.

A completely randomized design was used with eight replicates. For *T. inodorum* seedlings, electrical treatments consisted of four levels of voltage (5, 10, 15 and 20 kV) and four exposure times (0.2, 0.4, 0.6 and 1.2 s) and an untreated control. For *A. fatua*, the two highest voltage levels in combination with 0.6 and 1.2 s were not tested since treatments at 5 and 10 kV with even 0.2 and 0.4 s already cut the coleoptile of most seedlings. This meant that for *A. fatua*, there were 13 treatments (including the untreated control) compared to the 17 treatments for *T. inodorum*.

The experiment was terminated 4 weeks after the treatments by cutting the seedlings at the soil surface. The samples of shoot biomass were dried at 105°C for 24 h and subsequently weighed.

2.2.2 | Experiment 2: Adult plants of annual weeds

Seeds of *A. fatua* and *T. inodorum* were sown on the 1st of February 2017, in 1.5 L square plastic pots (13.5 × 13.5 × 23 cm) filled with the same fertilised peat substrate as in Expt 1 and placed in a greenhouse chamber under the same temperature regime and light conditions, and watered with Wallco nutrient solution, as in Expt 1.

Electrical treatments were conducted 6 weeks after sowing, when *A. fatua* had reached development Stage 33, according to Zadok's scale (Zadoks et al., 1974). *T. inodorum* plants had seven branches and were in the initial bolting stage, corresponding to development stage V3, as defined for *Matricaria chamomilla* (Pirzad et al., 2010). No plants had flowers at treatment.

A completely randomized design was used with eight replicates. However, in some pots, the weed plants did not develop further after thinning and were discarded, resulting in 126 *T. inodorum* and 125 *A. fatua* plants (i.e., seven to eight replicates per treatment). The full combination of four voltage levels (5, 10, 15 and 20 kV) and four exposure times (0.5, 1.5, 4.5 and 13.5 s) and an untreated control, was tested for both species. As in Expt 1, one electrode was put in contact with the soil while the other one was placed on the basal part of the stem of the plant.

The experiment was terminated 4 weeks after treatment, when the plant was cut at surface level. The plant material was separated into vegetative and reproductive biomass, dried at 105°C for 24 h and weighed. For *T. inodorum*, the reproductive biomass consisted of the capitulum, including the involucral bracts, while for *A. fatua*, it consisted of the entire panicle (i.e., spikelet + panicle axis). The number of capitula and spikelets per plant were counted for *T. inodorum* and *A. fatua* respectively.

2.2.3 | Experiment 3: Established *E. repens* plants

Rhizomes of *E. repens* were collected from a field close to the campus of the Swedish University of Agricultural Sciences, Uppsala (59°19′ N, 18°4′ E), just prior to the start of the experiment. On the 13th of September 2017, the rhizomes were rinsed in water and cut into fragments of 7 cm, with two to three nodes per fragment. Rhizome fragments were planted in 20 L buckets (23 cm high, 30 cm diameter on top, 24 cm diameter in bottom) filled with the same fertilised peat substrate as in Expts 1 and 2, with one fragment placed at 5 cm depth in each bucket. Buckets were placed in a completely random order in a greenhouse with the same temperature regime and light conditions as in Expts 1 and 2. Water was added when needed, and nutrients corresponding to 18 g m^{-2} were supplied with Wallco nutrient solution on three occasions: (1) 7.5 g N pot^{-1} given at emergence, (2) 5 g N pot^{-1} 3 weeks after emergence and (3) 5 g N pot^{-1} 34 days after emergence.

As the electrical treatment was to be conducted on newly emerged shoots from well-established plants, aboveground biomass was cut 34 days after emergence, with the resulting biomass being dried at 105°C for 24 h and weighed (mean 2.46 g ± 0.970 standard deviation). The electrical treatment was conducted 14 days after the shoot biomass was cut, when shoots had once more developed two fully developed leaves.

A completely randomized design was used with 12 replicates. The full combinations of three voltage levels (5, 15 and 20 kV) and five exposure periods (0.2, 0.5, 1.5, 4.5 and 13.5 s) plus an untreated control. Ten kV was originally included in the experiment, but the samples from the 10 kV treatment were discarded by accident prior to weighing and could not be included in analyses. As in Expts 1 and 2, one electrode was put in contact with the soil while the other one was placed on the basal part of the stem of one of the shoots.

Three weeks after electrical treatments, half of the pots (i.e., six per treatment) were harvested to determine shoot and rhizome biomass. Aboveground shoots were cut at the soil surface, and rhizome plus roots were separated from the soil and carefully rinsed in water. Samples were subsequently dried at 106°C for 24 h and weighed. Rhizomes in the remaining pots were used for testing the effect of the electrical treatment on *E. repens* bud sprouting. From each pot, ten 2 cm rhizome pieces were cut with 1 cm on each side of a node and distributed equally in two petri dishes. Rhizome pieces were placed on filter paper wetted with deionized water, and petri dishes were subsequently placed in a climate chamber with a diurnal temperature regime of 18°C for 18 h and 10°C for 6 h. The sprouting test was terminated after 3 weeks when the number of sprouted shoots >5 mm was determined.

