Department of Primary Industries and Regional Development

GOVERNMENT OF WESTERN AUSTRALIA

What is the best fit for electric weed control in Australia?

2024 Final Project Report

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Key findings

- Damage to plants is immediate, enabling rapid assessment of coverage to ensure that areas are not missed (Figure 1).

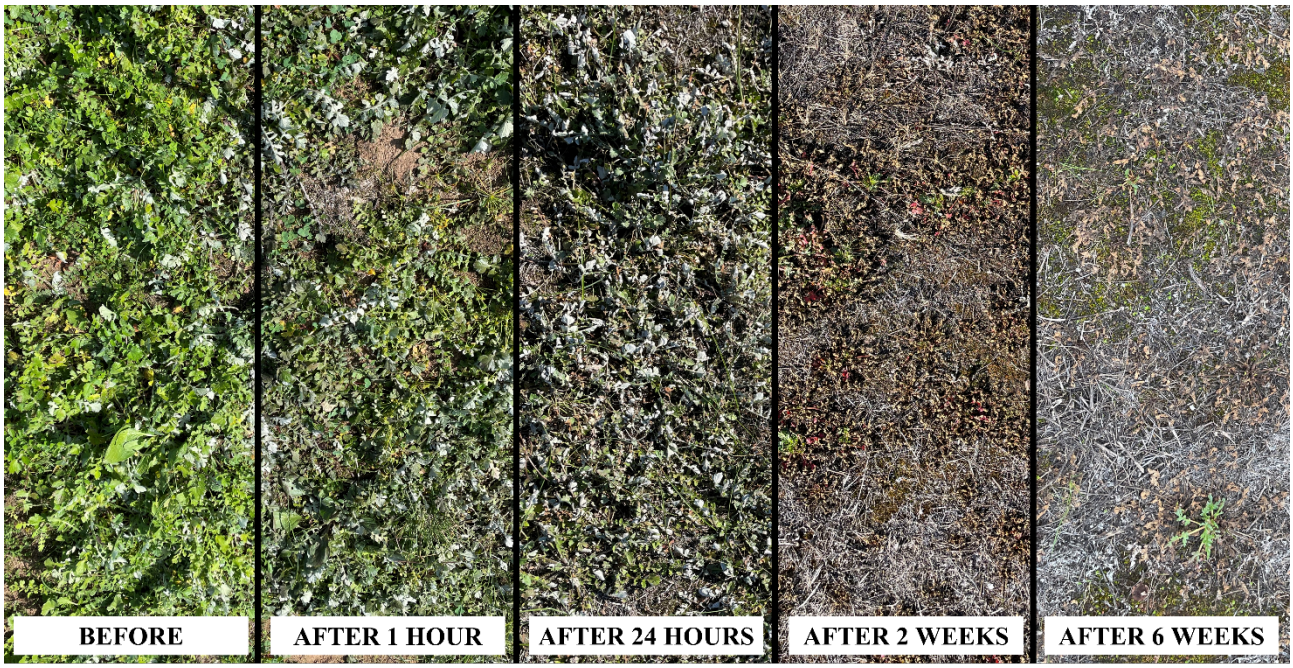


Figure 1. An image of plants before and 1 h, 24 h, 2 weeks and 6 weeks after electric weed control treatment at 2 km h^{-1}.

- Broad leaf weeds were controlled more effectively than grass weeds when using the electrical weed control method. Except for a few species, grass weed control is excellent when applied at the appropriate application speed (Table 1).

Table 1. Weed control achieved for various weed species with electric weed control under different trial conditions.

Weed species	Control	Comments
Annual ryegrass (*Lolium rigidum* Gaud.)	Over 90% at 1.5 km h^{-1}, 40-95% at 3 km h^{-1}.	Easy to kill young plants, however, results are variable at later growth stages and with increased application speeds.
Kikuyu (*Cenchrus clandestinus* Hochst. ex Chiov.)	Over 95% at 1.5 and 3 km h^{-1}	Plants were mature, dense, and damp at 1.5 km h^{-1}, and at early tillering at 3 km h^{-1}.
Wild radish (*Raphanus raphanistrum* L.)	Over 80% at 2-4 km h^{-1}	Mature plants may resprout.
Capeweed (*Arctotheca calendula* (L.) K.Lewin)	Over 85% at 2-4 km h^{-1}	
Erodium (*Erodium* spp.)	Over 85% at 2-4 km h^{-1}	

Couch grass (*Elymus repens* (L.) Gould)	Does not give full control of mature plants at 2 km h^{-1}	
Guildford grass (*Romulea rosea* (L.) Eckl.)	Does not give full control of mature plants at 2 km h^{-1}	Need to assess bulbs to determine mortality.
Soursob (*Oxalis pes-caprae* L.)	Over 85% at 2-4 km h^{-1}	
Medic (*Medicago* spp.)	Over 85% at 2-4 km h^{-1}	
Winter grass (*Poa annua* L.)	Does not give full control of mature plants at 2 km h^{-1}	
Cape tulip (*Moraea flaccida* (Sweet) Steud.)	All above ground vegetation removed at 2-4 km h^{-1}	Some bulbs were still alive. Regrowth/survival in the subsequent year was reduced for electric weed control at 2 km h^{-1} compared to herbicide or electric weed control at 4 km h^{-1}.
Windmill grass (*Chloris truncata* R.Br.)	Partial control (35-90%) with double application treatments at 2-4 km h^{-1}	A clump of windmill grass includes multiple plants. It is very difficult for any weed control technique to target all plants in the clump.
Wireweed (*Polygonum aviculare* L.)	Over 95% at 2-4 km h^{-1}	
Sowthistle (*Sonchus oleraceus* L.)	Over 95% at 2-4 km h^{-1}	
Flatweed (*Hypochaeris radicata* L.)	60-90% at 2-4 km h^{-1}	
Annual veldt grass (*Ehrharta longiflora* Sm.)	Over 90% at 1.4 km h^{-1}	
Silver grass (*Vulpia myuros* (L.) C.C. Gmel.)	Over 90% at 1.4 km h^{-1}	
Wild oats (*Avena fatua* L.)	Over 90% at 1.4 km h^{-1}	
Common dandelion (*Taraxacum officinale* L.)	Over 90% at 1.4 km h^{-1}	

- Manufacturer recommendation is to treat dry plants, but performance at the appropriate speeds (1 km h^{-1} for grasses) gave over 90% control of wet plants, when using a 36 kW or 24 kW application at 1.5 km h^{-1}.
- While manufacturer recommendations are to target weeds in dry soil, electric weed control efficacy following 2-3 mm simulated rainfall events did not indicate that surface soil moisture impacted control. However, 20 mm of rainfall did reduce grass control efficacy at an application speed of 2 km h^{-1}. An application speed of 1 km h^{-1} would have improved control. Therefore, in conditions of high surface soil moisture, application speed should be considered.

- A project highlight was that electric weed control provided over 95% control of wet, fully mature, and exceptionally dense kikuyu at 1.5 km h^{-1} at a viticulture site (with wet topsoil due to recent rainfall). This species is often difficult to fully control with herbicide.
- Damage to soil biota (i.e., bacteria and archaea in the 16s community, fungi in the ITS community and free-living nematodes) was not evident under any electric weed control treatment used at viticulture sites.
- Plants infested with rhizoctonia (a soil pathogen physically attached to the plant roots) were exposed to repeat applications of electric weed control, at low speed, i.e., an unrealistically high 'dose' of electrical voltage. No damage to rhizoctonia was evident.
- Results from viticulture weed control trials and the rhizoctonia trials both confirm no evidence of damage to the soil biota. This result highlights the potential for this technology to be used by organic growers.
- Using the technology to simulate inter-row weed control resulted in no reduction of biomass or yield to non-target plants in the neighbouring row of lupins. There was likewise no impact on lupin seed quality (seed weight, seedling emergence or seedling vigour). Inter-row electric weed control was tested at crop anthesis, in moist soil, when damage to crop yield was most likely to occur.
- Electric weed control was found to be highly effective on herbicide resistant weeds. Specifically, annual ryegrass with high resistance to group 1, 2 and 9 herbicides had biomass reduced by over 90% following electric weed control applications at 2 and 4 km h^{-1} compared to the application of herbicide (glyphosate 1.5 L ha^{-1}, group 9).
- Power output and GPS location are recorded by the tractor. The machinery specifications indicate that power output varies due to weed biomass, but this has not yet been studied. Visual analysis of power output highlights that there is variation due to plant biomass. However, statistical correlation was not determined due to issues with the geographic reference system used by the XPower machine. Discussion is continuing to rectify this to adjust the analysis and investigate potential for weed incidence mapping.
- Fire risk resulting from application is very low in winter/spring but is significant when residue is dry in summer or early autumn. The risk was affected by residue type with oat hay having higher incidence of fires compared to barely straw. However, the average surface area of the residue or biomass did not alter fire risk during electric weed control application.
- Electric weed control is more expensive than herbicides. Specifically, to complete an application using the XPower with XPU applicator at 2 km h^{-1}, the cost would be \$210.55 ha^{-1}. Much of the cost for electric weed control is labour. If this is removed from the equation, the cost of electric weed control is reduced to \$85.55 ha^{-1} (cost of fuel). Therefore, electric weed control is likely a viable solution for weed management in small areas, high value crops, where herbicide use is restricted or problem areas such as where herbicide development has occurred.
- There is potential for the machine to have immediate value for winter and spring weed control in the viticulture and horticulture industries, as well as for urban and industrial management. Summer or autumn control is not safe in Australia due to fire risk.

Background

The Department of Primary Industries and Regional Development (DPIRD) and CNH have completed an Australian-first project to determine the best fit for electric weed control in Australia. The project was also supported by the Grains Research and Development Corporation (GRDC), Wine Australia, AHA Viticulture and the Cotton Research and Development Corporation (CRDC). Electric weed control (or electroweeding) offers an alternative non-selective weed control method to reduce chemical use. It can be used across a variety of industries including viticulture, horticulture, orchards and for urban/industrial weed control. This technology is already utilised across Europe; DPIRD and CNH were seeking to prove the concept of its applicability in Australian systems with the hope it will be certified for use here in the coming years.

The machinery used in this study was produced by the German company Zasso™ in collaboration with CNH. Electric weed control is performed using electricity generated by an XPower unit on the rear linkage of a tractor. The resulting voltage is transferred to weeds using 1) an XPS (viticulture/horticulture) applicator, at 55 cm width, on either side of the tractor or 2) XPU (urban) applicator, at 1.2 m width on the front of the tractor (Figure 2). DPIRD used this technology to conduct a series of field trials, with applicator and height specified for each experiment. A range of data were captured by the XPower unit during operation, some of which were included in the results section. Where power (W) was reported, it was an average of power delivered by twelve high voltage inverters (used by the XPU unit) or six inverters (used by one side of the XPS unit).



Figure 2. CNH tractor with Zasso XPower (energy unit) on the rear linkage with XPS (viticulture application unit), and XPU (urban application unit) on the front. Note that a tractor can carry either applicator, in varying configurations.

Electroweeding works through the conversion of power take off (PTO) power into a high voltage current in the rear power unit which is transferred to the applicator unit containing electrodes. As the tractor moves forward, these electrodes touch the plants and transfer the current through their shoots and roots. The current transforms to heat energy and bursts the plant's cells, killing it or supressing growth. The current then goes into the soil and a second row of electrodes of the opposite charge pull the current back up, closing the circuit. The efficacy of the application is dependent on achieving the right application conditions, as also needs to occur with herbicide applications. Over the project span, DPIRD tested a range of different application conditions theorised to effect application efficacy.

Manufacturer recommendations for electric weed control include application speeds of 2-4 km h^{-1} for broad leaf weeds and 1-3 km h^{-1} for grass weeds. Control is optimised when plants are dry and when surface soil moisture is low (i.e., not to be used during or directly after rainfall). Theoretical knowledge indicates that efficacy will be greater in dry soil, although this has not been tested. Field tests in Europe indicate that control is likely to be reduced where weeds are mature or dense, as for any other weed control tactic. In this report there are experiments where these recommendations were not used, for the purpose of scientific enquiry. Use patterns contrary to manufacturer recommendations are clearly labelled and should not be applied in field conditions.

Electric weed control of annual ryegrass at varying development stages and impact on seed production

Applying weed control tactics to weeds at any stage of development may result in full mortality or, alternatively, result in reduced growth and seed production. When plants are mature (or stressed by environmental factors), it is more difficult to completely kill the plant with herbicide or alternative weed control tactics. As a result, it is a common practice to apply non-selective herbicide like glyphosate or paraquat/diquat at sublethal rates when plants are at the reproductive stage, known as 'crop topping' or 'spray topping' (Steadman et al., 2006). For example, annual ryegrass (*Lolium rigidum* Gaud.) may be sprayed with glyphosate or paraquat/diquat at heading (seed head emerges), anthesis (flowering), or during the milk to early dough stages of seed development (Steadman et al., 2006). Through this practice, seed viability is reduced. The surviving seeds produce seedlings with reduced vigour, which increases the comparative competitiveness of the crop in the following season.

It is possible that applying a sublethal 'dose' of electrical current to annual ryegrass plants will have a similar impact on seed development. In electric weed control, dose is determined by the length of time electrodes stay in contact with the plant, and so is increased at lower speeds. The highest recommended speed for grass control is 2 km h^{-1}, and greater speeds would deliver a sub-lethal dose of electrical current to the plants.

Note: The following experiments use application speeds of 3, 5 or 7 km h^{-1} for control of mature grass weeds; contrary to manufacturer recommendations (non-compliant with manual requirements). These experiments were conducted for scientific purposes and the use pattern should not be applied in field conditions.

2022 Experiment:

Key findings

- Sub-lethal rates of electrical current were applied to annual ryegrass, with the aim of reducing growth/seed production without killing plants (as for the practice of crop topping with herbicides).
- Electric weed control treatments were appropriate to avoid killing plants, in that density, biomass and seed head production were similar between treatments at the end of the year.
- Results confirm the manufacturer recommendations; speeds of 3 km h^{-1} or more have no impact on grass weed control.
- Electric weed control did affect seed viability. Plants had more unviable (empty seed with incomplete embryos) seed following applications of 3-5 km h^{-1} at tillering.

Aim

To determine the impact of potentially sublethal application of electrical current for grass weed control (3, 5 or 7 km h^{-1}) on annual ryegrass seed production, seed viability and seedling vigour.

Method

Site: DPIRD Northam Research Station (-31.6532, 116.6951).

Soil type: Brown sandy loam (5% gravel), nitrate nitrogen 6 mg kg^{-1}, phosphorus (Colwell) 38 mg kg^{-1}, potassium (Colwell) 114 mg kg^{-1}, sulfur 3.2 mg kg^{-1}, organic carbon 0.76%, conductivity 0.030 dS m^{-1}, $pH_{(CaCl2)}$ 4.4, $pH_{(H2O)}$ 5.6.

Applicator: XPU (36kW) for the application at early tillering and XPS (36kW) for the application at late tillering or heading/anthesis.

Treatments:

- Annual ryegrass at early tillering (0, 3, 5 or 7 km h^{-1}, 5/8/2022)
- Annual ryegrass at late tillering (0, 3, 5 or 7 km h^{-1}, 31/8/2022)
- Annual ryegrass at heading to anthesis (0, 3, 5 or 7 km h^{-1}, 24/10/2022)

Note: An application speed of zero indicates the untreated control plots.

Measurements:

- Soil moisture to a depth of 12 cm.
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Annual ryegrass survival.
- Annual ryegrass biomass at senescence.
- Annual ryegrass seed production, germinability and viability*. Seed was assessed as germinable (i.e. seedling emerges), non-germinable (viable but dormant, no seedling) or unviable (seed visually empty, no embryo present, or degraded following the addition of water).
- Seedling vigour**.

Randomised block design with three replications, plots of 2 m by 10 m. Annual ryegrass was sown at a density of 200 seeds m^{-2}.

*To assess seed viability, 50 seeds per plot were placed in petri dishes on moist filter paper and placed in a germination cabinet, maintained at a 12 h temperature cycle of 15-20ºC. Germinated seeds (showing a cotyledon and radicle of at least 1 cm length) were assessed after 16 days.

**To assess seedling vigour, 20 seeds per plot were placed in pots (of 30 cm by 15 cm by 5 cm height) filled with sand, at a depth of 2 cm. Emergence and total seedling biomass were assessed when the eldest seedlings reached 3-leaf stage.

Conditions at treatment:

- Plants were dry.
- Volumetric soil moisture (top 12 cm of soil) averaged 11.4%, 5.6% and 3.6% at early tillering, late tillering and heading application times.

Results

At each application time, environmental conditions were ideal to achieve optimal control. Volumetric soil moisture in the top 12 cm was low and plants were evenly spaced but not dense (bare ground visible between plants). The reduction in soil moisture over time is a response to the change in seasonal conditions at each application time. The average power delivered during each application was lowest at the late tillering stage (353 W inverter^{-1} s^{-1} compared to 526 W inverter^{-1} s^{-1} or 581 W inverter^{-1} s^{-1} at early tillering or maturity; P: 0.001, LSD: 115.5). Average power varied with speed of application (with 0, 723, 589 and 636 W inverter^{-1} s^{-1} at application speeds of 0, 3, 5 and 7 km h^{-1}; P<0.001, LSD:133.4). However, this significant difference is mainly due to power output of 0 W inverter^{-1} s^{-1} at a speed 0 km h^{-1}. There was not a significant interaction between growth stage and application speed on power output (Table 2).

Annual ryegrass density two weeks after electric weed control treatment reduced over time for all speed treatments from an average of 79 plants per m^2 at early tillering to 44 at late tillering and 25 at heading-anthesis (P<0.001). This is likely due to density dependant mortality as the plants aged. While plant density was slightly lower in the early tillering treatments compared to the control, application speed or the interaction between plant age and application speed had no significant impact on plant density (Table 2).

Table 2. Mean speed of application and average power applied during each treatment and annual ryegrass density two weeks later.

Annual ryegrass growth stage	Speed (km h^{-1})	Average power (W inverter^{-1} s^{-1})	Plant density (m^{-2})
Early tillering	0	0	104.9
	3.0	758	77.3
	5.0	706	73.3
	6.6	641	58.7
Late tillering	0	0	44.9
	3.0	574	33.3
	5.1	421	54.7

	6.9	418	41.3
Heading to anthesis	0	0	21.3
	2.9	837	43.0
	5.1	640	17.0
	7.1	849	18.0
P		0.189	0.055

As stated, the aim of this experiment was to investigate seed production and viability following sub-lethal application rates, rather than kill the annual ryegrass. As expected, at senescence there was no effect of treatment time (P: 0.109), application speed (P: 0.128), or their interaction (P: 0.216), on annual ryegrass density, biomass, head number or seed number per plant (data not presented).

However, following the application of electric weed control, ryegrass seed germinability was lower in the early and late tiller at 3 km h^{-1}, and the later tiller at 5 km h^{-1} treatments (P: 0.007, Figure 3). The reduced germinability was because these treatments had a higher proportion of unviable seed (P: 0.005). The number of dormant seeds was consistent between treatments (P: 0.248; data not presented). Of the viable seeds (empty seed removed from the sample), seedling vigour was not affected. Total emergence (P: 0.671) and seedling biomass (P: 0.767) was consistent across all treatments (Figure 4).

As expected, the selected treatment times and application speeds did not achieve plant mortality or changes to growth or seed production. An application speed of 1-2 km h^{-1} is recommended for the control of mature grass plants. Speeds of 3, 5 and 7 km h^{-1} are not recommended for control of any weed species. However, speeds of 3 and 5 km h^{-1} reduced ryegrass seed viability by preventing embryo formation in a proportion of seeds.

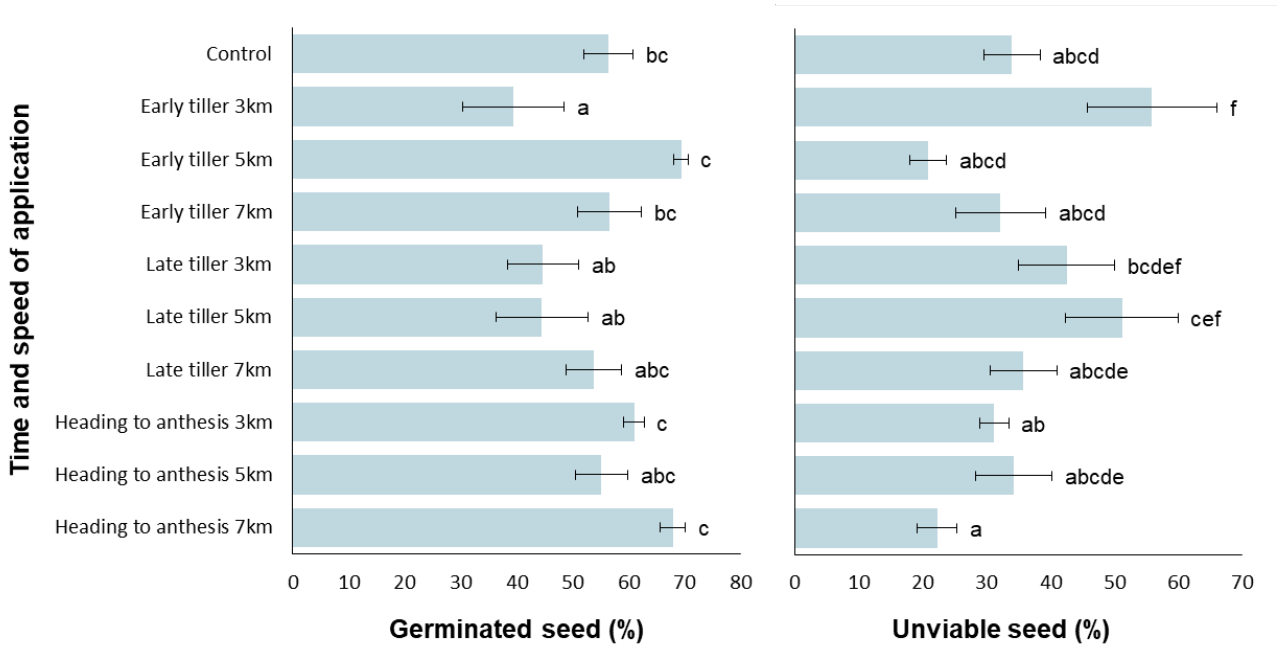


Figure 3. The proportion of germinated (left) and unviable (right) annual ryegrass seed following electric weed control application (mean ± s.e.).

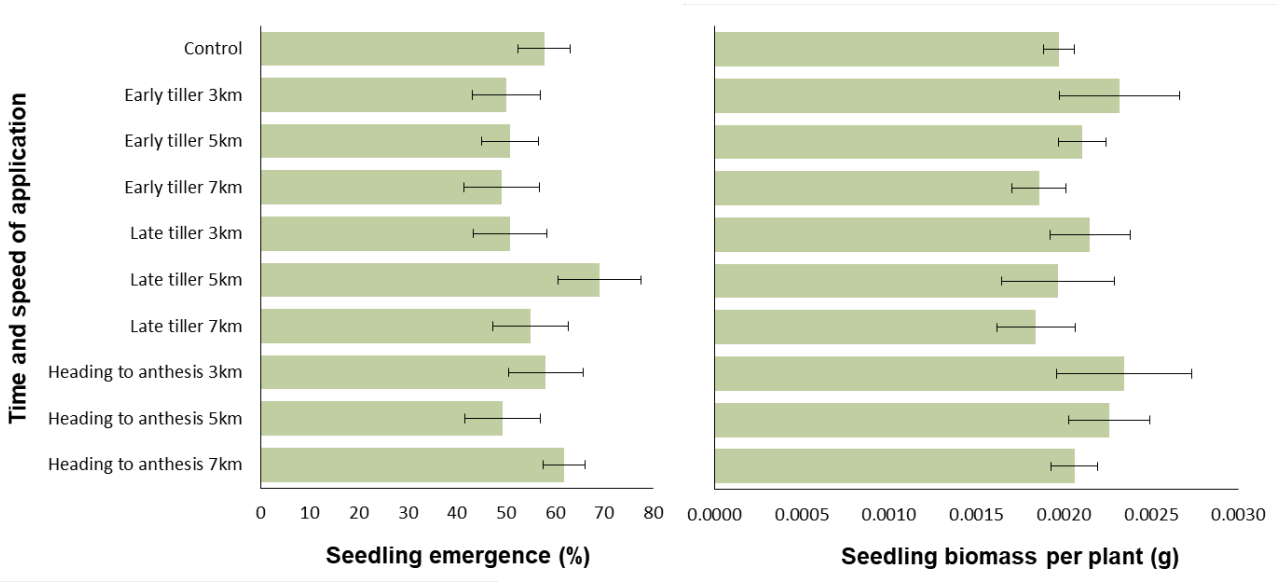


Figure 4. The proportion of annual ryegrass seedling emergence (left) and seedling biomass (right) following electric weed control application (mean ± s.e.).

2023 Experiment:

Key findings

- Sub-lethal rates of electric weed control or herbicide killed half of annual ryegrass plants in a crop-topping treatment.
- Seed viability was reduced in all weed control treatments compared to the control.

Aim

To determine the impact of sublethal application of electrical current to annual ryegrass at anthesis or grain fill (i.e., crop topping) on weed seed production, seed viability and seedling vigour, compared with crop topping via herbicide application.

Method

Site: DPIRD Wongan Hills Research Station (-30.8465, 116.7416).

Soil type: Light grey sandy loam (5-10% gravel), nitrate nitrogen 1 mg kg^{-1}, phosphorus (Colwell) 29 mg kg^{-1}, potassium (Colwell) 149 mg kg^{-1}, sulfur 4.8 mg kg^{-1}, organic carbon 1.07%, conductivity 0.076 dS m^{-1}, $pH_{(CaCl2)}$ 6.8, $pH_{(H2O)}$ 7.5.

Applicator: XPU (36kW)

A bare area was sown to annual ryegrass at 200 seeds m^{-2}. Treatments included electric weed control of annual ryegrass at anthesis and electric weed control or herbicides at late anthesis/grain fill. Plots were 2 m by 10 m in a randomised block design with five replications.

Treatments:

Application time 1 (6/10/2023) – annual ryegrass at mid to late anthesis (flowering)

- Untreated control
- Electric weed control annual ryegrass at 3, 5 or 7 km h^{-1}

Application time 2 (10/10/2023) – annual ryegrass at late anthesis to early grain fill

- Untreated control
- Electric weed control at 3, 5 or 7 km h^{-1}
- Glyphosate 958 g a.i. ha^{-1} (Roundup UltraMAX® 570 g a.i. L^{-1}, Bayer Crop Science Australia)
- Paraquat 200 g a.i. ha^{-1} (Paraquat 250 g a.i. L^{-1}, Genfarm)
- Saflufenacil 24 g a.i. ha^{-1} (Sharpen® 700 g a.i. kg^{-1}, BASF Australia), paraquat 100 g a.i. ha^{-1}, methyl esters 1% (MSO® 630 g a.i. L^{-1}, Loveland Agri Products)

Measurements:

- Soil moisture to a depth of 12 cm.
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Annual ryegrass survival.
- Annual ryegrass biomass at senescence.
- Annual ryegrass seed production, germinability and viability.
- Seedling vigour.

Seed viability and seedling vigour were assessed as in 2022.

Conditions at treatment:

- Plants were dry.
- Volumetric soil moisture (top 12 cm of soil) averaged 1.3% at the first application time and 1.0% at the late application time.
- There were issues with the electric application at the first treatment time because the soil was very dry. The electrodes which are responsible for detecting residual current behind the machine did not register properly due to the dry conditions.

Table 3. The average tractor speed and power applied for electric weed control on each date, at each treatment speed.

Treatment speed	6/10/2023		10/10/2023	
	Speed (km h^{-1})	Power (W $inverter^{-1}$ s^{-1})	Speed (km h^{-1})	Power (W $inverter^{-1}$ s^{-1})
3 km h^{-1}	2.89	855	3.07	504
5 km h^{-1}	4.52	729	5.31	448
7 km h^{-1}	6.52	537	6.49	477

Results

Two weeks after the application of each treatment approximately half of the half of the annual ryegrass plants were killed compared to the control, although there were slightly fewer plants in the 3 km h^{-1} than the 7 km h^{-1} treatment (Table 4). As noted, the application of these treatments was not designed to kill plants but aimed to reduce annual ryegrass seed set.

