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Electric interrow control of lupine plants does not adversely affect the neighboring non-target lupine plants

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Abstract

Interrow weed control is used in a wide range of crops, traditionally applied via physical cultivation or banded herbicide application. However, these methods may result in crop damage, development of herbicide resistance, or off-target environmental impacts. Electric interrow weed control presents an alternative, although its potential impact on crop yield requires further investigation. One of the modes of action of electric weed control is the continuous electrode–plant contact method, which passes a current through the weed and into the roots. As the current passes into the roots, it can potentially disperse through the soil to neighboring root systems. Such off-target current dispersion, particularly in moist topsoil with low resistance, poses potential concern for neighboring crops when electric interrow weed control is applied. This research evaluated the continuous electrode–plant contact method, using a Zasso™ XPower machine, in comparison with mowing across three trials conducted in 2022 and 2023. Both treatments were used to remove target lupine (*Lupinus albus* L.) plants adjacent to a row of non-target lupine. Electric weed control was applied to plants in dry soil or following a simulated rainfall event. The trials demonstrated that electric weed control and mowing did not reduce density and biomass of neighboring non-target lupine plants compared with the untreated control. Likewise, pod and seed production, grain size, and protein, as well as grain germinability and vigor of the resulting seedlings, were not reduced by these weed control tactics. This research used technology that was not fit for purpose in broadscale grain crops but concludes that electric weed control via the continuous electrode–plant contact method or mowing did not result in crop damage. Therefore, it is unlikely that damage will occur using commercial-grade electric weed control or mowing technology designed for large-acreage interrow weed control, thus offering nonchemical weed management options.

Introduction

Interrow weed control is a critical practice in a range of agricultural enterprises, from small-scale vegetable crops to large-acreage grain production (Ozaslan et al. 2024; Peltzer et al. 2009). To date, interrow weed control has involved physical cultivation, the application of nonselective herbicide via shielded sprayers, or mowing (Hashem et al. 2011; Ozaslan et al. 2024; Peltzer et al. 2009). However, physical cultivation and use of herbicides have been associated with environmental concerns. For example, cultivation can lead to soil compaction, nutrient leaching, erosion, and adverse impacts on soil biota (Rowland et al. 2023; Tran et al. 2023). Use of herbicide is increasingly discouraged due to the risks of herbicide resistance, crop damage, and yield loss (Peltzer et al. 2009). Mowing has demonstrated effectiveness, as reported by Rowland et al. (2023) in a soybean [*Glycine max* (L.) Merr.] crop, where it reduced weed biomass by 60% and increased yield by 14% compared with a non-weeded control. However, its efficacy can be variable due to the weed's ability to resprout (Hashem et al. 2011; Peltzer et al. 2009). Because of these limitations, there is a need for alternative interrow weed management technologies that reduce soil disturbance or chemical use, including thermal weed control methods such as lasers, flaming, microwaves, and electrical control (Loddo et al. 2021; Rowland et al. 2023; Slaven et al. 2023; Tran et al. 2023). For example, electric interrow weed control has been shown to provide up to 95% control efficacy in vegetable crops (Koch 2022). For large-acreage grain crops, the speed and scale of new technologies such as electric weed control are sometimes too low for practicality (Rowland et al. 2023; Slaven et al. 2023). However, the emergence of precision agriculture and autonomous vehicles is a reality for agriculture (Loddo et al. 2021; Slaven et al. 2023; Tran et al. 2023). Autonomous vehicles increase the potential use and practicality of these alternative weed control tactics with slow application speeds by reducing the cost of labor during application.

While electric weed control mitigates those risks posed by physical cultivation or herbicide for interrow weed management, published field data for this technique are scarce, and the potential for crop damage or yield loss has not been investigated (Rowland et al. 2023; Slaven et al. 2023). During application of electric weed control via the continuous electrode–plant contact method, an electrode makes physical contact with the target plant, allowing an electrical current to flow through the plant and the roots and into the soil. The current then returns to the machine as a ground contact device closes the circuit (Bauer et al. 2020; Vigneault and Benoit 2001). This method of weed control is nonselective, and once the electrical current enters the roots of the target plant, there is a possibility for it to disperse into the surrounding soil. Moreover, the extent of current dispersal depends on both soil moisture and characteristics, with dry or sandy soil (low organic carbon, electrical conductivity, etc.) exhibiting greater resistance and less current dispersal compared with moist soil or soils with higher clay content (Slaven et al. 2023). Consequently, the dispersing current may potentially impact the roots of neighboring, non-target plants (Slaven et al. 2023; Vigneault and Benoit 2001). A study by Vigoureux (1981) reported varying levels of control for weedy (bolting) beet plants in sugar beet (*Beta vulgaris* L.) crops when electric weed control was applied under different soil moisture conditions, with improved control (80% to 92%) in dry soil conditions compared with moist conditions (29% to 67%). Likewise, Borger and Slaven (2024) noted reduced control of rigid ryegrass (*Lolium rigidum* Gaudin) following application of simulated rainfall to increase volumetric soil moisture from 9.2% to 16.2%. This suggests that efficacy of electric weed control, as well as current dispersal, may be influenced by soil moisture levels, as the current is more likely to remain localized in the target plant in dry conditions. However, the difference in control efficacy could also be attributed to variations in weed recovery rate between moist and dry soil conditions (Slaven et al. 2023).

There is little evidence to indicate whether electric weed control applied to interrow weeds would damage the neighboring crop plants. Brighenti and Brighenti (2009) investigated interrow electric weed control in a soybean crop, using prototype machinery at 4,400 V or 6,800 V in each of two experiments. Their findings indicated 90% to 100% control of prevalent weeds without impact to the crop yield. However, they observed a direct correlation between yield and weed biomass, with lowest yield in the untreated control. Therefore, yield loss was likely related to weed competition. Their investigation did not assess potential damage of electric weed control to crop growth in the absence of weeds. Thus, research is required to assess the impact of electric weed control to neighboring crop plants in the absence of interspecies competition. Bongard et al. (2022) demonstrated the efficacy of combining electric weed control via the XPower with a prototype XPR applicator (continuous electrode–plant contact method), with a regionally appropriate banded herbicide regime, in the row of sugar beet crops. While electric weed control combined with herbicide controlled 94% of Canada thistle [*Cirsium arvense* (L.) Scop.], field bindweed (*Convolvulus arvensis* L.), and common lambsquarters (*Chenopodium album* L.) compared with 84% control efficacy achieved by herbicide alone, the study did not assess crop damage or yield. A review by Slaven et al. (2023) found no evidence in the literature of damage from electric weed control (continuous electrode–plant contact method) in horticulture (i.e., damage to mature vines and tree crops). However, mature vines and tree crops have deep, well-established root systems, as the plants may be several decades old. Damage may occur due to treatment around younger plants with a potentially shallow and less well-established root system. For example, the manual of the Zasso™ XPower machine with XPS applicator advises against treatment around young, unlignified vines due to potential damage (CNH 2023). An annual crop plant will have a less-extensive root system than a mature tree or vine, and so is more likely to be subject to injury. Research is required to determine potential damage to non-target annual crop plants from electric weed control in the absence of crop–weed competition.

