A Comprehensive Guide to Electrical Weed Management

January 2024. Report number 01-2024 V1.1

Dr Charles N Merfield. MRSNZ
The BHU Future Farming Centre
Permanent Agriculture and Horticulture Science and Extension
www.bhu.org.nz/future-farming-centre

Live, like you'll die tomorrow;
Farm, like you'll live for ever.

Disclaimer

This report has been prepared by The BHU Future Farming Centre, which is part of The Biological Husbandry Unit Organics Trust. While every effort has been made to ensure that the information herein is accurate, The Biological Husbandry Unit Organics Trust takes no responsibility for any errors, omissions in, or for the correctness of, the information contained in this paper. The Biological Husbandry Unit Organics Trust does not accept liability for error or fact or opinion, which may be present, nor for the consequences of any decisions based on this information.

Copyright and licensing

© The Biological Husbandry Unit Organics Trust 2024. This document is licensed for use under the terms of the Creative Commons Public Licences Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) https://creativecommons.org/licenses/by-sa/4.0/. Any use of this document other than those uses authorised under this licence or copyright is prohibited.

Citation Guide

Merfield, C. N. (2023). A comprehensive guide to electrical weed management V1.1. The BHU Future Farming Centre Bulletin, 2024(1), 64. https://www.bhu.org.nz/future-farming-centre/information/bulletin/2024-v1/

About the author

Dr Charles 'Merf' Merfield is one of the world's leading thermal and physical weeding experts with over 30 years experience, including practical on-farm use, machinery design and research. His first experience with thermal weeding was flame weeding was in the late 1980's at Sunnyfields Organic in the UK with an Aeromatic-Barter open flame burner. Over the following 20 years he optimised the design of naturally aspirated flame weeders using both vapour and liquid fuel takeoff[1]. In the early 1990s, using the Lincoln University flame weeder (de Rooy, 1992), he developed post-crop-emergence selective thermal weeding based on plant morphology in crops such as beetroot, carrots and onions (Dastgheib *et al.*, 2010). He also re-invented the direct-fired steam boiler as part of his PhD and reconfigured it into a direct-fired steam weeder[2] (Merfield, 2006; Merfield *et al.*, 2009). This culminated in designing and building a six meter wide 1.2 megawatt steam weeder - the largest and most powerful steam weeder ever built. He has been following and working with electrical weed management since its revival in the mid 2010s (Merfield, 2016).

---

[1] https://www.physicalweeding.com/flameweeding/index.html

[2] https://www.physicalweeding.com/steamweeding/index.html

Table of contents

List of figures

Chapter 1. Introduction

1.1. Key points

- This report is a comprehensive guide to electrical weed management (EWM);
- This is in the context of the multiple challenges facing herbicides;
- And also within the context of integrated weed management (IWM);
- EWM can be a direct replacement for herbicides, including glyphosate;
- But, within IWM the use of EWM should be focused on ecological weed management and agroecology not just substituting EWM for herbicides.

This report is a comprehensive guide to electrical weed management (EWM). It is written for farmers, growers and other land managers, e.g., urban areas, as well as scientists and engineers working with EWM. EWM is considered a challenging technology as it requires an understanding of multiple, quite different disciplines including electrical engineering, agricultural engineering, botany, and farming. In particular it is the interaction of electricity with plant biology which is at the heart of EWM. Electrical engineering and botany are two very disparate sciences. Few people having a good understanding of both, so it is considered essential that specialists from both disciplines at a minimum need to be involved in EWM research. This report therefore aims to bring all the key disciplines and issues together and integrate them into a coherent whole.

1.2. The multiple challenges facing herbicides

The revival of EWM is within the context of the multiple challenges facing herbicide based weed management which include:

- Evolved resistance;
- No new herbicide Group (mode / site) of action discovered since the introduction of the ALS (inhibition of acetolactate synthase) herbicides in 1983;
- The high cost, length of time and difficulty of new pesticide development and registration;
- Withdrawal / prohibition of existing herbicides due increased scientific understanding of their negative impacts, and;
- Increasing consumer concern about pesticides as a whole.

These challenges led the then Editor of the world's leading weed science journal 'Weed Research' to posit the post-herbicide era (Marshall, 2010). With the multiple challenges facing herbicides a new direction for weed management is required.

1.3. The future - integrated weed management

The international weed science community is clear that the future of weed management is integrated weed management (IWM) (Riemens *et al.*, 2022). IWM is based on prioritising the non-chemical approaches of ecological, biological and physical weed management and reserving chemical weed management i.e., herbicides, as a tool of last resort. However, many non-chemical approaches are not as easy to use, reliable and effective as herbicides. In contrast EWM can be a direct substitute for herbicides. The most important herbicide that EWM can substitute for is glyphosate.

1.4. Electrical weed management as a substitute for herbicides including glyphosate

Glyphosate is unique among herbicides in that it is broad spectrum (kills all vascular plants) and is systemic (is translocated / moves though the whole plant including the roots) so kills the whole plant not just the foliage (Duke & Powles, 2008). EWM, like glyphosate, is broad spectrum (it kills everything), and is partly systemic (it travels from the plants foliage, through the hypocotyl and into the top of the root system before exiting into the soil (section Chapter 7)) so kills many plants outright. EWM can therefore be a direct replacement for glyphosate. By using different application approaches (section 8.6) it can also replace a range of other herbicides, e.g., selective herbicides.

With a growing number of companies producing an expanding range of electrical weeders, coupled with a increasing amount of independent research and practical experience of farmers and growers validating EWM's capabilities, EWM is therefore considered to have an important, even vital, role in the future of weed management.

1.5. An ecological perspective of weeds

While integrated weed management (IWM) is the future of weed management it is important that ecological approaches are given the greatest emphasis within IWM if we are to address the global threats to society, such a biodiversity loss and climate breakdown. Agroecology (Gliessman, 2014) and ecological weed management (Liebman *et al.*, 2001) take a different perspective to intensive agriculture as to what is a weed. The view of intensive agriculture is that all non-crop plants are weeds and should be eliminated. However, most non-crop plants / species do not harm the crop, in terms of reducing yield, contaminating harvest and so on. Rather, the opposite is often true, non-crop plants can provide multiple benefits such as stabilising yield, reducing the dominance of harmful weeds, and providing a wide range of ecosystem services such as soil health, biodiversity, pest management and supporting pollinators (Jordan & Vatovec, 2004; Ziska & Dukes, 2010; Adeux *et al.*, 2019). Eliminating all non-crop plants is therefore often counter productive. This in turn has led to a redefining of weeds to "…plants causing significant harm…" with non-harmful, non-crop plants called "*aliae plantae*" (other plants) (Merfield, 2022). It is thus important to use EWM within a whole-of-system, agroecological and ecological weed management perspective, not an intensive agricultural mindset.

Ecological weed management and agroecology are also whole-of-system approaches. This includes the 'Many Little Hammers' concept (Liebman & Gallandt, 1997) whereby the 'sledgehammer' of a small number of herbicide applications is replaced by a multitude of 'little hammer' interventions starting with farm system design, rotations, pre and well as post crop planting weed management techniques and minimising weed seed rain (Merfield, 2019).

While EWM has the potential to be a direct substitute for herbicides EWM cannot replace all herbicides in all situations, by a considerable margin. Intensive agriculture permitted the compartmentalising of agriculture that came with the pesticides and mineral fertilisers. If EWM is used in such a mindset it is considered unlikely to reach it's full potential.

This report is consequently written from an agroecological / ecological weed management and whole-of-system perspective.

Chapter 2. Electrical weed management - nomenclature

2.1. Key points

- There is no standardised nomenclature for EWM with many terms used;
- Electrical weed management (EWM) is proposed as the best overarching term;
- Electrothermal and electrobiological are proposed as the two main sub-divisions within EWM;
    - Electrothermal is defined as heating the plants to lethal temperatures;
    - Electrobiological is defined as not heating plants to lethal temperatures, rather, it causes lethal changes to the plants' biochemistry and/or physiology.

Electrical weed management (EWM) does not have a standardised nomenclature. Names that have been used include: electrothermal, electroweeding, electrophysical, electrocution, electricide, digital herbicides, and electrotechnology. In addition there are multiple descriptions of the different forms of electricity used, e.g., high frequency AC voltage, high frequency electricity, pulsed high voltage discharges, micro electric shocks, electric pulse discharge, pulsed arc discharge, electrostatic fields, electrical discharges, electric shocks, and electro impulses.

Electrical weed management (EWM) is proposed as the preferred terminology, as it has the same linguistic structure as integrated weed management (IWM). 'Weed management' is preferred to 'weed control', the control of weeds having long been abandoned by the weed science community (Naylor, 2002).

In this report 'electrothermal' will be used to differentiate EWM approaches where the electricity heats water in the plants, typically to boiling point, destroying the plant tissues and 'electrobiological' where the electricity energy is insufficient to cause significant heating, instead the electricity disrupts the plants biological systems (Chapter 6). EWM is thus the overarching term for both electrothermal and electrobiological. The term 'electrical weeder' is used when discussing both electrothermal and electrobiological weeders.

Chapter 3. A brief history of electrical weed management

3.1. Key points

- EWM, in the form of electrothermal, was first developed and patented in the late 1800s;
- It was only in the 1970s-80s that significant amounts of research occurred, along with the first commercial machine - the Lasco lighting weeder;
- However, EWM lost out to herbicides, particularly the relatively new glyphosate and weed wipers;
- With the challenges now facing herbicides, the time is now considered ripe for ongoing research, development and commercialisation of EWM.

EWM and more specifically electrothermal, is a form of thermal weeding. Thermal weeding is probably one of the most obscure, even esoteric, branches of non-chemical weed management, itself a niche sub-section of weed management and science. Thermal weeding uses heat or cold to kill or reduce plant biomass. Apart from ionising radiation (due to its inherent danger), all possible thermal approaches have been tried. These includes open flame, infrared light, steam, hot water, lasers, electrothermal microwaves, ultraviolet light, focused sunlight, dry ice, and liquid nitrogen. Most have been found wanting on economic, practicality and/or safety grounds. Of those that are viable, flame weeding has been the dominant form, mostly being used in direct-sown organic vegetables and some row crops. Steam weeders are gaining ground, particularly for urban areas and perennial crops. Lasers were first tested in the early 1970s but looked for many years to be of research interest only. It is only in the last few years that they have become a viable tool as part of Level 3 robotic weeders (Merfield, 2023a).