2.2.4 | Experiment 4: Small *E. repens* plants

Rhizomes of *E. repens* were collected from an organically managed arable field close to Uppsala (59°49′ N 17°48′ E) on the 4th of September 2024 and kept in a dark and cold room. On the 13th of September, rhizomes were cut into 5 cm pieces, weighed and put into different weight categories. Round plastic pots (18 cm high, 22 cm diameter) were filled with the same fertilized peat substrate used in Expts 1–3. Two rhizome pieces, one from weight category 0.3–0.39 g and one from weight category 0.4–0.59 g, were sown per pot at approximately 2 cm depth. The pots were placed in a climate room where light was provided by Light4Food lamps, situated 1 m above the table, with a central light strip (Philips LED, 77 W, Poland) and side lights located to the left and right (Philips LED lighting IBRS, 55–60 W, the Netherlands). The lamps had a light intensity of 150 μmol s^{-1} $m-2^{-2}$ and were kept on for 16 h day^{-1}. Temperature was 20 ± 1°C. No extra fertilisation was added, but plants were watered as needed. On the 30th of September (17 days after sowing), the plants were treated. Prior to treatments, the number of shoots and shoot developmental stages were assessed. On average, the shoots had one or two leaves at treatment, though a few had not fully developed one leaf, and some were developing their third leaf.

A completely randomized design was used with 10 replicates. The experiment included four exposure times (0.2, 0.4, 0.6 and 1.2 s) as well as an untreated control. All treatments were conducted with 5 kV since this was the most promising voltage from Expts 1–3. Similarly to the other experiments, one electrode was placed on the leaf sheath of the plant and the other in contact with the soil. Unlike Expt 3, where only one shoot was treated, all shoots were treated in Expt 4 to make it more likely that the treatment was effective. Any rhizome that did not produce shoots or only produced shoots after the treatments was excluded from analyses.

The plants were assessed for damage 4 days after treatment. Sixteen days after treatment, the number of shoots was assessed again, and the biomass was harvested—dividing it into rhizome and shoot biomass per plant and drying it for 24 h at 80°C before weighing.

2.3 | Statistical analyses

All analyses were conducted in R (version 4.3.0; R Core Team, 2023) using RStudio (version 2023.09.1), with the nlme package when linear mixed models (LMM) were used. Mortality data was not analysed because they were either very high or very low (>95% or <5%). Post hoc analyses were performed using the multcomp package (cld() function, $\alpha = 0.05$). The normality of residuals was assessed using qqnorm (), qqline(), and shapiro.test(). Data transformations were applied when they improved model fit (Table 1).

2.3.1 | Experiment 1

Shoot biomass was analysed using two linear models (LM). The first included *Treatment* (including the untreated control) as a fixed factor. The second modelled *Voltage level*, *Exposure Time* and their interaction as fixed factors—excluding the untreated control. For *A. fatua* seedlings, 0.6 and 1.2 s exposure times were excluded from the second model due to incomplete data at 15 and 20 kV.

2.3.2 | Experiment 2

Similar LMs as in Experiment 1 were used to analyse vegetative biomass, reproductive biomass, total aboveground biomass and the number of capitulum/spike per plant.

2.3.3 | Experiment 3

Two LM models were used for rhizome, shoot and total biomass (i.e., shoot plus rhizome biomass). The first modelled *Treatment* as a fixed factor, while the second included *Voltage level*, *Exposure Time* and their interaction as fixed factors. For *E. repens* bud sprouting, where each pot included results from two non-independent petri dishes, a LMM was used with pot as a random factor (but otherwise the LMM were identical to the LMs used for analysing biomass). The dry weight of shoots 14 days prior to treatment was included as a covariate in all models for Experiment 3.

TABLE 1 Model significance levels (*p*-values) for the one- and two-factor models performed on Expt 1 (seedlings of the annual grass *Avena fatua* and annual dicotyledon *Tripleurospermum inodorum*), Expt 2 (adult plants of *A. fatua* and *T. inodorum*) and Expt 3 (established plants of the perennial grass *Elymus repens*). The one-factor model tested the effect of the treatment (including the untreated control) and the two-factor model tested the voltage level, exposure time and their interaction (not including the untreated control). In Expt 3, the covariate was the *E. repens* shoot biomass from the cut 14 days before the electrical treatments. *p*-Values equal to or lower than 0.05 are in bold. DW, dry weight.

		A. fatua seedlings	*A. fatua* adult plants				*T. inodorum* seedlings	*T. inodorum* adult plants				Established *E. repens* plants			
		Shoot DW	Vegetative DW	Reproductive DW	Total DW	Spikelets per plant	Shoot DW	Vegetative DW	Reproductive DW	Total DW	Capitulum per plant	Shoot DW	Rhizome DW	Total DW	Bud sprouting
One-factor model	Treatment	**>0.001**	**>0.001**	0.07	**>0.001**	0.6	**>0.001**	**>0.001**	**>0.001**	**>0.001**	**0.002**	**0.004**	**0.003**	**0.013**	0.7
	Covariate											**>0.001**	**>0.001**	**>0.001**	0.3
Two-factor model	Voltage (V)	**0.02**	**0.003**	0.06	**>0.001**	0.1	0.5	**>0.001**	**>0.001**	**>0.001**	**>0.001**	0.3	0.3	0.8	0.9
	Exposure time (ET)	0.1	**>0.001**	0.6	**>0.001**	0.8	0.7	**>0.001**	**>0.001**	**>0.001**	**0.004**	**>0.001**	**>0.001**	**0.002**	0.3
	V × ET	0.3	0.2	0.1	**0.04**	0.8	0.2	0.1	0.8	0.4	0.5	0.8	0.8	0.2	0.7
	Covariate											**>0.001**	**>0.001**	**>0.001**	0.4
Transformation									log + 0.1	log+0.1	log + 1				