While electric weed control is not currently applied for interrow weed control of annual crops, advances in technology highlight the potential for this use pattern in the imminent future. For example, Zasso™ plans to release the XPower with XPR applicator for this purpose (Koch 2022). However, the potential impact of this technology on neighboring annual crop plants remains unexplored. The aim of the current study was to investigate potential damage to annual crop plants resulting from interrow application of electrical current to adjacent plants, particularly in soils with varying water content. Lupine (*Lupinus albus* L.) was selected as the test species due to its prior use in interrow weed control studies utilizing herbicides, cultivation, or mowing (Hashem et al. 2011; Peltzer et al. 2009). Our hypothesis was that greater crop damage would occur following application of electric weed control to the interrow space compared with mowing, due to the movement of electrical current through the soil from the target plant to the non-target plants. Mowing served as a comparison, because this method of interrow weed control had minimal risk of causing any crop damage (particularly in small-plot experiments that do not use commercial machinery that may touch the non-target crop plants or cause soil compaction). Compared with mowing, other methods of interrow weed control like cultivation or herbicide may result in soil throw or spray drift, resulting in damage to non-target plants (Hashem et al. 2011; Peltzer et al. 2009). Additionally, we hypothesized that the extent of crop damage would be influenced by moisture levels, with greater damage expected in moist soil conditions compared with dry soil.

Materials and Methods

Field Experiment Implementation

For the three field experiments, a weed-free lupine crop with a 22.5-cm row spacing was identified. At all sites, the crops did not have weeds, except for some very sparse *L. rigidum* in Experiment 1. To maintain uniformity, weed control via electric weed control or mowing (depending on the trial) was applied to a row of lupines, and then crop yield was assessed in the neighboring, non-target row of lupines. In the control plots, neighboring lupine plants were not removed. Weed-free sites were selected because the experiments aimed to assess potential crop damage or yield reduction caused by the dispersion of electrical current to the roots of neighboring (non-target) plants. The power output and resulting current delivered by an electric weed control applicator into the soil is dependent on plant density. Less power is delivered to bare ground or small, sparse weeds compared with large, dense weeds (CNH 2023). Therefore, to ensure a consistent output of power and accurately assess crop damage, it was necessary to ensure that electric weed control was applied to an evenly spaced, consistent line of plants. In all experiments, weed control (i.e., control of the row of target lupine plants) was performed when the crop reached maturity (anthesis and seed set), ensuring that the roots between plants at a 22.5-cm row spacing would be in physical contact, as indicated by Chen et al. (2014) for lupines in Western Australia. Weed competition can also have an

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Table 1. Experimental year, location, soil characteristics, lupine growth stage, treatment application date, and soil moisture (initial soil moisture and moisture directly after simulated rainfall) data.

Experiment	1	2	3	
Year	2022	2022	2023	
Location	Wongan Hills Research Station (30.8496°S, 116.7372°E)		Northam (31.6511°S, 116. 6984°E)	
Soil characteristics[a]	Yellow-gray sandy loam (5% gravel); nitrate nitrogen: 8 mg kg^{-1}; phosphorus (Colwell): 32 mg kg^{-1}; potassium (Colwell): 36 mg kg^{-1}; sulfur: 6.2 mg kg^{-1}; organic carbon: 0.53%; conductivity: 0.056 dS m^{-1}; $pH_{(CaCl2)}$: 6.4; $pH_{(H2O)}$: 7.2		Light brown sandy loam (5–10% gravel); nitrate nitrogen: 8 mg kg^{-1}; phosphorus (Colwell): 39 mg kg^{-1}; potassium (Colwell): 84 mg kg^{-1}; sulfur: 2.1 mg kg^{-1}; organic carbon: 0.8%; conductivity: 0.035 dS m^{-1}; $pH_{(CaCl2)}$: 4.8; $pH_{(H2O)}$: 5.8	
Lupine growth stage[b]	Principal growth stage 6; flowering		Early growth stage: between principal growth stages 5 and 6; inflorescence emergence and flowering	Late growth stage: between principal growth stages 6 and 7; flowering and seed/pod production
Treatment date	September 2, 2022		August 17–18, 2023	August 31, 2023
Initial soil moisture	1.38 ± 0.18%	2.07 ± 0.18%	3.32 ± 0.26%	0.85 ± 0.09%
Soil moisture following simulated rainfall		5.39 ± 1.03%	10.25 ± 1.39%	3.52 ± 0.60%

[a]Results of a test from CSBP Soil and Plant Analysis Laboratory (2 Altona Street, Bibra Lake, WA 6163, Australia; CSBP Ltd 2010; Rayment and Lyons 2011).
[b]Principal growth stages for dicotyledonous weed species as described by Hess et al. (1997).

Table 2. Details of the electric weed control treatments applied in each experiment, including application speed and power output averaged over the 12 inverters.