Table 4. Annual ryegrass density two weeks after treatment of electric weed control (EWC) or herbicide (P<0.001, LSD: 3.485).

Application time	Treatment	Plant density (m^{-2})
NA	Control	21.6
Anthesis	EWC 3 km h^{-1}	10.0
Anthesis	EWC 5 km h^{-1}	12.8
Anthesis	EWC 7 km h^{-1}	14.0
Grain fill	EWC 3 km h^{-1}	8.4
Grain fill	EWC 5 km h^{-1}	9.6
Grain fill	EWC 7 km h^{-1}	12.0
Grain fill	Glyphosate	6.0
Grain fill	Paraquat	10.4
Grain fill	Pyraflufen-ethyl + paraquat	11.2

By senescence, there was no effect of the application of the weed control treatments on annual ryegrass density or biomass (data not presented). Annual ryegrass head number was also uniform between treatments (P: 0.067, data not presented). However, seed number per plant was greatest following the application of electric weed control at 7 km h^{-1} or sledge and paraquat at late flowering (P: 0.019; Figure 5).

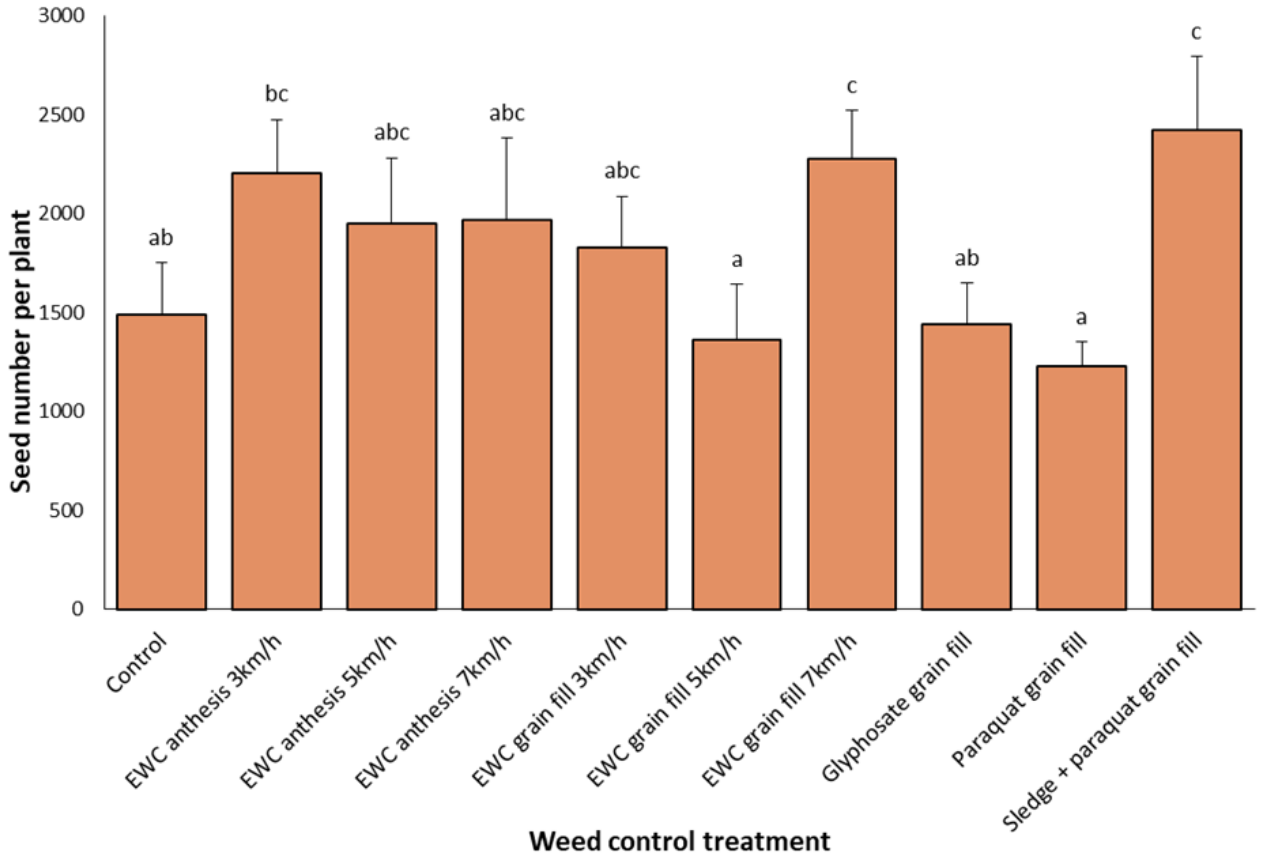


Figure 5. Mean number of seeds at senescence per annual ryegrass plant, following electric weed control application (mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

Seed germination was lowest following herbicide treatments but also reduced following electric weed control at seven and sixteen days after seeding (P<0.001, Figure 6).

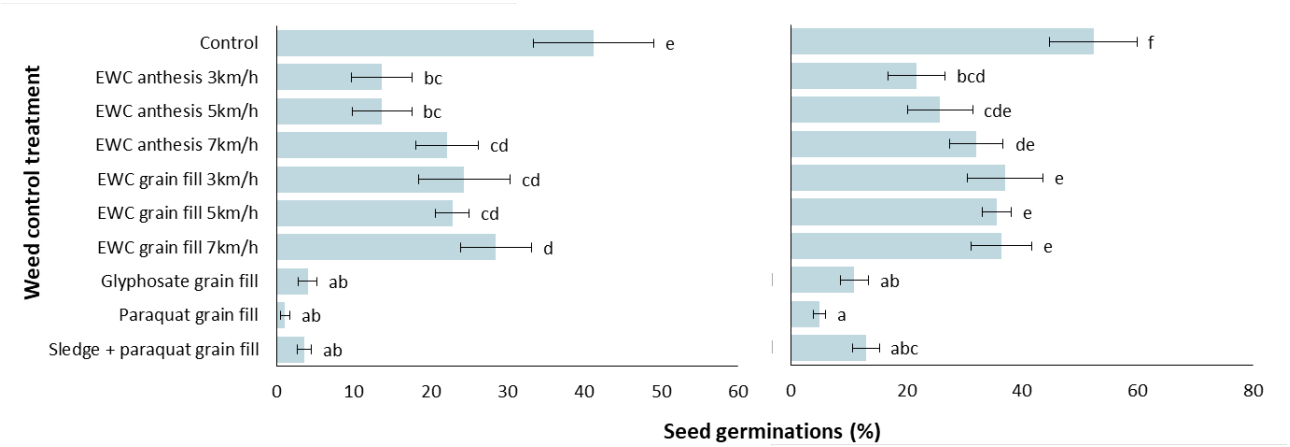


Figure 6. The proportion of annual ryegrass seed germinations seven (left) and sixteen (right) days after seeding (mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P=0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

Similarly, the number of unviable seeds was increased following the application of all weed control treatments (P<0.001; Figure 7). Application of herbicide increased the proportion of dormant seeds, but electric weed control did not (as for the experiment in 2022, P<0.001).

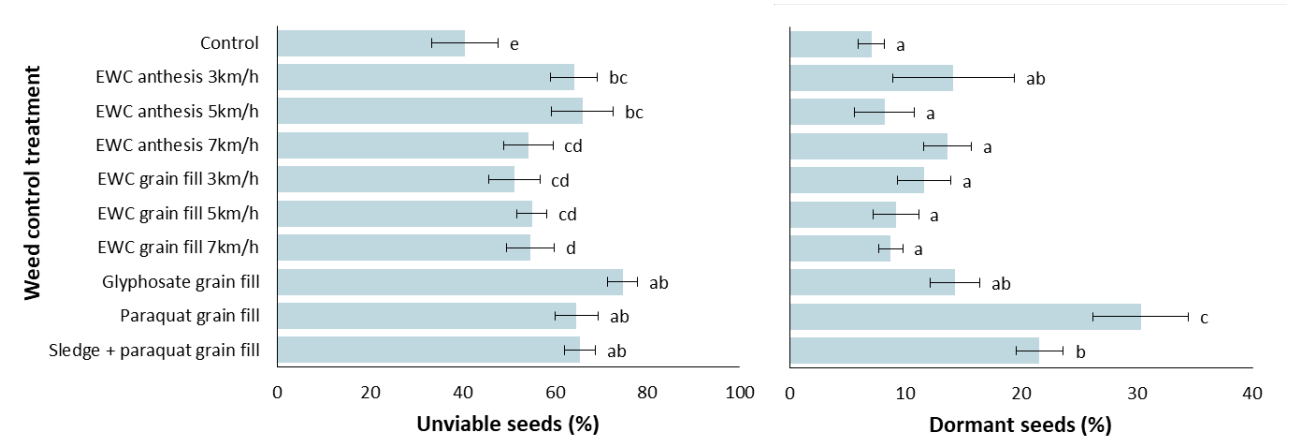


Figure 7. The proportion of unviable (left) and dormant (right) annual ryegrass seed sixteen days after seeding (mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

Of the viable seeds, seedling emergence seven days after sowing was reduced in the glyphosate and paraquat treatments (P: 0.049; Figure 8). However, by day sixteen, this difference was no longer observed (P: 0.066). By day 24, the emergence was still equivalent (P: 0.0115, average emergence of 57%) and dry biomass was likewise similar between treatments (P: 0.0621, average dry biomass of 0.0207 g, data not presented).

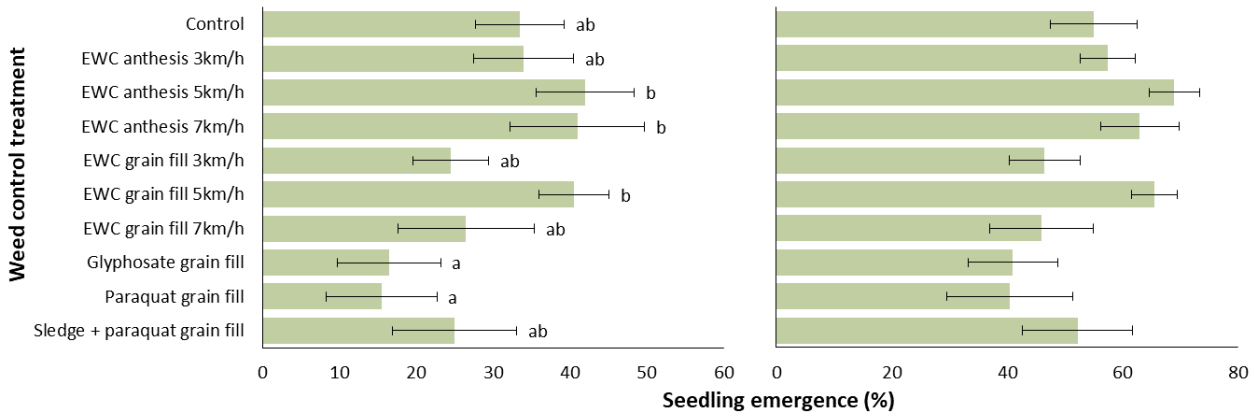


Figure 8. The proportion of annual ryegrass seedling emergence seven (left) and fourteen (right) days after seeding (mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

This trial confirms established knowledge that a low rate of herbicide application at maturity (crop topping or weed wiping) reduces seed viability. However, the trial also confirmed that there is potential for electric weed control to be used in a similar fashion. While application speeds of 3, 5 and 7 km h^{-1} are not recommended and did not reduce plant density, biomass, head production or seed number, they did reduce seed viability. Further research should occur to confirm these findings and to determine the optimum application timing and speeds to maximise seed set control.

Control of annual ryegrass, wild radish, and kikuyu in varying levels of soil moisture

Studies have established that the damage to the weed's root system from electric weed control is more severe when the soil is dry (reviewed by Vigneault & Benoit, 2001). This is possibly because the electric current is less likely to dissipate in dry soil as the soil's resistance increases with decreasing moisture (Slaven et al., 2023b). For example, a study by Vigoureux (1981) found that complete control of weed beet in sugar beet crops ranged from 29-67% when electric weed control was applied in moist soil conditions but increased to 80-92% in dry conditions. However, the exact water content of these soils was not specified, the soil type had a greater clay content than generally occurs in Australian agricultural soils and little research has occurred into this effect since. Further, soil moisture will change with depth and if growth points of the target plants are not destroyed, sufficient soil moisture may increase the probability of plant regrowth following electric weed control. Therefore, research is needed to determine the optimum soil conditions under which electroweeding should occur.

2022 Experiment:

Key findings

- Topsoil moisture did not significantly impact electric weed control efficacy, but further research is required in conditions of higher soil moisture.
- Electric weed control effectively reduced weed density and biomass compared to the untreated control.
- Full weed control was not achieved but was not expected at the selected application speed of 3 km h^{-1}. The speed was selected to ensure a range of different control levels, as it would not be possible to assess the impact of surface soil moisture if treatments achieved complete weed control. Manufacturer recommendations are to use lower speeds to control mature weeds.

Aim

To investigate the effect of varying levels of soil surface moisture on the efficacy of electric weed control on annual ryegrass, kikuyu, and wild radish.

To determine if there is a variation in the efficacy of electric weed control according to weed species.

Method

Site: DPIRD Northam Research Station (-31.6532, 116.6951).

Soil type: Brown sand (5% gravel), nitrate nitrogen 11 mg kg^{-1}, phosphorus (Colwell) 51 mg kg^{-1}, potassium (Colwell) 161 mg kg^{-1}, sulfur 3.7 mg kg^{-1}, organic carbon 0.83%, conductivity 0.037 dS m^{-1}, $pH_{(CaCl2)}$ 4.4, $pH_{(H2O)}$ 5.5.

Applicator: XPU (36 kW)

Treatments:

- Weed control: untreated or electric weed control – applied at 3 km h^{-1} on 12/8/2022.
- Weed species: annual ryegrass (*Lolium rigidum* Gaud.), wild radish (*Raphanus raphanistrum* L), and kikuyu (*Cenchrus clandestinus* Hochst. ex Chiov.) – seeded at 200 m^{-2}).
- Water applied: 0 mm, 2 mm and 3 mm of irrigation, directly before electric weed control.

Measurements:

- Prior to treatment application:
  - Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
  - Soil moisture to 12 cm depth in each plot
- Two weeks after treatment application:
  - Weed density (two quadrats of 50 x 50 cm per plot)
  - Above ground dry biomass (one quadrat of 50 x 50 cm per plot)

Environmental conditions at treatment:

- Plants were dry to damp (due to the application of soil moisture treatments).
- Ryegrass at late tillering; kikuyu at early tillering; wild radish at anthesis (flowering).
- Volumetric soil moisture (at 12 cm depth) was:
  - 0 mm – 16.54%; 2 mm – 19.46%; 3 mm – 18.97%

    - Note: the 0 mm treatment was significantly lower than the 2 mm and 3 mm treatments (P<0.05), but there was not a significant difference between the 2- or 3-mm treatments.
- Average power ranged from 1,155 – 3,053 W inverter^{-1} s^{-1}. Differences may be attributed to the different species or as the kikuyu plants were small and patchy (power use lower over bare ground).

Results

Electric weed control reduced the weed density and above ground biomass compared to the control, with a significant interaction between species (Table 5). The greatest biomass was in the wild radish plots because wild radish is a larger plant than the grass species.

Table 5. The effect of electric weed control application efficacy on weed density and above ground dry biomass of annual ryegrass, kikuyu and wild radish, two weeks after application. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Weed control	Weed species	Weed density (plants m^{-2})	Dry biomass (g m^{-2})
None	Kikuyu	98 (9.89)	21 (1.34)
	Ryegrass	79 (8.89)	105 (2.03)
	Wild radish	64 (7.98)	305 (2.49)
Electric weed control	Kikuyu	2 (1.45)	1 (0.21)
	Ryegrass	51 (7.15)	30 (1.51)
	Wild radish	35 (5.92)	129 (2.23)
P (LSD)		<0.001 (1.56)	0.018 (0.43)

*Note that a square root transformation was applied to the weed density data and a logarithmic (base 10 + 1) transformation to the dry biomass data to normalise residual distribution prior to analysis. The back-transformed means are presented in the table, with the transformed means in brackets. The LSD value should be applied to the transformed means in brackets.

The impact of the moisture treatment on weed density and dry biomass was not significant (Table 6). Further, there was no significant interaction of the moisture treatment with electric or weed species (data not presented). However, due to unusually high rainfall in 2022, it was difficult to apply electric weed control to dry soil. The soil in the 0 mm rainfall treatment was close to field capacity, and so there was little difference in soil moisture following the simulated rainfall. Possibly the relationship will be significant with higher soil moisture. Research will continue in 2023.

Full weed control was not achieved but was not expected at an application speed of 3 km h^{-1}. Weeds were mature, and manufacturer recommendations are for applications speeds of 1-2 km h^{-1} to achieve full mortality of mature plants. In the current experiment, the speed was selected to ensure a range of different control levels, as it would not be possible to assess the impact of surface soil moisture if treatments achieved complete weed control.

Table 6. The interaction between soil moisture and electric weed control application efficacy on weed density and above ground dry biomass (averaged over annual ryegrass, kikuyu and wild radish), two weeks after application. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Weed control	Rainfall treatment	Volumetric soil moisture (%)	Weed density (plants m^{-2})	Dry biomass (g m^{-2})
None	0 mm	16.54	77 (8.76)	79 (1.90)
	5 mm	19.46	79 (8.91)	100 (2.00)
	10 mm	18.97	83 (9.09)	84 (1.92)
Electric weed control	0 mm	16.54	31 (5.53)	23 (1.37)
	5 mm	19.46	21 (4.57)	17 (1.24)
	10 mm	18.97	19 (4.41)	12 (1.10)
P (LSD)			0.390 (1.57)	0.492 (0.37)

*Note that a square root transformation was applied to the weed density data and a logarithmic (base 10) transformation to the dry biomass data to normalise residual distribution prior to analysis. The back-transformed means are presented in the table, with the transformed means in brackets. The LSD value should be applied to the transformed means in brackets.

2023 Experiment:

Key findings

- Topsoil moisture reduced annual ryegrass control when rainfall was simulated at 20 mm.
- This finding is in line with manufacturer recommendations to avoid weed control directly after rainfall.
- The application speed was 2 km h^{-1}, and the weeds were dense and at the tillering stage. An application speed of 1 km h^{-1} would be more appropriate for grass at this development stage.

Aim

To investigate the effect of varying levels of soil surface moisture on the efficacy of electric weed control on annual ryegrass.

Method

Site: DPIRD Wongan Hills Research Station (-30.8465, 116.7409).

Soil type: Yellow grey sandy loam (15-20% gravel), nitrate nitrogen 9 mg kg^{-1}, phosphorus (Colwell) 36 mg kg^{-1}, potassium (Colwell) 159 mg kg^{-1}, sulfur 6.7 mg kg^{-1}, organic carbon 1.16%, conductivity 0.082 dS m^{-1}, $pH_{(CaCl2)}$ 6.5, $pH_{(H2O)}$ 7.2.

Applicator: XPU (36 kW)

Treatments:

- Control (no treatment) following 0 mm, 10 mm or 20 mm simulated rainfall.
- Electric weed control following 0 mm, 10 mm or 20 mm simulated rainfall.

Simulated rainfall was applied to plots of annual ryegrass (of 2 m by 5 m), directly prior to electric weed control at a speed of 2.02 km h^{-1} (23/8/2023). The trial was arranged in a split plot block design with electric weed control or no treatment as the main plot factor and rainfall as the subplot factor, with six replications.

Measurements:

- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Soil moisture to 12 cm depth in each plot
- Three weeks after treatment application:
    - Weed density
    - Above ground dry biomass

Environmental conditions at treatment:

- Plants were at late tillering and dense. Plants were slightly damp in the simulated rainfall treatments (volumetric soil moisture at 12 cm depth in Table 7).
- Average power was 2517 W $inverter^{-1}$ s^{-1} and remained consistent between applications.

Results

Surface soil moisture increased the survival of annual ryegrass following electric weed control, with plant density and biomass significantly greater following 20 mm rain compared to 0 mm of rain (Table 7). This finding is in line with manufacturer

recommendations to avoid treatment directly after rainfall, on moist plants, but in contrast to the trials of inter-row weed control in lupins that suggest that soil moisture did not have a large impact on weed control efficiency.

It should be noted that the weeds in this trial were mature and dense. The electric weed control application speed of 2 km h^{-1} was too fast to effectively control all plants, even where soil moisture was low, and plants were dry. Mature grasses should be treated at 1 km h^{-1} (manufacturer recommendations) and a slower application speed would improve control regardless of soil moisture.

Table 7. The interaction between soil moisture (following application of 0-, 10- or 20-mm rainfall) and electric weed control application on annual ryegrass density and biomass, with the P and LSD values for means separation.

Weed control	Rainfall treatment	Volumetric soil moisture (%)	Density (plants m^{-2})*	Biomass (g m^{-2})
None	0 mm	3.05	94 (9.68)	244
	10 mm	7.51	84 (9.14)	262
	20 mm	10.26	95 (9.74)	274
Electric weed control	0 mm	3.05	43 (6.58)	68
	10 mm	7.51	54 (7.35)	141
	20 mm	10.26	77 (8.79)	200
			0.001 (1.730)	<0.001 (64.80)

*Data were subject to a square root transformation. Back transformed means are presented with transformed data in brackets. The LSD value should be applied to the transformed means.

Impact of electric weed control on rhizoctonia infestation

It has been speculated that as the electrical current travels into the soil during electroweeding applications, there may be an impact on soil biota. Initial studies of macro- and mesofauna including earthworms (*Lumbricina* spp.) and springtails (*Collembola* spp.) by Koch et al. (2020) have determined that population densities of the soil biology before and four weeks after electrical treatment were either comparable, or more stable, than those following the application of mechanical and chemical weeding techniques. However, no studies have yet quantified the effect on microbial populations, and lack of damage to soil microbial populations is particularly important to organic growers both globally and in Australia. Further, research on soil biota has not focussed on the effects on soil biology directly in contact with the weed's root system such as is the case for the crop root pathogen rhizoctonia (R*hizoctonia solani* AG8). If such effects do occur to the soil biota, there is the possibility that electric weed control applications can be used in a farming systems approach to not only control weeds, but also assist with the management of soil-based root pathogens.

2022 Experiment:

Key findings

- Electric weed control did not influence the population of the root pathogen rhizoctonia, even at the slowest application speed, and with repeated application of the same site.
- A single application of electric weed control at 1.4 km h^{-1} controlled mature, dense annual ryegrass, with full senescence occurring after 2-3 weeks.

Aim

To determine if using electroweeding as a weed control method will affect levels the soil-based root pathogen rhizoctonia.

Method

Site: Muresk Research Institute (-31.7567, 116.6780).

Soil type: Grey sandy loam (5-10% gravel), nitrate nitrogen 3 mg kg^{-1}, phosphorus (Colwell) 40 mg kg^{-1}, potassium (Colwell) 46 mg kg^{-1}, sulfur 3.1 mg kg^{-1}, organic carbon 0.61%, conductivity 0.042 dS m^{-1}, $pH_{(CaCl2)}$ 6.0, $pH_{(H2O)}$ 6.7.

Applicator: XPS (one side; 36 kW)

Treatments:

- Untreated control
- One application of electric weed control
- Two applications of electric weed control
- Three applications of electric weed control

Electric weed control was applied at 1.4km h^{-1} on 31/8/2022. This was the lowest possible speed (i.e., highest possible 'dose' of electricity). The low application speed and repeat application (i.e., one, two or three applications to the same plot) aimed to cause maximum potential damage to the rhizoctonia.

Plots were arranged in a randomised block design; four replications.

Measurements:

- Prior to treatment application:
  - Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
  - Average soil volumetric water content to 12 cm
  - Soil rhizoctonia content of each plot (assessed by SARDI, https://pir.sa.gov.au/research)
- One, three and six weeks after treatment application:
  - 3 x normalised difference vegetation index (NDVI) measurements per plot
  - Soil rhizoctonia content of each plot

Conditions at treatment:

- Ryegrass was at late tillering and growth was dense (very little bare ground visible between plants).
- Volumetric soil moisture (at 12 cm depth) was 18.6%.

Results

There was no impact of electric weed control on rhizoctonia populations following one, two or three applications of electric weed control at the slowest possible speed (highest 'dose' of electric weed control). There were no significant changes in the rhizoctonia population depending on electric weed control treatment, or over time, as well as no interaction between the two factors. This is a positive result. Electric weed control, applied in three applications and lowest speed to the same plot did not damage soil pathogens physically attached to the plant roots. Therefore, this weed control method is unlikely to negatively impact other soil biota, although this area needs further research.

Treating mature annual ryegrass (in a single application) at a speed of 1.4 km h^{-1} fully controlled all plants, with senescence at 2-3 weeks after application. As expected, NDVI of the weeds was significantly lower when electric weed control was applied, compared to the control ($P<0.001$; LSD 0.037, Figure 9), and electric weed control caused NDVI to reduce over time ($P<0.001$; LSD: 0.037).

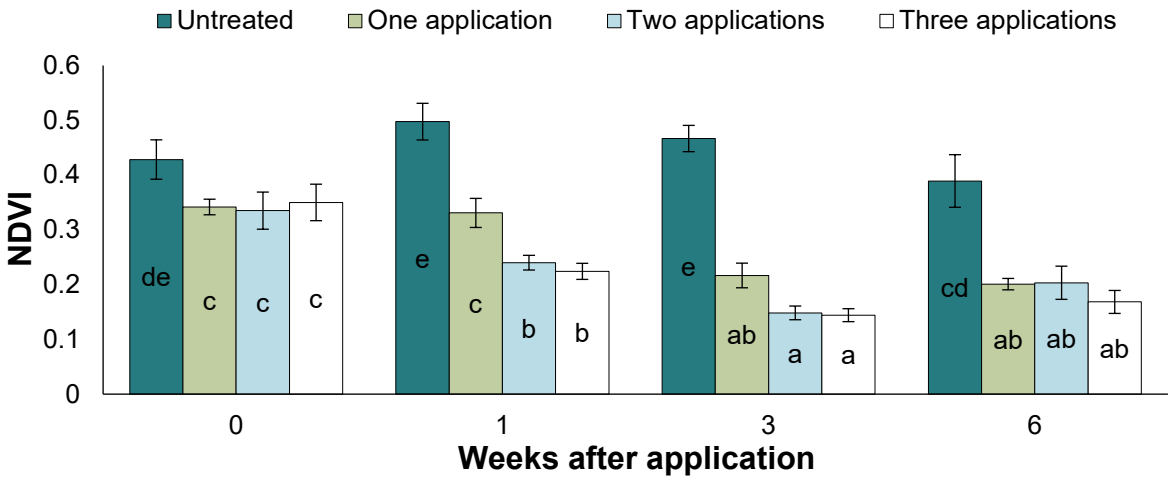


Figure 9. Effect of one, two or three applications of electric weed control at 1.4 km h^{-1} on normalised differential vegetation index (NDVI) of the weed population over time (n = 6; mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test.

Identify two field sites in high value, wide row pulse crops in broad scale grain cropping enterprises and apply inter-row weed control via herbicide or electrocution

Application of non-selective herbicide via shielded sprayers is used to control weeds between the rows of wide row crops (Peltzer et al., 2009). This practice is discouraged in broad scale grain crops due to risks including herbicide resistance, crop damage, yield loss and increased cost of weed control (Peltzer et al., 2009). Application of electric weed control between the rows could remove the risk of herbicide resistance. However, damage to the crop and a reduction in yield is still possible. Electric weed control kills plants upon direct contact, but the electric current passes through the plant into the roots and may spread to the roots of neighbouring plants. There is no evidence that electric weed control applied to inter-row weeds would damage the crop if direct contact between the above ground crop biomass and electrodes was prevented (Lutman, 1980). This can be achieved by ensuring the weeds are spatially separate from the crop during treatment to minimise crop damage while ensuring adequate weed control (Lutman, 1980). For example, Brighenti and Brighenti (2009) investigated inter-row electric weed control in soybean, using 4400 V or 6800 V in each of two experiments. With the tractor engine at 2200 rpm, 90-100% of peanuts (*Euphorbia heterophylla* L.), morning glories (*Ipomoea* spp.), guanxuma (*Aids* spp.), jam grass (*Brachiaria plantaginea* (lyink) Hitchc.) and crabgrass (*Digitaria* spp.) were controlled without impacting crop yield. The extent of weed control is likely to be affected by soil moisture (as the electrical current is less likely to dissipate to neighbouring crop plants in dry soil), and manufacturer recommendations include application to dry soil (Vigneault & Benoit, 2001). For example, a study by Vigoureux (1981) found that complete control of weed beet in sugar beet (*Beta vulgaris* L.) crops ranged from 29-67% when electric weed control was applied in moist soil conditions but increased to 80-92% in dry conditions. However, the level of soil moisture has not been assessed in prior studies.