The first electrothermal weeder patent was in 1893 then another 1895 with a range of further patents over the following decades (see Bloomer *et al.*, 2022, for a detailed list). However, little came of electrothermal until the 1970-80s when there was a pulse of research in Europe, the United States and the Soviet Union (Diprose & Benson, 1984a; Diprose & Mattsson, 1993), (Figure 1) with the first commercial machine, the Lasco Lightning Weeder coming to market, (Figure 2).

Figure 1. British Sugar Corp electrothermal weeder developed by Dr Mike Diprose in the 1970s and 1980s. Photos Dr Mike Diprose.

Figure 2. Lasco Lighting Weeder 1980s. Photos Lasco via Dr Mike Diprose.

Most of these weeders were based on killing weeds overtopping the crop, though other approaches, such as replacing the hoes in interrow hoes with electrodes were also trialled, along with non-agricultural uses such as clearing scrub and on railway tracks, Figures 3 to 5.

Figure 3. Electrothermal interrow hoe. Photos Lasco via Dr Mike Diprose.

Figure 4. Railway weeding system. Photos Lasco via Dr Mike Diprose.

Figure 5. Large self-propelled weeder for scrub control. Note driver is wearing a Faraday suit. Photos Lasco via Dr Mike Diprose.

While effective, and economic over larger areas, electrothermal weeders were competing with herbicides, including the relatively new glyphosate (sold as Roundup® by Monsanto) which came to market in 1974 (Duke & Powles, 2008). Weed wipers (Harrington & Ghanizadeh, 2017) were also newly developed which killed crop-overtopping weeds in the same way as the main electrothermal machines of that time. While there was growing concern about negative non-target impacts of pesticides, along with the first cases of evolved resistance (Heap, 2023), these were not at sufficient levels to make electrothermal more attractive, so its development was abandoned (Diprose *et al.*, 1980a).

Fast forward to the 21st century and the context is very different. Evolved resistance and the scientific evidence for the harms caused by herbicides continues to expand, resulting decreasing herbicide effectiveness, increasing legislative restrictions, and consumer resistance. Thus over a century after the concept was conceived the time is now considered ripe for EWM. This coupled with vastly improved electrical and electronic science and technology mean that EWM is now positioned to be a back to the future technology for weed management (Merfield, 2016). Chapter 11 details electrothermal weeders developed over the last two decades.

Chapter 4. Previous scientific reviews of electrical weed management

There have been a number of review papers and reports on EWM from the 1980s onwards. These are provided here for the reader wishing to get deeper and different perspectives of the technology and its development. In chronological order.

- The effect of externally applied electrostatic fields, microwave radiation and electric currents on plants and other organisms, with special reference to weed control (Diprose & Benson, 1984a);
- Electrical methods of killing plants (Diprose & Benson, 1984b);
- Energy aspects of weed electrocution (Vigneault *et al.*, 1990);
- Non-chemical weed control-trends in European practice-with special reference to electrical weed control (Diprose & Mattsson, 1993);
- Electrical weed control: Theory and applications (Vigneault & Benoît, 2001);
- Electrical weed control in the UK – the current situation (Diprose *et al.*, 2009);
- Desk Study: Electrical weed control in Field Vegetables (Reed, 2009);
- An economic assessment of electric weed control and comparable alternatives (ADAS UK Ltd., 2014);
- Exploring the potential of electric weed control: A review (Slaven *et al.*, 2023).

Chapter 5. Energy, power and electricity basics

5.1. Key points

- A basic knowledge of the physics of energy, power and electricity are required to understand EWM;
- Energy comes in many forms (e.g., chemical and electrical) and is measured in joules (J);
- Power is the ability to do work. It is one J per second and is measured in watts;
- Electricity's main two forms are direct current (DC) and alternating current (AC);
- The frequency of AC is measured in hertz, with mains frequency electricity being the most dangerous;
- Using electronic control many more complex forms of electricity can be created, e.g., pulsed DC;
- Volts is a measure of the 'pressure' of electricity for both DC and AC;
- Amps (amperes) is a measure of electrical current (flow) for both DC and AC;
- Amps, volts and watts are related though the formula V × A = W. Electrothermal uses high volt, low amp systems;
- Electrical resistance is measured in ohms;
- A key issue in EWM is the decreasing resistance of plants during treatment;
- Electric refers to electrical equipment that transforms electrical energy into other forms of energy. Electronic equipment uses electrical energy to manipulate information. This is a key difference between the original weeders and modern designs.

Some basic information about the physics of electricity is vital to understand EWM and how to use it optimally.

5.2. Energy - joules

Energy is one of the most fundamental concepts in physics. The word come from Ancient Greek and means 'activity'. Some of the main forms of energy are:

- Kinetic energy of a moving object;
- Potential energy stored by an object, e.g., a ball at the top of hill;
- The elastic energy stored in a solid object;
- Chemical energy associated with chemical reactions;
- The radiant energy carried by electromagnetic radiation, such as light and heat;
- The thermal energy contained within an object, i.e., how hot it is, and;
- Electrical energy.

The law of conservation of energy states that energy cannot be created or destroyed, it can only be turned from one form to another. For example, the chemical energy in diesel can be turned into mechanical energy in an engine. However, while one form of energy can be transformed into another, most transformations are not 100% efficient, some of the energy is 'lost' as heat, i.e., thermal energy. For example the maximum efficiency of a diesel engine is around 55%[3], with the resultant heat dissipated through the cooling system. Thus transforming other forms of energy into heat is effectively 100% efficient, such as using electrical energy to heat a plant.

Energy is measured in joules (J). A joule at human scales is a very small amount of energy: that required to lift an apple (of mass 102 g) up 1 m. As a joule is so small, typically kilojoule (kJ) 1,000 J, and megajoule (MJ) 1,000,000 J are used. For example diesel contains 46 MJ per kg and 36 MJ per litre.

---

[3] https://en.wikipedia.org/wiki/Diesel_engine

The energy used by EWM, as well as other forms of thermal weeding, directly relates to the amount of fuel (typically diesel in a tractor) that is used. The lower the energy used the less fuel consumed and therefore the lower the running costs.

Calorie is an imperial unit of energy equal to 4.2 J. It is often used to denote the (chemical) energy content of food.

5.3. Work and power - watts

When energy (joules) is used to 'do work', i.e., power something, for example a light bulb, a domestic heater or a car engine, the amount of work produced is measured in watts (W). One W is one J per second, so it is also a tiny amount at human scales, so many common power sources are rated in kilowatts (kW) - 1,000 W. Some examples are: modern LED or fluorescent light bulbs are 10 to 20 W, a domestic heater is typically 2 kW and the 2023 basic Toyota Corolla internal combustion engine is 72 kW.

The imperial measure of power is horse power (HP) which is literally the amount of power generated by an average horse, defined as lifting 550 pounds by 1 foot in 1 second. One HP = 0.75 kW.

5.3.1. Kilowatt-hour

A kilowatt hour (kW h) is the amount of energy (joules) delivered by one kilowatt of power for one hour, which is 3,600 kJ. It is a non-scientific unit that is commonly used as a billing unit by electric power companies. It is also often used incorrectly.

5.4. Electricity

Electricity is where things start to become more complicated. However, for the purposes of EWM there are only a few key properties of electricity to understand.

5.4.1. Power

As a form of energy, electricity can power things, i.e., do work, such as turn an electric motor to convert the electricity energy to kinetic (motion) energy, or, to heat something up, like a cooking pot on a stove or heat a plant. The more power (watts) the faster the electricity can heat an item up, a 3 kW heater will heat a room three times faster than a 1 kW heater. Another example, a 50 kW tractor can plough a field just well as a 500 kW tractor, but the 500 kW tractor will be able to plough it ten times as fast (500 / 50 = 10) everything else being equal.

5.4.2. Current - AC:DC

The movement of electricity is its current, which is measured in amperes, commonly shortened to amps (A). Electricity can only flow through a conductor (e.g., a copper wire) and is stopped by an insulator (e.g., plastic). Using a water analogy, current / amps is equivalent to the flow of water (litres per minute) in a pipe: the bigger the pipe the more water can flow down it. Thus the larger the current, the more electricity is 'flowing'.

Current has two main forms: direct current (DC) and alternating current (AC). Direct current is a unidirectional flow, like water flows through a pipe, for example from the positive terminal on a battery to the negative terminal via some form of circuit, e.g., through a light bulb. Alternating current periodically reverses direction, i.e., it's polarity (positive and negative) flips back and forward, producing the 'classic' sine wave shown in Figure 6. This is akin to water pulsing backwards and forwards in a pipe.

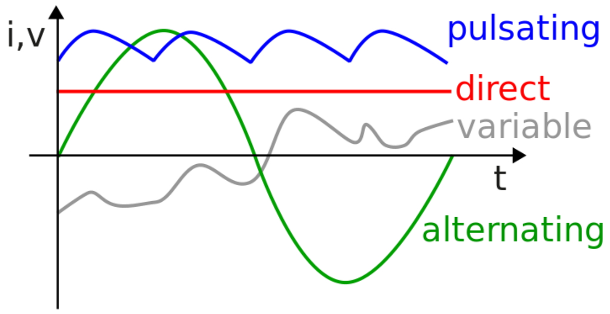

Figure 6. Different forms of electrical current. Source en.wikipedia.org/wiki/File:Types_of_current.svg

Beyond standard AC and DC, modern electronic control systems can create a highly diverse variety of forms of electricity, e.g., pulses of DC (Figure 6) and non-sinusoidal AC wave forms. A common example of pulsed electricity is electric fences which use very short duration (milliseconds) high voltage pulses (e.g., 5,000 V) interspersed by longer periods (seconds) where there is no current. Pulsed forms electricity are proving important for advanced EWM (section 8.8).

5.4.2.1. Alternating current frequency - hertz

For AC the frequency at which the current reverses polarity is measured in hertz (Hz). The electrical systems in most countries run at 50 to 60 Hz for reasons to do with the design of alternators (AC electrical generators) and AC motors. It is also the most dangerous frequency as it blocks the electrical signals in nerves which causes muscles to lock up / become ridged. This includes the heart (which is 'just' a muscle) where the interference of the nerve signals causes it to stop beating and thus cause death. Much higher frequencies, i.e., thousands, to tens of thousands of hertz, do not interfere with nerve signals so pose a low to no risk in terms of causing muscles to lock up. The energy contained in high frequency electricity can still however cause other damage, such as significant tissue heating, e.g., an internal burn.

5.4.2.2. Current 'flow' and 'movement'

With DC current the electricity, or more precisely the electrons, move / flow through the circuit. It is thus correct to talk of positive and negative terminals.