Treatment	Application details	Experiment 1	Experiment 2	Experiment 3	
				Early growth stage	Late growth stage
Electric weed control	Speed	1.4 km h^{-1}	1.4 km h^{-1}	2.1 km h^{-1}	1.5 km h^{-1}
	Power	1,141 ± 24 W $inverter^{-1}$ s^{-1}	2,019 ± 33 W $inverter^{-1}$ s^{-1}	2,794 ± 3 W $inverter^{-1}$ s^{-1}	727 ± 67 W $inverter^{-1}$ s^{-1}
Electric weed control following simulated rainfall	Speed		1.4 km h^{-1}	2.1 km h^{-1}	1.5 km h^{-1}
	Power		2,059 ± 29 W $inverter^{-1}$ s^{-1}	2,806 ± 2 W $inverter^{-1}$ s^{-1}	752 ± 69 W $inverter^{-1}$ s^{-1}

inconsistent impact on crop growth and yield. Therefore, a secondary benefit of weed-free sites was that their use ensured that the non-target lupines in the control plots where the neighboring lupine plants were not removed by interrow weed management would be subject to consistent levels of competition. This approach minimized confounding factors, facilitating a more accurate assessment of the effects of electric weed control on crop performance.

In the following three experiments, electric weed control was conducted using a tractor (New Holland TS100A, CNH Australia, 31-35 Kurrajong Road, St Marys, NSW, Australia) equipped with an XPower power supply unit. The applicator was an XPS (rear mounted) in 2022 or an XPU (front mounted) in 2023. The XPS features two 55-cm-wide applicators, one on each side of the power unit', to the side of the wheelbase. The XPU has a single 1.2-m application across the front of the tractor, with the capacity to be offset (i.e., shifted left or right) from the tractor wheelbase by 50 cm to allow it to contact plants next to the tractor. Note that treatment by either applicator ensures that the tractor is not driving directly next to the row (i.e., applicators are offset from the wheelbase), and there is no physical contact with or soil compaction close to the non-target plants. Each applicator has three arrays of electrodes that are powered by the power supply unit, using 12 inverters to deliver 36 kW (3 kW per inverter). The speed of application was dependent on site, as it was necessary to travel slightly faster when the soil was soft (greater moisture content; Table 1) in the first application time of Experiment 3. However, manual recommendations for broadleaf control are application speeds of 2 to 4 km h^{-1}, so all speeds (1.4 to 2.1 km h^{-1}) were sufficient to control mature lupines (CNH 2023). Interrow mowing was simulated by using handheld clippers (Ryobi 18V Hedge and Grass Shears, Bunnings, Corner Oliver Street and Peel Terrace, Northam, WA, Australia) to remove the row of lupines at a height of 5 cm.

Experimental Design

For Experiments 1 and 2, a bulk lupine crop sown on May 18, 2022, was identified. In Experiment 1 (2022), plots measuring 1.57-m wide (i.e., seven rows of lupines at 22.5-cm spacing) by 50-m long were established in a randomized block design with four replications (Table 1). Treatments included electric weed control or an untreated control. Electric weed control was applied using the XPS applicator to each side of the plot along the two outer rows of lupines (Table 2). In the control treatments, the outer lupine rows were left intact. All treatments were applied at anthesis or later, as a standard age for interrow weed control via herbicide application in the region (Hashem et al. 2011). Measurements (see "Measurements in the Field Experiments") were taken from the row of non-target lupines directly adjacent to the outer rows.

In Experiment 2 (2022), plots of 1.12-m wide (five rows of lupines on 22.5-cm spacing) by 10-m long were established in a randomized block design with four replications. In each plot, the single row of non-target lupines in the center of the five rows was used for sampling. Treatments were applied (on the same date as Experiment 1; Table 1) to the two rows of target lupines to either side of the center row. In Treatment 1, control plots, the two rows of lupines growing on either side of the central row were left intact. In Treatment 2, electric weed control, the XPS applicator was used to electrocute the two outer rows of lupines to either side of the central row. In Treatment 3, electric weed control in moist soil, the entire plot area was exposed to a simulated rainfall event with water delivered via a handheld sprayer system at a rate of 20 L m^{-2} (i.e., 20 mm of rain). After "rainfall," the two rows of lupines to either side were electrocuted as for Treatment 2. In Treatment 4, mowing, clippers were used to remove the two rows of lupines on either side of the central row.

In Experiment 3 (2023), a bulk lupine crop sown on April 24, 2023, was identified. Plots measuring 0.67 m (three rows of lupines on 22.5 cm spacing) by 10 m were marked in four banks in a randomized row-column design with four replications. A central row of lupines was marked in each plot, as for Experiment 2. Each plot was surrounded by bare ground, that is, no plants aside from the non-target plants and the row of treated plants. Experiment three replicated Experiment 2, with the same treatments. The single row of lupines on either side of the central row was retained (control) or treated with electric weed control (using the XPU applicator), electric weed control in moist soil, or with mowing. However, the experiment was conducted twice, with treatments applied at an early or late growth stage (Table 1). An additional control (i.e., two controls per block) was included to improve the statistical comparison of treatments with the control, and to ensure an even treatment number to allow blocking in two directions (to give greater control over spatial variability). Although Experiment 3 treatments replicated Experiment 2, the two times of application of each treatment (early or late) were randomized within the trial to allow comparison of growth stages and comparison with the treatments.

Measurements in the Field Experiments

Directly before treatment application, volumetric soil moisture was assessed to a depth of 12 cm (HydroSense II Handheld Soil Moisture Sensor, Campbell Scientific Australia, 411 Bayswater Road, Garbutt, QLD, Australia) at six locations per plot. During the electric weed control treatments, the XPower power unit on the rear linkage of the tractor recorded speed of operation and power output from each of the 12 inverters per second. Power output per inverter (W s^{-1}) was calculated by averaging the power output over the 12 inverters and then over the plot application time (Table 2). Speed data were not analyzed, as the operator aimed to maintain a consistent speed throughout the treatment process. Tractor power output may be affected by plant density or soil conditions, so an unpaired *t*-test was used to compare average power output between treatments (GenStat; VSN International 2024).

Immediately following treatment application, visual assessment of target lupine plants was used to confirm that all plants had been treated with electric weed control or mowing. Treatment effects were visible, as electric weed control results in immediate wilting and darkening of plant foliage. A visual assessment was also used to assess potential damage to non-target lupine plants resulting from the treatment of target plants. Visual assessment was repeated 1 wk after treatment and again at crop senescence to assess mortality of target plants (i.e., to check for regrowth following treatment). However, there were no signs of survival or regrowth of the treated plants in both electric weed control and mowing plots. For the non-target lupines, the number of plants was assessed in 2 linear meters of crop in the central row of each plot. The aboveground plant biomass in the 2 linear meters was harvested, and samples were weighed. Yield was assessed by manually counting pod number and seed number and determining seed weight. Seed were subjected to XDS near-infrared spectroscopy (Infratec™ NOVA FOSS, FOSS Pacific, 5/3-5 Anzed Court, Mulgrave, VIC, Australia) to assess grain protein and moisture. Average grain moisture was 9.72 ± 0.04%, 9.51 ± 0.05%, and 9.63 ± 0.04% in Experiments 1, 2, and 3. Protein results were adjusted to 10% moisture to standardize comparisons between treatments and account for differences in moisture content. Seed from each treatment was retained to assess germination and seedling vigor.