The XPU and XPS units are not designed for inter-row weed control in grain crops. However, if future technology were designed for this purpose, weed control in Australia would likely be performed when soil was moist, as seasons with high rainfall are those times of year with greatest weed emergence and growth in-crop. The two trials in this section aimed to test the efficiency of inter-row electric weed control, in the presence and absence of additional soil moisture.

Note: The XPS and XPU are not designed for inter-row weed control in grain crops. Further, this trial aimed to maximise plant damage, to test potential damage that may result from this use pattern. These experiments were conducted for scientific purposes and the use pattern should not be applied in field conditions.

2022 Experiments:

Key findings

- Increased volumetric soil moisture did not impact power application for electric weed control.
- There was no impact of electric weed control (in soil with a dry or moist surface) on the density, biomass, or yield of neighbouring (non-target) lupin plants.
- In trial two, lupin biomass and yield were lower in the control plots compared to the plants in those plots subject to inter-row electric weed control. However, this was likely due to the increased intra-plant competition in the control plots, rather than any impact of electric weed control (i.e., lupin plants in inter-row electric weed control plots had neighbouring rows of plants removed via electric weed control, but plants in the control plots did not have neighbouring rows of plants removed).
- Inter-row weed control treatments had no impact on lupin grain germination or early vigour of the resulting seedlings.
- The XPS and XPU are not marketed for inter-row weed control in grain crops. Technology that was fit for purpose would offer improved inter-row weed control, and plastic shielding around the electric weed control units to guarantee no contact to non-target plants.

Trial 1

Aim

To determine the impact of electric weed control applied to weeds in the inter-row space of a lupin crop, compared to no weed control, on crop growth and grain yield.

Method

Site: DPIRD Wongan Hills Research Station (-30.8496, 116.7372).

Soil type: Yellow grey 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.

Applicator: XPS (36 kW)

A bulk, weed free lupin crop was identified. Plots of 1.57 m wide (i.e., seven rows of lupins at 22.5 cm spacing) by 50 m long were marked (randomised block design, four replications). The three rows of lupins in the centre of each plot were retained. Treatments of electrocution for weed control were applied in September to a singular side of the plots along the two outer rows of lupins. In the no weed control treatments, the outer lupin rows were left untouched. The row of lupins neighbouring the treated or untouched outer rows (non-target plants) was sampled with the measurements below.

Treatments:

- Untreated control
- Electric weed control at 1.4 km h^{-1} (2/9/2022)

Measurements:

- Soil moisture to a depth of 12 cm
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)

- Lupin plant number and biomass
- Lupin grain yield (pod number, seed number and seed weight)
- Lupin protein and moisture content*
- Lupin seed viability** and initial seedling vigour***

*Lupin protein and moisture content were determined by running each sample through Near-infrared spectroscopy (NIRS) analysis (FOSS Infratec™ NOVA). Protein values were then standardised assuming a moisture content of 10% in all samples.

**To assess seed viability, 50 seeds per plot were placed in petri dishes on moist filter paper and placed in a germination cabinet, maintained at a 12 h temperature cycle of 15-20^{o}C. Germinated seeds (showing a cotyledon and radicle of at least 1 cm length) were assessed after 16 days.

***To assess seedling vigour, 20 seeds per plot were placed in pots (of 30 cm by 15 cm by 5 cm height) filled with sand, at a depth of 2 cm. After 16 days, emergence and total seedling biomass was assessed.

Conditions at treatment:

- Plants were dry and at anthesis (flowering)
- Volumetric soil moisture (at 12 cm depth) was 1.3%

Results

Electric weed control and mowing killed the targeted lupin plants, with no evidence of regrowth at the time of sampling the non-target lupin plants at harvest. Electric weed control had no effect on the density or biomass of the non-target lupin plants in the central row of the plot (Table 8). Further, the number of pods per plant, number of seeds and seed weight were similar between the control and the electric weed control treatment. The weight of individual seeds, protein and germination were also similar between treatments (Table 9). The assessment of seedling vigour indicated no difference in emergence or seedling biomass (Figure 10).

Table 8. The effect of inter-row electric weed control on the average plant density, as well as biomass, number of pods, number of seeds, and seed weight per plant for lupin plants in the row neighbouring each treatment. The P and LSD values are presented for each comparison.

Treatment	Number of plants (m^{-1})	Dry biomass (g $plant^{-1}$)	Number of seed pods* ($plant^{-1}$)	Number of seeds* ($plant^{-1}$)	Seed weight* (g $plant^{-1}$)
Control	12.2	131.2	26.1 (1.34)	122.7 (1.99)	20.1 (1.22)
Electric weed control	10.0	110.9	22.6 (1.35)	105.5 (2.02)	18.3 (1.26)
P (and LSD)	0.453 (8.33)	0.620 (117.40)	0.956 (0.45)	0.899 (0.47)	0.825 (0.45)

*Note that a logarithmic (base 10) transformation was applied to normalise residual distribution prior to analysis. The back-transformed means are presented in the table, with

the transformed means in brackets. The LSD value should be applied to the transformed means in brackets.

Table 9. The effect of inter-row electric weed control on lupin grain quality, including individual seed weight, seed protein and germination of lupin seeds harvested from plants in the row neighbouring each treatment. The P and LSD values are presented for each comparison.

Treatment	Seed weight (g seed^{-1})	Seed protein (%)	Seed germination (%)
Control	0.169	27.9	99.7
Electric weed control	0.174	28.1	100.0
P (and LSD)	0.155 (0.009)	0.529 (1.01)	0.351 (0.59)

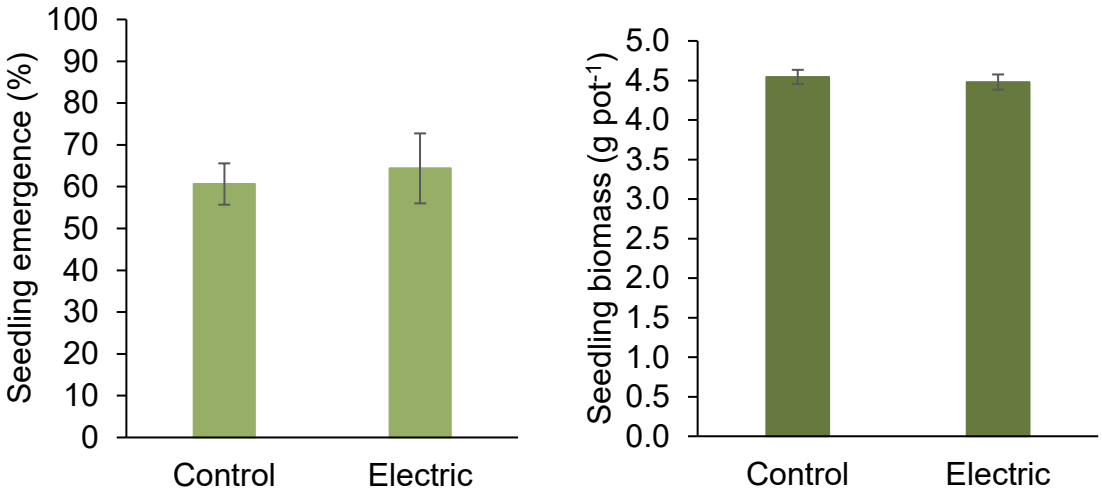


Figure 10. The emergence (P: 0.700, LSD: 22.09) and seedling biomass (P: 0.670, LSD: 0.34) of 20 lupin seeds sown in pots. Vertical bars indicate the standard error of 8 replications.

Trial 2

Aim

To determine the impact of inter-row electric weed control in dry or moist soil on crop yield and grain quality.

Method

Site: DPIRD Wongan Hills Research Station (-30.8496, 116.7372)

Applicator: XPS (36 kW)

A bulk, weed free lupin crop was identified on 2/9/2022. Plots of 1.12 m wide (5 rows of lupins on 22.5 cm spacing) by 10 m long were marked (randomised block design, four replications). In each plot, a single row of lupins was identified in the centre of each plot. In treatment 1 – control plots, the single row of lupins was left untouched, with two rows of lupins growing on either side. In treatment 2 – mowing, the single row of lupins was left untouched, and handheld clippers were used to remove the two rows of lupins on either side, at a height of 5 cm. In treatment 3 – electric weed control, the XPS was used to electrocute the two outer rows of lupins to either side of the centre row. Following electrocution, the dying plants were removed with the handheld clippers to avoid any mulching effects. In treatment 4 – electric weed control after rain, the entire plot area was exposed to an artificial rainfall event, where water was delivered at a rate of 20 L m^{-2}. Directly after 'rainfall' the two rows of lupins to either side of the centre row were electrocuted and then removed as for treatment 3.

Treatments (applied on 2/9/2022):

- Treatment 1: control – untouched lupin crop.
- Treatment 2: mowing – a single row of lupins was retained, and handheld clippers used to remove rows of lupins to either side.
- Treatment 3: electric weed control – electric weed control (1.4 km h^{-1}) used to kill the lupin rows to either side of a single row of lupins, before removing dying plants with handheld clippers.
- Treatment 4: electric weed control after rain – water applied to the entire plot at a rate of 20 L m^{-2}, electric weed control used to kill the lupin rows to either side of a single row of lupins, before removing dying plants with handheld clippers.

Measurements:

- Soil moisture to a depth of 12 cm.
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Lupin biomass
- Lupin grain yield (pod number, seed number and seed weight)
- Lupin protein and moisture content*
- Lupin seed viability and initial seedling vigour**

*Lupin protein and moisture content were determined as for the prior experiment.

**Seed viability and seedling vigour assessed as for the prior experiment.

Conditions at treatment:

- Plants were dry, at anthesis (flowering)
- Volumetric soil moisture (at 12 cm depth) was 2.1% for the treatments with dry soil 5.4% for the treatments with an artificial rainfall event (20 L water m^{-2})

Results

There was no significant difference in power output at a soil moisture content of 2.07% (2019 W interter^{-1} s^{-1}) and 5.39% (2059 W interter^{-1} s^{-1}, P: 0.889).

Treatments had no impact on plant density, but dry biomass, seed pods, number of seeds and seed weight per plant was reduced in the control treatment compared to mowing or electric weed control (Table 10). The control plots had plants growing either side of the row of non-target lupin plants which were harvested, compared to the treated plots where the plants to the side of the non-target plants were removed by mowing or electric weed

control. These plants would increase intra-species competition for resources during anthesis and seed production, compared to the treated plots where the plants to the side were removed. Tobiasz-Salach et al. (2023) demonstrated increased number of seeds per pod and seed weight per plant when lupin seeding density was reduced, highlighting the impact of intra-species competition. For all treatments, weight of individual seeds was similar between treatments, but seed protein was slightly greater in the control plots compared to electric weed control treatments, likely due to reduced yield (Table 11). Germination was 100% in all treatments. Seedling emergence and biomass of the seedlings was similar between treatments (Figure 11).

Table 10. The effect of inter-row electric weed control or mowing on the average plant density, as well as biomass, number of pods, number of seeds, and seed weight per plant for lupin plants in the row neighbouring each treatment. The P and LSD values are presented for each comparison.

Treatment	Number of plants (m^{-1})	Dry biomass (g $plant^{-1}$)	Number of seed pods ($plant^{-1}$)	Number of seeds ($plant^{-1}$)	Seed weight (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)	0.525 (4.24)	0.011 (40.96)	0.011 (8.75)	0.011 (40.90)	0.008 (6.61)

Table 11. The effect of inter-row electric weed control or mowing on lupin grain quality, including individual seed weight, seed protein and seed germination of lupin seeds harvested from plants in the row neighbouring each treatment. The P and LSD values are presented for each comparison.

Treatment	Seed weight (g $seed^{-1}$)	Seed protein (%)	Seed germination (%)
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)	0.061 (0.010)	0.012 (0.54)	NA

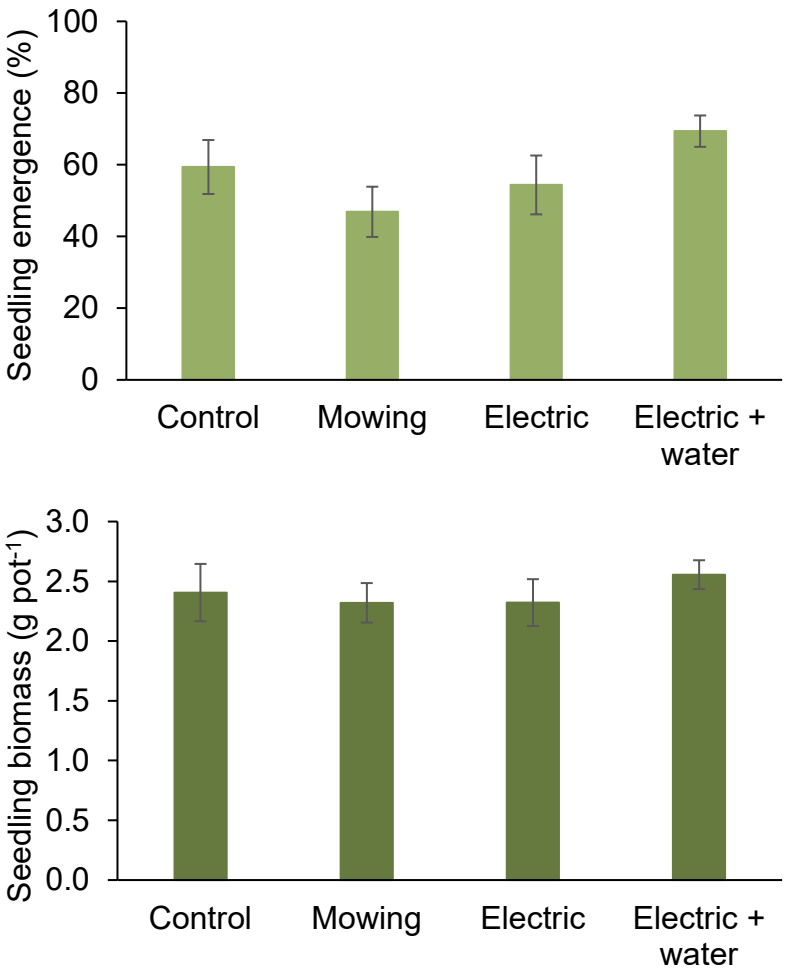


Figure 11. The (P: 0.054, LSD: 16.02) and seedling biomass (P: 0.595, LSD: 0.41) of 20 lupin seeds sown in pots. Vertical bars indicate the standard error of 8 replications.

As stated previously, this inter-row electric weed control application was performed at a late plant development stage (anthesis) to reduce the potential for the crop to recover from any damage prior to harvest, using technology not fit for purpose. It is common for herbicides to be applied to young or pre-emergent crops and cause some damage/reduction to growth, which the plants then recover from over the course of the growing season. By comparison, using herbicides for crop-topping when the crop is at anthesis or seed production commonly causes a yield reduction (Walsh & Powles, 2009). Therefore, using inter-row electric weed control against younger plants that have time to recover from any damage, using inter-row technology fit for purpose, is likely to guarantee this weed control technique causes no reduction to yield.

2023 Experiment:

Key findings

- Plant development stage affected electric weed control power delivery, but surface soil moisture had no impact on power requirements.
- Early application of artificial rainfall increased yield due to dry seasonal conditions, but electric weed control treatments did not reduce growth or yield.

Aim

To determine the impact of early or late application of electric weed control or mowing, in dry or wet surface soil conditions, compared to no weed control, on crop growth and grain yield.

Method

Site: Northam, WA (-31.6360, 116.6916).

Soil type: 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.

Applicator: XPU (36 kW)

A bulk lupin crop was identified and plots of three rows of lupins by 10 m were marked in six banks (randomised row-column design, four replications). In each of the following treatments, plants on the outer row on each side were left unaffected (control), removed with a standard Honda 4-stroke lawn mower at a height of 12 cm (mowing) or removed via electric weed control. Where the treatment required moist surface soil, artificial rainfall to 10 mm was applied to the whole plot directly prior to treatment. The biomass and yield of the centre row of non-target plants was assessed to determine potential crop damage from applying mowing or electric weed control to the neighbouring plant rows.

Treatments:

1. Untreated control
2. Mowing – early application
3. Mowing – late application
4. Electric weed control – early application
5. Electric weed control – late application
6. Electric weed control – early application on moist surface soil
7. Electric weed control – late application on moist surface soil

Early treatment was on 17/8/2023 (mowing) or 18/8/2023 (electric weed control) and the late treatments on 31/8/2023.

Measurements:

- Soil moisture to a depth of 12 cm
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Lupin plant number and biomass at maturity
- Lupin grain yield (pod number, seed number and seed weight)

- Lupin seed viability and initial seedling vigour in 2024*

*To assess seed viability, 50 seeds per plot were placed in petri dishes on moist filter paper and placed in a germination cabinet, maintained at a 12 h temperature cycle of 10-20^{o}C. Germinated seeds (showing a hypocotyl of at least 1 cm length) were assessed after 16 days.

To assess seedling vigour, 20 seeds per plot were placed in pots (of 30 cm by 15 cm by 5 cm height) filled with sand, at a depth of 2 cm. After 16 days, emergence and total seedling biomass was assessed.

Conditions at treatment:

Table 12. Electric weed control treatment application date, plant growth stage and conditions at treatment, power output (with volumetric soil moisture) and application speed.

Treatment date	18/8/2023	31/8/2023
Plant growth stage	Between principal growth stage 5 and 6; inflorescence emergence and flowering.	Between principal growth stage 6 and 7; flowering and seed/pod production.
Conditions at treatment	Plants were slightly damp in those plots where simulated rainfall was applied.	Plants were dry.
Average power for electric weed control (and volumetric soil moisture at 12 cm depth)	2800 W inverter^{-1} s^{-1} Dry soil: 2794 W (3.32%) Wet soil: 2806 W (10.25%)	740 W inverter^{-1} s^{-1} Dry soil: 727 W (0.85%) Wet soil: 752 W (3.52%)
Application speed	2.1 km h^{-1}	1.48 km h^{-1}

Results

The power output was significantly different between growth stages, with an average of 2800 ± 7.0 at anthesis and 734 ± 34 W interver^{-1} s^{-1} at grain fill ($P < 0.001$, Table 12). However, the soil moisture content at both application times had no significant impact on power output at either the first application time with soil moisture at 3.32% or 10.25% (P: 0.242) or the second application time with soil moisture at 0.85% or 3.52% (P: 0.236).

The number of plants was similar (Table 13). Plant dry biomass was close to a significant difference (P: 0.051) as the electric weed control following artificial rainfall treatment at the early plant growth stage had higher biomass than the other treatments at the early growth stage (Table 13). Likewise, the number of pods per plant, number of seeds per plant or seed weight was also greater following electric weed control with water at the early plant growth stage. The yield increase from the electric weed control following water at the early growth stage likely resulted from the reduced plant competition (i.e. plants removed by the weed control tactic) and increased soil moisture at time of treatment (3.32% to 10.25% soil moisture). The 2023 season was an unusually dry (annual rainfall of 269 mm, compared to the long-term average of 426 mm) and lupin yield in the southern half of Australia is highly affected by drought stress during seed production (Reader et al., 1997; Palta et al., 2004). The treatments had no impact on grain quality, with no differences between seed weight or

protein (Table 14). Likewise, there was no impact on germinability, emergence or seedling biomass (Table 14, Figure 12).

Table 13. The effect of inter-row electric weed control or mowing at two different growth stages on the average plant density, as well as biomass, number of pods, number of seeds, and seed weight per plant for lupin plants in the row neighbouring each treatment. The P and LSD* values are presented for each comparison.

Treatment	Plant growth stage	Number of plants (m^{-1})	Dry biomass (g $plant^{-1}$)	Number of seed pods ($plant^{-1}$)	Number of seeds ($plant^{-1}$)	Seed weight (g $plant^{-1}$)
Control		10.9	22.1	4.2	66.7	8.2
Mowing	Stage 5/6 (anthesis)	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	Stage 6/7 (grain fill)	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		0.689	0.051	0.018	0.021	0.036
LSD min replication		3.55	12.07	2.35	37.00	4.64
LSD max-min replication		3.07	10.45	2.03	32.05	4.02

*The experimental design had two control treatments in each block. The control should be compared to treatments using the LSD for maximum-minimum replication and comparisons between treatments should use the LSD for minimum replication.

Table 14. The effect of inter-row electric weed control or mowing at two different growth stages on lupin grain quality, including individual seed weight, seed protein and seed germination of lupin seeds harvested from plants in the row neighbouring each treatment. The P and LSD values are presented for each comparison.

Treatment	Plant growth stage	Seed weight (g $seed^{-1}$)	Seed protein (%)	Seed germination* (%)
Control		0.123	28.0	97.5 (1.59)
Mowing	Stage 5/6	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	Stage 6/7	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		0.136	0.585	0.251
LSD min replication		0.008	0.32	1.28
LSD max-min replication		0.007	0.28	1.11

*Note that a square root transformation (of 100%-germination%) was applied to normalise residual distribution prior to analysis. The back-transformed means are presented in the table, with the transformed means in brackets. The LSD value should be applied to the transformed means in brackets.

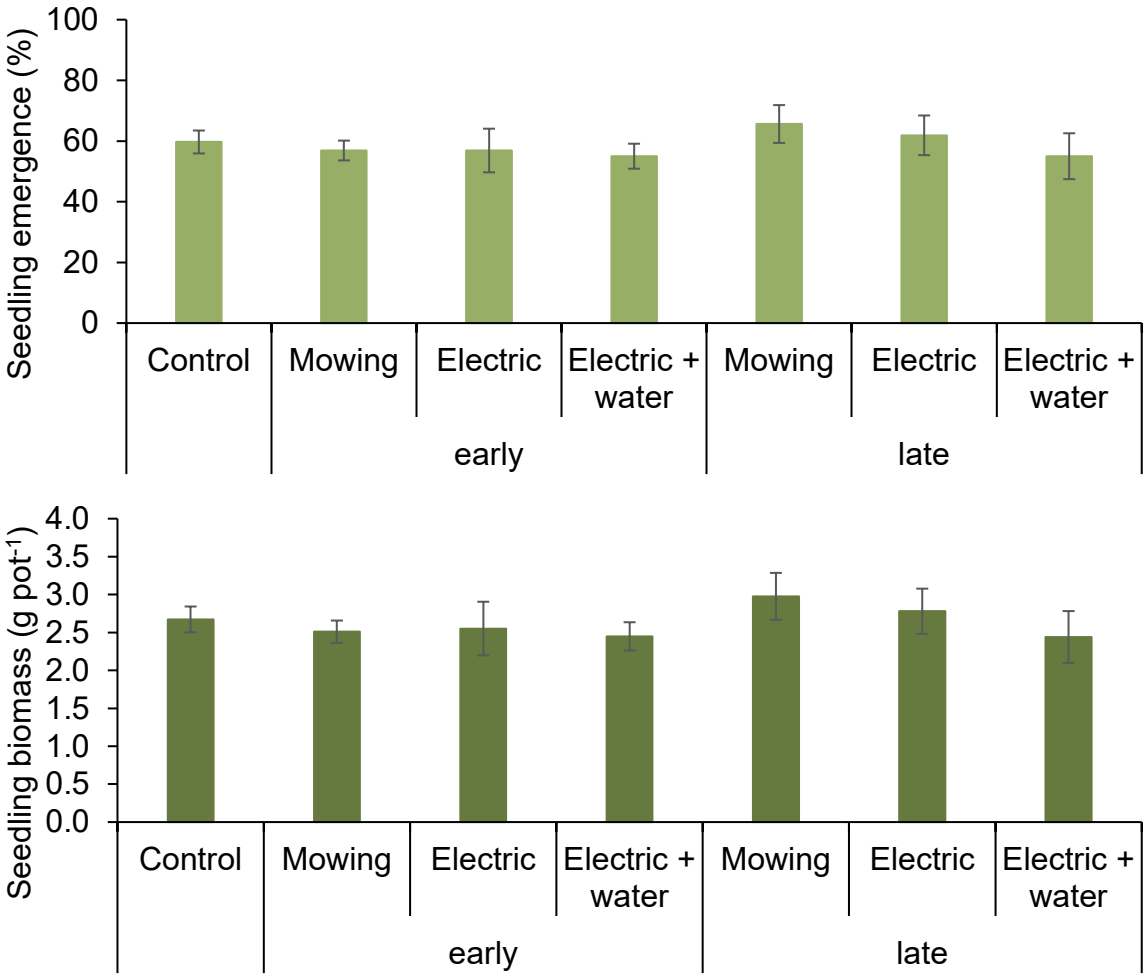


Figure 12. The emergence (P: 0.808, LSD max-min: 14.5) and seedling biomass (P: 0.746, LSD max-min: 0.671) of 20 lupin seeds sown in pots, obtained from plants from the control, and early or late mowing or electric weed control treatments (applied with or without water). Vertical bars indicate the standard error of 8 replications, or 16 replications for the control.

This research concludes that electric inter-row weed control does not impact lupin yield, but more research is required to assess electric weed control at younger plant growth stages, or in alternative crops. Since electric weed control was successful in killing all

targeted lupin plants, this method will be effective for control of blue lupin (*Lupinus cosentinii* Guss), which is particularly difficult to control selectively in lupin crops (Hashem et al., 2011).

Electric weed control in viticulture

The XPS is designed to control weeds in viticulture or horticulture systems. The applicators are 55 cm wide and are designed to control weeds directly adjacent to a row of vines. The applicator has a swinging ‘intercept’ arm, designed to control weeds directly under the row of vines. The XPS model commonly used in Europe has a 24 kW supply unit. The equipment currently being tested in Australia has a 36 kW supply unit. A supply unit delivering 36 kW may potentially be more expensive than a 24 kW unit, and it is necessary to compare efficiency of the two different application rates in Australian viticulture.

A key part of organic food production is maintenance of soil biota. Initial studies of macro- and mesofauna, including earthworms (*Lumbricina* spp.) and springtails (*Collembola* spp.), have determined that the population densities before, and four weeks after, electrical treatment were either comparable or more stable than those following the application of mechanical and chemical weeding techniques (Koch et al., 2020). However, there is little published research on the topic and no information on the impact of soil microbes (Fierer et al., 2020). All weed control techniques are likely to affect soil biota, if only by the removal of above ground plant biomass. The impact of electric weed control needs to be compared to other weed management strategies in viticulture, including use of herbicide or physical removal of weeds (mowing/slashing/grazing).

2022 Experiments:

Key findings

- Electric weed control using 24 or 36 kW controlled weeds equally well at 1.1km h^{-1}.
- Electric weed control efficiency was comparable to herbicide use, even though both sites had predominately grass weed species that were dense, mature, and wet at the time of application. Topsoil was also wet, due to recent rainfall. These are the worst possible conditions for electric weed control efficiency.
- There were no changes to the bacteria and archaea populations (16s soil biota community) between any of the weed control treatments and the control. Therefore, electric weed control did not affect or reduce the tested soil biota, at two or five weeks after treatment.

Aim

To determine the efficiency of electric weed control in Australian viticulture enterprises (at a rate of 24 or 36 kW) compared to other weed control techniques (herbicide or mowing).

To determine the impact of weed control techniques in viticulture on soil microbial incidence and diversity.

Method

Applicator: XPS (one side)

Two sites were identified on commercial viticulture enterprises, in collaboration with AHA Viticulture (Table 15). On each site, four rows of vines were identified, and plots of 1 m by 10 m were established on the rows, with a 10 m buffer between treatments (randomised block design with four replications). The line of vines was in the centre of each plot.

Table 15. Details of the two viticulture sites used in the following experiments.