2.3.4 | Experiment 4

Shoot, rhizome and total biomass (i.e., shoot plus rhizome biomass) were analysed per *E. repens* plant using LMM with *Exposure Time* (including untreated control) as a fixed factor and pot as a random factor to account for within-pot dependency. Shoot number, which could not be tied with certainty to specific rhizomes pre-treatment, was analysed per pot. A LMM was used for shoot number with *Exposure Time*, *Sampling Time* and their interaction as fixed factors, and pot as a random intercept. Sampling time was treated as a repeated measure with an autoregressive correlation structure (corCAR1).

3 | RESULTS

3.1 | Experiment 1: Seedlings of annual weeds

Voltage and exposure time did not have a significant effect on *T. inodorum* seedlings as, except for a few outliers, all voltage and exposure combinations resulted in 100% mortality and thus zero biomass (see Figure 1A; Table 1). For *A. fatua*, there was a significant effect of voltage (Tables 1 and 2). The lower the voltage, the more the shoot biomass was reduced compared to the untreated control (Figure 1B). The 5 kV treatments all reduced *A. fatua* seedling shoot biomass by more than 99% compared to the untreated control and resulted in 66% less shoot biomass compared to the 20 kV treatments (Table 2). However, the plants still displayed some minor green biomass 4 weeks after the treatment, so they could not be declared fully dead. Photos of treated *T. inodorum* and *A. fatua* seedlings are provided in Figure S1A,B.

3.2 | Experiment 2: Adult plants of annual weeds

For adult *T. inodorum* plants, vegetative and reproductive biomass, as well as capitulum per plant, were affected by the electrical treatment. The lower the voltage and the higher the exposure time, the greater the effect (Tables 1 and 2). The 5 kV treatment at 1.5, 4.5 and 13.5 s reduced the total aboveground biomass (vegetative + reproductive) by 80%, 87% and 94%, respectively, compared to the untreated control (Table 1). Despite a reduction ranging from 58% to 97% in the number of capitulum per plant for the 5 kV treatments compared to the untreated control (Figure 2C), a contrast between them was not quite significant ($p = 0.06$). However, 5 kV treatments had 86% fewer capitulum per plant than the 10–20 kV treatments (Table 2; Figure 2C).

The effect on adult *A. fatua* plants was not as strong or as consistent as on *T. inodorum*. Five kV at 4.5 s and 10 kV at 13.5 s reduced the vegetative biomass by 47% and 57%, respectively, compared to the untreated control. The 0.5 s treatment resulted in significantly more *A. fatua* vegetative biomass than the other exposure times (Table 1), while 10 kV resulted in 23% less total aboveground biomass than 15 and 20 kV (Table 2). Visually, there was little evidence that

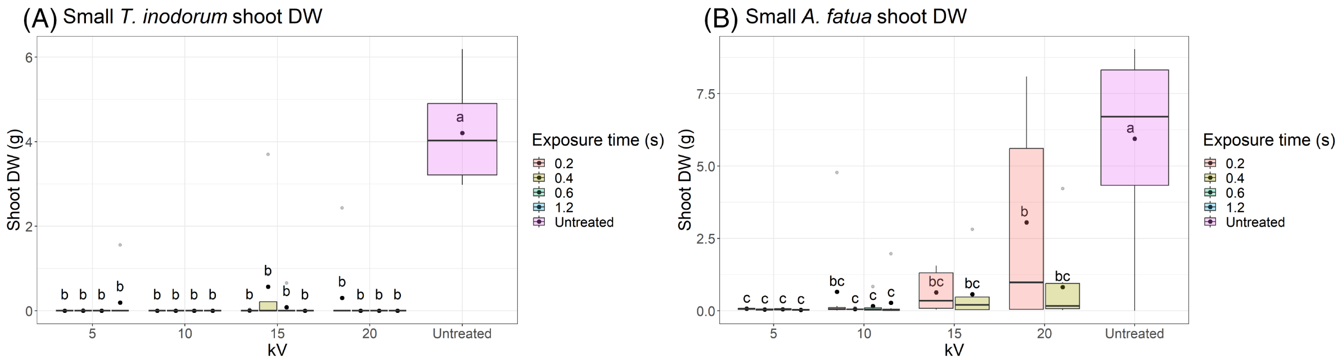

FIGURE 1 Results from Expt 1 shows the shoot dry weight (DW) per plant when the low-energy electrical weed control method was applied to seedlings of (A) *Tripleurospermum inodorum* (scentless mayweed) and (B) *Avena fatua* (wild oats) at four voltage levels (5, 10, 15 and 20 kV) and four exposure times (0.2, 0.4, 0.6 and 1.2 s), at 18 and 14 days after sowing, respectively, with an untreated control as comparison. Boxplots show the raw data, while black dots show the model mean. Letters indicate significant differences at $\alpha = 0.05$.

the adult *A. fatua* plants had been affected by the treatments. Photos of treated *T. inodorum* and *A. fatua* adult plants are provided in Figure S1C,D.