As AC current is constantly reversing polarity the electricity / electrons, it is technical **incorrect** to say the electricity moves / flows through the circuit as the electricity is pulsing back and forward with the reversing polarity. Thus is also incorrect to talk of positive and negative terminals in an AC circuit, as the terminals are constantly changing polarity. However, within this report, for the sake of simplicity, and, to follow common language usage, AC circuits may be described as having positive and negative terminals, and also describe electricity as flowing in the circuit.

5.4.2.3. Electrical phases

Domestic AC electricity comes in a single 'phase', i.e., there is a single sine wave in the circuit (Figure 6). For higher power uses, three phase electricity[4] is used. This is where there are three AC sine waves out of sync (120 degrees out of phase) with each other (Figure 7).

---

[4] https://en.wikipedia.org/wiki/Three-phase_electric_power

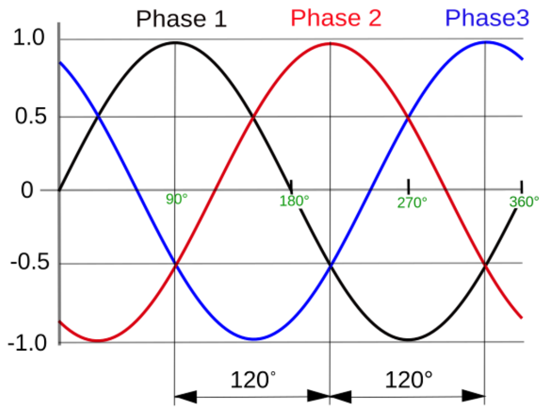

Figure 7. Three phase AC waveform. Source commons.wikimedia.org/wiki/File:3_phase_AC_waveform.svg

Three phase electricity requires the use of an additional wire, so a three phase circuit has four wires in total, one for each phase and one neutral.

Some newer electrothermal weeders are using multiple (polyphase) systems. These are not the same as standard 3 phase mains power. Using advanced electronic control systems, they may be using two or more phases. While there is no independent research on polyphase systems, that this approach has been used by commercial companies, indicates there are likely advantages to it.

5.4.3. Volts - pressure

Returning to the water analogy, while current (amps) is equivalent to the flow of water, the voltage (volts, V) is equivalent to the pressure of water. At higher voltages (pressure) more electricity can be ‘forced’ down a smaller conductor such as metal wire and plant stem. Continuing the water analogy, where a water pipe ends with a closed tap there is no flow of water (current / amps) but there is water pressure (volts). The same for electricity, in an open circuit there is no current (amps) but there is voltage, only when the circuit is closed, e.g., an electrode contacts a plant, does current flow.

5.4.4. Amps, volts and watts

Amps, volts and watts are related though the formula V × A = W. Thus a high voltage and low amperage circuit can have the same wattage (power) as a low volt high amp circuit. Electrothermal weeding systems use higher voltages e.g., 5 to 15 kV and low amps e.g., 1 to 5 A. Arc welders are an example of the opposite, using low voltage and high amps.

5.4.5. Resistance - ohms

Electrical resistance is measured in ohms (symbol Ω). Using the water analogy resistance is equivalent to the friction of water flowing down a pipe. Resistance is ‘managed’ in electrical circuits by having thicker wires, using materials with lower resistance / that are good conductors (e.g., copper) and/or increasing the voltage (pressure). Consequently low volt, high amp circuits, like a welder, need thick cables made of good conductors. High volt, low amp circuits, like electrothermal weeders, can use thinner conductors (cables) with very good insulation.

Resistance is a particular issue for electrothermal weeding as plants initially have a high resistance, then as the plant’s tissues and cells start to disintegrate, their resistance drops and they become moderate to good conductors, creating the problem of power sharing (section 8.6).

5.4.6. Path of least resistance

The concept of electricity following the ‘path of least resistance’ is not technically correct. Electricity follows all possible paths through the circuits available to it, but, the ‘amount’ of electricity following each path is inversely proportional to their resistance. This means that when the possible paths are of similar resistance the electricity will flow through all of them in similar amounts. Where one path is of very low resistance and another of very high resistance, then, most or all of the electricity will follow the low resistance path. This is of particular importance in electrothermal weeding in particular as it is the cause of power sharing (section 8.6).

5.4.7. Electrical circuit

With the exception of electrostatic fields (see below) for AC or DC electricity to be able to kill a plant it needs an electrical circuit[5] where the electricity can 'move' in a closed loop, where the plant forms part of the circuit.

5.4.8. Electrostatic fields

An electrostatic field (static electricity) is an electric field that is static in time, i.e., there is no electricity flowing. A field can be formed by placing two conductors apart from each other (i.e., not touching) and connecting to a voltage source, or one to a voltage the other to an earth (Diprose & Benson, 1984a). An example is the Van de Graaff generator which when touched by a person causes their hair to stand on end. Electrostatic fields are only used in long duration electrobiological weed control systems (section 6.2).

5.4.9. Electric vs. electronic

There is an important distinction between the terms 'electrical' and 'electronic'.

Electrical devices use the energy of an electrical current and transform it in simple ways into some other form of energy such as heat, for example a domestic oven[6]. Electronic devices use electrical energy to manipulate information, the computer being the archetypal example[7]. Electronics is a subset of electrics, more properly called electrical engineering[8].

The first and basic designs of electrothermal weeders were / are entirely electric. More recent / advanced designs have complex electronic systems controlling the electric circuits killing the plants.

These electronic systems allow approaches such as polyphase systems (section 5.4.2.3), sensing of step voltages (section 14.4), sensing of plant conductivity and altering current and voltage to match. Thereby significantly improving the efficiency and effectiveness of the weeders, thus reducing the amount of power used, and/or increasing the treatment speed and size of the machines. The disadvantage of electronic controlled weeders is complexity, cost and size of the power generation and electronic control systems.

Where this report uses the term 'electrical weeder' (Chapter 2) this includes both weeders that only use electrical systems and those that use both electronic and electrical systems.

---

[5] https://en.wikipedia.org/wiki/Electrical_network

[6] https://en.wikipedia.org/wiki/Electricity

[7] https://en.wikipedia.org/wiki/Electronics

[8] https://en.wikipedia.org/wiki/Electrical_engineering

Chapter 6. Types of electrical weed management

6.1. Key points

- Electrothermal EWM heats plants to lethal temperatures, typically water's boiling point, causing catastrophic destruction of plant tissues;
- Electrobiological heats plants by a few degrees, if at all, with the details of the mode of action unknown, but, likely to be interfering with the plants biochemical systems and/or physiology;
- Electrothermal is the main focus of this report;
- Most electrothermal treatments are short durations — milliseconds to tens of seconds;
- Most electrobiological treatments are long duration — hours at a minimum, through weeks, to permanent installations;
- However, a new short duration electrobiological approach holds the potential for exceptionally low energy use and potentially solving some of the issues with electrothermal of not being able to reach plant organs required to achieve complete plant death.

The first electrothermal weeders killed plants by heating them with high voltage electricity. Today there are an increasing diversity of approaches. This report proposes the twin concepts of 'electrothermal' and 'electrobiological' and differentiates between short vs. long duration treatments.

6.2. Electrothermal vs electrobiological

Electrothermal is defined as EMW where there is sufficient energy applied to heat the target plant above lethal temperatures. For most plants and other living things this is above 60°C at which point the heat starts to cause damage, such as denaturing of proteins, which are sufficient to cause death of the treated parts. More typically electrothermal will heat the water in the plant to 100°C, the boiling point of water, causing the water in the plant cells to turn into steam which bursts the cell walls destroying them and thus killing the effected parts of the plant. See Merfield (2013a) for more detailed information about thermal impacts on plants including seeds.

Electrobiological is defined as EWM where there is insufficient energy applied to increase the temperature of the plant by more than a few degrees Celsius above ambient temperatures and strictly below lethal temperatures, i.e., less than 50°C. The cause of plant mortality in electrobiological treatments are unknown, but, it is hypothesised that the electricity is interfering with plant biochemistry or physiology such as cell wall permeability or causing programmed cell death (apoptosis) (Matsuda *et al.*, 2020a; Matsuda *et al.*, 2020b; Bloomer *et al.*, 2022; Matsuda *et al.*, 2023; Matsuda & Toyoda, 2023; Toyoda, 2023).

Electrothermal and electrobiological are considered very different modes of action, particularly electrical current vs. electrostatic systems, as different as contact and systemic herbicides, or even chemical and non-chemical weeding. Therefore, comparisons between the two techniques and inferring from one to the other, for example the effect of soil moisture on treatment efficacy, are considered to be completely unsound (Chapter 12).

6.3. Short vs. long treatment durations

Short EWM treatment durations are defined as milliseconds to a few tens of seconds. This has been the main approach used in electrothermal weeding. Typically a tractor mounted weeder moves across a field, with the electrode briefly contacting each weed or a hand held applicator touches one weed for a few seconds, then, is moved to another one.

Long EWM treatment durations are defined as applications lasting hours at a very minimum through days and weeks to permanent installations. This is typically associated with electrobiological treatments where the electrode is in continual contact with the plant for the full duration of treatment, (e.g., Matsuda *et al.*, 2020a; Matsuda *et al.*, 2020b; Matsuda & Toyoda, 2023; Toyoda, 2023).

Despite electrothermal being associated with short durations and electrobiological with long durations there are new short duration electrobiological approaches being developed (Bloomer *et al.*, 2022) which are as potentially revolutionary within EWM as EWM is revolutionary within weed management as a whole.

This report is focused on short duration electrothermal as farm ready machinery is being sold and used, while the potential of electrobiological systems is still being investigated.

Chapter 7. The basics of how electrical weeders work

7.1. Key points

- Electrothermal weeders work by passing an electrical current through a plant, which heats it up to the point of killing the tissues traversed by the electricity;
- Typically the electricity is applied to the plant's foliage, traverses the hypocotyl and exits into the soil from the top of the root system;
- If the electricity is able to destroy the hypocotyl, for many plants that will cause complete plant death, even if not all of the foliage and/or the root systems are destroyed.

Electrothermal weeders work by passing an electrical current though a plant. Short duration electrobiological weeders also pass a current through plants. Most long duration electrobiological weeding systems use electrostatic fields (section 5.4.8) (Matsuda *et al.*, 2020a; Matsuda *et al.*, 2020b; Matsuda & Toyoda, 2023; Toyoda, 2023) which are not covered in this report. The key difference between electrothermal and short duration electrobiological is the amount of energy imparted into the plant (section 6.2).