Name	Springfield	Peccavi
Location	-33.6810, 115.0810	-33.6966, 115.0850
Treatment date (mowing and electric weed control)	16/9/2022	15/9/2022
Vine development	Initial shoot growth	Budburst
Predominant weed species	Kikuyu (*Cenchrus clandestinus* Hochst. ex Chiov.)	Annual ryegrass (*Lolium rigidum* Gaud.) and other grass species (90% ground cover), vetch (*Vicia sativa* L.) and other broad leaf weeds (10% cover)
Initial weed cover	77.5-98.1% grass, 1.9-22.5% broadleaf weeds	49.9-78.8% grass, 21.3-50.1% broadleaf weeds
Volumetric soil moisture	27%	25%
Soil type	Brown-grey loam (15-20% gravel), nitrate nitrogen 3 mg kg^{-1}, phosphorus (Colwell)	Brown-grey loam (15-20% gravel), nitrate nitrogen 5 mg kg^{-1}, phosphorus (Colwell)

	247 mg kg^{-1}, potassium (Colwell) 292 mg kg^{-1}, sulfur 10.2 mg kg^{-1}, organic carbon 2.3%, conductivity 0.081 dS m^{-1}, $pH_{(CaCl2)}$ 5.6, $pH_{(H2O)}$ 6.6	152 mg kg^{-1}, potassium (Colwell) 117 mg kg^{-1}, sulfur 11.8 mg kg^{-1}, organic carbon 4.4%, conductivity 0.116 dS m^{-1}, $pH_{(CaCl2)}$ 5.4, $pH_{(H2O)}$ 6.2

Treatments:

- Untreated control
- Mowing (using a lawn mower under the vines to stimulate grazing)
- Electric weed control 24 kW
- Electric weed control 36 kW
- Herbicide

Mowing was performed with a standard Honda 4-stroke lawn mower with a catcher on the rear, to simulate grazing. Electric weed control was applied to each side of the row of vines in the centre of each plot. One side of the XPS was switched on to drive down each side of the row without impacting the adjacent rows. The XPS has 12 high voltage inverters (delivering 3 kW each to achieve 36 kW); six on each side. When one side is turned on, the function of the six inverters is displayed as a circle on the user interface. The unit was used as normal with all six inverters to supply a 36 kW treatment. To switch to a 24 kW treatment, two of the six inverters were switched off. The herbicide treatment was glyphosate 1296 g a.i. ha^{-1} (Crucial 600 g a.i. L^{-1}, Nufarm, SL) plus amitrole/ammonium thiocyanate 720/634 g a.i. ha^{-1} (Amitrole T 250/220 g a.i. L^{-1}, Nufarm, SL) applied in 240 L water ha^{-1}. Note that due to equipment issues, herbicide was applied a week after the other treatments.

Measurements, on day of treatments:

- Soil moisture to 12 cm
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Weed incidence (species)
- Weather
- Soil characteristics - collect 10 soil cores with 4 cm auger

2 weeks after treatment:

- Soil microbes - sample 10 subsamples per plot with 2 cm diameter auger*
- NDVI for weeds and vines**

5 weeks after treatment:

- Soil microbes
- Weed incidence (species)
- Weed biomass
- NDVI

*Soil microbes were assessed by the Australian Genome Research Facility (AGRF, https://www.agrf.org.au/) in Dec 2022. AGRF used DNA extraction and NextGen sequencing of the 16s soil microbiome (i.e. those species in the soil microbiome with the 16s ribosomal RNA gene), which includes bacteria and archaea populations (Akaçin et al., 2022). Results, including alpha-diversity (i.e., observed species at a local scale) and beta-

diversity (i.e., differences in treatments, sampling times and site locations) were analysed by the team of Professor Timothy Cavagnaro (University of Adelaide) in 2023.

**NDVI (normalised difference vegetation index) was assessed using a Trimble GreenSeeker. The NDVI of vines was assessed by measuring individual vines with a white sheet of material hanging behind the vine, using the method of Mazzetto et al. (2009).

Conditions at treatment:

- Speed – 1.1 km h^{-1}.
- Average power – 2900 W $inverter^{-1}$ s^{-1} at 36 kW (averaged over six inverters) and 1988 W $inverter^{-1}$ s^{-1} at 24 kW (averaged over six inverters with two inverters delivering 0 W). Power applied at 36 kW from each transformer was close to the maximum of 3000 W $inverter^{-1}$ s^{-1}, as the weeds were mature, dense and wet. Topsoil was also wet due to the recent rainfall.

Results

There was no evidence of damage to vines (Table 16). Treatments at both sites were at the budburst to initial shoot growth stage of vine development (Table 15). The NDVI assessment indicated that immediately after treatment, or two to five weeks later, there was no difference in vine growth between treatments.

Both sites were predominately grass weeds (Table 15), with an average of 90% grass at Springfield and 68% grass at Peccavi. Weed distribution was even across both sites. There was no bare ground and no significant difference between grass or broadleaf species incidence between treatments (data not presented).

The conditions at application were poor. The topsoil volumetric soil moisture was high at both sites due to recent rainfall (no variation between plots, P: 0.493 at Springfield, P: 0.184 at Peccavi, Table 15). High surface soil moisture levels would allow the electricity to disperse from the plant roots to the surrounding soil, reducing the efficiency of weed control and maximising any potential harm to the soil biota. Mature, damp weeds and high surface soil moisture are the worst possible conditions for electric weed control. As a result, a speed of 1 km h^{-1} was selected in line with manufacturer recommendations.

Table 16. The normalised difference vegetation index (NDVI) values for the vines directly after treatment (zero weeks), two weeks and five weeks after application. The probability values from the analysis are presented.

Location	Treatment	0 weeks	2 weeks	5 weeks
Springfield	Control	0.065	0.12	0.57
	Mowing	0.068	0.12	0.52
	Herbicide	0.043	0.12	0.50
	24 kW	0.058	0.13	0.43
	36 kW	0.068	0.13	0.55
	P (and LSD)	0.757	0.991	0.242
Peccavi	Control	0.03	0.04	0.55
	Mowing	0.04	0.06	0.45
	Herbicide	0.03	0.04	0.43

	24 kW	0.01	0.03	0.51
	36 kW	0.03	0.04	0.45
	P (and LSD)	0.153	0.645	0.563

As stated, herbicide application was later than electric weed control, evident in the higher weed NDVI values and lower percent biomass reduction at two weeks (Table 17). At five weeks, the NDVI assessments of weed growth indicated that all treatments had less weeds than the control. There was no significant difference between electric weed control at 24 kW or 36 kW and herbicide at Peccavi, although at Springfield the herbicide treatment had a slightly lower NDVI than the 24 kW treatment. Mowing at both sites had slightly higher weed NDVI.

Weed biomass at Springfield was similar in the herbicide and electric weed control treatments, although slightly higher in the mown treatments. At the Peccavi Estate, weed biomass was similar after each of the weed control treatments, and lower than the biomass in the control plots.

Table 17. The dry weed biomass and normalised difference vegetation index (NDVI) values for the vines and weeds, at five weeks after application. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Location	Treatment	2 weeks		5 weeks		
		Biomass (% reduction)	NDVI	Biomass (% reduction)	NDVI	Biomass (g m^{-2})
Springfield	Control	0	0.59	0	0.52	336
	Mowing	50	0.33	29	0.37	128
	Herbicide	0	0.58	90	0.18	17
	24 kW	85	0.31	71	0.25	66
	36 kW	90	0.28	74	0.20	47
	P (and LSD)	<0.001 (3.98)	<0.001 (0.101)	<0.001 (11.7)	<0.001 (0.064)	<0.001 (75.8)
Peccavi	Control	0	0.72	0	0.61	183
	Mowing	50	0.34	29	0.36	48
	Herbicide	0	0.72	85	0.22	47
	24 kW	89	0.29	74	0.23	53
	36 kW	93	0.31	85	0.17	72
	P (and LSD)	<0.001 (2.44)	<0.001 (0.147)	<0.001 (8.70)	0.002 (0.184)	0.008 (74.3)

Assessment of the alpha diversity of the 16s communities (via Shannon's index, Faiths Phylogenetic Diversity, and Pielous' Evenness analysis) indicated no difference between the experimental treatments at each site and sampling time (Figure 13).

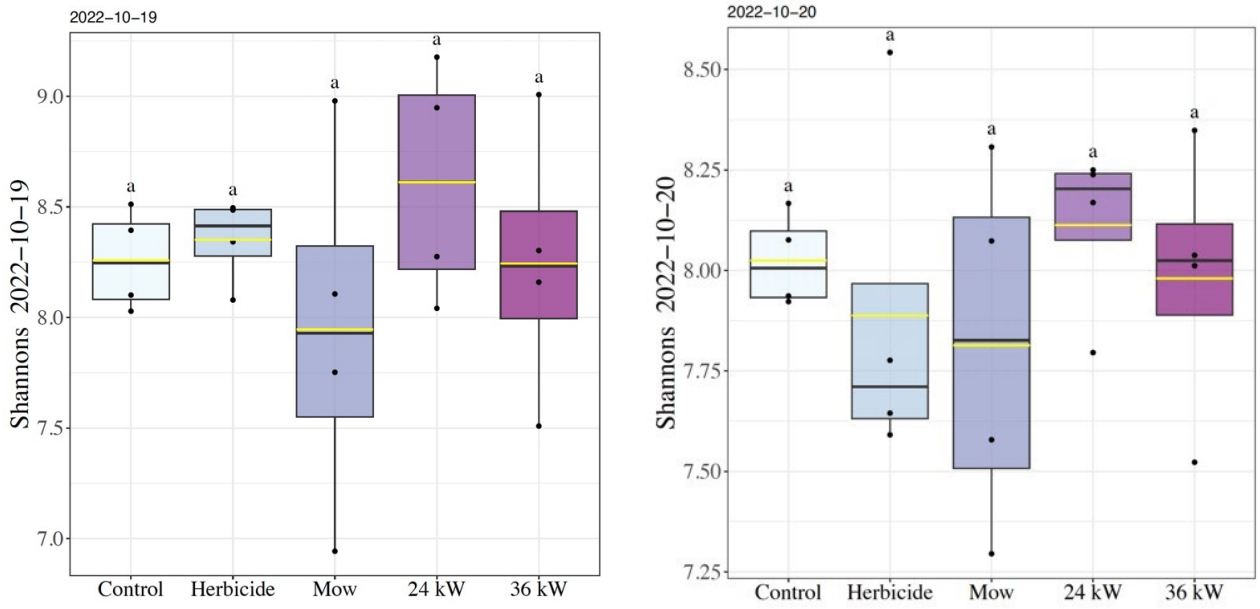


Figure 13. Alpha diversity of 16s communities assessed on 19 or 20 October 2022 at the Springfield (left) and Peccavi (right) estate. The letter above the boxes (a) indicates the result of a Tukey's post-hox multiple comparison test after fitting a linear mixed model and comparing predicted means, confirming no differences between treatment means.

The analysis identified 839,996 and 1,063,109 operational taxonomic units (i.e. groups of closely related individuals) in soil collected on the 27 September 2022 and 19 October 2022 from the Springfield site, and 883,712 and 903,676 operational taxonomic units in the soil collected on the 27 September 2022 and 20 October 2022 from the Peccavi site. The most common taxa at both sites (a third of all taxa observed) were Solirubrobacterales; an unspecified group of Actinobacteria; Vicinamibacterales; and Gaiellales. Assessment of beta diversity (via an unweighted UniFrac analysis) indicated differences in the 16s communities between sites, but no impact of treatment or sampling time (Figure 14, 15, 16).

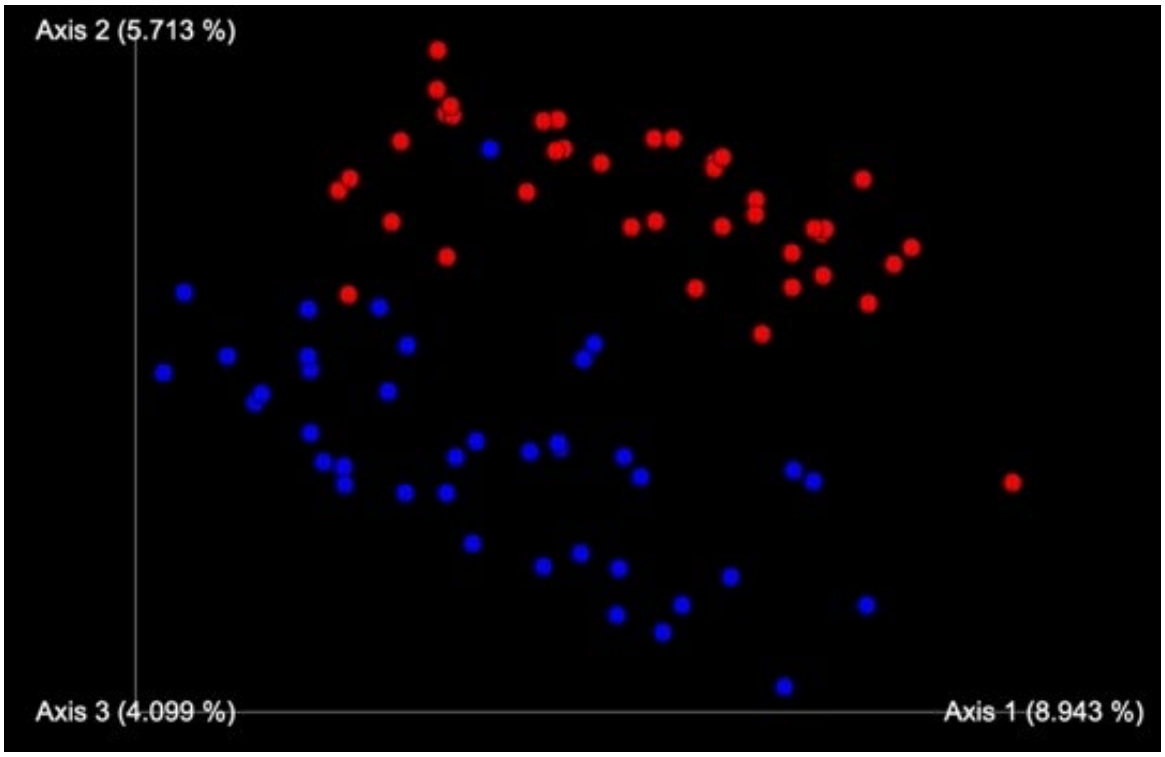


Figure 14. Beta diversity (unweighted UniFrac) of the 16s community at the Springfield (blue) and Peccavi (red) sites.

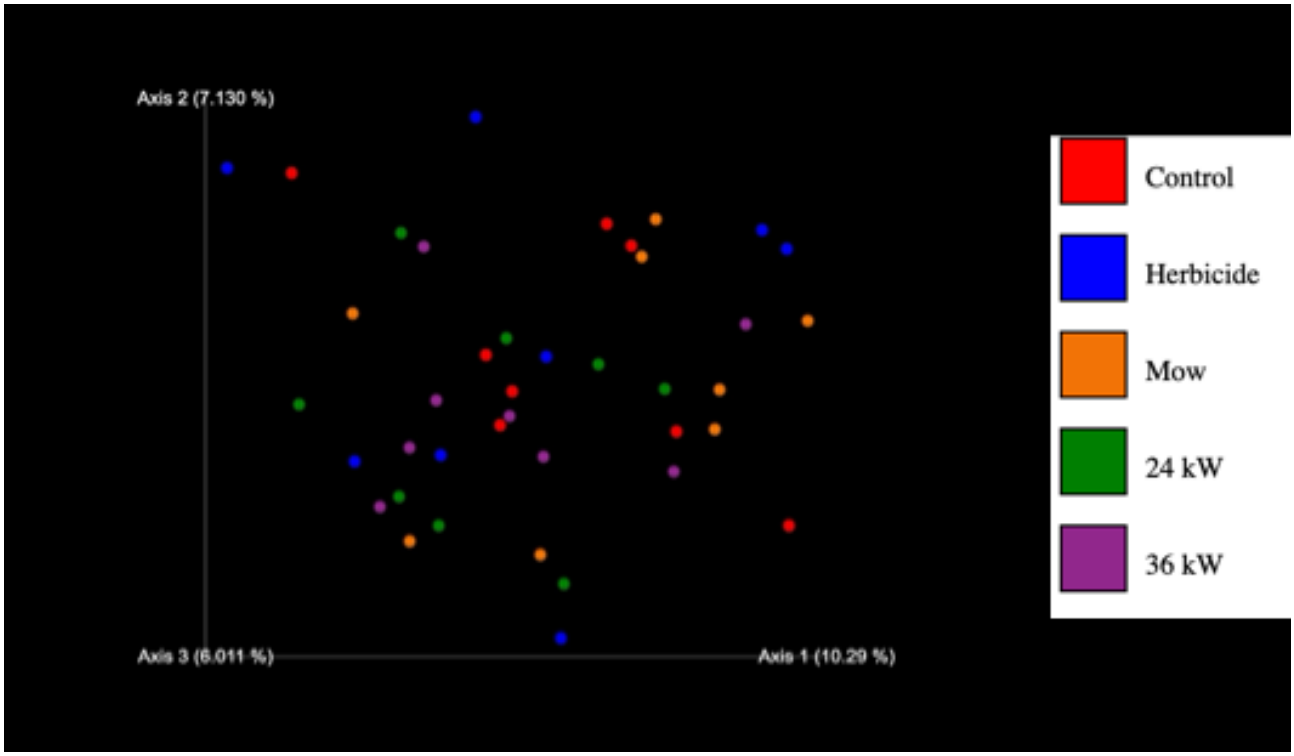


Figure 15. Beta diversity (unweighted UniFrac) of the 16s community under different weed control treatments at the Springfield site (both sampling times).

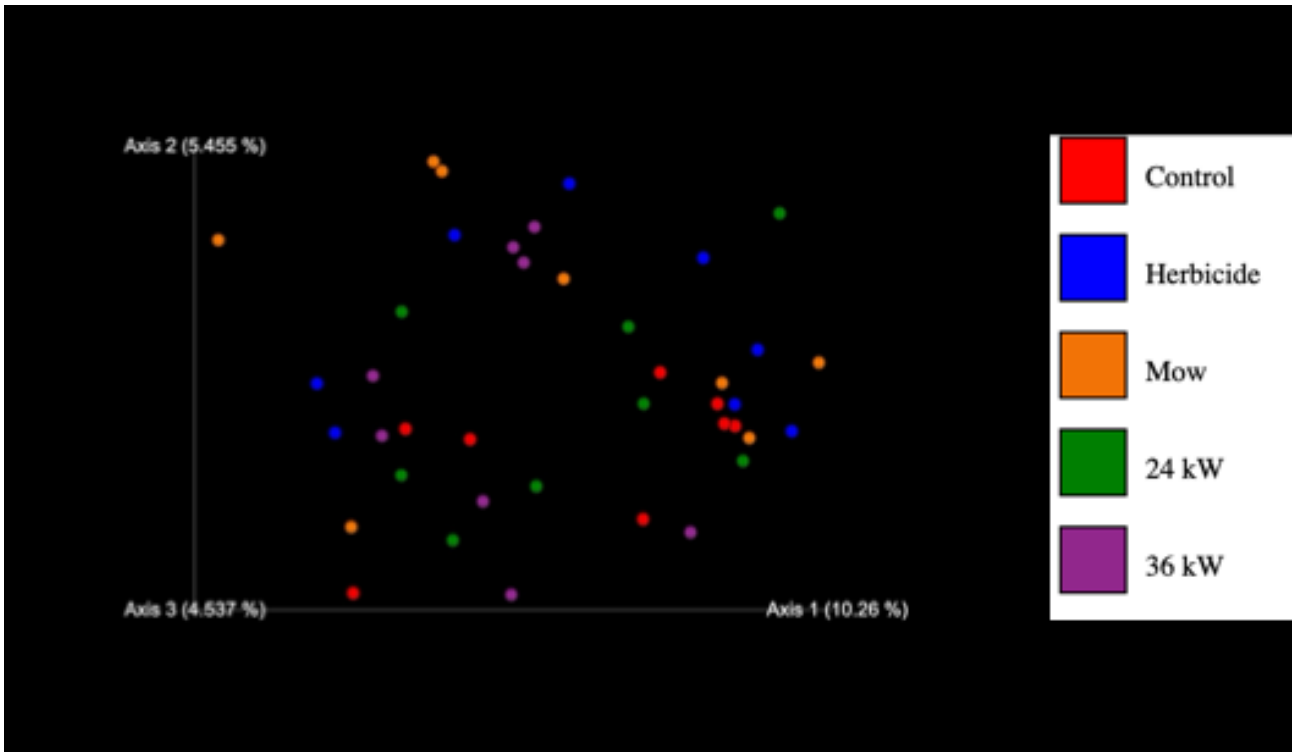


Figure 16. Beta diversity (unweighted UniFrac) of the 16s community under different weed control treatments at the Peccavi site (both sampling times).

It is important to note that DNA can persist in the soil following death of cells, and this analysis cannot categorically rule out a treatment impact on the 16s soil biome. However, if the communities had been affected, there should have been a shift in community structure between sampling times, due to differences in post-treatment recovery times of different taxa. In this study there was no impact of sampling time. There is no evidence that electric weed control affects the soil biome. There was likewise no impact of herbicide on the soil biome. Prior studies have observed an impact of herbicide use on soil biota, but effects have been small (changes to specific taxa rather than a large shift in community composition) and temporary (Rose et al., 2016).

As stated, conditions were not optimal for any form of weed control. While the forecast was for fine weather, there was rainfall prior to application. Both sites had not been grazed earlier in the year and weed species were large and healthy. Regardless, electric weed control was highly successful, comparable to herbicide and better than mowing. The electric weed control treatments did not kill a 5 cm strip directly under the vines (Figure 17) because the dense weed growth prevented the applicators from extending fully under the vines.



Figure 17. Application with the XPS at 24 kW (left) or 36 kW (right), two weeks after treatment.

2023 Experiments:

Key findings

- Electric weed control using 36 kW applied at 1.4 km h^{-1} offered the greatest level of weed control compared to the other treatments at both trial sites.
- Electric weed control efficiency at both 24 and 36 kW was comparable to herbicide use, and greater than mowing.
- There were no changes to the soil microbial population following the application of electric weed control; alpha and beta diversity of the 16s (bacteria and archaea) or ITS (fungi) communities. However, the herbicide treatment had reduced ITS beta diversity at one site five weeks after treatment.
- There were no changes to the nematodes and soil characteristics due to the weed control treatments at one week after treatment. At five weeks after treatment, select nematode groups were reduced in one site in those treatments with greatest weed control (electric weed control or herbicide), likely due to reduced plant and root biomass (i.e., reduced nematode food source).

Aim

To determine the efficiency of electric weed control in Australian viticulture enterprises (at a rate of 24 or 36 kW) compared to other weed control techniques (herbicide or mowing).

To determine the impact of weed control techniques in viticulture on soil bacteria, fungi and free-living nematode incidence and diversity, as well as select soil characteristics.

Method

Applicator: XPS (one side)

Two sites were identified on commercial viticulture enterprises, in collaboration with AHA Viticulture (Table 18). On each site, four rows of vines were identified, and plots of 1 m by 10 m were established on the rows at Peccavi and 1 m by 9 m at Paganin. A 6 m buffer was also included at both sites between treatments (randomised block design with four replications). The line of vines was in the centre of each plot.

Table 18. Details of the two viticulture sites used in the following experiments in 2023.

Name	Peccavi	Paganin
Location	-33.9482, 115.1567	-33.6874, 115.0857
Treatment application date	12/9/2023 (herbicides applied 14/9/2023)	14/9/2023
Vine development	Budburst	Budburst
Predominant weed species	Annual veldt grass (*Ehrharta longiflora*), silver grass (*Vulpia myuros*) and other grass species (97% ground cover), as well as vetch and other broadleaf weeds (3%).	Burr medic (*Medicago polymorpha*), annual ryegrass, wild oats (*Avena fatua*), kikuyu, annual veldt grass and common dandelion (*Taraxacum officinale*).

Volumetric soil moisture (%)	22.1 ± 1.7	22.7 ± 1.0
Dry residue loading (kg/ha)	2612.5 ± 304.6	2242.9 ± 170.8

Treatments:

- Untreated control
- Mowing (using a lawn mower under the vines to stimulate grazing)
- Electric weed control 24 kW
- Electric weed control 36 kW
- Herbicide

Treatments were applied as in 2022. Mowing was performed with a standard Honda 4-stroke lawn mower with a catcher on the rear, to simulate grazing. Electric weed control was applied to each side of the row of vines in the centre of each plot. One side of the XPS was switched on to drive down each side of the row without impacting the adjacent rows. The unit was used as normal to supply a 36 kW treatment. To switch to a 24 kW treatment, two high voltage inverters were switched off as previously explained in the 2022 methods. The herbicide treatment was glyphosate 1296 g a.i. ha^{-1} (Crucial® 600 g a.i. L^{-1}, Nufarm, SL) plus amitrole/ammonium thiocyanate 720/634 g a.i. ha^{-1} (Amitrole T 250/220 g a.i. L^{-1}, Nufarm, SL) applied in 240 L water ha^{-1}.

Measurements, on day of treatments:

- Soil moisture to 12cm
- Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard)
- Weed incidence (species)
- Weather

1 week after treatment:

- Soil microbes - sample 10 subsamples per plot with 2 cm diameter auger*
- Free living nematodes - sample 20 subsamples per plot with 2 cm diameter auger**
- Soil characteristics (CSBP)
- NDVI for weeds and vines***

5 weeks after treatment:

- Soil microbes
- Free living nematodes
- Soil characteristics
- Weed dry biomass
- NDVI for weeds and vines

*Soil microbes was assessed by the Australian Genome Research Facility (AGRF, https://www.agrf.org.au). Analysis was conducted as for the 2022 trials with the addition of the ITS soil microbiome to analyse the fungal community by the team of Professor Timothy Cavagnaro now at Flinders University (2023).

**Nematodes were assessed by the South Australian Research and Development Institute (SAARDI; https://pir.sa.gov.au/research/services/crop_diagnostics/nematode_screening).

***NDVI (normalised difference vegetation index) was assessed using a Trimble GreenSeeker as for the 2022 trials.

Conditions at treatment:

- Speed – 1.4 km h^{-1}.
- Average power –
    - Peccavi: 1725 W $inverter^{-1}$ s^{-1} at 36 kW (averaged over six inverters) and 977 W $inverter^{-1}$ s^{-1} at 24 kW (averaged over six inverters with two delivering zero W). This average power output is low compared to 2022 as the third and fourth inverters only produced 66-151 W $inverter^{-1}$ s^{-1}.
    - Paganin: 1773 W $inverter^{-1}$ s^{-1} at 36 kW and 965 W $inverter^{-1}$ s^{-1} at 24 kW. Again, the third and fourth transformers produced 68-155 W $inverter^{-1}$ s^{-1}.

Results

The conditions at application consisted of high topsoil volumetric soil moisture and mature weeds (Table 18). However, there was no evidence of damage to vines following the treatments (Table 19). The NDVI assessment indicated that immediately after treatment and five weeks later, there was no difference in vine growth between treatments at both sites. However, one week after treatment at Peccavi, there was a significant effect of the treatments on the vine NDVI. Significantly higher NDVIs were observed following the herbicide and electric weed control at 24 kW applications compared to the other treatments and the control. As the lower NDVI values were also observed within the control treatment plots, it is likely that this difference occurred due to variable growth in the vines, rather than due to the weed control treatments. Further, no difference was detected by week five.

Table 19. The normalised difference vegetation index (NDVI) values for the vines directly after treatment (zero weeks), two weeks and five weeks after application. The probability values from the analysis are presented, with LSD for means separation where the P value is significant.

Location	Treatment	0 weeks	1 week	5 weeks
Peccavi	Control	0.09	0.08	0.75
	Mowing	0.06	0.06	0.74
	Herbicide	0.10	0.12	0.76
	24 kW	0.10	0.11	0.74
	36 kW	0.06	0.08	0.73
	P (and LSD)	0.281	0.038 (0.038)	0.960
Paganin	Control	0.10	0.14	0.75
	Mowing	0.09	0.15	0.78
	Herbicide	0.07	0.13	0.78
	24 kW	0.09	0.14	0.78
	36 kW	0.06	0.17	0.79
	P (and LSD)	0.682	0.844	0.425

At one week, the NDVI assessments of weed growth indicated that all treatments had less weeds than the control (Table 20). Significantly lower NDVI values were observed in the electric weed control treatments compared to the herbicide and mowing applications. At

five weeks, the NDVI of the weeds in the control and mowing treatments were statistically similar at both sites, likely due to regrowth after the mowing treatments. However, the electric weed control treatment at 24 kW at Paganin was also similar to the control. At this sampling time, electric weed control at 36 kW and the herbicide treatment offered the greatest reduction in NDVI compared to the control.