ANOVA was performed on lupine density, biomass, yield, and grain quality data, and LSD was used for means comparison. Each experiment was analyzed separately to allow the two application timings (early and late growth stage) in Experiment 3 to be compared (as opposed to a joint analysis of the treatments in Experiment 2, Experiment 3 timing one and Experiment 3 timing two). For Experiment 3, an unbalanced design (i.e., two control treatments) necessitated the generation of two LSD values. The comparison between the control and the other treatments required the LSD for maximum and minimum replication and the comparison between the treatments required the LSD for minimum replication. To ensure consistent variance, a logarithmic (base 10) transformation was performed on the number of seed pods per plant, number of seeds per plant, and seed weight data from Experiment 1. Where a transformation was used, means are presented as both transformed and back-transformed values, with the LSD applied to the transformed values.

Climate Data

At the end of the season, climate data for the experimental year and long-term average data were obtained from two weather stations: Wongan Hills (Station 008137) and Northam (Station 10111) (Bureau of Meteorology 2023). For each site, the average maximum and minimum temperatures during the experimental year were similar to the long-term averages and similar between sites (data not presented; Bureau of Meteorology 2023). By comparison, rainfall data were not similar between sites or similar to the long-term averages. Rainfall in Wongan Hills 2022 totaled 461 mm, greater than the long-term average rainfall of 387 mm (Figure 1). Rainfall in Northam 2023 was 269 mm, which was lower than the long-term average of 426 mm.

Germinability of Seeds from Non-target Plants

To assess germinability of the seed from non-target plants in the central row of each plot, 50 seeds were taken from each of the two samples harvested from each plot and placed on filter paper in petri dishes, with 6 ml of distilled water added (on March 7, 2023, or January 29, 2024). Seeds were maintained in a germination cabinet at a 12-h temperature cycle of 10 to 20 C. Additional distilled water was added when required to ensure petri dishes remained moist. After 16 d, germinated seeds (i.e., those seeds with emerged hypocotyls of at least 1-cm length) were counted. An ANOVA was performed on the germination data, and LSD was used for means comparison. To ensure consistent variance, germination data from Experiment 3 required a square-root transformation. Where a transformation was used, means are presented as both transformed and back-transformed values, and the LSD should be applied to the transformed values.

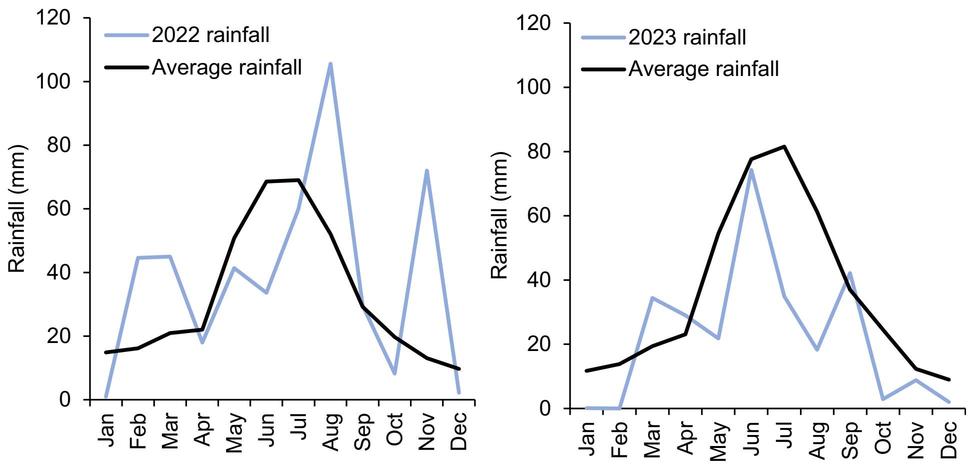

Figure 1. Total monthly rainfall for 2022 in Wongan Hills (left) and 2023 in Northam (right) compared with the long-term average monthly rainfall for each site (1907–2024 at Wongan Hills and 1877–2024 at Northam) (Bureau of Meteorology 2023).

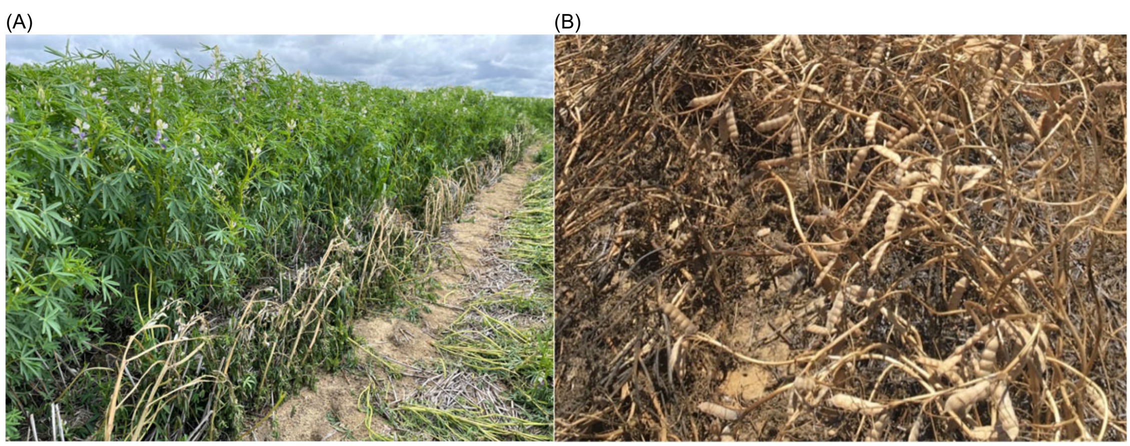

Figure 2. (A) A row of senescing target lupine plants at 1 wk after treatment with electric weed control on the right side of the row of the untreated, non-target plants. (B) A row of dead target lupine plants on the left side of the untreated, non-target plants at harvest. There was no evidence of target plants resprouting following electric weed control.