3.3 | Experiment 3: Established *E. repens* plants

Neither shoot biomass nor rhizome biomass of established *E. repens* plants were significantly affected by voltage level, but the longer the exposure time, the greater the reduction in biomass (Tables 1 and 2; Figure 3A,B). However, no treatment significantly reduced the established *E. repens* biomass compared to the untreated control, and visually there was no indication that the treatment had affected the established *E. repens* plants, not even the treated shoot. There was no effect of treatment or voltage, or exposure time on the sprouting capacity of isolated buds from rhizome nodes.

3.4 | Experiment 4: Small *E. repens* plants

Some shoots, especially those in the 0.6 and 1.2 s treatment, were severed by the treatment. By 4 days after the treatment, all treated shoots were clearly dying (see Figure S2A,B). The shoots that resprouted did so primarily from the treatment point—with the first reemerging leaf often fused to the stem, creating a leaf loop (see Figure S2C). At harvest, 16 days after treatment, all treated plants had significantly less shoot biomass (−75 to −88%; $p > 0.001$) and rhizome biomass (−28 to −30%; $p > 0.001$) compared to the untreated control (Figure 4A,B). Since not all shoots had resprouted or been replaced by new shoots or tillers, the number of shoots + tillers was significantly lower for all treatments compared to the untreated control (−56 to −70%; $p = 0.001$), as well as compared to pre-treatment levels (exposure time × sampling time, $p > 0.001$). There were no significant differences between the plants treated at different exposure times for any measurement. Only untreated control plants produced any new rhizomes or tillers.

4 | DISCUSSION

The first hypothesis, which stated that the low-energy electrical control method would kill annual plant seedlings, was fully supported for *T. inodorum*—while *A. fatua* seedlings were controlled but not fully killed. More than 95% of treated *T. inodorum* plants were instantly killed, with many treatment combinations resulting in 100% mortality. *A. fatua* seedlings were not fully killed, but many treatment combinations resulted in such a large reduction in shoot biomass (>99%) that it is unlikely that these plants would have offered any competition to a crop or been able to set seed. Similarly to our results, Bloomer et al. (2022, 2023), Lati et al. (2021) and Matsuda et al. (2023) found that low-energy electrical weeding is effective in controlling seedlings of many plant species (e.g., *Trifolium pratense* L. [red clover], *Trifolium repens* L. [white clover], *Lolium multiflorum* Lam. [Italian ryegrass], *Chenopodium album* L. [lamb's quarters], *Amaranthus powellii* S. Wats. [green amaranth], *Amaranthus deflexus* L. [low amaranth], *Solanum nigrum* L. [black nightshade], *Solanum nitidibaccatum* Bitter [hairy nightshade], *Polygonum aviculare* L. [common knotgrass] and *A. fatua*). It is difficult to compare prototypes without access to both machines, but the method tested here seems to be more similar to the multiple-pulse device used in Bloomer et al. (2022), which generates DC pulses of up to 10 kV, rather than the devices used in Lati et al. (2021), which generated up to 40 kV of DC or 2.2 kV of AC. In support of our findings, both the above authors and authors testing other electrical methods have found a greater effect on dicotyledons than on grasses. For example, Tatnell et al. (2020) reported a greater effect of the RootWave Pro technology against dicotyledons, including the perennial weed *C. arvense*, compared to grasses. The most likely explanation is differences in morphology and anatomy (Lati et al., 2021; Slaven et al., 2023). Many different traits have been pointed to as potentially explaining the difference in efficacy, such as protective leaf layers and leaf waxiness (Lati et al., 2021), plant water content (Schreier et al., 2022), having multiple branches (Bloomer et al., 2022; Schreier et al., 2022), but a detailed study of the mechanisms that explain inherent plant susceptibility to electrical treatments is lacking. Other

TABLE 2 The mean, standard error (SE) and significance level (letters indicate significant differences at $\alpha = 0.05$) for the total harvested dry weight (i.e., both vegetative and reproductive biomass for adult *Avena fatua* and *Tripleurospermum inodorum* plants, and both shoot and rhizome biomass for established *Elymus repens* plants) comparing treatments with different kilovolts (kV), milliampere (mA) and their corresponding Watt (W). Significant differences are highlighted in bold.

			Total harvested dry weight															Capitulum/spikelets per plant					
			Small *T. inodorum*			Small *A. fatua*			Adult *T. inodorum*			Adult *A. fatua*			Established *E. repens*			Adult *T. inodorum*			Adult *A. fatua*		
kV	mA	W	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.
20	0.83	16.6	0.08	0.07	a	1.76	0.38	**a**	16.0	2.79	**a**	43.3	1.80	**a**	10.9	0.44	a	5.0	1.6	**a**	3.1	0.54	a
15	1.2	18	0.16	0.07	a	0.63	0.41	**ab**	11.2	1.96	**a**	42.6	1.77	**a**	10.7	0.47	a	5.6	1.7	**a**	3.0	0.53	a
10	1.6	16	0.00	0.07	a	0.36	0.41	**ab**	8.9	1.56	**a**	33	1.71	**b**	-	-		6.8	2.0	**a**	1.5	0.51	a
5	2	10	0.05	0.08	a	0.06	0.41	**b**	2.6	0.48	**b**	38.3	1.77	**ab**	11.1	0.45	a	0.8	0.5	**b**	2.7	0.53	a

factors such as soil type, soil moisture content, electrode placement, electrical equipment, energy level, DC versus AC etc. can also influence efficacy and make it harder to explain the underlying mechanisms (Lati et al., 2021; Slaven et al., 2023).