Visual assessment of weed control at Peccavi found that all the weed control treatments were significantly greater than the control both one and five weeks after their application (Table 20). At one week, the herbicide treatment showed the least control, however, by five weeks it was comparable to the application of electric weed control at 24 and 36 kW. Similar trends were observed at Paganin with the herbicide treatment being comparable to the control after a week, but not after five.

At both sites weed biomass was significantly reduced following the application of all weed control treatments compared to the control (Table 20). However, electric weed control or herbicide had greater biomass reduction than mowing.

Table 20. The dry weed biomass and normalised difference vegetation index (NDVI) values for the weeds at one and five weeks after the 2023 weed control treatment applications. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Measure	Treatment	Peccavi		Paganin	
		1 week	5 weeks	1 week	5 weeks
Weed NDVI	Control	0.52	0.37	0.49	0.25
	Mowing	0.33	0.32	0.32	0.26
	Herbicide	0.32	0.14	0.41	0.21
	24 kW	0.23	0.16	0.23	0.22
	36 kW	0.22	0.15	0.26	0.18
	P (and LSD)	<0.001 (0.06)	<0.001 (0.05)	<0.001 (0.05)	0.005 (0.04)
Visual Control (%)	Control	0.00	0.00	0.00	0.00
	Mowing	60.00	18.75	50.00	31.25
	Herbicide	17.50	90.00	15.00	86.25
	24 kW	43.75	80.00	58.75	86.25
	36 kW	62.50	91.25	56.25	88.75
	P (and LSD)	<0.001 (16.13)	<0.001 (10.92)	<0.001 (20.91)	<0.001 (8.92)
Biomass (g m^{-2})	Control	NA	33.49	NA	21.11
	Mowing	NA	10.72	NA	9.12
	Herbicide	NA	2.54	NA	3.68
	24 kW	NA	2.93	NA	1.28
	36 kW	NA	0.64	NA	0.76
	P (and LSD)	NA	<0.001 (8.36)	NA	<0.001 (7.24)

Assessment of the alpha diversity of the 16s communities (via Shannon's index, Faiths Phylogenetic Diversity, and Pielous' Evenness analysis) indicated no difference between the experimental treatments at each site and sampling time (Figure 19). Similarly, no difference was determined in the alpha diversity of the ITS community (Figure 20).

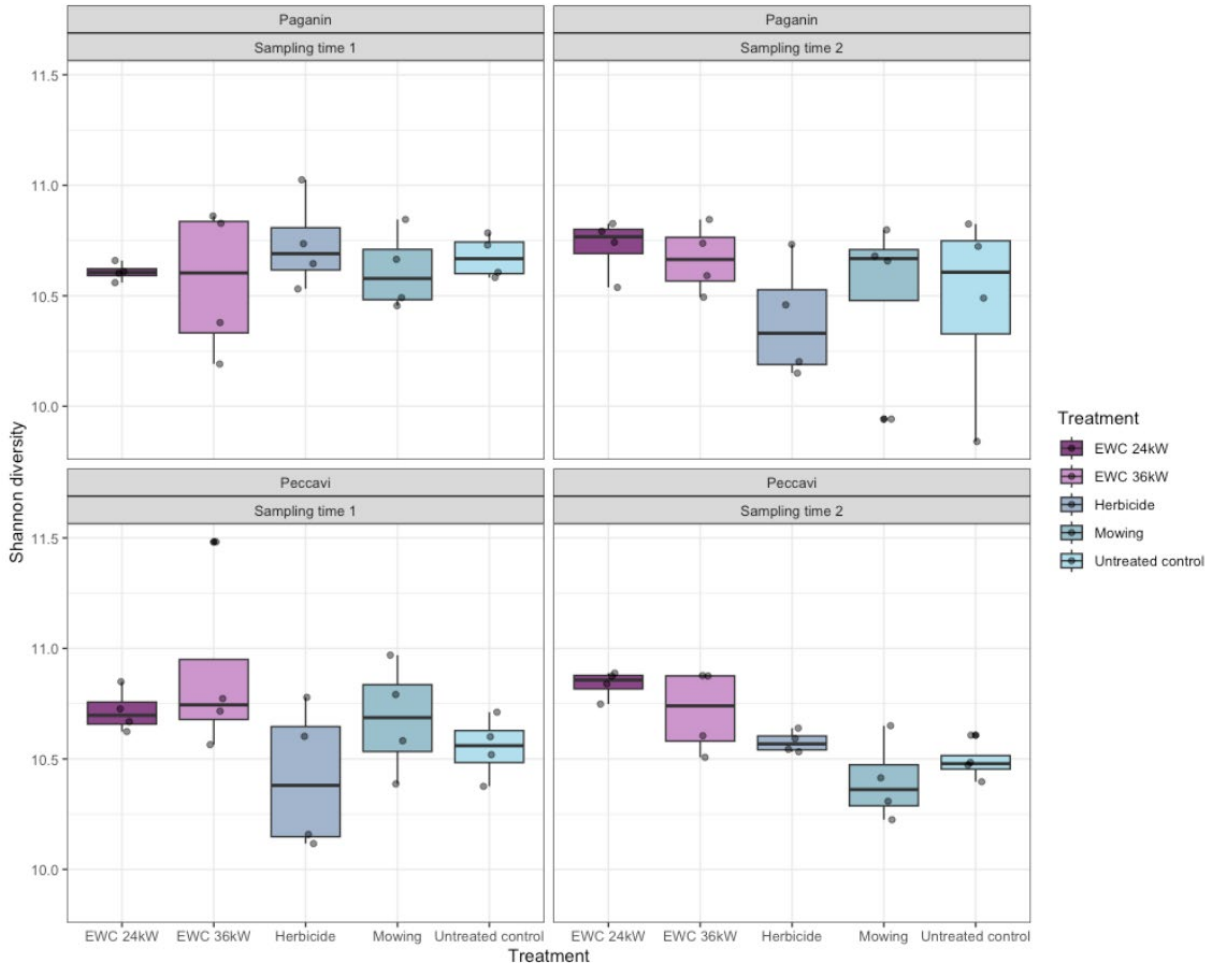


Figure 19. Alpha diversity of 16s communities assessed on 14 September 2023 at the Paganin (top) and Peccavi (bottom) trial sites.

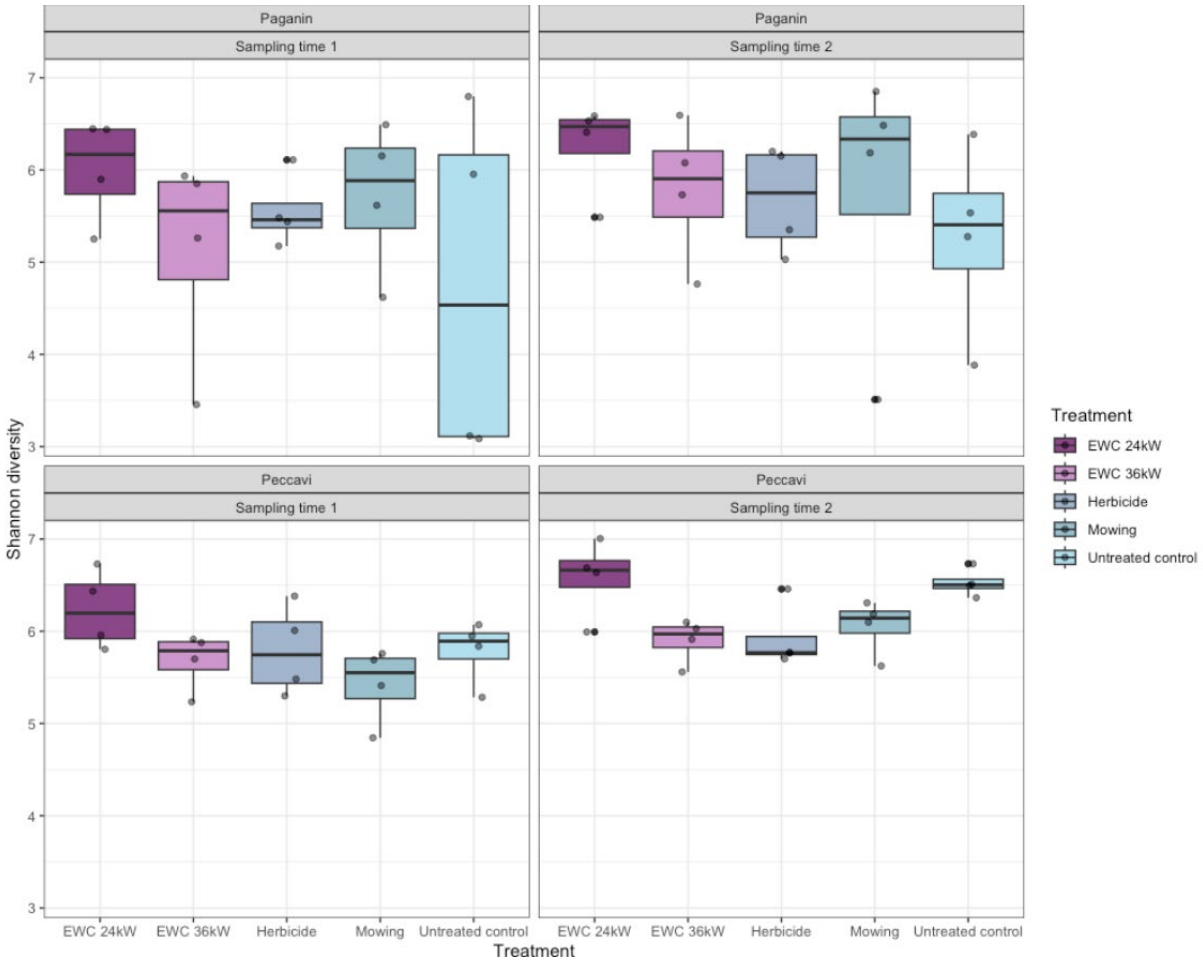


Figure 20. Alpha diversity of ITS communities assessed on 14 September 2023 at the Paganin (top) and Peccavi (bottom) trial sites.

The taxa summary revealed no obvious differences among the trial sites, sampling times or weed control treatments. This analysis most frequently observed 16s community taxa from the orders Solirubrobacterales, Rhizobiales, Propionibacteriales, and Micrococcoales which accounted for a third of all taxa observed at both Paganin and Peccavi. No differences were likewise observed for the ITS community, and the most frequently observed taxa were from the orders Filobasidiales, Eurotiales, Agaricales, Chaetothyriales, and Pleosporales.

Assessment of beta diversity (via an unweighted UniFrac analysis) indicated slight differences in the 16s communities between sites and sampling dates, irrespective of weed control treatment (Figure 21). Further analysis performed at an individual site level revealed separation between sampling times at Paganin, but no clear separation of samples among treatments at either sampling time (Figure 22 left). Similar trends were observed for Peccavi (Figure 22 right).

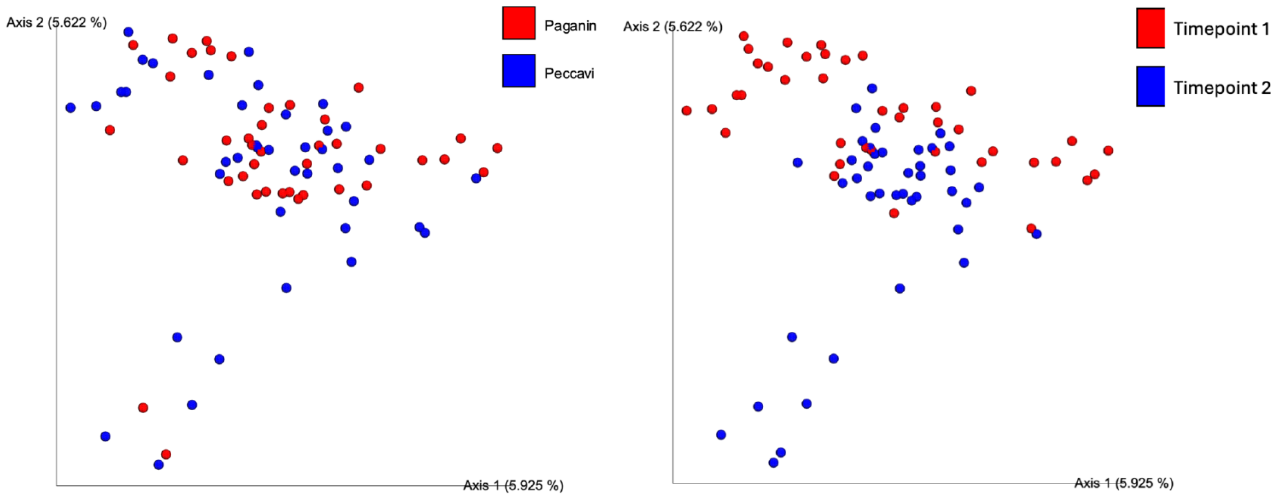


Figure 21. Beta diversity (unweighted UniFrac) of the 16s community at each of the trial sites (Paganin or Peccavi; left) and at each sampling timepoint (right).

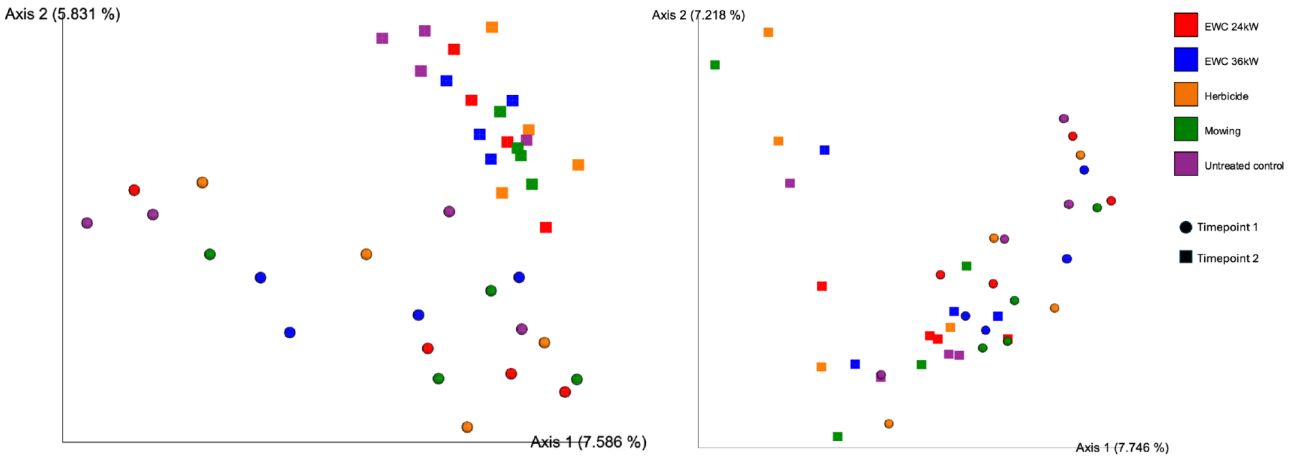


Figure 22. Beta diversity (unweighted UniFrac) of the 16s community under different weed control treatments at the Paganin (left) and Peccavi (right) trial sites (both sampling times).

When analysing the beta diversity of the ITS community irrespective of weed control treatment, there was a clear difference between the two trial sites (Figure 23 left), but no difference observed between the sampling times (Figure 23 right). Further analysis performed on the Paganin and Peccavi data at an individual site level revealed no separation between the sampling times or among treatments at either sampling time (Figure 24). However, a pairwise comparison (PERMANOVA) of the Paganin data determined a significantly lower ITS beta diversity in the herbicide treatment at the second sampling time compared to the untreated control (P: 0.027). PERMANOVA analysis of Peccavi revealed no significant differences between ITS beta diversity.

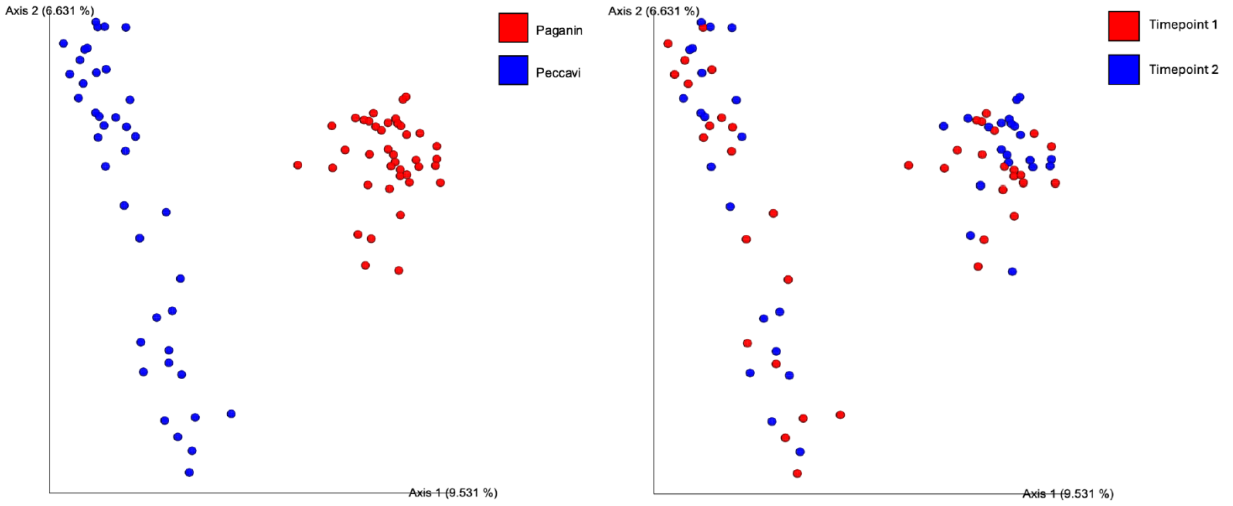


Figure 23. Beta diversity (unweighted UniFrac) of the ITS community at each of the trial sites (Paganin or Peccavi; left) and at each sampling timepoint (right).

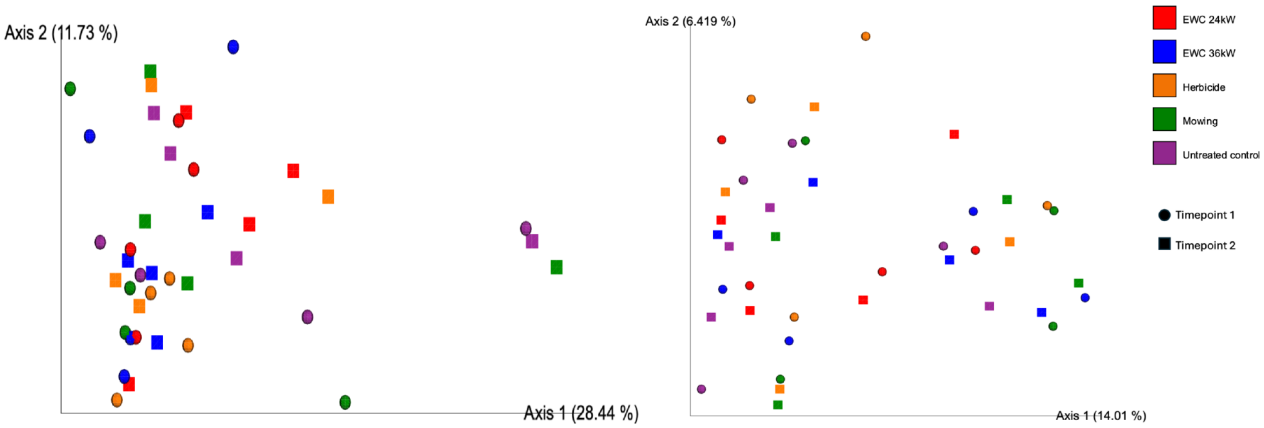


Figure 24. Beta diversity (unweighted UniFrac) of the ITS community under different weed control treatments at the Paganin (left) and Peccavi (right) trial sites (both sampling times).

At both trial sites in 2023, there was little effect of the weed control applications on the abundance of free-living soil nematodes (Table 21). At Paganin, the nematode population was not affected after the application of the weed control treatments. However, at Peccavi, the abundance of Dorylaimida and Tylenchinae were found to reduce five weeks after both the application of the electric weed control and herbicide treatments. No reduction was observed one week after the treatment. This indicates that the reductions aren't likely due to the treatments themselves, but rather due to the removal of weed biomass in these treatments. Studies have shown that weed presence and diversity is positively associated with nematode diversity and abundance (Yeates et al., 1993; Thomas et al., 2009; Niu et al., 2022). Specifically, Dorylaimida are omnivorous and Tylenchinae root hair feeders and fungivores (Linsell et al., 2014). Therefore, weed population removal in these treatments likely reduced the root biomass and the fungi associated with decomposition, removing the nematode's food source. Further, these changes did not significantly affect the Maturity Index for each treatment (data not presented); a measure of the impact of disturbances with the ability to monitor changes in structure and functioning of the below-ground ecosystem.

Table 21. The abundance of free-living nematode groups one and five weeks after the 2023 weed control treatment applications. The probability and least significant difference (LSD) values from the analysis are presented for means separation. Not applicable (NA) is used when statistical outputs aren't relevant to results as no nematodes were detected in the samples.

Nematode Family	Treatment	Nematode abundance (kDNA copies/g Sample)			
		Peccavi		Paganin	
		1 weeks	5 weeks	1 weeks	5 weeks
Aphelenchoididae	Control	6.2	11.5	3.6	8.8
	Mowing	6.1	6.1	3.6	6.5
	Herbicide	4.9	7.4	4.2	7.7
	24 kW	6.3	8.0	3.1	5.8
	36 kW	7.9	6.2	5.8	6.0
	P (and LSD)	0.750	0.135	0.380	0.733
Aphelenchidae	Control	145.2	377.4	52.4	116.0
	Mowing	128.6	214.2	46.7	54.3
	Herbicide	101.2	195.0	60.0	120.1
	24 kW	161.0	186.6	78.5	78.2
	36 kW	148.2	174.2	80.6	169.9
	P (and LSD)	0.289	0.105	0.445	0.070
Cephalobidae	Control	365.7	879.9	176.2	267.1
	Mowing	216.9	395.6	186.0	227.9
	Herbicide	210.9	312.6	265.9	321.8
	24 kW	326.2	370.6	207.4	196.4
	36 kW	239.9	440.9	202.4	293.9
	P (and LSD)	0.673	0.226	0.737	0.622
Dorylaimida	Control	262.5	850.6	153.0	351.7
	Mowing	295.1	648.7	105.7	231.1
	Herbicide	265.8	362.0	130.6	373.8
	24 kW	384.3	443.9	107.7	195.9
	36 kW	295.9	431.3	129.2	296.6
	P (and LSD)	0.426	0.013 (282.0)	0.586	0.421
Mesorhabditinae	Control	34.8	45.3	23.6	17.2
	Mowing	28.6	39.5	9.3	8.4
	Herbicide	24.9	49.6	42.5	11.2
	24 kW	37.9	24.3	20.3	7.4
	36 kW	48.8	129.2	33.7	39.1
	P (and LSD)	0.742	0.199	0.282	0.053

Mononchida	Control	10.7	8.8	21.43	55.1
	Mowing	17.8	7.4	20.7	53.8
	Herbicide	7.5	4.6	41.5	47.6
	24 kW	14.9	10.7	37.8	174.9
	36 kW	7.3	3.4	37.3	50.5
	P (and LSD)	0.217	0.630	0.756	0.686
Panagrolaimidae	Control	235.0	338.7	88.8	48.9
	Mowing	145.9	215.2	48.0	23.1
	Herbicide	165.3	285.7	63.3	96.3
	24 kW	239.6	291.5	80.7	64.7
	36 kW	221.8	196.8	124.5	164.6
	P (and LSD)	0.936	0.870	0.157	0.312
Rhabditinae	Control	0.7	0.6	0.5	1.5
	Mowing	0.4	0.7	0.2	0.6
	Herbicide	0.9	1.0	0.3	3.3
	24 kW	0.4	0.2	1.7	1.0
	36 kW	0.7	3.7	0.9	2.3
	P (and LSD)	0.615	0.176	0.113	0.441
Tylenchinae	Control	131.3	513.6	78.2	265.3
	Mowing	112.1	217.7	108.6	212.4
	Herbicide	91.8	121.7	121.9	271.9
	24 kW	108.8	151.4	72.7	221.6
	36 kW	127.8	164.7	78.2	171.4
	P (and LSD)	0.770	0.004 (195.9)	0.610	0.761

The soil characteristics at each site were also minimally affected by the application of the weed control treatments (Table 22). At Peccavi, no soil characteristics were significantly altered compared to the control both one and five weeks after the weed control applications. However, at Paganin, there was a significant reduction in the soil organic carbon content five weeks after the application of the electric weed control treatments (Table 23). No reduction was observed at one week. This effect is likely due to the reduction in weed biomass in this treatment (Table 20), which removed the source of fresh organic matter return to the soil.

Table 22. The values of select soil characteristics averaged over the weed control treatments at each site both one and five weeks after the 2023 treatment applications.

Soil Characteristic	Peccavi		Paganin	
	1 weeks	5 weeks	1 weeks	5 weeks
Ammonium nitrogen (mg/kg)	6.2	19.0	4.1	2.8

Nitrate nitrogen (mg/kg)	5.3	15.2	4.6	2.4
Phosphorus (mg/kg)	156.7	186.9	52.6	75.4
Potassium (mg/kg)	146.9	195.0	184.2	193.0
Sulfur (mg/kg)	8.2	20.9	7.5	6.6
pH ($CaCl_2$)	5.8	5.6	5.9	5.9
Electrical Conductivity (dSm)	0.1	0.1	0.1	0.1

Table 23. Organic carbon (%) one and five weeks after the 2023 weed control treatment applications. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Treatment	Peccavi		Paganin	
	1 weeks	5 weeks	1 weeks	5 weeks
Control	4.16	4.90	2.77	3.27
Mowing	4.12	5.13	2.80	3.23
Herbicide	3.56	4.06	2.93	3.14
24 kW	3.78	4.45	2.81	2.58
36 kW	3.89	3.61	2.79	2.89
P (and LSD)	0.609	0.256	0.979	0.007 (0.372)

Fire risk from electric weed control in controlled conditions

The conservation cropping system is common to Australian broad-scale grain industries, and residue and/or mulch is also frequently maintained in horticultural and viticultural systems (Llewellyn et al., 2012; Devetter et al., 2015). High levels of surface plant residue may also be seen in urban and industrial settings. While there are many environmental benefits from retaining residue, surface residues pose a fire risk. The Bureau of Meteorology monitors climatic conditions throughout Australia and advises fire danger ratings for every town from low-moderate to catastrophic. It is common in spring/summer for agricultural communities to be advised of a ‘harvest ban’ or ‘vehicle movement ban’ in locations when the fire risk is too high. Potential fire risk from electric weed control will vary broadly, mainly due to the time of year, but requires investigation.

2022 Experiment:

Key findings

- Fire risk was related to operation speed and type of residue, but not to biomass of residue.
- Fire risk is too high to allow operation in sites with dry residue over summer.
- **Note that for all other trial treatments in this report (in the other experiments), there were zero fires. Normal operation in winter or spring was not a fire risk.**

Aim

To determine the likelihood of fires resulting from operation of electric weed control machinery in sites with dry crop residue.

Method

Site: DPIRD Northam Research Station (-31.6532, 116.6951)

Applicator: XPU (36 kW)

Treatments:

- Residue type – barley straw or oat hay
- Residue biomass – 50, 250, 450 or 650 g m^{-2} (500, 2500, 4500 or 6500 kg ha^{-1})
- Speed of operation – 1, 3 or 5 km h^{-1}

Residue was spread over an area of 1 m^{-2} and the XPU unit was driven over the top at the appropriate speed (split plot design with three replications). The surrounding area was clear, and the ground was wet, to avoid damage from resulting fires.

Measurements:

- Visual assessment of fire, assessed as smouldering or open flames.
- Surface area of each of the residue type was determined from three replicates using analysis through ImageJ (University of Wisconsin, 1675 Observatory Drive, Madison WI 53706) following scanning with an Epson Perfection V850 Pro (Epson, 3 Talavera Road, Macquarie Park NSW 2113).

Conditions at treatment:

- Speed – 1.1, 2.8, 4.9 km h^{-1}

Results

Over 72 plots, we started a fire in 29%. Of those fires, 41% had smouldering residue and 59% had open flames. The machinery cannot be safely operated on dry residue. It should be noted that in every other experiment over all treatments there were zero fires. Normal operation in winter or spring did not pose a significant fire risk.