Vigor of Seedlings from Non-target Plants

To assess seedling vigor of the seeds produced by the non-target plants, 20 seeds were taken from each of the two samples harvested from each plot. They were sown in pots (of 30 cm length by 15 cm width by 5 cm height) filled with sand, at a depth of 2 cm (on March 17, 2023, or January 29, 2024). Pots were arranged in a randomized block design with the same replication structure as the trials, maintained in a 12-h temperature cycle of 10 to 20 C and watered (overhead sprinkler irrigation) to ensure that the surface soil remained damp. After 16 d, emerged seedlings were counted. Seedlings were cut off at the base of the hypocotyl and dried at 60 C for 3 d, and dry biomass was assessed. ANOVA was applied to the emergence and biomass data, and LSD was used for means comparison.

Results and Discussion

As stated, visual assessment of the target lupine plants indicated that electric weed control and mowing had 100% control, with no evidence of survival or regrowth of target plants at 1 wk after treatment or at harvest when the non-target lupine plants were sampled (Figure 2). It is likely that these interrow weed control methods will be effective for control of blue lupine (*Lupinus cosentinii* Guss.), which is particularly difficult to control selectively in lupine crops (Hashem et al. 2011). Initial research indicated that electric weed control is comparable to control provided by herbicides for a range of broadleaf and grass species (Koch 2022; Slaven and Borger 2024; Slaven et al. 2023), but further research is required to assess efficacy on additional weed species at different ages and densities.

Visual assessment of non-target lupine plants in all experiments at the time of application and 1 wk after application indicated no initial plant damage (Figure 2). Electric weed control directed to target plants makes the foliage visibly wilt following application, but this wilting was not apparent for the non-target plants that had no direct contact with the applicators. There were no signs of physical damage to the non-target plants due to the passage of machinery, but treatments were designed to avoid physical contact with non-target plants.

In Experiment 1, electric weed control had no effect on the density or biomass of the non-target lupine plants in the central row of the plot (Table 3). Further, the number of pods per plant, number of seeds, and seed weight were similar between the control

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Table 3. The effect of interrow electric weed control on the average plant density (per linear meter), as well as biomass at harvest, number of pods, number of seeds, and seed yield per plant for lupine plants in the row neighboring each treatment, in Experiment 1.

Treatment	No. of plants	Dry biomass	No. of pods[a]	No. of seeds [a]	Seed yield [a]
	m^{-1}	g $plant^{-1}$	——plant^{-1}——		g $plant^{-1}$
Control	12.2	131.2	21.9 (1.34)	97.7 (1.99)	16.6 (1.22)
Electric weed control	10.0	110.9	22.4 (1.35)	104.7 (2.02)	18.3 (1.26)
P (and LSD)[b]	0.453 (8.33)	0.620 (117.40)	0.956 (0.45)	0.899 (0.47)	0.825 (0.45)

[a]A logarithmic (base 10) transformation was applied before analysis. The back-transformed means are presented in the table, with the transformed means in parentheses. The LSD value should be applied to the transformed means.
[b]The P-values and LSD values are presented for each comparison.

Table 4. The effect of interrow electric weed control on lupine grain quality, including individual seed weight, seed protein, and germination of lupine seeds harvested from plants in the row neighboring each treatment in Experiment 1.

Treatment	Seed weight	Seed protein	Seed germination
	g $seed^{-1}$	——%——	
Control	0.169	27.9	99.7
Electric weed control	0.174	28.1	100.0
P (and LSD)[a]	0.155 (0.01)	0.529 (1.01)	0.351 (0.59)

[a]The P-values and LSD values are presented for each comparison.

and the electric weed control treatment. The weight of individual seeds, protein, and germination of the seed retained from each treatment were likewise similar (Table 4). The assessment of seedling vigor indicated no difference in emergence or seedling biomass (Figure 3).

In Experiment 2, the treatments had no impact on plant density, but dry biomass, seed pods, number of seeds, and seed weight per plant were lower in the control treatment compared with mowing or electric weed control (Table 5). This discrepancy can be attributed to the presence of the plants growing either side of the row of non-target lupine plants in the control plots, which were not removed via interrow weed control tactics. In the treated plots, the plants on either side of the non-target lupine plants were removed by mowing or electric weed control. The presence of the neighboring plants in the control plots would increase intraspecies competition for resources during anthesis and seed production compared with the treated plots. Tobiasz-Salach et al. (2023) demonstrated reduced number of seeds per pod and seed weight per plant when lupine seeding density was increased, highlighting the impact of intraspecies competition in determining reproductive success of individual plants. For all treatments, weight of individual seeds was similar between treatments, but seed protein was slightly lower in the electric weed control treatments compared with the control plots, likely due to increased yield and the resulting protein dilution (Table 6). Electric weed control and mowing had no effect on germination of the seed retained at harvest, with 100% germination observed in all treatments (Table 6). Seedling emergence and biomass were also similar between treatments (Figure 4).

In Experiment 3, despite the similarity in the number of plants across treatments, a nearly significant difference ($P = 0.051$) was observed in dry biomass per plant. At the earlier plant growth stage, electric weed control following simulated rainfall had a higher biomass than the other treatments (except for mowing; Table 7). Likewise, the number of pods per plant, number of seeds per plant, and seed yield were also greatest following electric weed control with water at the early plant growth stage and higher in the mowing treatment than in the control. The enhanced growth after mowing at the early growth stage compared with the control is again likely due to altered intraspecies competition for resources during anthesis and seed production, as mentioned previously. The yield increase with electric weed control following water at the early growth stage likely resulted from the reduced plant competition and increased soil moisture at time of treatment (3.32% to 10.25% soil moisture). As stated, 2023 was an unusually dry year (Figure 1), and lupine yield is highly sensitive to drought stress during seed production, particularly in the rainfed Mediterranean climate of southern Australia (Palta et al. 2004; Reader et al. 1997). The treatments had no impact on grain quality, with no differences between seed weight or protein (Table 8). Likewise, there was no impact on germinability, emergence, or seedling biomass (Table 8; Figure 5).