Figure 8 is a diagram of how electrical current passes through a plant. The electricity is applied to the plants foliage using an electrode. A wide range of different electrode designs are used, from a simple handheld rod, to tractor mounted banks of flexible metal strips (section 8.5). Depending on the electrode design and the plants morphology (Chapter 8) the electrode may contact just the top of the plant, may 'wipe' over a larger area of foliage, or specifically target a particular area, e.g., just above the hypocotyl. For many plants, particularly annuals, the electricity will traverse and destroy the hypocotyl, which will completely kill the plant (section 9.4.1.2). The electricity carries on into the root system from where it exits into the soil and returns to the weeder via its electrical earth which is in contact with the soil / earth (hence the name 'electrical earth') (Figure 8).

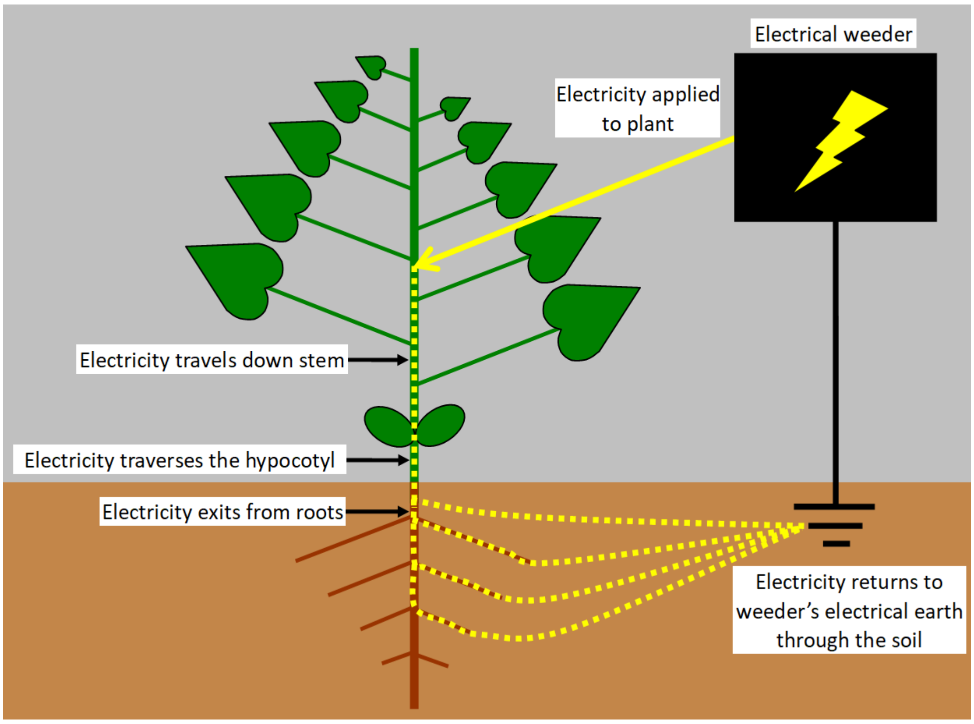

Figure 8. Schematic diagram of the basic mode of action of electrical weeder. Electricity from the electrical weeder is applied to the plants foliage (not necessarily at the top of the plant), the electricity flows down the plant stem, through the hypocotyl, into the root system, where it exits to the soil, potentially through multiple paths, and returns to the electrical earth of the weeder.

In electrothermal weeders the electricity causes the plant tissues to heat up (Chapter 6), typically to the boiling point of water, which causes the water in the cells to turn into steam, rupturing them and thus killing all plant parts affected by the electricity. If the electricity has killed the parts of the plant essential for its growth and survival, particularly the hypocotyl, the plant will be completely killed (section 9.4.1.2). Death of plant tissues not directly affected by the electricity may take some time. For example, untreated above ground foliage may still be receiving water via the xylem (which is already dead), so may not immediately wilt before browning off and dying. It is thus important to understand how the electricity is interacting with the plant's morphology and how and where the electricity was applied to understand what short and longer term results should be (Chapter 8).

7.2. Forward speed and electrode contact area

To kill a plant the electrode must contact the plant for sufficient duration that the electricity has time to overcome the plants initial high resistance and for cellular breakdown to allow the electricity to reach and lethally damage the critical plant parts (section 9.2). This puts a limit on travel speed. This can be addressed by moving from single bar electrodes, through racks of electrode bars on the same circuit (Figure 1), to double and poly-electrode systems (Chapter 8). Forward speed also has important implications and interactions with power sharing (section 8.6) and aspects of plant morphology such as stem thickness (section 9.4.3) and forms of electricity, e.g., voltage.

7.3. Managing different densities of plants

Counterintuitively, where there is a large amount of vegetation, and where there is control over weeder voltage (pressure) and amperage (power), it is better to lower volts and increase amps. Conversely where weeds are sparse but have long thin stems, volts should be increased and amps decreased (Diprose, M. pers. comm.)

Chapter 8. Electrothermal weeder design

8.1. Key points

- The original / basic electrothermal weeder designs mostly uses off the shelf components and generates high voltage mains frequency (50-60 Hz) electricity, applied through simple electrodes, e.g., horizontal bar;
- More modern / advanced designs use electronic control and monitoring systems, often using very high frequencies, with multiple independent circuits / phases / electrodes to reduce power sharing, while improving efficiency and safety;
- Power sharing is where one plant touching a shared electrode is already breaking down under treatment so has high conductivity when another plant with high resistance touches the shared electrode and is unaffected as the electricity as most of the electricity flows through the plant with high conductivity, meaning the second plant survives;
- As the generation of electricity is separate from application, the potential uses of electrothermal are only limited by the creation of suitable applicators for a given situation.

Electrothermal weeder designs are rapidly evolving from the original / basic single horizontal bar electrode using only electrical control to approaches to much more complex advanced designs with complex electrodes and electronic control of the electricity.

8.2. Original / basic designs

The approach used in the 1980s was a simple system of generating AC mains (240 V) current using an alternator[9] (generator[10] / dynamo[11]) driven by a tractor's PTO shaft, mounted in a protective container, in turn mounted on the tractor's three point linkage, henceforth 'generation box' (Figure 2). The mains electricity was then transformed into high voltage through a transformer, also in the generation box. The electrodes were horizontal metal bars, typically placed in front of the tractor (Figure 2), so the tractor tyres don't squash weeds, and for visibility and safety - the driver can more easily see people, animals and other obstructions in front of a tractor than behind. A high voltage cable transferred the electricity from generation box on the back of the tractor to the electrodes on the front. Typically there was a single circuit for all electrodes, with a few having separate circuits for each electrode. The earth return was via metal wheels on the generation box. See Figures 1 & 2 for examples of these designs. Both Lasco and Weed Zapper use this design.

The advantages of this original / basic approach is simplicity. Machines can be built using off the shelf equipment, e.g., mains transformers, insulators etc., and the design is proven and understood. The key issues with this basic design is power sharing (section 8.6) and having the highest energy use. Then other issues, such as the danger of mains frequency electricity, also come into consideration.

8.3. Modern / advanced designs

More modern / advanced designs have electronic systems that control the electricity used to treat the plants. They also typically have duel or multiple circuits with electrodes for each circuit and duel or multiple phases (see below). This allows them to better manage power sharing (section 9.2) and improve efficiency which allows faster work speeds and larger treatment widths. The downside is the complex electronics and often large size of the generation box.

---

[9] https://en.wikipedia.org/wiki/Alternator

[10] https://en.wikipedia.org/wiki/Electric_generator

[11] https://en.wikipedia.org/wiki/Dynamo

8.4. Closing the circuit — earth electrode location

All electrothermal and short duration electrobiological weeders need to create an electrical circuit where the plant(s) being treated form part of that circuit. In the original designs and some modern weeders, the circuit is created through the soil by having an electrical earth contact (typically metal wheels) so when the electrode touches the foliage the electricity flows down the plant stem, into the roots, out into the soil and back to the earth contact and complete the circuit (Chapter 7).

The basic designs typically have the earth wheels mounted on the generation box, which is simple and avoids the need for more cables running front to back of the tractor. However, it creates a longer distance for the electricity to travel through the soil from the roots of the weeds being electrocuted at the front of the tractor to the earth wheels at the back, which can be a distance of some 14 meters. Where soil has high resistance (Chapter 10) several kilovolts of electricity can be lost, to compensate voltages are raised by 3 - 5 kV root mean square (RMS) (Diprose M., pers. comm.).

There are two main alternative approaches. To have the earth wheels close to the electrodes or, have additional plant contacting electrodes that complete the electrical circuit, a 'double electrode' or 'multiple electrode' system. Figure 9 shows a diagram of a double electrode system. The electrodes are sufficiently separated such that they cannot touch each other and short out. The first electrode touches one plant, the electricity flows down that that plant, into the roots and out into the soil. It then enters the roots of another plant being touched by a second electrode, travels up that plant to the electrode to complete the electrical circuit.

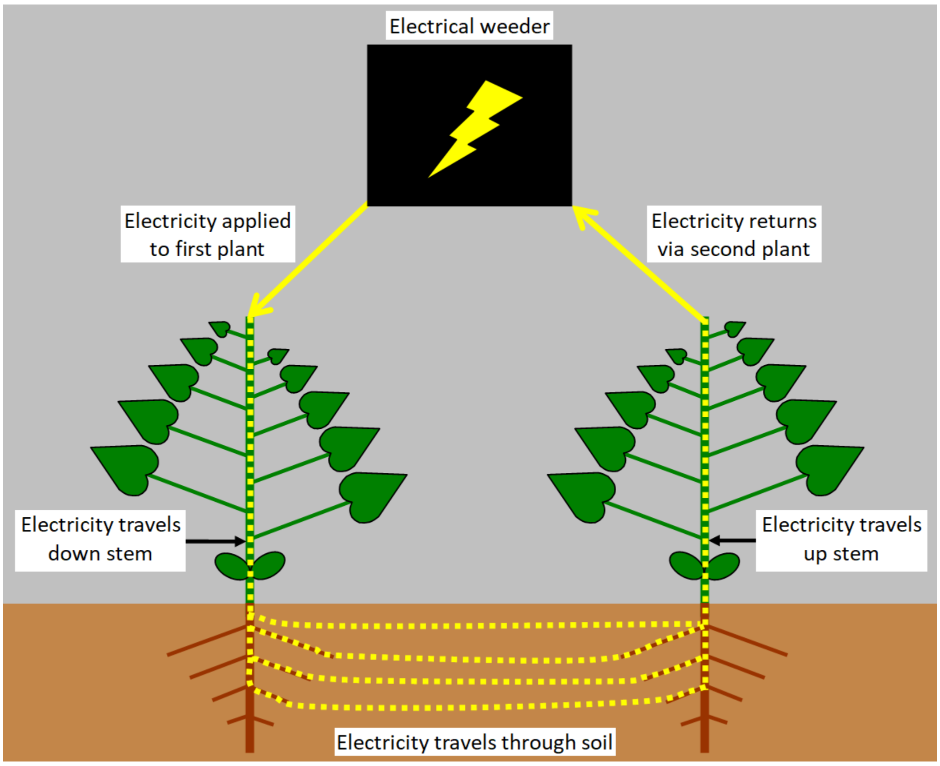

Figure 9. Schematic diagram of a double electrode system. The first electrode applies electricity to the first plant, then electricity travels down the plant's stem, into the roots and then exits into the soil, where it travels to a second plant which is in contact with a second electrode, enters the plant roots, travels up the stem and back to the weeder.