The second hypothesis, which stated that the low-energy electrical treatment would significantly reduce the biomass of adult annual plants, was supported for the annual dicotyledon *T. inodorum*, but the effect was not very clear on the annual grass *A. fatua*. This further emphasizes the differences in susceptibility between grasses and dicotyledons, but also the differences in susceptibility between plants of different sizes and ages. Older plants are not only bigger than younger plants, but may also contain a higher proportion of, for example, lignin and cellulose, which may reduce the efficacy of electrical treatments by making the plant cells more resistant to bursting (Slaven et al., 2023). This research clearly shows that to achieve a high efficacy, low-energy weed control must be conducted before the weeds grow too large and established. Moreover, it shows that the control window differs between weed species, similar to other weed control measures such as herbicides and tillage (DiTommaso & Prostak, 2021). An encouraging result is that even adult *T. inodorum* plants were reduced by 80% after 1.5 s, showing that the window for effective control is quite long for this species. In comparison, the window for effective control is clearly much shorter for *A. fatua*. Similarly to our results, Lati et al. (2021) found that the efficacy of their low-energy weed treatment against *T. pratense* L. (red clover) declined from 2 to 4 to 6 weeks after sowing.

The third hypothesis, which stated that the low-energy electrical treatment would reduce both the shoot and rhizome biomass of the perennial weed *E. repens*, was supported for small, but not established *E. repens* plants. Even the 0.2 s treatment at 5 kV was sufficient for killing the shoots of small *E. repens* plants, forcing them to resprout and causing a delay in shoot development, and thus significantly reducing both the shoot and rhizome biomass, as well as the number of shoots, compared to the untreated control. In contrast, while the efficacy of the low-energy electrical control method did increase against established *E. repens* plants with increasing exposure time, even the longest (13.5 s) was not sufficient to reduce the shoot or rhizome biomass, or bud sprouting, compared to the untreated control. The control efficacy might have been higher if all shoots of the established *E. repens* plants had been treated as the small *E. repens* plants were, but perhaps not much higher. After all, even 13.5 s was not sufficient to have a visible effect on the treated shoot of the established *E. repens* plants. In comparison, even 0.6 s was sufficient to sever—potentially through localized hotspots (Slaven et al., 2023)—both *E. repens* shoots in Expt 4 and annual weed seedlings in Expt 1. One explanation for this discrepancy is that even though the shoots were technically at the same developmental stage (around two leaves), the established *E. repens* plants in Expt 3 had larger and sturdier shoots as a result of having sprouted from rhizomes grown for more than a month under abundant light and nutrient conditions, compared to the newly harvested rhizomes in Expt 4 (cf. rhizome weights in Figures 3B and 4B). A single cut of shoot biomass, as was performed in Expt 3, 2 weeks before treatments, has a limited effect on *E. repens* and so