This research concludes that interrow electric weed control or mowing within a lupine crop did not reduce the biomass of adjacent non-target lupine plants, yield, or seed quality compared with the untreated control. These findings suggest that these weed management tactics do not pose a risk to the productivity or quality of lupine crops. The biomass and yield of the lupine crops were highly variable between the experiments in 2022 and 2023, but as stated, 2022 rainfall was above average and 2023 was an unusually dry year. It has previously been indicated that lupine growth and yield is highly variable, affected by abiotic stresses like water stress, water logging, low radiation, or low temperatures during winter or dry conditions and high temperatures during seed production in spring (Palta et al. 2004; Reader et al. 1997). The lack of damage to crop yield or biomass from electric weed control contrasts with other methods of interrow weed control, which often result in crop damage. Traditional methods such as tillage can cause physical damage to crops from implements traversing the row or soil throw, while herbicide applications may lead to damage due to drift or residual movement in the soil or in the crop residue (Peltzer et al. 2009). However, while the current study investigated immediate signs of wilting or physical damage to the non-target plants, it did not assess root biomass. Further research is required to determine whether any reduction in root growth occurs, which the plants may or may not subsequently recover from before harvest.

This study likewise found no impact of treatments on individual seed size, germinability, or early seedling vigor and biomass. This is a valuable finding for growers who retain their crop seed to resow in the subsequent year and need to know that weed management tactics will not impact the early vigor of the following crop. In lupines, seed-quality traits are correlated. For example, Berger et al. (2017) related early vigor (i.e., biomass at 45 d after sowing) to seed weight in *L. albus*, narrowflower lupine (*Lupinus angustifolius* L.), and European yellow lupine (*Lupinus luteus* L.). In the current experiments, there was no significant difference between the weight of individual seeds, even in Experiment 2, where the control had significantly fewer seeds per plant and increased protein.

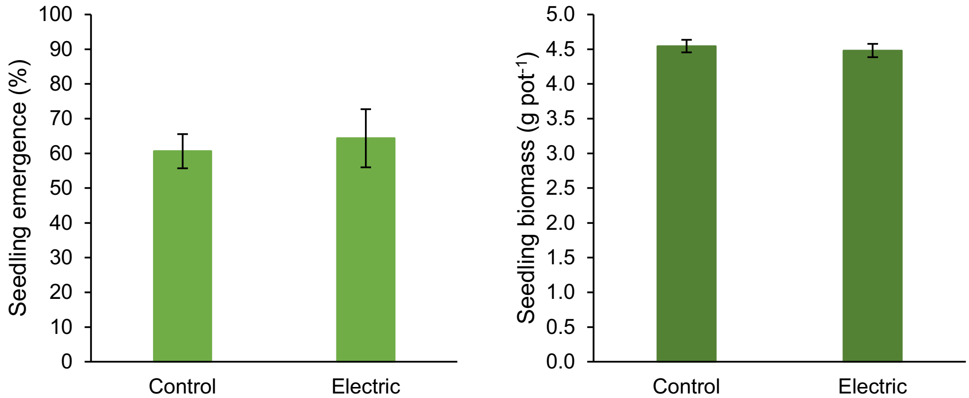

Figure 3. The emergence (P = 0.700, LSD = 22.09) and seedling biomass (P = 0.670, LSD = 0.34) of 20 lupine seeds sown in pots, obtained from plants from the control or electric weed control treatments in Experiment 1. Vertical bars indicate the standard error of eight replications.

Table 5. The effect of interrow electric weed control or mowing on the average plant density (per linear meter), as well as biomass at harvest, number of pods, number of seeds, and seed yield per plant for lupine plants in the row neighboring each treatment, in Experiment 2.

Treatment	No. of plants	Dry biomass	No. of pods	No. of seeds	Seed yield
	m^{-1}	g $plant^{-1}$	——————$plant^{-1}$——————		g $plant^{-1}$
Control	13.0	59.2	12.1	49.6	8.0
Mowing	13.2	133.9	28.2	125.6	20.4
Electric weed control	14.0	123.9	25.7	108.9	18.8
Electric weed control after watering	15.6	114.1	23.7	106.4	17.7
P (and LSD)[a]	0.525 (4.24)	0.011 (40.96)	0.011 (8.75)	0.011 (40.90)	0.008 (6.61)

[a]The P-values and LSD values are presented for each comparison.

Table 6. The effect of interrow electric weed control or mowing on lupine grain quality, including individual seed weight, seed protein, and seed germination of lupine seeds harvested from plants in the row neighboring each treatment in Experiment 2.

Treatment	Seed weight	Seed protein	Seed germination
	g $seed^{-1}$	——————%——————	
Control	0.160	28.3	100
Mowing	0.164	27.9	100
Electric weed control	0.173	27.3	100
Electric weed control after watering	0.168	27.7	100
P (and LSD)[a]	0.061 (0.010)	0.012 (0.54)	NA

[a]The P-values and LSD values are presented for each comparison.

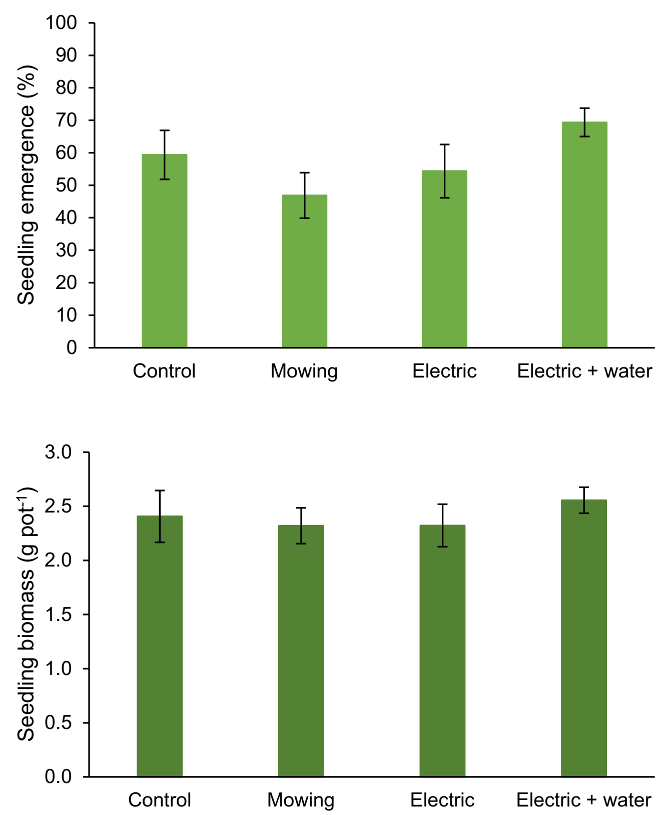

Figure 4. The emergence (P = 0.054, LSD = 16.02) and seedling biomass (P = 0.595, LSD = 0.41) of 20 lupine seeds sown in pots, obtained from plants from the control, mowing, or electric weed control treatments with or without water in Experiment 2. Vertical bars indicate the standard error of eight replications.