This has the advantage of minimising the soil transmission distance as the two electrodes are close to each other. There may also be an improved plant kill as the plants get electrocuted by each electrode, i.e., it is treated twice, however there is no independent research verifying this. One potential issue is that if the plant cover is scarce, and the soil surface is dry so is a poor conductor, the return circuit may be compromised and plants are not killed due to poor flow of electricity.

Weeders are also not limited to just two electrodes. Particularly using polyphase systems (section 5.4.2.3), there can be multiple independent electrodes. This can include having more complex electrode shapes further increasing the electrode contact area resulting in multiple electrical paths through the plants.

This leads to a third approach - plant foliage only circuits: where there is sufficient foliage all or the majority of the current flows through the foliage from one electrode to another Figure 10.

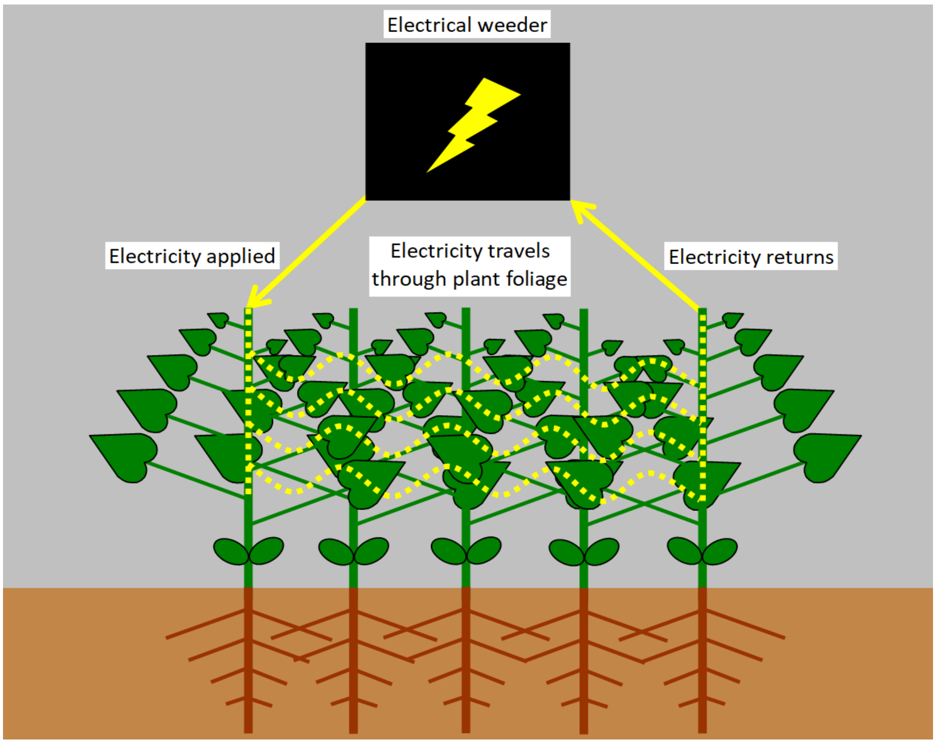

Figure 10. Schematic diagram of a plant foliage circuit. Where there is sufficient plant foliage, current applied by one electrode to one part of the plant canopy results in the electricity flowing through the canopy to a second or multiple electrodes before returning to the weeder.

This would mean there are no or minimal electrical energy losses to the soil. It will likely require continuous and substantial crop canopies, and potentially more complex electrode designs to ensure continual contact of all electrodes and suitable paths through the foliage for the electricity to ensure all of the foliage is treated.

Foliage only circuits are however less likely to kill plants outright, because there is no soil transmission, it is also unlikely electricity will traverse the hypocotyl and enter the top of the roots so the systemic kill of soil earthed systems will be lost. However, this may be of benefit if the focus is on uses such as crop desiccation (section 9.6) where completely killing the whole plant is undesirable.

8.5. Evolution of electrode designs

The electrothermal weeder electrode designs from the 1980s mostly had a horizontal bar / rod as the electrode, and were designed to kill weeds overtopping crops (Figure 2). An advance on single electrode bar was multi-electrode bar systems (racks) on the same electrical circuit to address power sharing (Figure 1). These horizontal designs are limited to this function as the length and mounting of the electrode bars means they would be unable to follow ground contours, so they could not kill low growing vegetation, e.g., pasture.

More recent approaches use banks of flexible metal strips around 20 cm wide, or short horizontal rods about half a meter long, perpendicular to the travel direction, underneath articulated hoods, which are able to follow ground contours. Further elaboration of these designs includes having additional flexible electrodes attached to the short horizontal rod electrodes parallel to the direction of travel, with opposite polarity so that the electricity has multiple paths it can take through the plants.

As Figure 3 of electrodes being used to replace horizontal knife blades on an interrow hoe, Figure 4 of a railway line weeding system, and Figure 5 of a self-propelled scrub weeder show, there is considerable potential for designing electrodes for a wide range of weeding scenarios. This is facilitated by the separation of electricity generation from application (section 8.6 below).

8.6. Separation of generation from application

A key aspect of EWM is that the electrical generation is separate from how and where it is applied. This creates flexibility in how and where the electricity is applied. For example, horizontal electrode bars can be used to kill crop-overtopping weeds. Flexible / floating electrodes can kill vegetation on the ground, both contiguous (broad acre) and incontiguous (in strips), e.g., under perennial crops and in annual row crops, or to replace flail mower heads on roadside and urban weed management equipment. Hand held and robotic electrodes can treat individual plants, from newly emerged seedlings to woody vegetation, and even individual parts of plants. This application flexibility means that EWM can be adapted to a wide range of weed management situations.

8.7. Power sharing: plants transforming from high to low resistance

'Power sharing' (Diprose M., pers. comm.) is where one plant has contacted an electrode and its electrical resistance is breaking down and it is becoming a good conductor (section 9.2). When a second plant then contacts the electrode, the second plant has high resistance, which, as electricity 'wants' to follow the path of least resistance (section 5.4.6) it preferentially continues to flow down the first plant rather than the second plant. If the second plant disconnects from the electrode before the first (e.g., if it is shorter) then it may be untreated and survive.

Power sharing is a significant challenge for electrothermal weeders. The original / basic designs with single horizontal electrodes are particularly susceptible. The electrothermal weeders developed for the British Sugar Corp in the 1980s had multiple horizontal electrode bars (racks) to address this issue, as can be see in Figure 1 (Diprose, M. pers. comm.).

Advanced weeder designs use multiple independent electrical circuits, each with their own electrodes, largely to address power sharing as well as providing other benefits. This means that if a plant that has contacted the electrode of one circuit has broken down and has become a good conductor, if another plant then touches the electrode of a second circuit, then its treatment is completely independent of the first plant on the first circuit. As the electrodes are between 20 to 50 cm wide, this means that the likelihood of power sharing resulting in untreated plants is significantly reduced. It is akin to having lots of tiny basic electrothermal weeders working side by side.

8.8. Electricity forms and management

Newer / advanced electrothermal weeders are diverging from the original 50 Hz, AC 5,000 - 15,000 high voltage systems, with the aims of improving safety and energy efficiency. For example very high frequency (hertz) systems > 1,000 Hz have been developed[12], along with Rectangular AC wave forms (de Andrade Coutinho Filho *et al.*, 2023). Pulsed DC very low power systems are being developed for short duration electrobiological approaches (Bloomer *et al.*, 2022), and multiple forms of pulsed electricity, some using extremely high frequencies, e.g., >50,000 have been researched for both

---

[12] https://rootwave.com/high-frequency-electricity-gives-better-weed-control-with-lower-energy-use/?avia-element-paging=3

electrothermal and long duration electrobiological (Mizuno *et al.*, 1990; Judaev, 2008; Ivanovich & Viktorovich, 2017; Lee *et al.*, 2018; Yudaev *et al.*, 2019; Matsuda *et al.*, 2020b; Toshpulatov, 2020). In advanced electronic controlled weeders the flow of electricity can be continually monitored to minimise sparks and power sharing and use multiple phases (section 8.6) (Eberius *et al.*, 2018). Considering the multiple forms and ways that electricity can be manipulated there is considered to be significant potential for ongoing development and improvements of EWM to improve efficacy, efficiency and safety.

8.9. Conclusions electrical weeder designs

It is considered that there is significant potential for continued improvement of EWM machinery, including novel uses. Electrobiological, both short and long duration, appears to hold significant possibilities with much lower energy use and potential to reach underground parts of plants that are beyond the reach of both herbicides and electrothermal.

Chapter 9. How electricity interacts with plant morphology, growth, tissue types and biomass

9.1. Key points

- Understanding how electricity interacts with plant morphology, growth, the effect of tissue types (e.g., green vs. woody) and plant biomass is key to understanding and effectively using electrothermal and EWM in general;
- A key issue at the heart of electrothermal is that plants initially have high resistance which transforms to high conductivity as their tissues break down during treatment. This creates the issue of power sharing which is an important driver of electrothermal weeder design;
- Plants only grow from their meristems (buds) but continue to grow their entire lives. Growth is defined as cell division, not just expansion / enlargement of tissues, e.g., a leaf expanding from a bud;
- This means that meristematic tissue is of high value to plants and causes significant growth setbacks if it is lost, while non-meristematic tissue, like leaves, are of low cost if they are lost;
- The hypocotyl — the junction between the true stem and true roots — is the Achilles' heal of many plants because its destruction is lethal for them;
- This means that to kill a plant, all the foliar meristems, or all the root meristems, or the hypocotyl have to be killed, to kill the plant as a whole;
- The exception to the above are plants that can dedifferentiate, i.e., generate true stem from true root meristems, true roots from true stem, and either true stem or root from the cambium meristem. These are difficult weeds to control by any means, chemical and non-chemical;
- Understanding how electricity applied to a given plants morphology creates a circuit through the plant, and if it is then able to destroy the hypocotyl or other key meristematic tissues to cause complete plant death, is critical to understanding EWM and theoretically predicting its outcome;
- The biomass of plants to be treated by an electrothermal weeder, is an important determinant of the energy and thus fuel required. It is also important in determining / ensuring that the electricity is able to kill the key parts of the plant to ensure complete death;
- The use of electrothermal for crop desiccation illustrates how the above knowledge can be used.