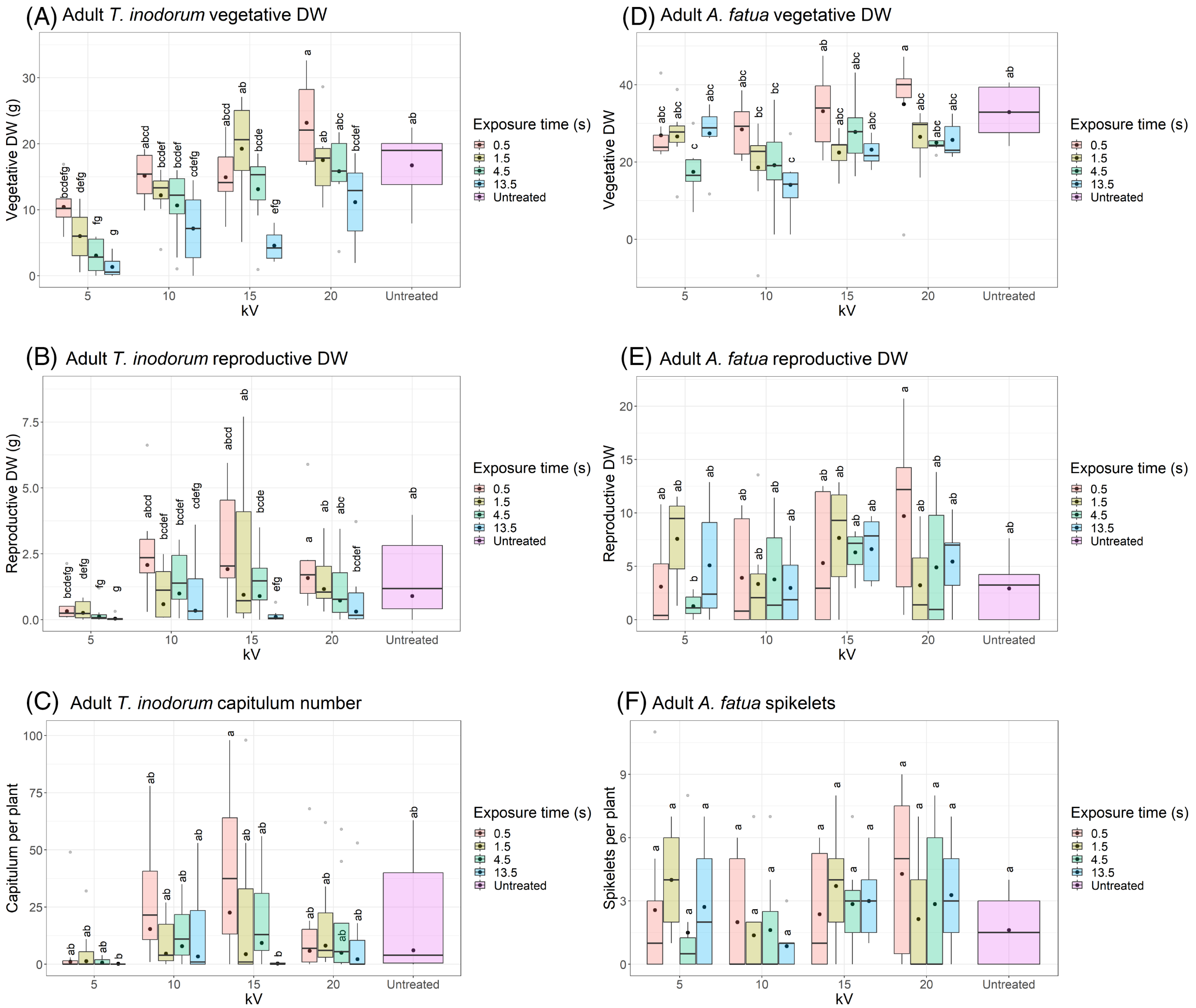

FIGURE 2 Results from Expt 2 shows the dry weight (DW) of the vegetative and reproductive parts of the aboveground biomass, and the number of capitulum or spikelet per plant, when the low-energy electrical weed control method was applied to adult plants of (A–C) *Tripleurospermum inodorum* (scentless mayweed) and (D–F) *Avena fatua* (wild oats) at four voltage levels (5, 10, 15 and 20 kV) and four exposure times (0.5, 1.5, 4.5 and 13.5 s), at 6 weeks after sowing, with an untreated control as comparison. Boxplots show the raw data, while black dots show the model mean. Letters indicate significant differences at $\alpha = 0.05$.

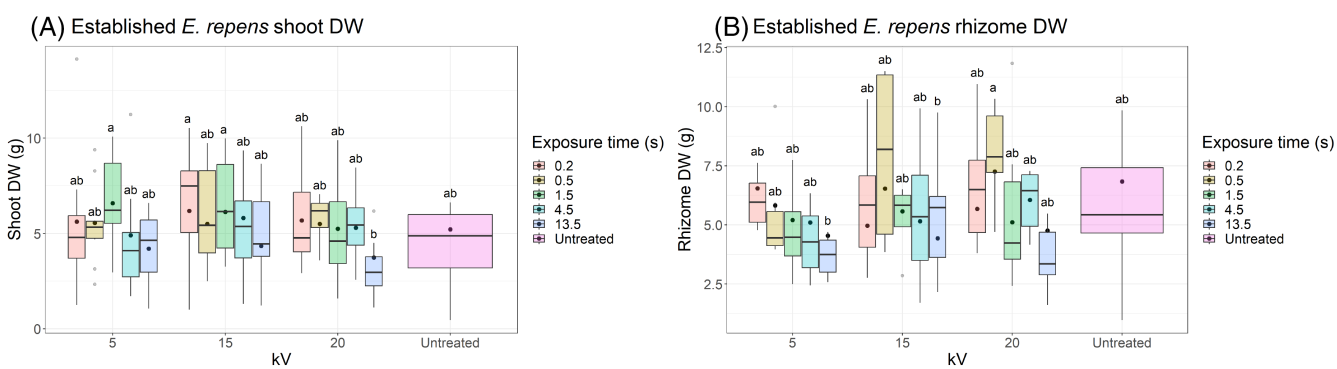

FIGURE 3 Results from Expt 3 shows the dry weight (DW) of shoot biomass (A) and rhizome biomass (B) when the low-energy electrical weed control method was applied to established plants of *Elymus repens* (couch grass) at three voltage levels (5, 15 and 20 kV) and four exposure times (0.5, 1.5, 4.5 and 13.5 s), 14 days after cutting the shoot biomass 34 days after sowing, with an untreated control as comparison. Boxplots show the raw data, while black dots show the model mean. Letters indicate significant differences at $\alpha = 0.05$.