The average power delivered by the transformers reduced with increasing speed of operation (Table 24). It was not affected by the residue type or biomass. The number of fires also reduced with increasing speed, from an average of 0.54 fires per m^{-2} of biomass to 0.08 fires at 5 km h^{-1}. Obviously slower speeds increase electrode contact time with the residue and increase the likelihood of fire. Note that speeds of 1-3 km h^{-1} are recommended for grass control, but speeds of 5 km h^{-1} are faster than manufacturer recommendations.

Table 24. Average speed of the tractor for each treatment, average power output by the inverters and number of fires. The probability and least significant difference (LSD) values from the analysis are presented for means separation.

Tractor speed (km h^{-1})	Average power (W $inverter^{-1}$ s^{-1})	Average number of fires
1.12	1358	0.54
2.85	1252	0.50
4.95	1026	0.08
P (LSD)	<0.001 (128.1)	0.025 (0.30)

Residue type had an impact on likelihood of fires, with oat hay more than twice as likely to have a fire than barley straw (average of 0.56 fires m^{-2} in oat hay and 0.19 fires m^{-2} in barley straw). This was expected, as the oat hay contained the very fine husks of oat seeds while the barley straw just had the grass stems (Figure 25). However, there was no difference (P: 0.654) between the average surface area of the oat hay (62.12 cm^2) compared to the barley straw (68.80 cm^2). The average surface area of annual ryegrass (90.66 cm^2) and kikuyu (106.63 cm^2) was also similar (P: 0.223). Surprisingly, the biomass of the residue (ranging from 500 kg ha^{-1} to 6500 kg ha^{-1}) did not affect likelihood of starting a fire.





Figure 25. Oat hay (top) or barley straw (bottom) spread over 1 m^2 at a biomass of 500 kg ha^{-1} (left) or 6500 kg ha^{-1} (right).

Apply electric weed control to fence lines or roadsides

While the market is still awaiting the release of an electric weed control device that can cover large areas at a reasonable speed, electric weed control is currently applicable to provide fallow control in smaller problem weed areas. For example, along fences or roadsides and in firebreaks where weed control is undertaken to reduce fire hazard, maintain visibility and protect native vegetation, as well as prevent weed spread and the establishment of new populations. In Australia, most of this management is completed using chemical applications and rates of herbicide resistance have been growing substantially (particularly to glyphosate). Due to resistance development, it is common to use two sequential applications of non-selective herbicide, referred to as a ‘double knock’. Choice of herbicide is severely limited in these areas to protect non-target vegetation. Therefore, electric weed control potentially offers a highly applicable non-chemical alternative to control weeds in these situations.

2022 Experiments:

Key findings

- Electric weed control in fallow areas was equivalent to, or better, than herbicide.
- Electric weed control was generally more successful for broad leaf weeds than grass species, as indicated by the manufacturer.
- Double applications of electric weed control were effective at reducing cape tulip viability in the following growing season with less bulbs surviving, and shoot, root and bulb biomass significantly reduced compared to the control.

Aim

To determine the applicability of fallow applications of electric weed control to remove natural and long-established weed populations along fences and roadsides.

Method

Table 25. Details of the two local government sites used in the following experiments.

Name	Northam 2022	Bassendean 2022
Location	Avon Valley Pony and Show Jumping Club (-31.6408, 116.6579)	Hamilton Street Reserve (-31.9153, 115.9498)
Applicator	XPU (36 kW)	XPU (36 kW)
Predominant weed species	Cape weed, erodium, couch grass, Guildford grass and soursob	Capeweed, erodium, winter grass, annual ryegrass, and medic
Volumetric soil moisture	First application: 11.6% Second application: 15.3%	First application: 15.3% Second application: NA
Soil type	Grey-brown sandy loam (5-10% gravel), nitrate nitrogen 3 mg kg^{-1}, phosphorus (Colwell) 12 mg kg^{-1}, potassium (Colwell) 153 mg kg^{-1}, sulfur 1.4 mg kg^{-1}, organic carbon 0.50%, conductivity 0.029 dS m^{-1}, $pH_{(CaCl2)}$ 5.7, $pH_{(H2O)}$ 7.1	Brown-black sandy loam (15-20% gravel), nitrate nitrogen 71 mg kg^{-1}, phosphorus (Colwell) 52 mg kg^{-1}, potassium (Colwell) 222 mg kg^{-1}, sulfur 9.3 mg kg^{-1}, organic carbon 1.39%, conductivity 0.194 dS m^{-1}, $pH_{(CaCl2)}$ 7.1, $pH_{(H2O)}$ 7.9
Measurements	Prior to treatment application: • Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard) • Average soil volumetric water content (%) to 12 cm • 3 x normalised difference vegetation index (NDVI) measurements per plot, two hours after treatment, as well as one, two, three, four, five and six weeks after treatment application. Six weeks after treatment application: • Weed control (%) visual assessment (from two quadrats of 50 x 50 cm per plot) • Dry biomass (average grams from two quadrats of 50 x 50 cm per plot)	

	• Weed species incidence (average number of individuals from two quadrats of 100 x 100 cm per plot)

Treatments:

Table 26. Treatments applied at the Northam site.

Treatment	Weed control	Speed or rate	Application timing
Untreated control	None	-	-
Single application	Electric weed control	2 or 4 km h^{-1}	30/6/2022
	Herbicide – glyphosate 570 g a.i. L^{-1}, (Roundup UltraMax® 1.5 L ha^{-1}, Bayer, SC)	855 g a.i. ha^{-1}	30/6/2022
Double application	Electric weed control	2 or 4 km h^{-1}	30/6/2022, then 15/7/2022
	Herbicide – glyphosate, then paraquat/diquat 135/115 g a.i. L^{-1} Spray.Seed 1.5 L ha^{-1}, Syngenta, SL)	855 g a.i. ha^{-1}, 202/172 g a.i. ha^{-1}	30/6/2022, then 15/7/2022

Table 27. Treatments applied at the Bassendean site. Note that the entire site was mown during the season prior to treatment.

Treatment	Weed control	Speed or rate	Application timing
Untreated control	None	-	-
Single application	Electric weed control	2 or 4 km h^{-1}	7/6/2022
Double application	Electric weed control	2 or 4 km h^{-1}	7/6/2022 then 28/7/2022

Cape tulip mortality:

Cape tulip, when treated with herbicide, generally shows senescence of the above ground biomass, while the bulb remains alive to resprout in the following year. To determine cape tulip mortality, twelve cape tulip plants were dug up from each treatment, six weeks after application of the weed control treatments. Bulbs were cleaned and visually inspected in the lab. Firm white bulbs were assessed as alive and soft, brown, degraded bulbs were assessed as dead.

Live bulbs were planted in pots of 1 kg capacity (3 bulbs per pot) and left in a screen house (28 pots in a randomised block design with four replications). Regrowth was monitored in 2023 for eight weeks after initial emergence, after which the pots were harvested. For the harvest analysis, bulbs within each cluster were classified as being either major (the most advanced bulbs off which smaller bulbs were growing) or minor (the smaller bulbs) as there were multiple bulbs present in each cluster. They major bulbs were then cut open and classified as dead or alive as previously defined. The total dry biomass of the roots, shoots and bulbs of each cluster was also determined.

Results

Northam

During the electric weed control applications in this trial, power output for the first application averaged 2931 W inverter^{-1} s^{-1} at 2 km h^{-1} and 2871 W inverter^{-1} s^{-1} at 4 km h^{-1}. On the second application, power output averaged 2568 W inverter^{-1} s^{-1} at 2 km h^{-1} and 2577 W inverter^{-1} s^{-1} at 4 km h^{-1}. There was no significant difference between the average power outputs of the two different speeds of application. However, there was a significant difference ($P<0.001$, LSD: 83.58) between the different application times. This is partially due to a malfunction of one of the transformers on the second application. However, if the data from the transformer delivering less power is removed, the average power output was still lower on the second application, probably due to reduced weed density and biomass. There was no significant interaction between the speed and timing of application. Note that the malfunction of the transformer was a temporary issue, and function returned to normal after these experiments with no intervention.

At the Northam trial site, the application of electric weed control (e.g., at 2 km h^{-1}) was effective at controlling the weed population (Figure 26). This was supported by NDVI assessments of weed growth, which indicated that all applications of herbicides and electric weed control had less weeds compared to the control ($P<0.001$, LSD: 0.10; Figure 27). On average, the lowest NDVI (i.e., best weed control) was observed following the double application of electric weed control at 2 km h^{-1}, followed by the double application at 4 km h^{-1}. The highest NDVI values were seen following the single application of herbicide or of electric weed control at 4 km h^{-1}. The double application of herbicide was similar to the single application of electric weed control at 4 km h^{-1}.



Figure 26. An application of electric weed control at 2 km h^{-1} was effective at killing all weed species present at the Northam trial site.

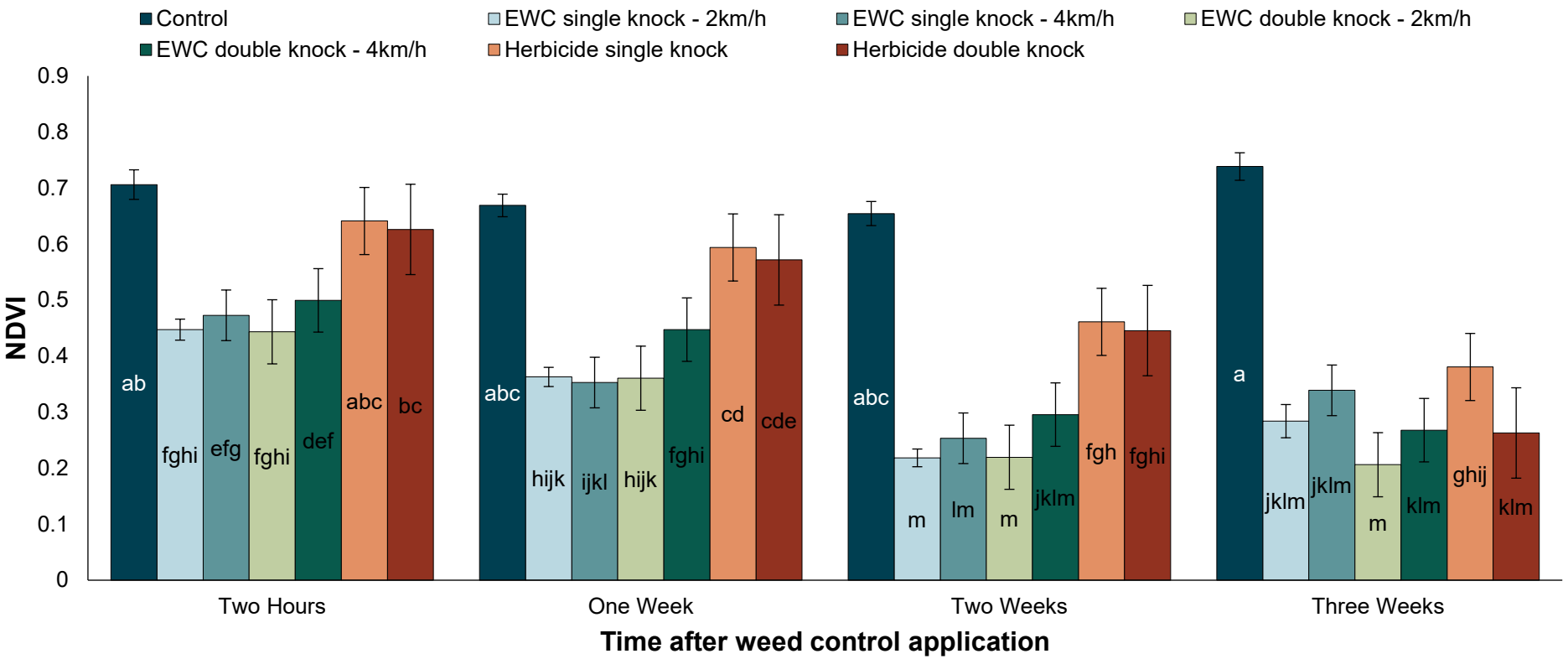


Figure 27. Effect of single or double application of electric weed control (EWC) at 2 or 4 km h^{-1}, or of herbicides, on normalised differential vegetation index (NDVI) of the weed population at the Northam trial site over time (n = 6; mean ± s.e.). Sampling times were two hours and one, two or three weeks following weed control application. Bars annotated with the same letter have means that were not significantly different at P=0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

Visual assessment of percent weed control (Figure 28A) showed that all treatments had significantly fewer weeds than the untreated control treatment (P<0.001, LSD: 14.31). Best control was achieved by the application of herbicides or the double application of electric weed control treatment at 2 km h^{-1}.

At the end of the trial, dry weed biomass (Figure 28B) was similar between the single and double application of herbicide and the electric weed control using a single application at 2 km h^{-1} and the double applications at 2 km h^{-1} and 4 km h^{-1} (P<0.001, LSD: 12.41). Weed biomass following a single application of electric weed control at 4 km h^{-1} was significantly greater than all other weed control methods, although still lower than the control.

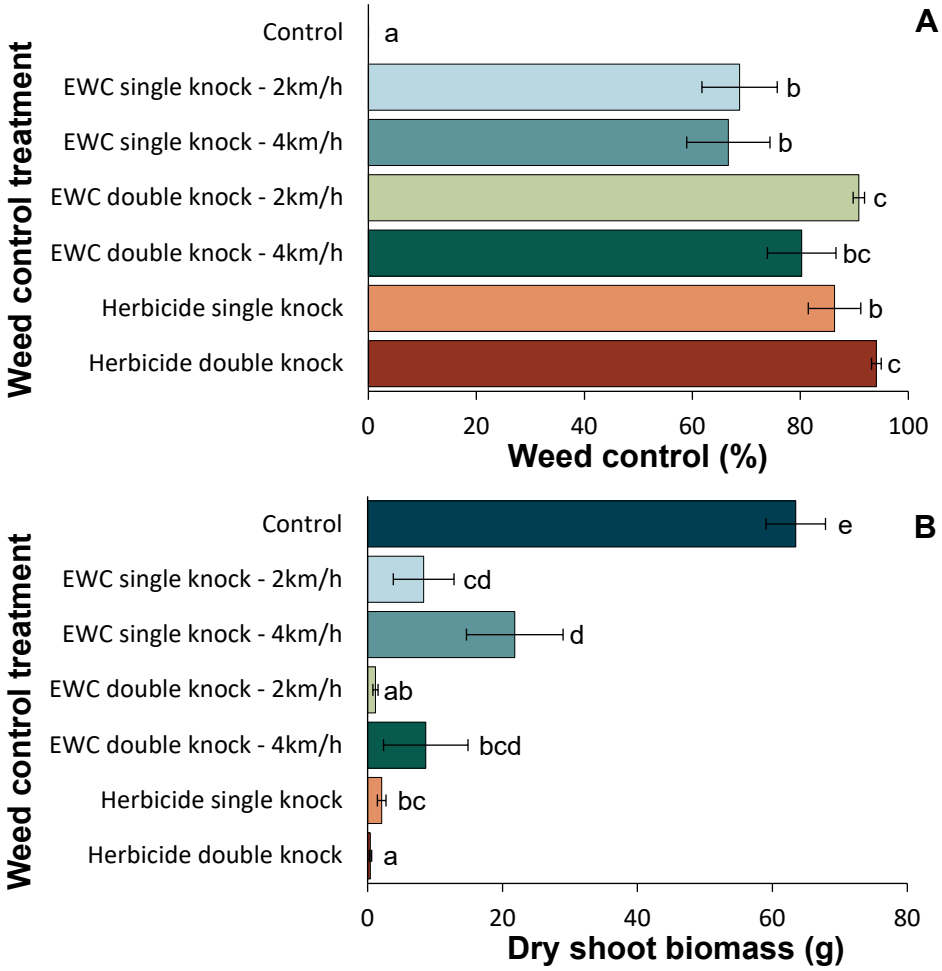


Figure 28. Effect of single or double electric weed control (EWC) application at 2 or 4km h^{-1}, or of herbicides, on percent control (A) and the dry shoot biomass (B) of the weed population at the Northam trial site (n = 6; mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P=0.05 according to a one-way post-hoc Fisher's Unprotected LSD test performed on the data. Note that a logarithmic (base 10) transformation was applied to the weed dry biomass data to normalise residual distribution prior to analysis.

Generally, control of broad leaf species was more successful than grass species (Figure 29). Grasses have multiple plants growing together. An example is windmill grass (*Chloris truncata* R.Br.), where a single 'clump' consists of many individual plants growing together. It is difficult for any weed control technique (electric weed control or herbicide) to kill all plants when some are shielded within the cluster.



Figure 29. The image on the left shows capeweed immediately after electric weed control at 2 km h^{-1}, on the top of the image. The capeweed at the bottom of the image was outside the treatment area. The image on the right shows windmill grass two weeks after electric weed control at 2 km h^{-1}. Half of each plant 'clump' was killed, indicating that the plants at the front of the clump shielded plants behind them.

Cape tulip (*Moraea miniate* spp.) is a species particularly difficult to control with herbicides, as the above ground biomass will senesce after treatment, but the bulb allows the plant to regrow. Electric weed control at 2 km h^{-1} removed the above ground biomass, and the remaining bulbs were smaller (Figure 30).



Figure 30. Cape tulip had above ground biomass killed by electric weed control at 2 km h^{-1}, but some survival at 4 km h^{-1}, three weeks after weed control at the Northam trial site (left). At 2 km h^{-1}, the bulbs were smaller after three weeks (right).

The visual assessment of bulb status (alive or dead) in the lab indicated that applications of electric weed control at 2 km h^{-1} and herbicides had significantly less live cape tulip bulbs when compared with the control or electric weed control at 4km h^{-1} (Table 28). In June 2023, the number of 'live' bulbs that resprouted after being left in pots was not significantly reduced following the herbicide or electric weed control applications. However, there was a delay in the bulb regrowth occurring following the electric weed control and herbicide treatments, particularly in the double applications (data not presented).

Table 28. The mean number of bulbs (out of twelve per treatment) that appeared to be alive six weeks following the application of the weed control treatments in June-July 2022 and the number of bulbs that had resprouted by 21 June 2023 (8 weeks after initial regrowth occurred).

Treatment	Live bulbs	Resprouting bulbs
Control	2.33	3.00
EWC single at 2 km h^{-1}	1.00	2.50
EWC single at 4 km h^{-1}	2.08	3.00
EWC double at 2 km h^{-1}	1.20	1.25
EWC double at 4 km h^{-1}	1.29	3.00
Herbicide single	1.33	2.50
Herbicide double	1.33	2.25
P (LSD)	<0.001 (0.610)	<0.001 (0.753)

At the completion of the subsequent pot trial with the cape tulip bulb clusters, the number of live bulbs was significantly reduced with the weed control treatments (Table 29). The best reduction was seen following the double application of electric weed control at 2 km h^{-1} and of herbicides. A single application of electric weed control at 4 km h^{-1} did not significantly reduce the number of live bulbs compared to the control. Shoot biomass was also affected with the single and double application of electric weed control at 2 km h^{-1}, as well as the herbicide treatments, being significantly lower than the control. For root biomass, all treatments except the single application of electric weed control at 4 km h^{-1} were significantly lower than the control. The application of all weed control treatments significantly reduced the bulb biomass compared to the control. The largest reduction was seen in single application of electric weed control at 2 km h^{-1}, and the least in the single application at 4 km h^{-1}.

Table 29. The mean number of live major bulbs per cluster and the dry shoot, root, and bulb biomass of the cape tulip clusters by 21 June 2023 (8 weeks after initial regrowth occurred).

Treatment	Live major bulbs	Dry biomass (g)		
		Shoot	Root	Bulb
Control	4.25	0.04	0.10	0.47
EWC single at 2 km h^{-1}	3.25	0.02	0.02	0.18
EWC single at 4 km h^{-1}	4.50	0.04	0.10	0.32
EWC double at 2 km h^{-1}	1.50	0.01	0.02	0.22
EWC double at 4 km h^{-1}	3.75	0.02	0.04	0.23
Herbicide single	2.50	0.01	0.01	0.23
Herbicide double	2.00	0.02	0.01	0.25
P (LSD)	0.001 (1.41)	0.008 (0.02)	<0.001 (0.04)	0.001 (0.12)

Bassendean

During the electric weed control applications, at the first application power output averaged 2934 W $inverter^{-1}$ s^{-1} at 2 km h^{-1} and 2806 W $inverter^{-1}$ s^{-1} at 4 km h^{-1}. On the second application, power output averaged 2713 W $inverter^{-1}$ s^{-1} at 2 km h^{-1} and 2750 W $inverter^{-1}$ s^{-1} at 4 km h^{-1}. There was no significant difference between the average power outputs of the two different speeds of application. However, there was a significant difference (P: 0.039; LSD: 130.49) between the different application times, again mainly due to reduced weed density at the second application. There was no significant interaction between the speed and timing of application.

The NDVI assessments of weed growth indicated that all applications of electric weed control had less weeds when compared with the control (P: 0.031, LSD: 0.170; Figure 31). The lowest NDVI was observed following the double application of electric weed control at 2 km h^{-1}, followed by the double application at 4 km h^{-1}. The NDVI values following the application of the single application electric weed control treatments at 2 and 4 km h^{-1} were greater than those for a double application at 2 km h^{-1}, but not significantly greater than the NDVI of the double application at 4 km h^{-1}.

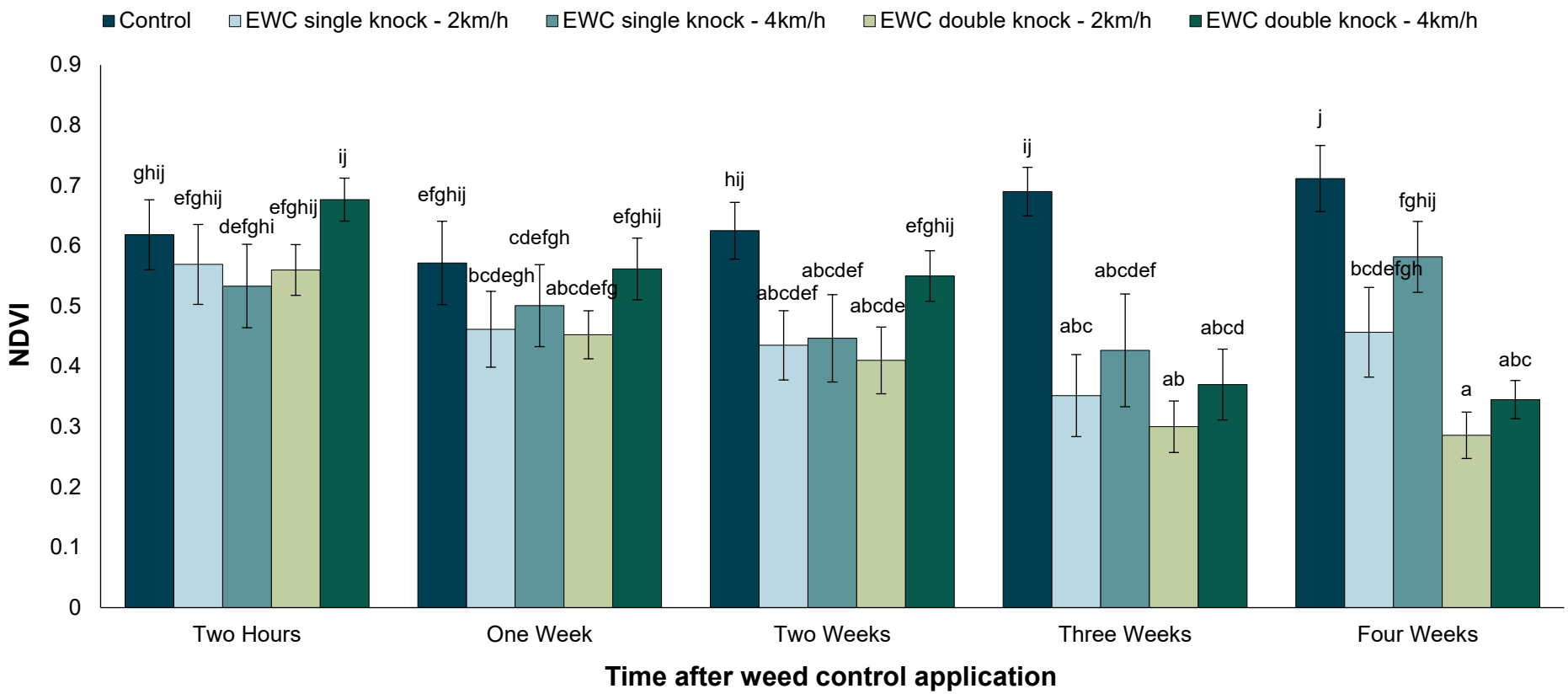


Figure 31. Effect of single or double electric weed control (EWC) application at 2 or 4km h^{-1} on normalised differential vegetation index (NDVI) of the weed population at the Bassendean trial site over time (n = 6; mean ± s.e.). Sampling times were two hours and one, two, three or four weeks following weed control application. Bars annotated with the same letter have means that were not significantly different at P=0.05 according to a two-way post-hoc Fisher's Unprotected LSD test performed on the data.

Visual assessment of percent control of the weeds and biomass at the completion of the experiment indicated a significant effect of treatment. All treatments had greater weed control than in the control plot, except for the single application of electric weed control at 4 km h^{-1} for both visual assessment (P: 0.023, LSD: 42.77; Figure 32A) and biomass (P<0.001, LSD: 14.29; Figure 32B). Poor control at 4 km h^{-1} was due to the high density of grass species at the Bassendean site; electric weed control should be applied at 1-3 km h^{-1} for grass control.

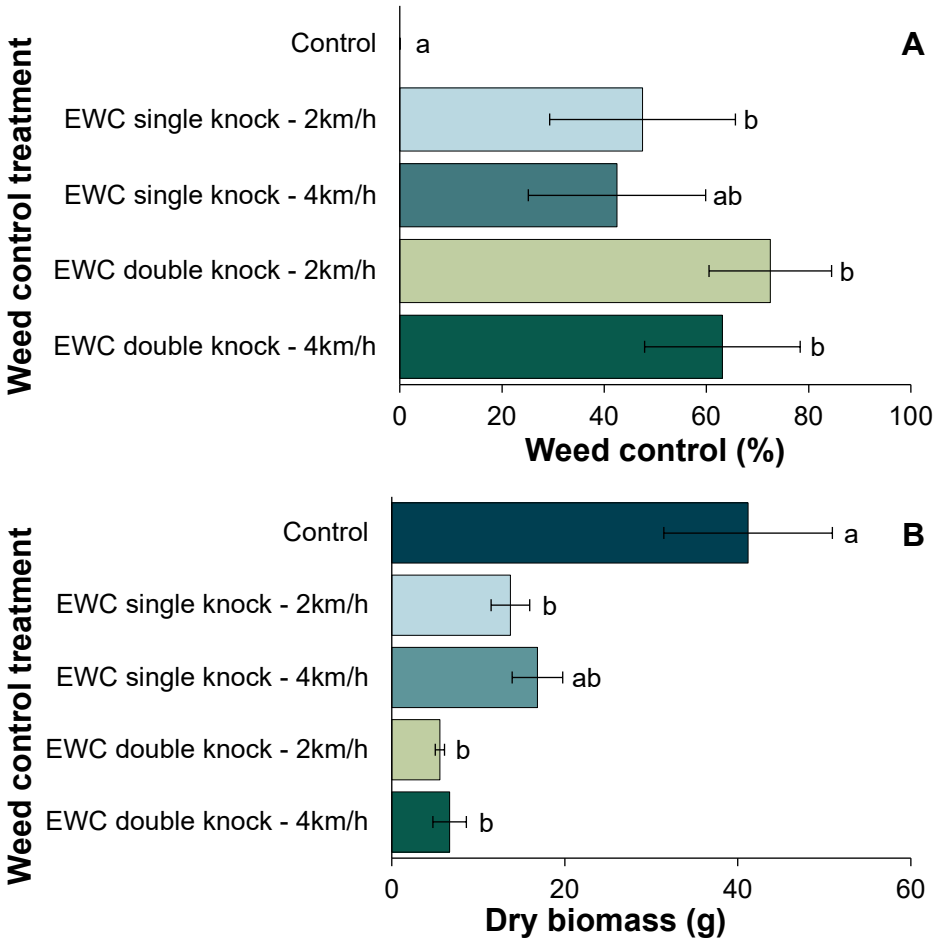


Figure 32. Effect of single or double electric weed control (EWC) applications at 2 or 4km h^{-1} on percent control (A) and the dry biomass (B) of the weed population at the Bassendean trial site (n = 6; mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a one-way post-hoc Fisher's Unprotected LSD test performed on the data. Note that a square root transformation was applied to the weed dry biomass data to normalise residual distribution prior to analysis.