In electrothermal weeding understanding how the electricity interacts with plant morphology, the way the plants grow, their tissue types and biomass is vital to understanding electrothermal's potential and limitations. This is akin to understanding how a given herbicide chemistry interacts with plant biochemistry, e.g., glyphosate acts by inhibiting the plant enzyme 5-enolpyruvylshikimate-3-phosphate synthase. Indeed, understanding how any form of physical weed management (e.g., knife blade hoes and flame weeders), interacts with plant growth, morphology and other factors such as soil conditions is vital for successful weed management. However, thermal weeding and electrothermal in particular have unique features in their interactions with plant growth and morphology that require more detailed knowledge and understanding. Unfortunately this knowledge is poorly understood in general. These interaction of EWM, and electrothermal in particular, with plant morphology have received limited attention in the research literature and most of the research was done in the 1980s. This section is therefore based on research and practical experience from physical weeding as a whole, and flame and steam weeding in particular.

9.2. Changes to plant resistance and conductivity during treatment - a critical feature of electrothermal weeding

Plants naturally have a high electrical resistance. The surface of their leaves and stems often have a waxy layer and other structures such as hairs (trichomes) to minimise water leaving or entering the plants. These structures also inhibit electricity entering the plant thus creating resistance. Individual plant cells have walls made of cellulose and lignin, which are electrical insulators. Thus, when electricity is initially applied to plants during electrothermal weeding there is high resistance to the electricity. As the electricity starts to heat the plant, destroying the cells, the cell contents leak out. These contain water, salts and other compounds, that are more conductive. The plants thus change from having a high resistance to lower resistance (low conductivity to high conductivity), so the electricity flows more easily down the plant (Diprose & Benson, 1984a, 1984b; Vigneault *et al.*, 1990; Diprose & Mattsson, 1993; Vigneault & Benoît, 2001; Slaven *et al.*, 2023).

This change from high to low resistance is a critical feature of electrothermal weeding. This change of resistance is often central to how the electricity interacts with plant morphology, as discussed in the rest of this section. It is also the cause of power sharing (section 8.6) which is a major problem in electrothermal weeders and is a key driver of electrothermal weeder designs.

If there is sufficient energy being delivered by the electricity, it can cause the complete destruction of plant structures such as leaves, petioles and stems, especially where they are thin. This involves the plant structure exploding from the internal pressure of steam being generated and/or the structure catching fire. When this happens clearly no more electricity can reach the plant structures below the destroyed section. This can mean that insufficient electricity reaches the critical plant parts required to achieve complete plant death.

This means that more electrical power (energy / amps) and voltage (pressure) is not always better. Less power and/or voltage may achieve a better result by allowing the electricity to travel further through the plant reaching the critical parts that need to be destroyed to achieve complete plant death.

9.3. True shoot and true stem - terminology

Some plant species have stems that grow underground, such as stolons, e.g., potato (*Solanum tuberosum*), rhizomes e.g., couch grass (*Elymus repens*), and bulbs and bulbils, e.g., *Oxalis* species. To a lesser extent there are species with roots that grow in the air, i.e., aerial roots, e.g., *Monstera* species and some vines. Underground stems are sometimes confused with roots. The terms ‘true root’ and ‘true stem’ thus are used to indicate that an organ growing underground is physiologically a stem and not a root, and vice versa a root growing in the air is a root not a stem.

9.4. Key aspects of plant morphology, growth and biomass

Determining and manipulating the form and path of the electricity through a plant and how that relates to parts of the plant critical for survival and growth and thus the plants ability or be killed by treatment is considered to be the key to electrothermal weeding. This is determined by plants morphology (phytomorphology), how they grow and the biomass of plant foliage. The following sections describe the key aspects of plant morphology and growth of relevance to physical, including electrical, weeding approaches. It then summarises how electrothermal interacts with those key aspects of plant morphology and growth to determine the outcome of a weeding event, e.g., whether a plant is killed or survives.

The key aspects of plant morphology and growth include:

- Meristems and plant growth;
- Dedifferentiation;
- True shoot and true stem;
- Plant leaf, stem, hypocotyl and root diameter and length;
- Plant stem structure and structural materials;
- Shoot and root morphology;
- Foliar biomass.

These all interact with the application method to determine the path the electricity takes through the plant and thus the effect it has. The interaction of electricity and plant morphology also needs to be viewed in the context of the aim of a particular electrothermal application: is it complete plant mortality, just growth suppression or another objective, e.g., pre-harvest crop desiccation. Depending on the desired outcome a different application method and electrical form and path through the plant may be required.

9.4.1. Meristems and plant growth

Growth in biology is defined as cell division, not, just the enlargement / expansion of a particular organ. The contrast of plants with vertebrate animals is instructive. In vertebrates every cell continues to divide over the entire life of the organism, but, they reach their full size at the end of their juvenile period when they become adults. In plants, cell division only occurs in the meristems (buds) but they continue to grow their entire lives. The main plant meristems are:

- The foliar meristems in leaf axils and terminal buds that produce leaves, stems and flowers;
- Root meristems which produce more roots, and;
- The cambium meristems that produces the xylem and phloem of the vascular system and cork (bark) layer.

Once a particular organ, e.g., a leaf, is formed no further cell division can occur in that organ. For example, Figure 11 shows a cross section through a *Gunnera* species bud showing a 4 cm long, fully grown leaf and petiole inside the bud and a fully expanded leaf and petiole which are over one meter across and tall. The leaf and petiole inside the bud has exactly the same number of cells as when they has expanded to their full size.

Figure 11. Cross section through a *Gunnera* species bud showing fully grown 4 cm long leaf blade and petiole inside the bud (left), the same leaf and petiole excised from the bud (center) and a fully expanded leaf and petiole (right) which is over a meter across and tall. The leaf and petiole inside the bud has exactly the same number of cells as when they expanded to their full size.

That plants continue to grow from the meristems throughout their life has major implications for physical weeding and especially EWM, flame and steam weeding.

9.4.1.1. High value meristems - low value non-meristematic tissues

If a plant looses non-meristematic tissue, such as a leaf, it can be easily replaced by a nearby meristem producing a new leaf. However, if a plant looses a meristem it causes much greater harm, because to replace the lost meristem, a meristem lower down the plant has to regrow all the plant parts between the lost meristem and itself. That takes considerable time, nutrients and energy.

In addition, there are significant differences in the resources within meristems and other tissues. Meristems consist of dense clusters of very small, undifferentiated cells rich in nutrients and energy. Leaves and stems contain much lower levels of resources. Structurally they are mostly composed of cellulose and lignin which are composed of carbon, oxygen and hydrogen which are never growth limiting nutrients, and most of their weight is water. Thus loosing leaves (e.g., from grazing, mowing or thermal treatment) is a relatively minor setback for a plant. In comparison loosing meristems causes much greater harm to a plant. Hence — 'Leaves are cheap - buds are expensive'.

9.4.1.2. The critical role of the hypocotyl and mesocotyle / coleoptile

The hypocotyl and mesocotyle / coleoptile is the area in a seedling between the radicle and the cotyledon leaf(s) (Figure 12).

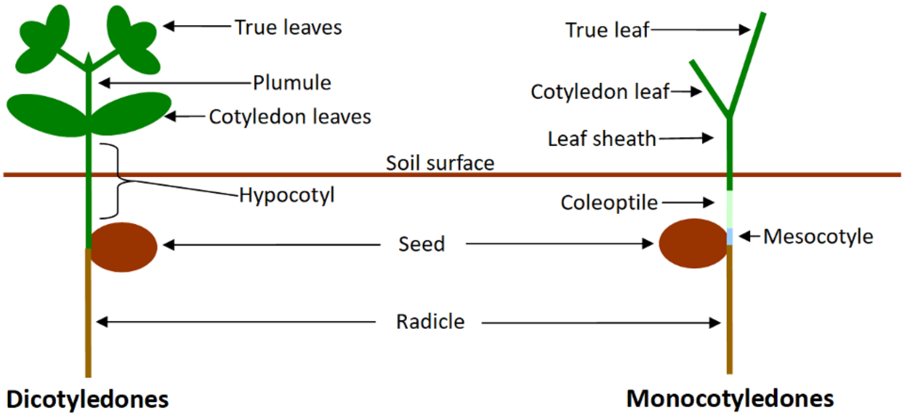

Figure 12. Diagram of dicotyledon and monocotyledon seedlings with a focus on the location of the hypocotyl and mesocotyle.

The hypocotyl / mesocotyle and coleoptile, henceforth just 'hypocotyl', is the junction between the photosynthesising aerial parts of the plant - true stem - and the nutrient and water gathering root system - true roots (section 9.3). The hypocotyl junction thus represents the key weak point in a plant's morphology. If the hypocotyl junction is destroyed / severed / or otherwise stopped from functioning then the plant will (eventually) die because the photosynthetic and nutrient & water gathering systems have been disconnected. In comparison, a plant can be defoliated down to the last foliar meristem, and/or have the roots cut off to the last root meristem and it can survive and regrow (given suitable environmental conditions). Severing the hypocotyl zone is the basis of girdling[13], e.g., ring-barking of trees and steam girdling used as a research tool, whereby a strip of cambium and phloem are killed but otherwise the plant stem is physically intact. Compared to the massive damage and loss of biomass if a plant is defoliated or de-rooted to the last meristems, which a plant can survive, the comparatively tiny amount of damage caused by girdling and other methods of destroying hypocotyl functioning is lethal, highlighting the hypocotyl as plants' 'Achilles' heel'. In most forms of EWM the electricity traverses the hypocotyl, destroying it. Destroying only the hypocotyl with EWM and no other part of the plant is therefore lethal for many plants, these same as for physical and steam girdling.

Thus to physically kill a plant one or more of the following has to be achieved:

- All the foliar meristems have to be killed;
- All the root meristems have to be killed, and/or;
- The hypocotyl has to be killed.

This highlights the critical importance of the hypocotyl and why, in many cases, it should be the target of EWM. The exception is for plants that can regrow from underground organs (not just true roots) which includes dedifferentiation of underground organs.