Therefore, emergence and early seedling biomass were expected to be similar between treatments.

Grain protein was not affected by the treatments, so it is likely that electric weed control or mowing had no impact on root nodulation, a crucial process for nitrogen fixation in legumes. The total quantity of nitrogen fixed by the rhizobia and the amount of nitrogen transferred from the sink of surplus nitrogen to the seed at grain fill both rely on plant growth and environmental factors (Ahemad and Khan 2013; Sandana et al. 2009). Because electric weed control did not affect plant growth (biomass or yield), it is unlikely to impact total nitrogen production or grain protein. However, the current study did not assess levels of rhizobia in the soil, nodulation, or total nitrogen production. Further research is required to explore the potential effects of electric weed control at varying times of the year on rhizobium inoculum in the soil, its

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Table 7. The effect of interrow electric weed control or mowing at two different growth stages on the average plant density (per linear meter), as well as biomass at harvest, number of pods, number of seeds, and seed yield per plant for lupine plants in the row neighboring each treatment in Experiment 3.

Treatment	Plant growth stage	No. of plants	Dry biomass	No. of pods	No. of seeds	Seed yield
		m^{-1}	g $plant^{-1}$	———plant^{-1}———		g $plant^{-1}$
Control		10.9	22.1	4.2	66.7	8.2
Mowing	Early growth stage	12.0	34.2	7.1	109.0	13.3
Electric weed control		11.9	26.4	5.3	82.6	10.5
Electric weed control after watering		9.4	39.3	7.9	124.1	15.2
Mowing	Late growth stage	11.7	26.5	5.3	79.7	10.0
Electric weed control		11.9	23.7	4.4	68.7	9.0
Electric weed control after watering		11.7	26.4	5.1	80.9	10.5
P[a]		0.689	0.051	0.018	0.021	0.036
LSD min replication[a]		3.55	12.07	2.35	37.00	4.64
LSD max–min[a] replication		3.07	10.45	2.03	32.05	4.02

[a]The P-values and LSD values are presented for each comparison. The control should be compared with treatments using the LSD for maximum–minimum replication and comparisons between treatments should use the LSD for minimum replication.

Table 8. The effect of interrow electric weed control or mowing at two different growth stages on lupine grain quality, including individual seed weight, seed protein, and seed germination of lupine seeds harvested from plants in the row neighboring each treatment in Experiment 3.

Treatment	Plant growth stage	Seed weight	Seed protein	Seed germination[a]
		g $seed^{-1}$	————%————	
Control		0.123	28.0	97.5 (1.59)
Mowing	Early growth stage	0.122	27.9	99.9 (0.25)
Electric weed control		0.127	27.7	99.5 (0.68)
Electric weed control after watering		0.122	28.0	99.4 (0.78)
Mowing	Late growth stage	0.126	27.9	98.2 (1.35)
Electric weed control		0.131	27.9	98.1 (1.39)
Electric weed control after watering		0.129	28.0	98.9 (1.07)
P[b]		0.136	0.585	0.251
LSD min replication[b]		0.008	0.32	1.28
LSD max–min replication[b]		0.007	0.28	1.11

[a]A square-root transformation (of the percent of nongerminated seed; i.e., 100% − seed germination%) was applied before analysis. The back-transformed means (as percent germination) are presented in the table, with the transformed means in parentheses. The LSD value should be applied to the transformed means.
[b]The P-values and LSD values are presented for each comparison.

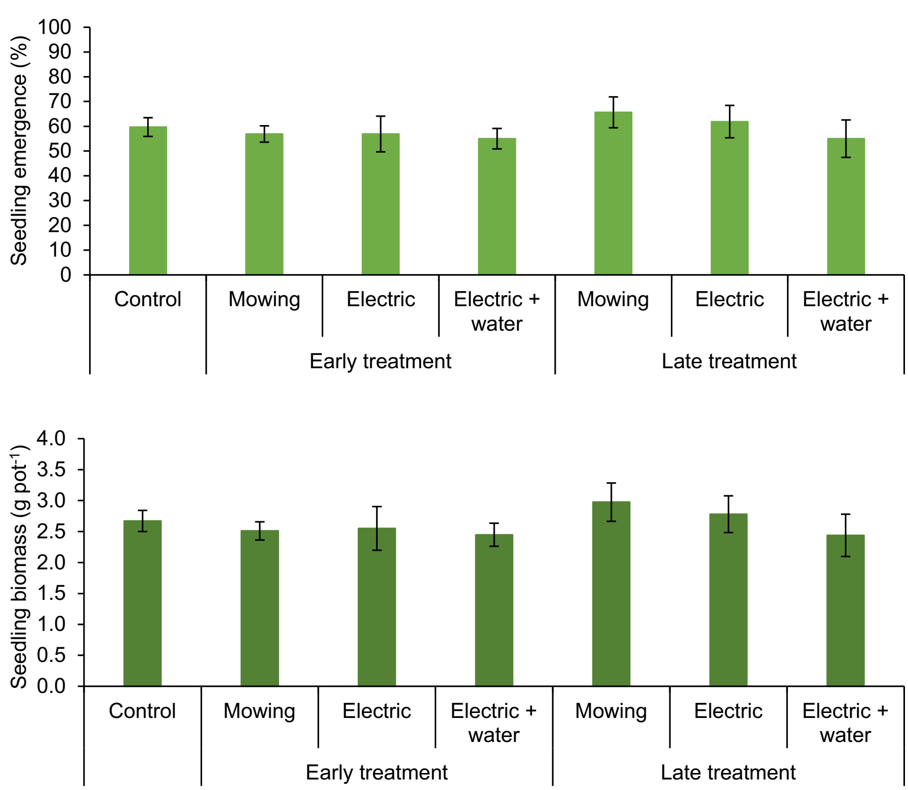

Figure 5. The emergence (P = 0.808, LSD max–min = 14.5) and seedling biomass (P = 0.746, LSD max–min = 0.671) of 20 lupine seeds sown in pots, obtained from plants from the control, and early or late mowing or electric weed control treatments (applied with or without water) in Experiment 3. Vertical bars indicate the standard error of 8 replications, or 16 replications for the control.