Electric weed control was more effective at controlling broadleaf species than grasses at the Bassendean trial site (Figure 33). For example, winter grass (*Poa annua* L.) was a predominate species at the site. This species is shorter than other species (e.g., annual ryegrass). It was often shielded from electric weed control applications by the broad leaf species present, and survived in the plots, especially following applications at 4 km h^{-1}.



Figure 33. Winter grass remaining four weeks after the application of electric weed control at 4 km h^{-1} at the Bassendean trial site while the broadleaf species were removed, at the top of the image. The bottom of the image is outside the treatment area, showing the original species composition. Application speeds of 4 km h^{-1} are not suitable for grass control.

2023 Experiments:

Key findings

- Electric weed control in fallow areas was equivalent to, or better, than herbicide.
- Electric weed control was found to be highly effective on suspected herbicide resistant annual ryegrass.

Aim

To determine the applicability of fallow applications of electric weed control to remove natural and long-established weed populations along fences and roadsides.

Method

Table 30. Details of the two sites used in the following experiments.

Name	Northam 2023	DPIRD 2023
Location	Avon Valley Pony and Show Jumping Club (-31.64074, 116.65705)	DPIRD Northam's Field Research Station (-31.65136, 116.69840)
Applicator	XPU (36 kW)	XPU (36 kW)
Predominant weed species	Cape weed, erodium, cape tulip, couch grass, soursob, windmill grass, annual ryegrass, and flat weed	Annual ryegrass, wild radish, wire weed and sow thistle
Volumetric soil moisture	First application: 17.6% Second application: 16.7%	First application: 32.0% Second application: 27.5%
Soil type	Light grey sandy loam (15-20% gravel), nitrate nitrogen 13 mg kg^{-1}, phosphorus (Colwell) 23 mg kg^{-1}, potassium (Colwell) 308 mg kg^{-1}, sulfur 3.8 mg kg^{-1}, organic carbon 1.38%, conductivity 0.084 dS m^{-1}, $pH_{(CaCl2)}$ 6.0	Brown-red clay (5% gravel), nitrate nitrogen 18 mg kg^{-1}, phosphorus (Colwell) 29 mg kg^{-1}, potassium (Colwell) 320 mg kg^{-1}, sulfur 7.6 mg kg^{-1}, organic carbon 1.16%, conductivity 0.148 dS m^{-1}, $pH_{(CaCl2)}$ 6.1
Measurements	Prior to treatment application: • Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard) • Average soil volumetric water content (%) to 12 cm • 3 x normalised difference vegetation index (NDVI) measurements per plot, twenty-four hours after treatment, as well as one, two, three, four, five and six weeks after treatment application. Six weeks after treatment application: • Weed control (%) visual assessment (from two quadrats of 50 x 50 cm per plot) • Dry biomass (average grams from two quadrats of 50 x 50 cm per plot)	

	• Weed species incidence (average number of individuals from two quadrats of 50 x 50 cm per plot)

Treatments:

Table 31. Details of the treatments applied at the 2023 field trial sites.

Treatment	Weed control	Speed or rate	Application timing	
			Northam 2023	DPIRD 2023
Untreated control	None	-	-	-
Single application	Electric weed control	2 or 4 km h^{-1}	21/6/2023	5/7/2023
	Herbicide – glyphosate 570 g a.i. L^{-1}, (Roundup UltraMax® 1.5 L ha^{-1}, Bayer, SC)	855 g a.i. ha^{-1}	21/6/2023	5/7/2023
Double application	Electric weed control	2 or 4 km h^{-1}	21/6/2022, then 5/7/2023	5/7/2023, then 18/7/2023
	Herbicide – glyphosate, then paraquat/diquat 135/115 g a.i. L^{-1} Spray.Seed 1.5 L ha^{-1}, Syngenta, SL)	855 g a.i. ha^{-1}, 202/172 g a.i. ha^{-1}	21/6/2022, then 5/7/2023	5/7/2023, then 18/7/2023

Cape tulip mortality:

To determine cape tulip mortality, the same methods as in 2022 were used. Twelve cape tulip plants were dug up from each treatment, six weeks after application of the weed control treatments. Bulbs were cleaned and visually inspected in the lab. Firm white bulbs were assessed as alive and soft, brown, degraded bulbs were assessed as dead.

Live bulbs were planted in pots of 1 kg capacity (3 bulbs per pot) and left in a screen house (28 pots in a randomised block design with four replications). Regrowth will be monitored in 2024 with assessments to include the number of bulbs growing and total biomass of the re-growth eight weeks after initial emergence.

Herbicide resistance testing:

A sample of annual ryegrass seed was collected from the 2023 DPIRD site on December 19, 2022. Following after-ripening, it was sent to Plant Science Consulting (https://www.plantscienceconsulting.com.au/) for herbicide resistance testing. Resistance was determined as the percent survival as compared to untreated plants three weeks after herbicide treatment; 100% refers to all plants surviving and 0% refers to death. The results are the mean of two replicate pots per herbicide rate. Included in the test was a susceptible (S) biotype and resistant (R) biotypes (data for the S and R biotypes is not shown). Depending on the percent survival, each treatment was assigned a resistance rating:

- No resistance (S): Plants died.

- Weak resistance (R): Surviving plants showed 70-90% stunting compared to untreated plants and recovery via the development of new shoots.
- Intermediate resistance (RR): Surviving plants showed 40-60% stunting compared to untreated plants and the development of new shoots.
- Strong resistance (RRR): Surviving plants showed virtually no herbicide symptoms.

Results

Northam 2023

During the electric weed control applications, power output at the first application averaged 2677 or 2696 W inverter^{-1} s^{-1} at 2 or 4 km h^{-1}. On the second application, power output averaged 2539 and 2599 W inverter^{-1} s^{-1} at 2 or 4 km h^{-1}.

At the Northam trial site electric weed control effectively controlled the weed population as seen in 2022. The NDVI assessments indicated that all weed control treatments resulted in weeds that were significantly less green compared to the control (Figure 34). Twenty-four hours (P: 0.001; LSD: 0.074), one week (P<0.001; LSD: 0.095) and two weeks (P<0.001; LSD: 0.081) after the first application the lowest NDVI (i.e., best weed control) was observed following the single and double applications of electric weed control at 2 km h^{-1}. At three (P<0.001; LSD: 0.077), four (P<0.001; LSD: 0.085) and five (P<0.001; LSD: 0.074) weeks the reduction in NDVI following the herbicide treatments increased to be comparable to the electric weed control applications. By week six (P<0.001; LSD: 0.087) the NDVI of the single application electric weed control treatments had increased, indicating plant regrowth. This was not observed in the double application treatments. The effect of application speed was also visible with lower NDVI values observed in both the single and double application electric weed control treatments at 2 km h^{-1} compared to their 4 km h^{-1} counterparts. However, the reduction in NDVI following the application of the electric weed control treatments remained comparable to the herbicide treatments, except when applied as a single application at 4 km h^{-1}.

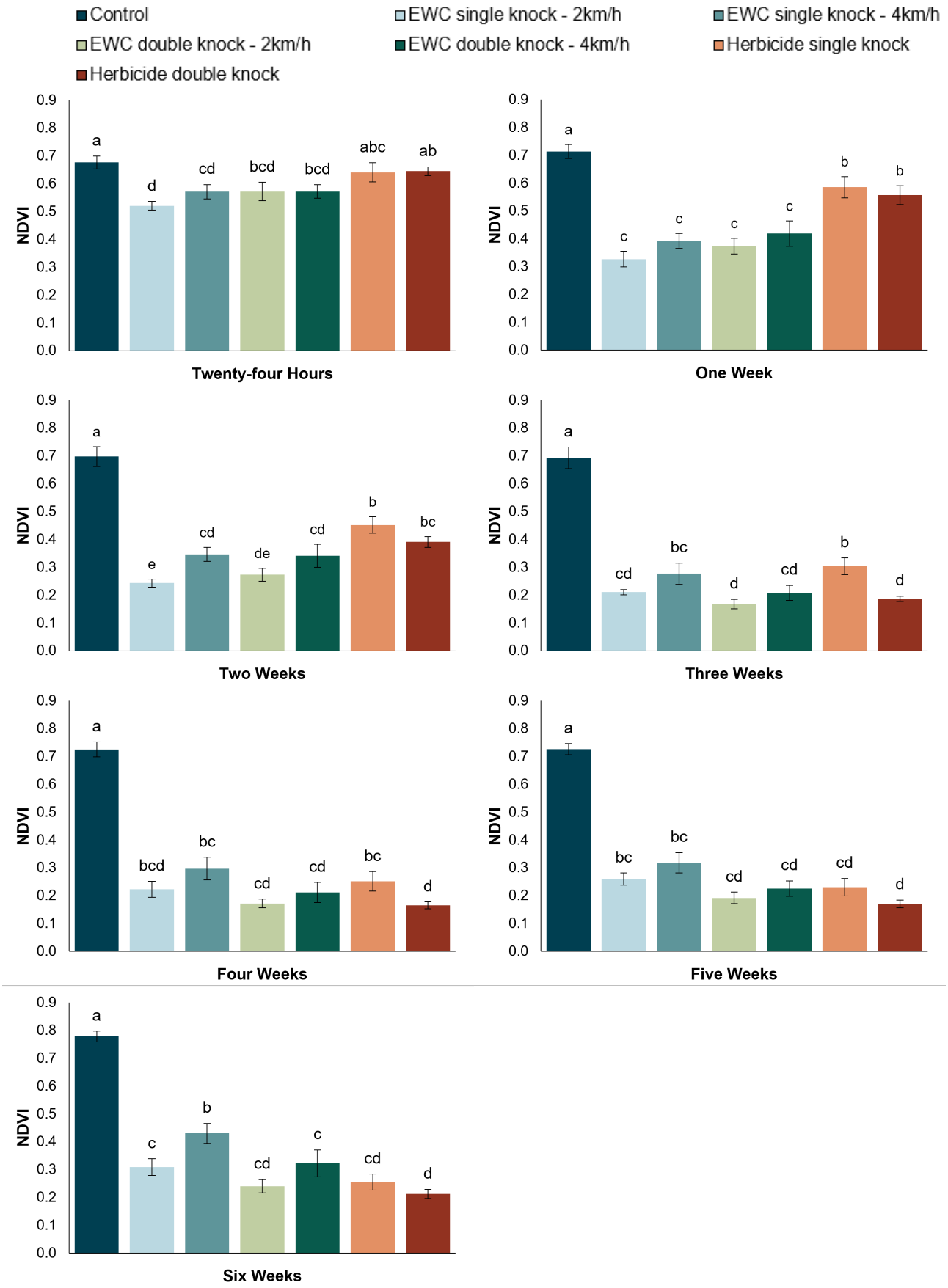


Figure 34. Effect of single or double electric weed control (EWC) or herbicide applications on normalised differential vegetation index (NDVI) of the weed population at the Northam trial site at various times after treatment (n = 6; mean ± s.e.). Bars annotated with the same letter have means not significantly different within the sampling time at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test.

Visual assessment of percent weed control (Figure 35A) showed that all treatments had significantly fewer weeds than the untreated control treatment with the best control observed following the single and double application of herbicide (P<0.001, LSD: 18.33). These findings were mirrored in the dry weed biomass (Figure 35B, P<0.001, LSD: 40.62). However, the difference between the herbicide and the double application of electric weed control was minimal. Weed biomass following a single application of electric weed control at 4 km h^{-1} was greater than all other weed control methods, although still lower than the control.

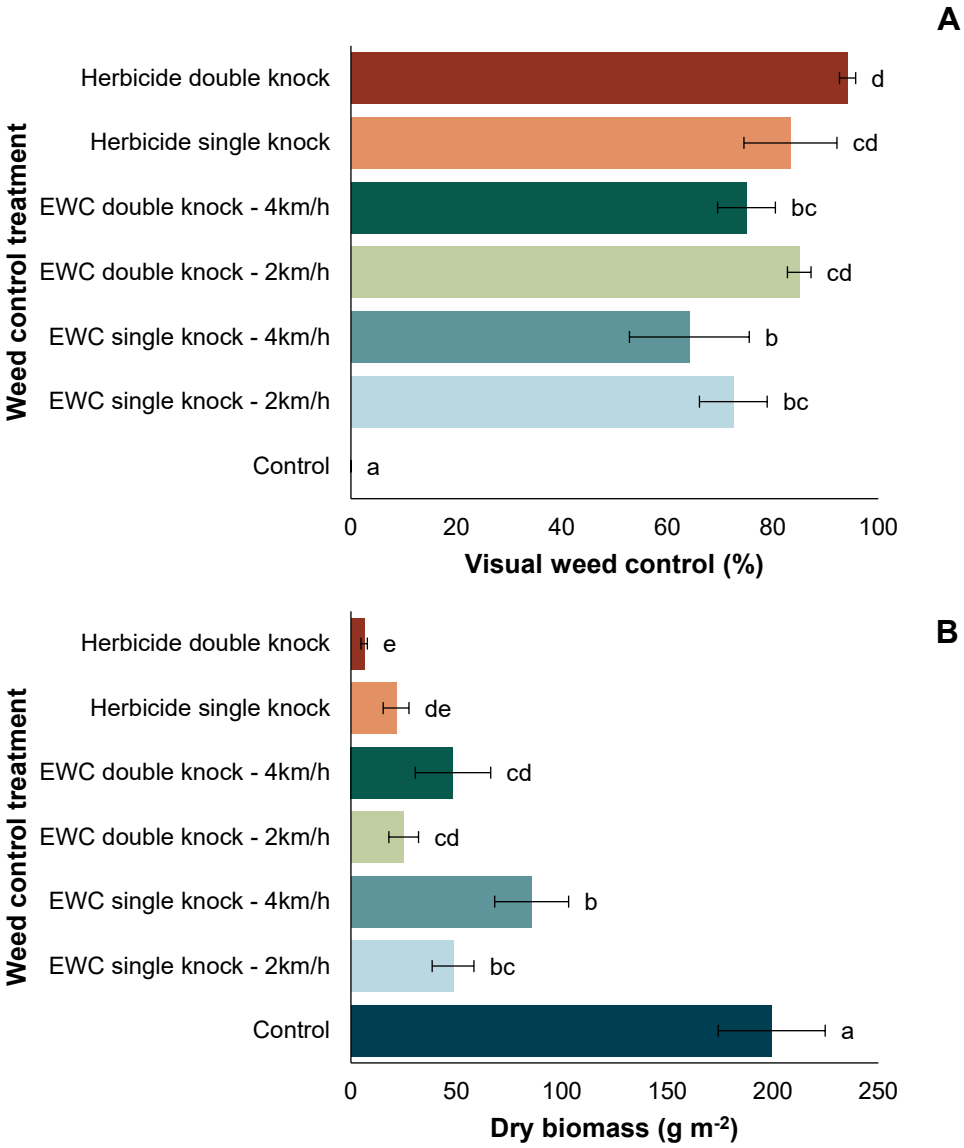


Figure 35. Effect of single or double electric weed control (EWC) application at 2 or 4km h^{-1}, or of herbicides, on percent control (A) and the dry shoot biomass (B) of the weed population at the 2023 Northam trial site (n = 6; mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P=0.05 according to a one-way post-hoc Fisher's Unprotected LSD test performed on the data. Note that a square root transformation was applied to the weed dry biomass data to normalise residual distribution prior to analysis.

As in 2022, cape tulip remained a difficult species to control. The weed control treatment applications resulted in smaller bulbs than in the untreated control (Figure 36). The visual assessment of bulb status (live or dead) in the lab indicated that applications of electric weed control and herbicides had significantly less live cape tulip bulbs when compared with the control (Table 32). Further analysis of cape tulip bulbs is continuing into 2024 to determine their ability to regrow in the subsequent season and the vigour (biomass) of the plants.

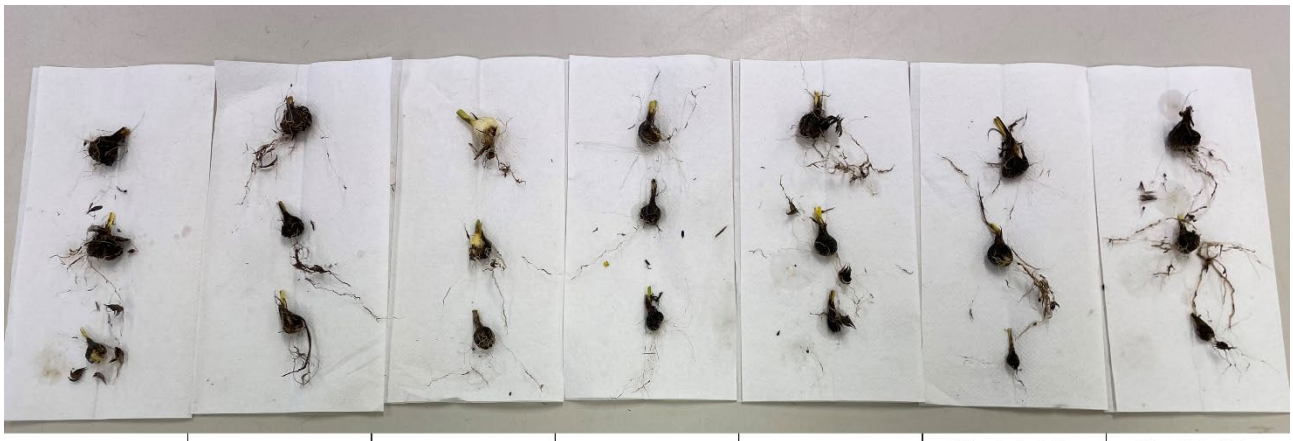


Figure 36. Cape tulip bulbs six weeks after the application of weed control treatments at the 2023 Northam site were smaller than those in the untreated control.

Table 32. The mean number of cape tulip bulbs per cluster (out of twelve bulb clusters per treatment) that appeared to be alive six weeks after the application of the weed control treatments.

Treatment	Live bulbs
Control	3.53
EWC single at 2 km h^{-1}	1.81
EWC single at 4 km h^{-1}	2.13
EWC double at 2 km h^{-1}	2.44
EWC double at 4 km h^{-1}	1.94
Herbicide single	1.63
Herbicide double	1.68
P (LSD)	<0.001 (0.624)

During the electric weed control applications, power output at the first application averaged 2720 or 2529 W inverter^{-1} s^{-1} at 2 or 4 km h^{-1}. On the second application, power output averaged 2057 and 1923 W inverter^{-1} s^{-1} at 2 or 4 km h^{-1}.

All applications of electric weed control had less weeds (lower NDVI values) compared with the control but varied over time (Figure 37). The NDVI of the control increased over time, due to continued growth of the ryegrass during the season. Twenty-four hours after the first application, there was no difference between the weed control treatments and the control (P: 0.265). However, all weed control treatments significantly reduced NDVI at one (P: 0.026; LSD: 0.084) and two (P<0.001; LSD: 0.093) weeks after the first application. After three (P<0.001; LSD: 0.074) and four weeks (P<0.001; LSD: 0.078), all weed control treatments continued to be effective, although control was reduced following the single application of herbicide. In weeks five (P<0.001; LSD: 0.064) and six (P<0.001; LSD: 0.077) the single application treatments began to show slight evidence of regrowth with an increase in NDVI. However, this did not occur for the double application electric weed control or herbicide treatments.

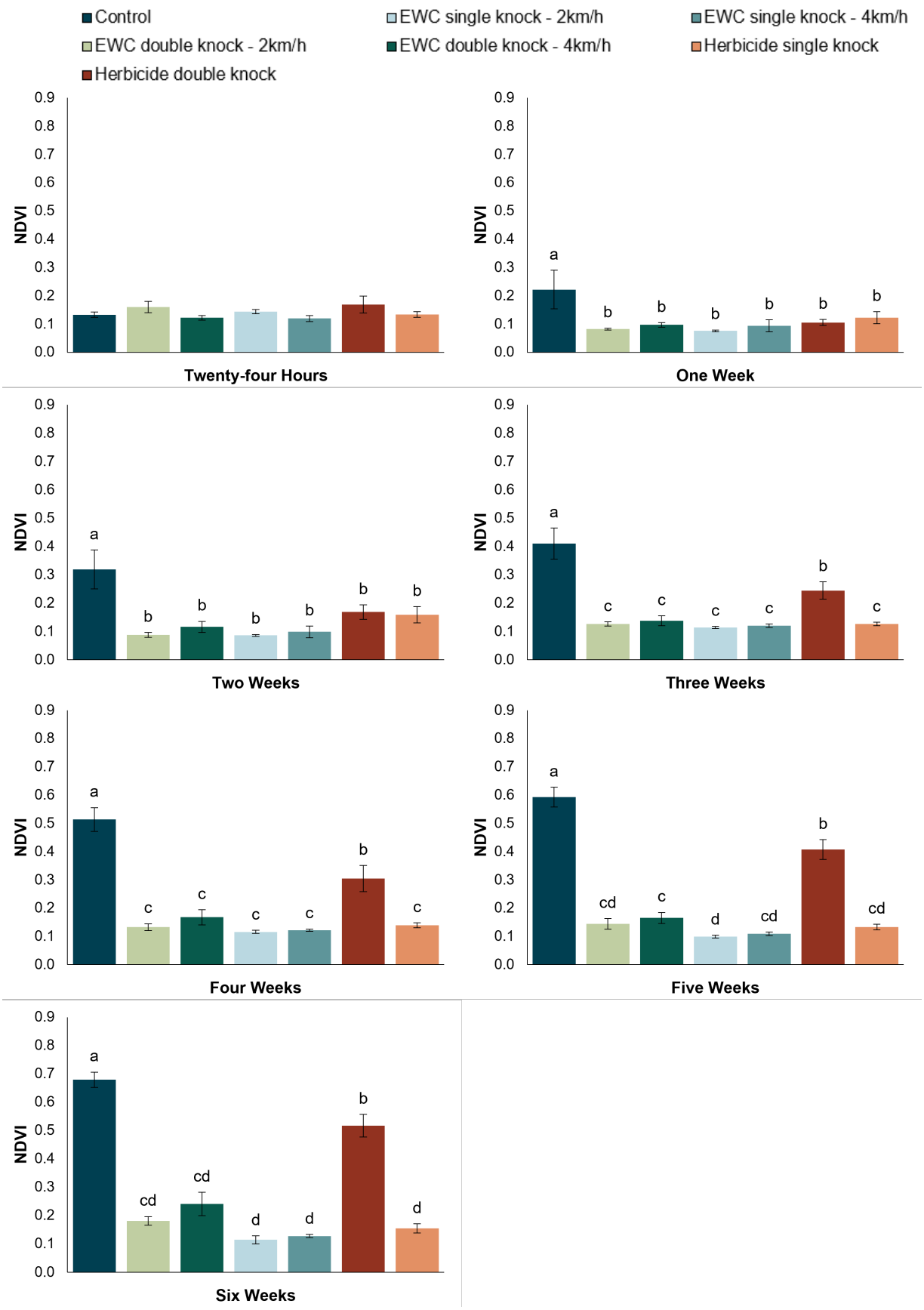


Figure 37. Effect of single or double electric weed control (EWC) or herbicide applications on normalised differential vegetation index (NDVI) of the weed population at the DPIRD trial site at various times after treatment (n = 6; mean ± s.e.). Bars annotated with the same letter have means not significantly different within the sampling time at P: 0.05 according to a two-way post-hoc Fisher's Unprotected LSD test. Unannotated sampling times had no significant differences.

Visual assessment of percent control and biomass of the weeds at the completion of the experiment indicated best control from electric weed control treatments and a double herbicide application (Figure 38). However, the single application of herbicide (glyphosate) was ineffective, likely due to herbicide resistance. Therefore, resistance testing for this ryegrass seed was performed and determined high resistance to group 1, 2 and 9 herbicides (Table 33). Therefore, electric weed control was highly effective at controlling herbicide resistant weed populations.

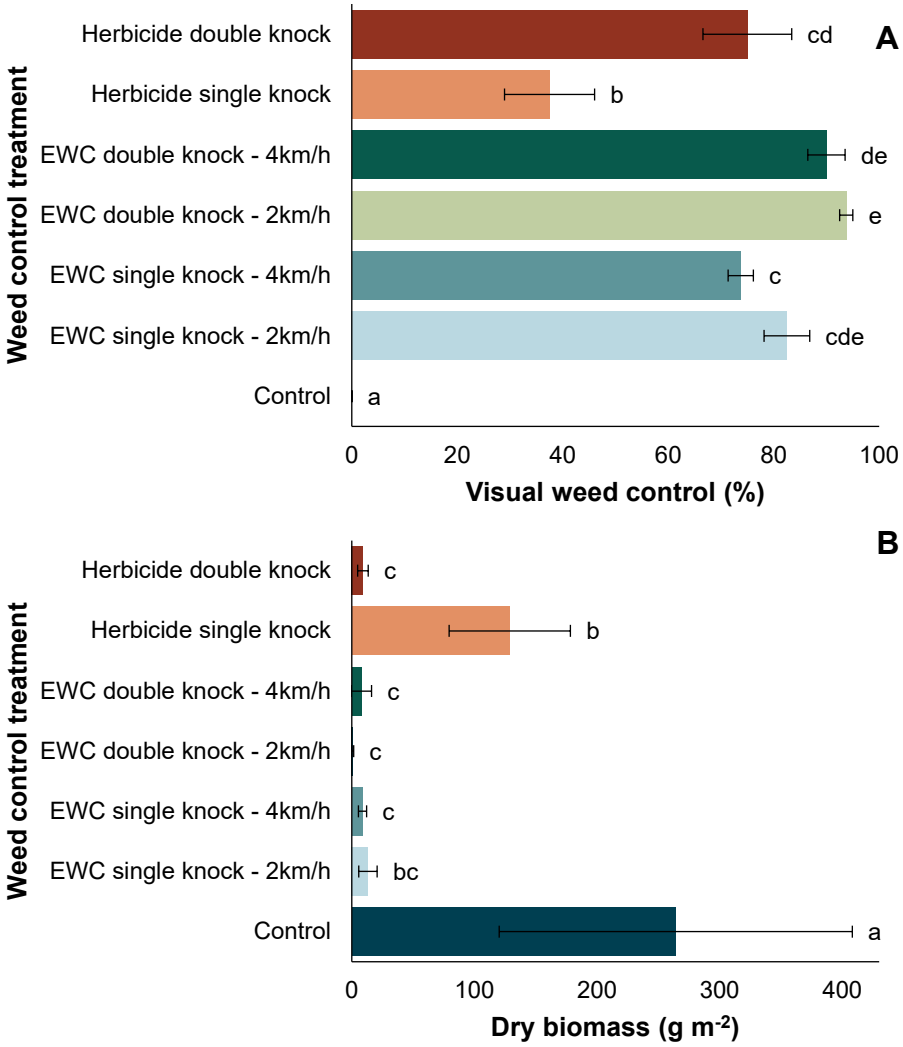


Figure 38. Effect of single or double electric weed control (EWC) applications at 2 or 4km h^{-1} on percent control (A; P<0.001, LSD: 15.01) and the dry biomass (B; P<0.001, LSD: 116.0) of the weed population at the 2023 DPIRD trial site (n = 4; mean ± s.e.). Bars annotated with the same letter have means that were not significantly different at P: 0.05 according to a one-way post-hoc Fisher's Unprotected LSD test performed on the data.

Table 33. Annual ryegrass herbicide resistance results determined 3 weeks after herbicide application. Data recorded as a percent of plant survival as compared to untreated plants.