---

[13] https://en.wikipedia.org/wiki/Girdling

9.4.2. Dedifferentiation

In most plants, particularly annuals and biennials, meristems can only produce specific tissues and more meristems like themselves, i.e., they have become differentiated or specialised. For example foliar meristems only produce stems, leaves, flowers and more foliar meristems, and root meristems only produce more roots and root meristems. Dedifferentiation is where a meristem of one type can turn into a different type of meristem and produce different plant tissues. For example, foliar meristems in leaf axils dedifferentiate to produce roots. Dedifferentiation is the basis for plant vegetative propagation, i.e., cuttings[14]. Figure 13 shows the four forms of dedifferentiation.

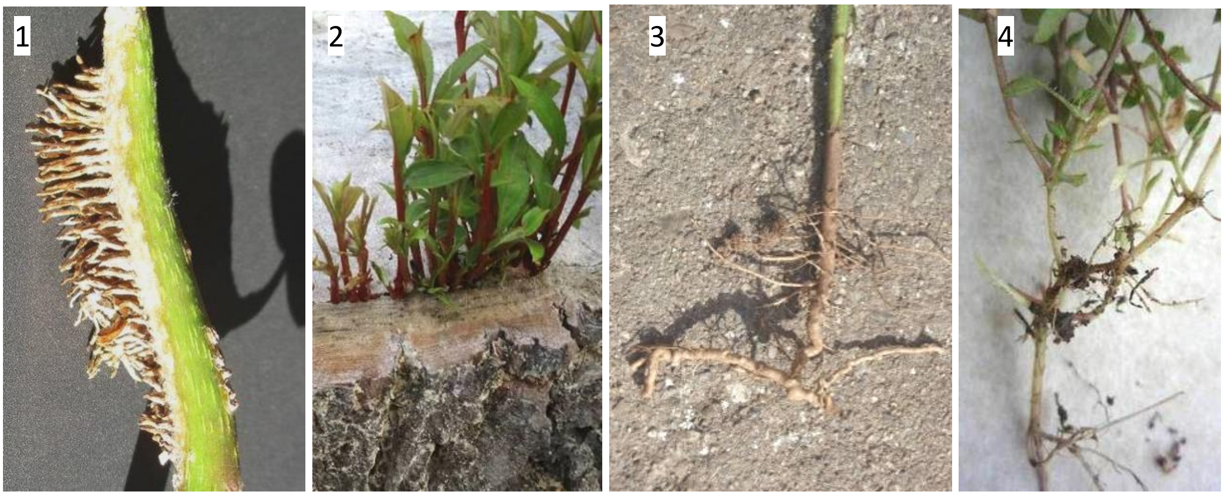

Figure 13. The four types of dedifferentiation. (1) Cambium dedifferentiating into roots in English ivy (*Hedera helix*). (2) Cambium dedifferentiating into shoots in willow (*Salix* species). (3) Creeping root producing vertical root that dedifferentiates into a shoot in creeping thistle (*Cirsium arvense*).
(4) Aerial meristems dedifferentiating into adventitious roots in chickweed (*Stellaria media*).

Dedifferentiation is uncommon in annual plants as their main evolutionary strategy is to produce large numbers of seeds (which are a special form of meristem). It is therefore mostly found in perennial plants, both herbaceous (pasture species) and woody (shrubs, trees, etc.).

Plants that can dedifferentiate often pose a particular challenge for physical weeding, including electrothermal, as they can regrow from meristems that have not been directly killed by the weeding technique. Some of the world's worst weeds, e.g., Californian / Canadian / creeping thistle (*Cirsium arvense*) and purple nutsedge (*Cyperus rotundus*) (Holm, 1991) are able to dedifferentiate, often as part of a vegetative propagation / creeping life strategy, which is why they are the most challenging of weeds to control.

Plants that can regenerate from underground organs, particularly if they are deep in the soil or only connected by thin roots or stems are hard to kill by any means, including by electrothermal. Plants that can dedifferentiate above-ground meristems, e.g., chickweed in Figure 13 and white clover (*Trifolium repens*) may be difficult to kill with electrothermal as any foliar meristems that survive have the potential to produce roots and regenerate. This is exacerbated in these three species by their thin stems and leaf blades on long thin petioles which have high resistance to electricity (section 9.4.3) or can be completely destroyed before sufficient electricity has reached the meristems (section 9.2).

It is considered particularly valuable to research electrobiological treatments, particularly long duration, on these challenging weeds as the low level electrical currents may be able to spread much further though the underground parts of the plants and kill them.

---

[14] https://en.wikipedia.org/wiki/Cutting_(plant)

9.4.3. Plant leaf, stem, hypocotyl and root diameter and length

Plant leaves, petioles, stems, hypocotyl and roots differ hugely in their diameter (cross sectional area) and length. For example the tall very thin stem, leaves and fibrous roots of wild oat (*Avena fatua*) compared with the thick fleshy stem, leaves and tap root of purslane (*Portulaca oleracea*). These different morphologies have large impacts on how they transmit electricity to the parts of the plant that need to be destroyed to kill the whole plant.

Using the water analogy of Chapter 5 thin stems are like a small narrow water pipe. It is hard to get much water to flow through a narrow pipe. To do so requires increased pressure. The same for electricity: thin plant parts, especially long thin plant parts, do not provide a good conduit for electricity so increased voltage (pressure) is required to get sufficient electricity to flow (Diprose, M. pers. comm.). In contrast, thick tissues, especially short ones, are much better conductors so lower voltages (pressure) can be used. Lower voltages also mean that the electricity can potentially travel further along the stems before they are destroyed. It also potentially uses less energy.

An additional issue with thin, and especially thin and long plant parts is that they quickly heat up and reach lethal temperatures. If electricity continues to be applied, the plant tissues can be completely destroyed, e.g., blow up, ignite. If this happens clearly no more electricity can flow down the plant, across the hypocotyl and into the roots. These thin tissues can therefore act rather like an electrical fuse, they quickly blow when too much electricity is applied, thus protecting the rest of the plant.

This contrasts with plants with thick fleshy stems such as creeping thistle (*Cirsium arvense*), horsetail (*Equisetum*) and English ivy (*Hedera helix*) where electricity has anecdotally been found to travel considerable distances though the stems, including underground, e.g., 20+cm, causing complete foliar destruction and potentially death of underground organs, e.g., rhizomes and creeping roots.

Where electricity is applied to plants can therefore have large implications if the plants are killed or not. For example, if electricity is applied to wild oats (see above) where they overtop a crop such as wheat, it will be challenging to get the electricity down the full length of the stem to the meristems at the base of the plant at soil level. If the wild oats had germinated in a fallow, e.g., post harvest, and the electricity could be applied as close to the ground as possible so there is the minimum distance for the electricity to travel down the thin stems, a complete kill of the plants would be much more likely. In comparison, creeping thistle (see above) has thick strong stems, such, that were electricity applied to the parts overtopping a crop there is a good chance the electricity will successfully transmit all the way down to ground level, and, as the stem continues into the soil, the electricity could continue down the stem underground for some distance, possibly even reaching the creeping roots.

9.4.4. Plant stem structure and structural materials

Plant stems vary in their internal structure. Some have hollow centers or centers filled with pith, e.g., species in the carrot family (Apiaceae). Others have solid stems that are fleshy throughout, e.g., English ivy (*Hedera helix*). There are indications that hollow pithy stems do not conduct electricity as well as solid stems, however research is limited.

Another factor regarding the flow of electricity down stems is that the xylem in a plant stem is dead, only the phloem and the meristematic cambium layer are alive. Xylem carries water and a small amount of dissolved nutrients from the roots to the foliage. Phloem carries photosynthates, mainly sucrose, from the leaves to the rest of the plant including the roots. Sucrose solutions are non-conductive. Xylem makes up the majority of a plant stem in woody species, while the phloem and cambium exist only as a thin cylinder. These factors may also have a role in the overall conductivity of the stems of woody species. However, no research has been found that looks at transmission through xylem vs. phloem vs. cambium.

As discussed in section 9.4.1 the xylem being dead does not need killing, rather to girdle a plant it is the living phloem and cambium that need to be killed. For plants with larger stems this may mean that the electrode may need to wrap around the entire stem, or, to be drawn around the whole stem, as with a girdling knife.

The main structural compounds in plants are cellulose, hemicellulose and lignin. Young, green, soft, supple plant structures are mostly made of cellulose. As structures become older, harder, and more ridged i.e., become woody, the amount of hemicellulose and lignin increases. There are indications that as plants become more lignified their electrical resistance increases and they become harder to kill, but again original research is limited.

The composition of the plant surface that the electrodes touch can also have an impact on the initial resistance of the plants. For example, Crop.Zone[15] have developed a proprietary salt based spray "volt.fuel" that is claimed to increase the conductivity of the plants and reduce the energy required. However, there is no known independent research on the use of conductive sprays.

While stem structure and structural materials of all plant parts are considered likely to impact on EWM, overall there is very limited original / peer reviewed research so there is need for a large amount of fundamental research in this area.

9.4.5. Shoot and root morphology

The shoot and root morphology of plants can have a large impact on the effectiveness of EWM, particularly electrothermal, based on most EWM approaches applying the electricity to the shoots and it exiting via the plant roots into the soil. This is because in most plants it is the hypocotyl zone / top of the root system that needs to be killed to completely kill the whole plant, rather than trying to kill all of the shoots and associated meristems. The plant's morphology, including the number of stems / shoots or lack of them, their arrangement, thickness (section 9.4.4) and the structural materials (section 9.4.4) can all have an impact. This section analyses the impact of shoot and root morphologies on EWM. However, to date there is very limited research of the interaction of plant morphology and EWM, and most of this has focused on issues such as electrode contact area and biomass (e.g., Vigneault & Benoît, 2001; Slaven & Borger, 2022) rather than examining the electricity's path through the plant, in relation to critical areas such as the hypocotyl. Thus there is also a clear need for considerably more research on this topic. This analysis is therefore based on wider experience in physical weed management.

9.4.5.1. Single stem and tap root

Starting with the most simple morphology: a single stem with limited side branches joined by a clear hypocotyl zone to a main tap root with thinner lateral roots. Examples of plants with this morphology include fat hen (*Chenopodium album*), linseed / flax (*Linum usitatissimum*) and many woody plants, e.g., trees and vines. Foliar applied electricity will flow down the stem through the hypocotyl and down the main tap root before exiting back to the soil. If the hypocotyl is destroyed and if the plant is unable to regenerate from unharmed underground organs the plant will be completely killed. The size of the stem will have a significant impact: for example, fat hen has a thicker stem while linseed is quite thin. Getting sufficient electricity down the thin linseed stem to kill the hypocotyl without completely destroying the stem before the hypocotyl is destroyed may require higher voltages. The fat hen stem would be expected to transmit sufficient electricity to destroy the hypocotyl under most scenarios. Trees have substantial stems (trunks), so the challenge is ensuring the electricity destroys the entire circumference of the stem, i.e., girdles the tree.