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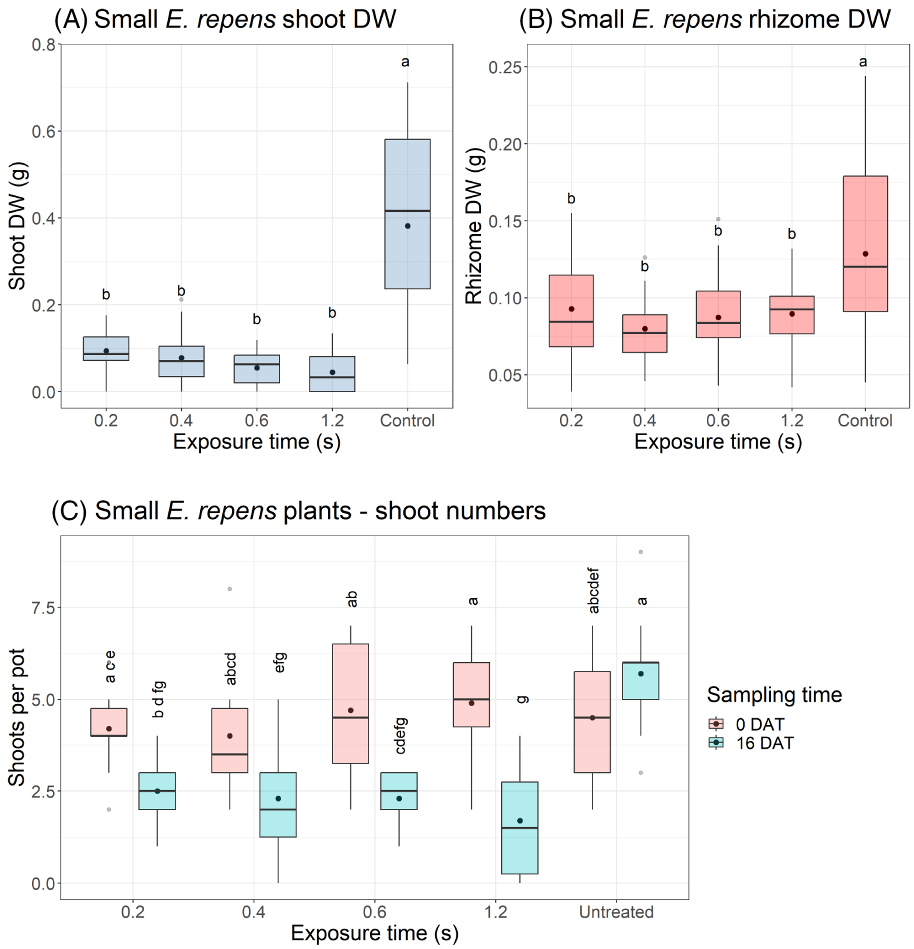

FIGURE 4 Results from Expt 4 shows the dry weight (DW) of shoot biomass (A) and rhizome biomass (B) per plant and number of shoots per pot (C), when the low-energy electrical weed control method was applied to small plants of *Elymus repens* (couch grass) at 5 kV and four exposure times (0.2, 0.4, 0.6 and 1.2 s), 17 days after sowing, with an untreated control as comparison. The plants were harvested 16 days after treatment (DAT). Boxplots show the raw data, while black dots show the model mean. Letters indicate significant differences at $\alpha = 0.05$.

would not have depleted many resources (e.g., Kolberg et al., 2018; Ringselle et al., 2015). This explanation is not entirely satisfactory though, and more studies may be needed to explain this discrepancy. The fact that the established *E. repens* plants had a larger rhizome network could also explain some of the reduced efficacy, as some of the current could have dissipated into the soil rather than traveling along the whole rhizome and root network. However, whether a larger rhizome network could also help explain why the treated shoot was not killed in Expt 3 is much less certain.

The combined results of Expts 3 and 4 raise some very interesting points. First, they clearly show that the electrical treatment, even applied at sub-second low-voltage levels, is sufficient to kill *E. repens* shoots and force them to resprout, which significantly reduces their available resources. But equally clearly, established *E. repens* plants are far more resistant, so the plants must be weakened beforehand. Consequently, the electrical treatment could be effective as part of a starvation strategy, for example on *E. repens* shoots reemerging following tillage (Ringselle et al., 2016), thus reducing the need for further tillage operations. Similarly to our results, Andreasen et al. (2024) found that 1.6 J mm^{-2} applied with lasers was sufficient for killing newly emerged *E. repens* plants with one shoot, while 8 J mm^{-2} was needed for killing plants with two shoots. Second, while the treatments seem to have a starvation effect by killing the shoots, there does not seem to be much direct damage to the *E. repens* rhizome network. There is some indication that a longer exposure time reduced both *E. repens* shoot numbers and shoot biomass more than a shorter exposure time in Expt 4 (Figure 4A,C) and the rhizome biomass in Expt 3 (Figure 3B), but never significantly. And there was no sign of damage on the rhizomes in either Expts 3 or 4, nor a reduction in rhizome bud sprouting capacity. Thus, while the electricity may have penetrated the rhizome network, the major damage the treatment caused was by forcing *E. repens* to resprout. Similarly, Feys et al. (2023) found that even though the RootWave Pro and XP300 could effectively reduce the shoot vitality of *C. esculentus*, it did not affect its belowground tuber vitality. Thus, to be able to resource-efficiently control perennial weeds with electrical weed control, more studies are needed that show how the energy flows from the treatment site to the underground storage organs of different perennial weed species (especially with different root/rhizome structures) and how the damage to these organs can be maximised.