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interactions with the plants, and its longevity within the crop rotation.

Interestingly, our study found no impact of soil moisture on electric weed control. Even with increased soil moisture from simulated rainfall, the neighboring, non-target plants were unaffected in the current trials, confirming the results of Koch (2022). However, Borger and Slaven (2024) noted reduced electric weed control efficiency following simulated rainfall to create wet topsoil, highlighting that slower application speeds (i.e., a higher "dose" of electrical current) may be required for optimal weed control in moist soil.

Other recent studies on electric interrow weed control have used the Weed Zapper™ and are not comparable to the current work (Rowland et al. 2023; Schreier et al. 2022). The Weed Zapper™ can only target weeds after they have grown above the crop canopy, in physical contact with or proximity to the copper boom. As a result, electric weed control in these studies provided poor weed control, because it was applied late in the growing season, only targeted selected (tall) weed species, and caused crop damage when the boom came into contact with the crop canopy (Fickett et al. 2013; Rowland et al. 2023; Schreier et al. 2022). By comparison, the current research used the XPower to apply electric weed control to "weeds" (i.e., rows of lupine plants) on the ground and found that electric weed control efficacy was comparable to mowing and did not result in crop damage. In the current research, the experimental design aimed to avoid direct contact of the applicators with the non-target crop plants and thus prevent damage to non-target plants via direct application of current or by physical contact of the machine. As stated, there was no sign of physical injury or wilting from electric weed control at time of application. However, it is important to note that the machinery used in the current work was designed for interrow weeding in viticulture or horticulture (XPS applicator) or for urban environments (XPU applicator), rather than grain crops. There are new iterations of the technology designed for interrow weed control in cropping, using shielded interrow units at ground level (Koch 2022). This system uses the same inverters as the current research, delivering the same power per second, but consists of interrow applicators that are designed to avoid physical contact with aboveground crop biomass and should minimize crop damage and avoid reductions to yield, as long as root damage to neighboring plants can be excluded, as for the current research. However, the current research cannot consider all forms of potential crop damage. Any interrow weed management technique that involves driving machinery through a crop is likely to result in a yield reduction (physical damage to the crop from the movement of machinery, soil compaction, etc.) unless the grower employs a controlled traffic farming system (Tullberg et al. 2007). This highlights the need for continued research on interrow electric weed control or mowing using commercial machinery designed for this specific purpose to provide insights into the practical application and potential benefits of these techniques in agricultural settings. Such research should also determine the machinery's commercial viability by considering both cost-effectiveness and scalability for on-farm use through comparison with other novel nonchemical weed control methods.

Power output was variable between experiments (Table 2), but contrary to expectations, electric weed control power output was not affected by soil moisture. At a soil moisture content of 2.07% and 5.39% in Experiment 2, there was no significant difference in power output ($P = 0.889$; Table 2). Likewise, in Experiment 3, power output remained unaffected by the soil moisture content at both the first application time with soil moisture at 3.32% or 10.25% ($P = 0.242$) and the second application time with soil moisture at 0.85% or 3.52% ($P = 0.236$; Table 2). However, in Experiment 3, the power output was significantly different between growth stages, with an average power output of 2,800 ± 7 W inverter^{-1} s^{-1} at anthesis and 734 ± 34 W inverter^{-1} s^{-1} at grain fill ($P < 0.001$). This divergence underscores the influence of plant development on the efficacy of electric weed control methods, with greater power output observed at the first application time because the plants were larger (CNH 2023). As lupine plants complete grain fill, leaves shed, and the plant biomass and moisture content are reduced (Hocking 1982).

As stated, the current research did not perform interrow weed control in a weedy site, but targeted rows of lupine plants as substitute "weeds" within a weed-free crop. Removing real weeds with technology fit for the purpose may impact the results. First, power output for interrow electric weed control may vary significantly when targeting actual weed species, as current is related to plant density and foliage contact time with the electrodes (CNH 2023). Second, controlling weeds may involve working closer to the non-target row of crop plants. If the plants subject to electric weed control were closer to the non-target plants, then any current moving through the soil from the roots of one plant to another would travel over a shorter distance. This may increase the potential damage to non-target plants. However, the lupine plants treated here were sufficiently mature that it is reasonable to assume their roots were in physical proximity to the roots of plants in the neighboring row, given that the rows were only 22.5 cm apart (Chen et al. 2014). This is a narrow spacing between plants, given that row spacing for lupine crops can be as wide as 76 cm or 90 cm (Bhardwaj et al. 2004; Hashem et al. 2011; Putnam et al. 1992). However, further research is required to understand the belowground behavior of the current flow during application, with simulations to determine the pathways of electricity through soil or roots. Further, plant and root density and biomass assessments are required to understand the thresholds for current passing into neighboring plants.

This research utilized machinery currently not fit for the purpose in large-acreage crops to apply electric weed control to plants on the ground (rather than plants growing above the crop canopy), simulating interrow weed control. It found that electric weed control efficacy in removing "weeds" (i.e., rows of lupine plants) was comparable to mowing and did not result in crop damage, even when soil moisture was increased (i.e., the soil's resistance to dispersal of the electrical current was reduced). Using this machinery, the experimental design aimed to avoid direct contact of the electrodes with the non-target crop plants to illustrate that it is unlikely that damage will occur using future commercial-grade electric interrow weed control. There are new iterations of this machinery designed for interrow weed control in cropping under development that use shielded interrow units at ground level designed to avoid physical contact with aboveground crop biomass (Koch 2022). However, further studies should explore the commercial viability of electric weed control systems for broadscale crops, considering both cost-effectiveness and scalability. The current research concludes that electric interrow weed control did not impact lupine yield, but more research is required to assess electric weed control at younger plant growth stages or in alternative crops.

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