Herbicide	Herbicide group	Herbicide resistance	
		Survival (%)	Rating
Clethodim 0.35 L ha^{-1} + 1% Hasten	Group 1 - DIMS	15	R
Clethodim 0.5 L ha^{-1} + 1% Hasten	Group 1 - DIMS	0	S
Clethodim 1 L ha^{-1} + 1% Hasten	Group 1 - DIMS	0	S
Decision 1 L ha^{-1} + 1% Hasten	Group 1 - Fops	100	RRR
Intervix 750 mL ha^{-1} + 1% Hasten	Group 2 - Imidazolinones	90	RRR
Glean 20 g ha^{-1} + 0.2% BS1000	Group 2 - Sulfonylureas	100	RRR
Trifluralin 1.5 L ha^{-1} + Boxer Gold 2.5 L ha^{-1}	Group 3 - Dinitroanilines	0	S
Trifluralin 1.5 L ha^{-1}	Group 3 - Dinitroanilines	10	R
Trifluralin 3 L ha^{-1}	Group 3 - Dinitroanilines	0	S
Glyphosate 1.67 L ha^{-1} + Clethodim 500 mL ha^{-1} + 1% Hasten	Group 9 - M	0	S
Glyphosate 1 L ha^{-1}	Group 9 - M	100	RRR
Glyphosate 2 L ha^{-1}	Group 9 - M	100	RRR
Glyphosate 2 L ha^{-1} followed by Paraquat 2 L ha^{-1}	Group 9 - M	0	S
Glyphosate 3 L ha^{-1}	Group 9 - M	100	RRR
Glyphosate 4 L ha^{-1}	Group 9 - M	100	RRR
Boxer Gold 2.5 L ha^{-1}	Group 15 - Group J	0	S
Sakura 118 g ha^{-1}	Group 15 - Group K	0	S
Sakura 118 g ha^{-1} + Trifluralin 1.5 L ha^{-1}	Group 15 - Group K	0	S
Paraquat 1.2 L ha^{-1}	Group 22 - L	35	RR
Paraquat 2 L ha^{-1}	Group 22 - L	0	S
Factor 180 g ha^{-1} + 1% Supercharge	Group 1 - DIMS	0	S

Mapping variable current application during electric weed control treatments

The XPower electric weed control machine used to complete the trials in this DPIRD project utilises variable power output. This means that the power applied during the treatment varies depending on the resistance of the weeds being treated (Vigneault & Benoit, 2001). This is mainly influenced by the amount of weed biomass, but also the weed morphology and anatomy, population structure and soil conditions (reviewed by Slaven et al., 2023a). As the power output varies, it is also likely that the fuel consumption may be affected with increased power output potentially leading to increased fuel usage. However, these effects have not been researched. The XPower records the electrical output every second of the application, along with the GPS location. Therefore, this data can be used to determine how the weed biomass effects the electrical current drawn from the XPower machine during electric weed control applications at constant application speeds. Further, it can be used to create a map of weed resistivity which could aid in the precision management of weed populations.

2023 Experiments:

Key findings

- Visual analysis of the power output during the electric weed control application highlighted that variation occurred depending on the weed biomass present (illustrated by the NDVI).
- Statistical correlation was not determined due to issues with the geographic reference system used by the XPower machine. Discussion is continuing to rectify the analysis.

Aim

To determine if the weed biomass effects the wattage of electrical current drawn from the XPower machine during electric weed control applications at constant application speeds.

Method

Two field trials were conducted to address this aim using the 2023 field trial sites from '*Apply electric weed control to fence lines or roadsides*'. At these sites, weed control treatments were applied as detailed in Table 31 to artificially create varying levels of weed biomass. Six weeks after the first of those treatment applications, drone photography for multi-spectral image analysis and biomass samples of each site were taken. Electric weed control was then applied to the whole trial area as in Table 34.

Table 34. Details of the electric weed control treatment applied in the following experiments.

Name	Northam 2023	DPIRD 2023
Location	Avon Valley Pony and Show Jumping Club (-31.64074, 116.65705)	DPIRD Northam's Field Research Station (-31.65136, 116.69840)
Applicator	XPU (36 kW)	XPU (36 kW)
Trial area (m^2)	1875 (75 m x 25 m)	1365 (65 m x 21 m)
Application speed (km h^{-1})	2.0 ± 0.0	2.1 ± 0.0
Volumetric soil moisture (%)	15.8 ± 1.3	30.5 ± 1.6
Dry residue loading (kg ha^{-1})	937.0 ± 412.3	297.2 ± 56.3
Fuel usage (L ha^{-1})	10.95	10.00
Measurements	Prior to treatment application: • Background soil analysis (CSBP standard soil test - https://csbplab.com.au/tests/soil/soil-standard) • Average soil volumetric water content (%) to 12 cm • Background average dry residue loading • Dry biomass (average grams from two quadrats of 50 x 50 cm per plot and additional from the buffer zones) • Drone NDVI photograph (P4 Multispectral DJI Drone) During treatment application: • XPower machine power output data	

	• Overall fuel usage

Results

Northam 2023

At the 2023 Northam trial site, NDVI was highly variable in response to the weed control treatments applied in '*Apply electric weed control to fence lines or roadsides*' (Figure 39). This highlights that the weed biomass was reduced following the treatment applications compared to in the control plots and buffer areas. This is supported in the data (Table 35) which indicated a progressive increase in weed biomass with the NDVI, except when the average biomass was abnormally high for the 0.6 – 0.7 NDVI range. This irregularity was likely due to the lack of sample replications that fell within this range.

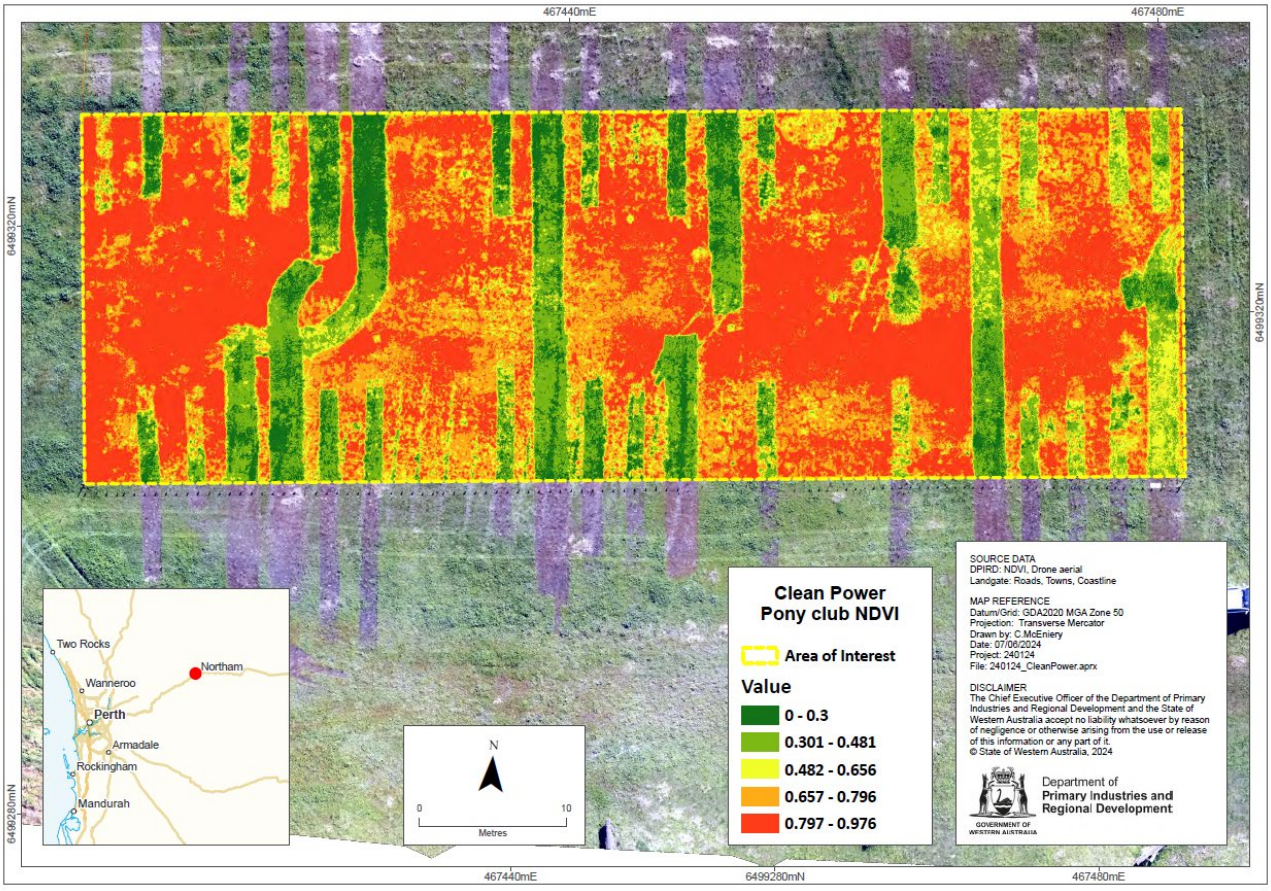


Figure 39. Normalised differential vegetation index (NDVI) of the 2023 Northam trial site as determined through P4 Multispectral DJI Drone photography.

Table 35. Weed biomass (mean ± s.e.) per range of the normalised differential vegetation index (NDVI) of the 2023 Northam trial site.

NDVI Range	Weed biomass (g m^{-2})
0.2 – 0.3	9.46 ± 1.78
0.3 – 0.4	32.24 ± 6.37

0.4 – 0.5	53.59 ± 12.99
0.5 – 0.6	78.34 ± 18.51
0.6 – 0.7	214.16 ± 11.12
0.7 – 0.8	161.39 ± 21.80
0.8 – 0.9	226.00 ± 44.43

During the electric weed control applications in this trial, power output averaged 2633 W inverter^{-1} s^{-1} and ranged from 1098 to 2850 W inverter^{-1} s^{-1} at an average application speed of 2.0 km h^{-1} (Figure 40). As expected from the information provided by the manufacturer, power output varied across the site. Initial visual analysis indicated that some of the areas of low-moderate power output overlap with areas where the biomass was artificially lowered with the weed control treatments applied in the 2023 field trial sites from '*Apply electric weed control to fence lines or roadsides*'. This indicates that the output was affected by the weed biomass present at the site.

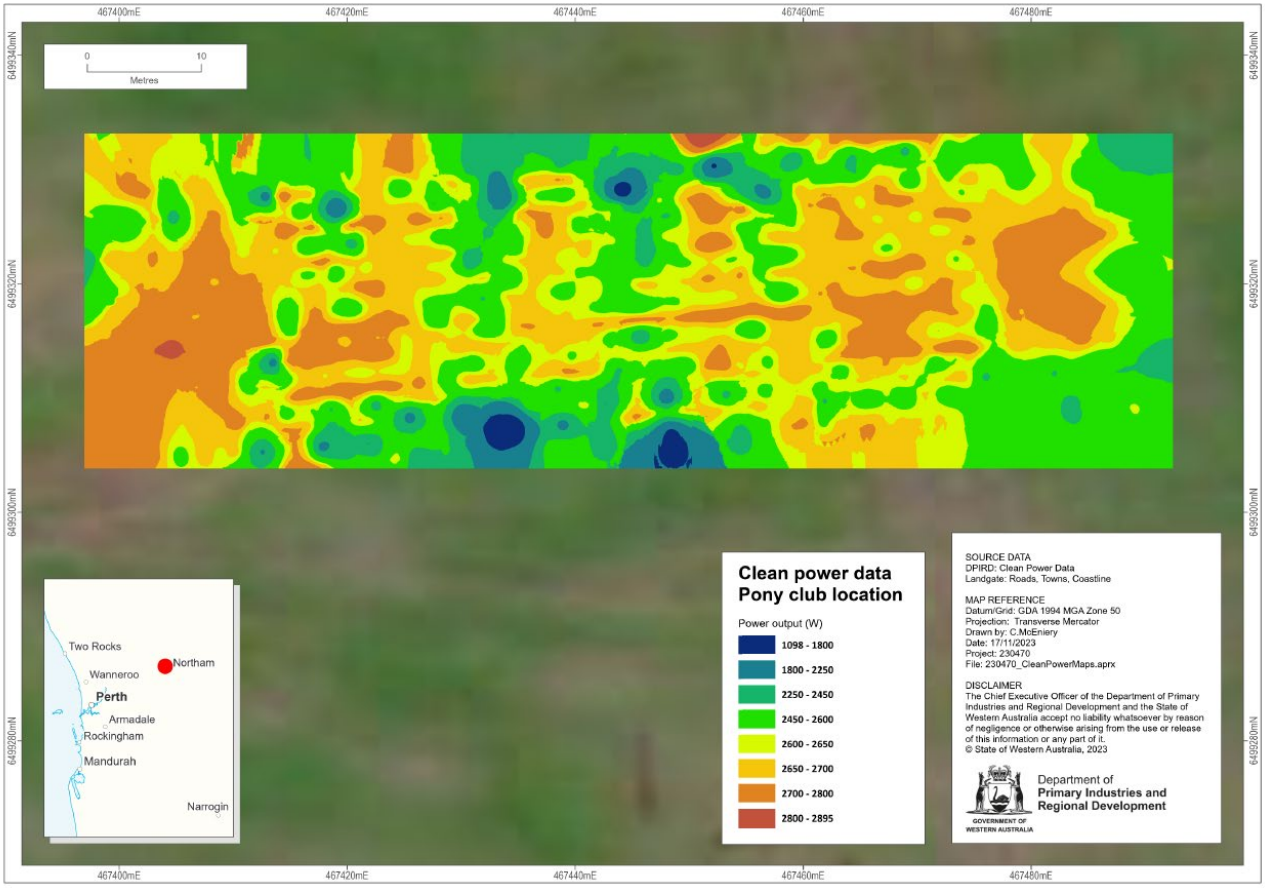


Figure 40. Variable power output of the XPower electric weed control machine at the 2023 Northam site as recorded by the machine at an average application speed of 2 km h^{-1}.

However, this visual trend could not be analysed due to an issue with the geographic reference system used by the XPower machine as it is designed for diagnostics and not for precision analysis. As the GPS antennae is located in the rear power output unit while the electrodes are in the front, there is a forward lag in data intake. The GPS antennae on

the machine is also only accurate within 2 m, creating additional variation. The combination of these two factors has meant that the NDVI and power output data are not overlayed correctly, hence the lack of correlation. Discussion is continuing with Zasso, CNH and GIS specialists to work to adjust data overlay.

DPIRD 2023

NDVI was also shown to be variable at the 2023 DPIRD site with reductions in biomass visible following the application of the weed control treatments of '*Apply electric weed control to fence lines or roadsides*' (Figure 41). At the trial, power output averaged 2805 W inverter^{-1} s^{-1} and ranged from 1746 to 2960 W inverter^{-1} s^{-1} at an average application speed of 2.1 km h^{-1} (Figure 42). As above, initial visual analysis indicates that the power output varied with some of the areas of low power output overlapping with areas where the biomass was artificially lowered. This is supported by a progressive increase in weed biomass with the NDVI (Table 36).

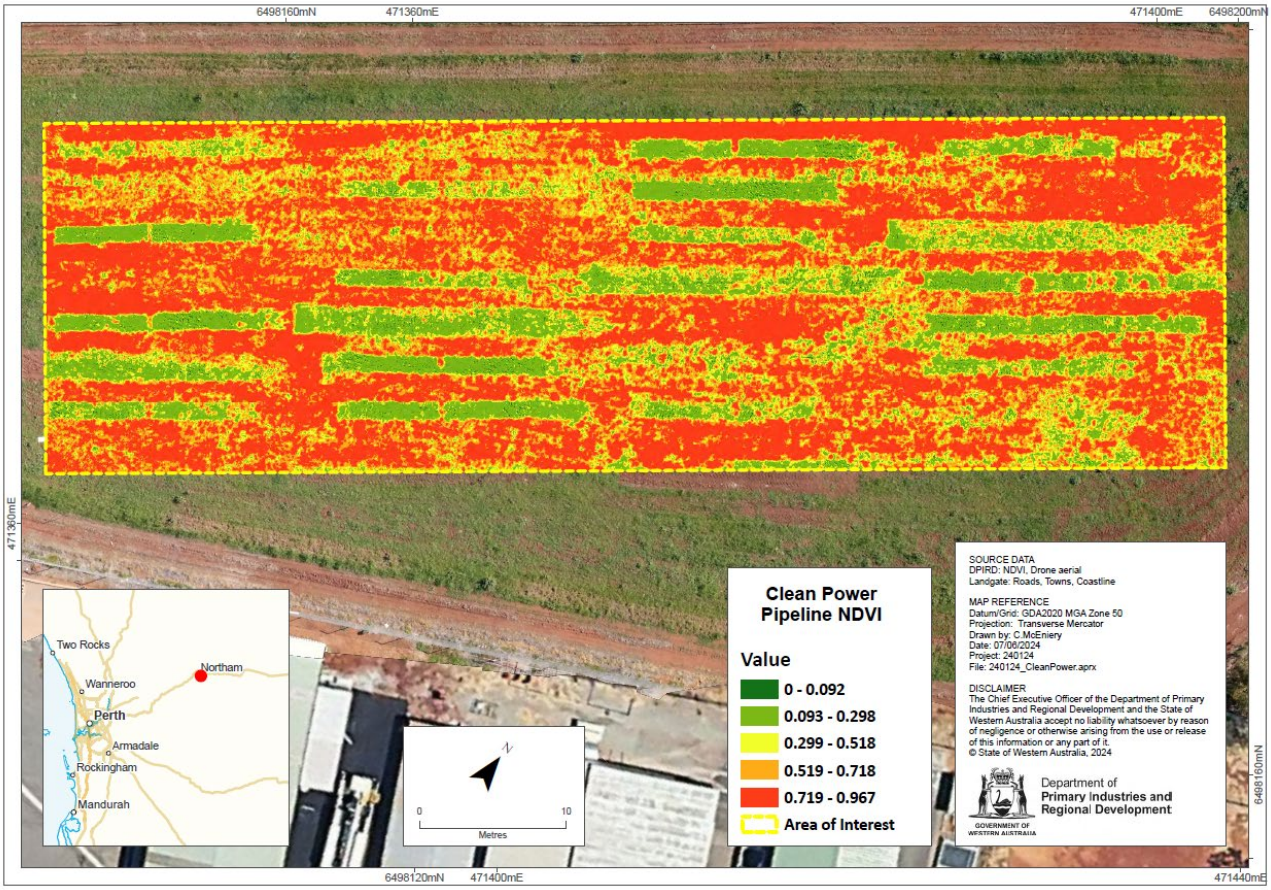


Figure 41. Normalised differential vegetation index (NDVI) of the 2023 Northam trial site as determined P4 Multispectral DJI Drone photography.

Table 36. Weed biomass (mean ± s.e.) per range of the normalised differential vegetation index (NDVI) of the 2023 DPIRD trial site.

NDVI Range	Weed biomass (g m^{-2})
0.1 – 0.2	0.41 ± 0.25

0.2 – 0.3	5.15 ± 1.38
0.3 – 0.4	13.26 ± 3.51
0.4 – 0.5	56.58 ± 20.82
0.5 – 0.6	36.75 ± 4.61
0.6 – 0.7	83.99 ± 23.49
0.7 – 0.8	147.10 ± 41.98



Figure 42. Variable power output of the XPower electric weed control machine at the 2023 DPIRD site as recorded by the machine at an average application speed of 2.1 km h^{-1}.

However, as at the Northam site, the NDVI and power output data could not yet be analysed, pending further data manipulation.

Economics of electric weed control

Patents for electric weed control have been issued since the 1890s, but it has historically been viewed as less cost-effective, more energy-intensive, and less efficient than conventional chemical or mechanical methods (reviewed in Vigneault et al., 1990). This view has occurred despite the potential benefits provided with minimum soil disturbance and no known reduction in soil health while also ensuring no chemical contamination of the soil, water, or air. Further, electric weed control applies to most areas where weed control occurs, including where herbicide use is restricted such as in organic farming or near waterways. Therefore, despite the historical drawbacks, there has been a recent resurgence of investment in the development of electric weed control machinery (e.g., the XPower, powered by Zasso™). However, the limitations of application speed, labour, and cost need to still be effectively studied on modern machinery.

The biggest impediment to the adoption of electric weed control in Australian grain cropping is the scale. Electric weed control application speed is comparatively slower than chemical applications (e.g., 1–4 km h^{-1} for the XPower) to ensure that sufficient voltage is applied per plant. In Australia, the average farm size of grain cropping enterprises is 4331 ha (Llewellyn et al., 2016). So, weed control at a low speed may not be logistically practical and labour will be a major economic consideration for electric weed control applications. However, there may be scope to combine the technology into fully automated agricultural systems.

2023 Analysis:

Key findings

- Applying electric weed control with the XPower with XPU applicator at 2 km h^{-1} was found to have a high application cost of \$210.55 ha^{-1}.
- While such applications may not be cost effective, they may be justified in certain situations where the value of controlling the weeds outweighs the cost of electric weed control. For example, when herbicide resistance is high, near waterways or irrigation channels where chemical use is restricted, or for organic growers.
- Alternatively, there may also be scope to combine the technology into fully automated agricultural systems which would reduce the application cost to \$85.55 ha^{-1}.

Aim

To determine the application cost of electric weed control using the XPower machine.

Cost of operation

Cost of application includes fuel use, labour, and machinery maintenance/depreciation. Cost of application was assessed in '*Mapping variable current application during electric weed control treatments*'. Application speed was 2 km h^{-1}. With the 1.2 m applicator width of using the XPower with XPU applicator at 2 km h^{-1}, 4.17 hours would be required to complete an application to a hectare.

Fuel: To determine the fuel requirement of the XPower, an engine fuel consumption gauge (SKU SFFM6060LKR, Scintex, www.scintex.com.au) flow meter was installed and used to monitor fuel requirement the trial site applications and fuel was calculated to be 10.48 L h^{-1}. Fuel cost was assumed to be \$1.96 L^{-1} of diesel. This value is the average of the current months' average fuel prices in the Wheatbelt region (FuelWatch, 2024). Therefore, fuel cost is \$85.6 ha^{-1}.

Labour: This cost was assumed to be \$30.00 per hour. The number of hectares applied per hour was calculated as: machine working width (m) × speed (km h^{-1}) / 10. Total labour cost was \$125 ha^{-1}.

The total application cost (\$/ha) was calculated as: (hourly labour cost + (fuel L h^{-1} × average fuel cost)) × hrs for 1 ha). Total cost: \$210.8.

Maintenance and depreciation: These costs were excluded from this analysis as there is insufficient literature available and a lack of published data on economic analysis to estimate a value.

Results: Current use patterns

Assuming labour and fuel, the costs associated with completing an electric weed control application at 2 km h^{-1} with the XPower machine were \$145.6.

However, this base cost is difficult to compare to herbicides. The cost of chemical weed control is the cost of the product ha^{-1}, and does not include labour, fuel or machinery maintenance/depreciation. However, obviously herbicide application has a low labour and fuel cost.

Given the cost of application, practical areas of use include:

- Problem areas where the value of controlling the weeds outweighs the cost of electric weed control. This can include fence lines in agronomic situations that are a

small area, with a limited number of herbicides that can be applied without killing desirable vegetation. Resistance development to key herbicides like glyphosate is also common on fence lines due to chemical overuse. An XPower UPU with a 1-3 m front is well designed for this use pattern.
- Areas where chemical weed control is not feasible. Chemical use is restricted near waterways, or in cotton irrigation channels.
- Small scale, high value crops, or for organic production.

Results: Future use patterns

There may be scope to combine the XPower technology into fully automated agricultural systems. Automated weed control technology is currently on ground in agronomic systems (i.e. automated sprayers) and is being trialled in a range of other systems (Yuan et al., 2023).

Electric weed control in a fallow or in row crops (i.e. cotton) will be easier to achieve once such a system is available and may reduce operating costs. For applications with the XPower, this would reduce the application by over half to $85.55. Blasco et al. (2002) developed a prototype of an autonomous machine and demonstrated its ability to control weeds in lettuce crops (species not defined). In the study, 84% of weeds with less than five leaves or less than 20 cm tall (multiple species) were accurately located, and 100% of located weeds were effectively controlled by 4 days after treatment. Commercially available machinery is also currently in development by RootWave in conjunction with Small Robot Company that utilises a weed-scouting robot, ‘Tom’, and a second electric application robot, ‘Dick’ (RootWave™, 2019; Carrington, 2021). The two robots communicate through the AI engine, ‘Wilma’, which plots the determined targets, allowing for effective control (Carrington, 2021).

Similarly, future fuel costs may be reduced by using electric vehicles powered by renewable energy in conjunction with this technology. While this may be around a decade or more away before being applicable to Australian growers, urban weed management by local governments is already looking to implement solar powered tractors within the next couple of years (personal communication).

It should be noted that the economic analysis was done using a prototype of the equipment, which has become obsolete over the two-year span of this project. Both the cost of machinery and the cost of application is reducing as the industry expands. Further, a range of new technologies fit for specific industries are being developed and released by Zasso™ and other companies, including the XPR for inter-row weed control, and a range of other products specifically designed for coffee, small crops, and fruit (Koch, 2022; Slaven et al., 2023b; Zasso™, 2024). These new configurations make application more practical and affordable.

Conclusions

Electric weed control was an effective weed management strategy. Control of broad leaf weeds was easier than grass weeds at higher operation speed. However, at the recommended speed, control of grass weeds was as effective as herbicide application even in the viticulture production system that contained mature, dense, wet plants (and wet topsoil), and where control should have been poor. There is an industry based 'understanding' that electric weed control would be less effective when surface soil moisture was high, and this was confirmed in 2023 when treating mature, dense annual ryegrass at 2 km h^{-1}. However, our research demonstrated that weed control in moist soils can be achieved with appropriate application speeds.

The level of control varies between weed species, as for any weed control technique. Plant age reduces control, as does high plant density or the tendency of plants to shade and protect smaller plants. For some species, electric weed control is superior to herbicide. For example, while both electric weed control and herbicide caused senescence of the above ground biomass of cape tulip plants, double applications of electric weed control were more likely to prevent growth of the bulbs in the subsequent year. More research is required to test electric weed control against a wider range of species, but this weed control technique is more versatile than most individual herbicides.

Electric weed control was successful at reducing weed biomass without affecting the soil biota. The soil microbiome was not affected by electric weed control in the viticulture trials or the trial on rhizoctonia. While the DNA sequencing used in the viticulture trials cannot categorically rule out damage to the soil microbiome (as the method can sequence both dead and live DNA), there was no change to the microbiome between sampling times. It is highly unlikely that no change would be observed between sampling times if the microbiome had been affected by weed control treatments. There was little direct impact on nematodes, although reduction in weed and root biomass can affect nematode populations in the long term. Rhizoctonia, which is physically attached to the weed roots, was not damaged by very slow and repeat application of electric weed control. No damage to the soil microbiome is good news for organic growers, such as in the viticulture industry.

This technology is not designed for inter-row weed control in broad acre crops, but our research has demonstrated that inter-row electric weed control does not damage the crop in the neighbouring rows. We trialled electric inter-row weed control in conditions designed to maximise crop damage, when the crop growth stage was at anthesis, and the surface soil was moist. Inter-row electric weed control applied to younger plants, with technology specifically designed for this use pattern, is likely to be a highly safe and effective form of in-crop weed control. However, further assessment with technology specifically designed for inter-row weed control is required to confirm these findings.

Fire risk from the machine was not evident in winter and spring. Fire risk when operating in completely dry residue (i.e., in summer or autumn) was much too high to allow use in these seasons in southern Australia as assessed in experimental conditions and on a viticulture estate.

Assessing the power applied during each experiment indicated that power varied due to weed presence (i.e., compared to bare ground). Further, weed density and speed of operation has been identified as valuable to examine. In 2023, analysis is occurring to determine the effect of weed biomass on the power output and fuel consumption of the machine. Analysis will also determine if this technology can be used to create a 'map' of weed incidence for future application in precision agricultural systems. However, further data manipulation is required before the analysis can be completed.

Applying electric weed control with the XPower with XPU applicator at 2 km h^{-1} had a high application cost of \$210.55 ha^{-1} with 10.48 L h^{-1} of diesel used. While such applications may not be cost effective, they may be justified in certain situations where the value of controlling the weeds outweighs the cost of electric weed control. For example, when herbicide resistance is high, near waterways or irrigation channels where chemical use is restricted, or for organic growers. Alternatively, there may also be scope to combine the technology into fully automated agricultural systems which would reduce the application cost by over half to \$85.55 ha^{-1}.

While research is ongoing, this project has demonstrated thus far that the XPS unit is a viable tool for spring weed control in Australian viticulture/horticulture and will find an immediate fit into these systems. Likewise, the XPU will contribute effectively to urban and industrial weed control in Australia.

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