The fourth hypothesis, which stated that the efficacy of the low-energy electrical treatment would increase with increasing voltage and exposure time, was supported for exposure time but not voltage. In general, a higher voltage did not improve efficacy and in some cases reduced it (i.e., for small *A. fatua* plants and large *T. inodorum* plants; Table 2). One explanation for this may be that the low voltage was compensated for by a higher amperage (cf. 2 mA for 5 kV and 0.83 mA for 20 kV). A higher amperage means a higher current flow and is an important aspect of what makes electricity dangerous (Edland, 1977). However, there seems to be a lack of studies on how different amperage levels affect the damage to plants. Bloomer et al. (2022), who also found a lower voltage to be more effective than a higher voltage, speculated that at higher voltages the fine leaf acts as an electrical fuse (i.e., since the contact point dies fast it prevents the current from impacting the rest of the plant). Further studies are needed to determine the exact mechanisms and how to maximise damage to plants while minimising the risk to the operator, the power usage and treatment times. Moreover, in the current study, we conclude that 5 kV is as or more effective than 10–20 kV, but further study is needed to determine if voltages <5 kV result in even better weed control. Bloomer et al. (2022) experiments included treatments at 6 and 3 kV and found that all *L. multiflorum* Lam. (Italian ryegrass) plants treated with 5 J or more at 3 kV died, while at 6 kV many plants survived, albeit with a reduced growth rate. In comparison, Feys et al. (2023) found no differences between 3, 4 and 5 kV in tuber or shoot vitality for *C. esculentus* plants treated with RootWave Pro.

In this study, the exposure time resulted in far greater differences in treatment effect for the adult annual plants and established *E. repens* plants than for the annual weed seedlings and small *E. repens* plants. Primarily, this was because even the shortest exposure time (0.2 s) was so effective against the seedlings and small *E. repens* plants that higher exposure times could not significantly improve upon the effect. Similar to our results, Lehnhoff et al. (2022) found that increasing the exposure time with a constant amperage of 2 mA (i.e., same as the 5 kV treatment in our study) resulted in an increased control effect of the shrub *Tamarix* spp. (tamarisk); though their shortest exposure time was 12 h.

4.1 | Implications for management

This study, together with previous studies (e.g., Bloomer et al., 2022; Lati et al., 2021; Matsuda et al., 2023), shows that low-energy electrical methods are effective even with sub-second exposure times against multiple weed species in the early stages of their development. The larger and older the weeds get, the longer the exposure time needed to control them. How quickly the efficacy is reduced as the plants develop varies between species and plant groups (e.g., dicotyledons are seemingly more susceptible than grasses). In this study, the lowest voltage level tested (5 kV) was seemingly more effective than a higher voltage (10–20 kV), regardless of size, plant species or developmental stage. These results indicate that the electrical method used can be energy efficient when controlling seedlings and small perennial plants since the combination of relatively low voltage and short exposure time results in a low energy use per weed plant (e.g., 2 J for a treatment of 5 kV at 0.2 s, depending on the resistance). The short exposure time needed for controlling seedlings (≤0.2 s) also makes the method more relevant under real world conditions, compared to a ≥ 1 s exposure time. Of course, a vehicle travelling at 10 km h^{-1} still moves 55 cm in 0.2 s, so an efficient application method will be required to achieve even moderate speeds. Previous studies (e.g., Bloomer et al., 2022; Lati et al., 2021) have pointed out that one of the most promising uses for this technology most likely is to attach it to an autonomous robot or tractor and use it as part of an integrated strategy (e.g., to clean up the remaining weeds after another weed control measure such as row-hoeing or herbicide spraying has removed most weed plants). Fewer weeds mean lower time requirements per square metre, and autonomous vehicles can work more hours in the day. Furthermore, Matsuda et al. (2023) showed that potentially low-energy electrical methods could also be used to prevent weed growth over an area, for example, in orchards.

A major limitation of this and most other studies on low-energy electrical weed control is that they have been conducted under controlled greenhouse conditions. Thus, while the shortest exposure time tested (0.2 s) might have been unnecessarily long for the seedlings under controlled conditions, at least for *T. inodorum*, the efficacy might differ under field conditions (Slaven et al., 2023). However, in a recent paper, Bloomer et al. (2024) showed that their low-energy weed control method had a comparable effect on weeds growing in bags filled with soil from a field, as weeds growing in that same field (either naturally occurring in the field, sown into the field or transplanted to the field). For low-energy electrical weed control to be adopted, more field trials are needed to determine the effectiveness of the treatment against different types of weeds under field conditions. Such trials should also determine the selectivity between the crop and weeds (i.e., can you treat the weeds without damaging nearby crop plants?), how the competitive relationship between crop and plant changes due to the treatment, and how well-integrated strategies work in practice. However, the current study shows that even sub-second applications at 5 kV are sufficient to kill seedlings of annual weeds and the shoots of small perennial weed plants—and can have a greatly reductive effect even on adult plants of some species. This indicates that the low-energy electrical method could work efficiently as a complement to herbicides and tillage, at least as part of an integrated strategy.

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CONFLICT OF INTEREST STATEMENT

Co-author M. Stankovic invented the technology used in the experiment and filed for the patent SE540099. In between the experiments and the submission of the manuscript, the patent was transferred to co-author V. Ninkovic's company Enlightened Detection AB, giving him a stake in the technology. The other authors, B. Ringselle and L. Andersson, have no stake in the company and declare no conflict of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/wre.70010.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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