---

[15] https://crop.zone/en/

9.4.5.2. Single tap root with multiple stems

The next morphology is a single taproot with multiple stems arising from the top of the root or from a crown, which is a short, vertical, non-creeping, underground stem. Examples include wireweed (*Polygonum aviculare*) the herbaceous perennials red clover (*Trifolium pratense*) and lucerne / alfalfa (*Medicago sativa*) and many woody perennials in the genus *Rubus* e.g., blackberry (*Rubus fruticosus*) and raspberry (*Rubus idaeus*). In this morphology there is no clear or single hypocotyl zone, and there may be multiple dormant foliar meristems in the crown. Electricity applied to one stem will travel down that single stem, into the crown and root, but, it may not destroy the whole crown / crown meristems. In plants with thin stems there may be insufficient electricity flowing down a single stem to kill the crown and root, e.g., only a vertical section of the crown and root may be destroyed. Electricity will therefore need to be applied to most if not all of the stems nearly simultaneously so that sufficient electricity reaches the crown and the root to kill them completely. This may be aided by removing most of the shoots (e.g., by mowing) so only short sections of stem are left, so, that the least amount of energy is lost heating the stems before the electricity reaches the crown and root. An other approach would be to directly target the crown, e.g., with manual or robotic systems, e.g., (Tatnell, 2021).

9.4.5.3. Herbaceous hemicryptophytes

Herbaceous plants are defined as plants 'whose stem does not become woody and persistent'. Hemicryptophytes are part of the Raunkiær system that categorizes plants according to life-form and the location of their 'resting buds'[16]. This describes hemicryptophytes as plants that 'have buds at or near the soil surface'. These are typically pasture plants, both grasses (monocotyledons) and broadleafs (dicotyledons). Grasses are discussed below.

The key aspect of herbaceous hemicryptophytes for EWM is that the buds are at ground level. This is what allows them to survive grazing and mowing as mostly only leaves, not meristems are removed by grazing and mowing (see section 9.4.1.1). The exception is flower stems which do contain meristems. Within this category are a wide diversity of plants, including stoloniferous and rhizomatous plants which are also discussed below.

9.4.5.4. Leaf blades on long thin petioles

One morphological trait among broadleaf herbaceous hemicryptophytes is leaf blades (lamina) supported on long, and often thin, petioles. Examples include white clover (*Trifolium repens*), docks (Rumex species) and plantain (*Plantago* species). While the large leaf blade may be an easy contact target for an electrode, the thin petiole has limited ability to transmit electricity, as it is like an electrical fuse (section 9.4.3), and it is likely to be destroyed before it can conduct sufficient electricity to the rest of the plant and its ground level meristems. Thus applying electricity to the leaves is likely to only result in temporary defoliation but not plant death.

For species such as docks that produce a flower spike that is both taller than the rest of the pasture and has a much larger cross sectional area, the flower spikes may provide a better target as it should be able to conduct more electricity down to the ground level meristems. This will likely need to be done while the spike is still green and growing rather than when maturing and increasingly lignified when it may be a poorer electrical conductor.

9.4.5.5. Rosettes

Rosette plants (acaulescent) typically have a single large tap root with a rosette / whorl of leaves produced from a highly shortened stem with negligible internodes. Examples include carrots (*Daucus carota* sub species *sativus*) and dandelion (*Taraxacum officinale*). The leaves can be flat on the

---

[16] https://en.wikipedia.org/wiki/Raunki%C3%A6r_plant_life-form

ground as in dandelion or held aloft as in carrot. These are to an extent similar to the morphology described above of a single taproot with multiple stems, the difference is that it is only leaves, not stems, that are above ground. These morphologies also lack a clear hypocotyl zone, as the top of the root, the stem, and leaf axil meristems are all merged into one dense mass of plant tissue. The challenge is to get sufficient electricity into the meristems in the leaf axils to kill all of them, or into the root system to destroy it. In plants with upright leaves, such as carrot, particularly where the leaves are thin or have thin petioles, sufficient leaves need to be simultaneously contacted by the electrodes to transmit enough electricity to kill all apical meristems and/or the top of the root. Flat rosettes such as dandelion are even more challenging in terms of achieving sufficient electrode contact with the leaves, and, not having electricity jump from the leaves direct to the earth. Weeders based on thin flexible metal strips that 'wipe' over the surface of the ground, e.g., Zasso (section **Error! Reference source not found.**) may be better able to effectively contact flat rosette plants. Or d irect application by manual or robotic weeders to the center of the rosette may be effective. It is noted that dandelion can dedifferentiate from true root, so, is able to regenerate from deep in the soil (Healy, 1953). This creates the additional challenge of getting sufficient electricity through enough of the root system so that regeneration is prevented.

9.4.5.6. Grasses

Grasses, including herbaceous species such as pasture grasses, e.g., ryegrasses (*Lolium* species), and cereals, e.g., wheat (*Triticum aestivum*) and maize / corn (*Zea mays* sub species *mays*) share the fundamental morphology of:

- Leaves that grow from meristems at the base of the leaf blade;
- A stem / culm that grows from a basal meristems often situated in the center of a whorl of leaf sheaths;
- A fibrous root system with many adventitious roots.

Having stems and particularly leaves that grow from the base enables them to survive being grazed by herbivores or mown without loosing valuable meristematic tissue (section 9.4.1.1).

There are then two main sub-groupings. Tussock / bunch forming grasses (caespitose) which are typically used in pasture and lawns and those that mainly consist of taller upright stems, e.g., cereals, bamboo, with multiple nodes and internodes above ground level. Many grasses produce tillers which are shoots that arise from the base of the plant. This is a form of vegetative propagation as the tillers in many species become independent of their parent plant, so there is no flow of electricity and herbicides among tillers. There are also many stoloniferous, and rhizomatous grasses, these morphologies are covered below.

Grasses are considered to be unable to dedifferentiate and therefore regenerate from true roots. In comparison true stem can clearly dedifferentiate to form roots as shown by the many rhizomatous and stoloniferous grasses species that produce roots from the stem, and adventitious roots produced from above ground stem nodes, e.g., maize. Thus the key to killing non-rhizomatous and stoloniferous grasses with EWM is to be able to kill the meristems at the bases of the leaf blades and stems. As the leaves are often thin, both the width and thickness of the blades, the challenge is to get enough electricity into the leaf base without destroying the leaf blade before the meristem is killed. Applying the electrode as close to the leaf base will likely assist with this. The cross sectional area of the stem varies from very thin in many bunch grasses, through moderate in cereals such as wheat and thick in maize and bamboo.

9.4.5.7. Rhizomes, stolons and creeping roots

Rhizomatous plants have creeping underground true stems that produce both roots and shoots from the stems, typically at the nodes. Examples include couch grass (*Elymus repens*) purple nut sedge (*Cyperus rotundus*) and horse tails (*Equisetum* species).

Stoloniferous plants have true stems that creep on the soil surface or just below it and produce both roots and shots from stem nodes. The stems are also called runners, e.g., in strawberry (*Fragaria × ananassa*). Other examples include white clover (*Trifolium repens*) creeping buttercup (*Ranunculus repens*). Potato (*Solanum tuberosum*) tubers are true stem and produced on the ends of stolons, even though they are deeper in the soil.

The difference between a rhizome and stolon is that a rhizome is part of the main stem or stems of a plant while a stolon is a side branch off the main stem.

Creeping roots are true roots that spread horizontally through the soil and are able to dedifferentiate and produce shoots (true stem). They are also often perennating organs as well. The most well known, and one of the world's worst weeds, is creeping thistle (*Cirsium arvense*). Creeping roots are much less common than creeping stems, either rhizomes or stolons. Most creeping stems can only produce roots as well as shoots from the meristems at the nodes, not the cambium meristems. Roots, as they don't have nodes, if they can dedifferentiate, can do so anywhere along their length.

These plants are often difficult to kill, especially those with a large root biomass at depth in the soil, as neither herbicides nor electricity can translocate through all of the underground biomass. Electrothermal treatment may well completely defoliate them, and destroy the meristems at the base of treated foliage, and even tens of centimetres into the soil, but, the plants will then regrow from undamaged meristems. Repeat treatment, potentially multiple times will be required to destroy the new shoots and their meristems.

As discussed in section 9.4.2 the potential for long duration electrobiological systems to kill weeds with rhizomes, stolons or creeping roots could be a valuable area of research.

9.4.5.8. Bulbs, corms and tubers

A bulb consists of a highly compressed stem forming a 'basal plate' from which a fibrous mass of adventitious roots grow downwards and scale leaves grow upwards to form the bulb. A corm is a short, vertical, swollen underground plant stem that serves as a storage organ, typically on or close to the surface. It may form as a single internode (the area between two nodes) or contain multiple nodes and internodes. A tuber, is also a swollen stem that grows horizontally as opposed to the vertical orientation of a corm. They are therefore swollen rhizomes or stolons (section 9.4.5.7).

Bulbs are therefore considered to be different than corms and tubers for EWM. Bulbs typically produce a number of thick fleshy leaves directly from the center of the basal plate, which contains the leaf meristems. The leaves should therefore effectively conduct electricity directly to the basal plate and destroy it, along with all the root and shoot meristems it contains. Anecdotal treatment of onion bulbs found that the whole bulb got very hot indicating they would be killed. Corms and tubers have their meristems around the outside surface of the organ in highly reduced leaf axils likely making them harder to kill as the electricity is considered more likely to flow through the fleshy center of the corms and tubers, less through the skin, which is also being cooled by the soil it is in contact with. They can also produce daughter tubers, which may be some distance from the parent stem and connected by a thin stolon, as in potatoes. They may therefore be particularly difficult to kill, and require multiple treatment of the regrowth. Corms that form from a single internode may be more susceptible to treatment than those with multiple internodes. This is another area in clear need of research.

9.4.6. Stale seedbeds - seedling stage weeds

The primary use of flame weeders (Chapter 15) has been false seedbeds (Merfield, 2015) whereby newly emerged weeds (cotyledon to 1-3 true leaves) are killed just before crop emergence. Using electrical weeders for false seedbeds appears challenging as the weeds are very small, e.g., < 1 cm, so getting the electricity into them and not having it short circuit though the soil would appear difficult. However, Zasso, which use ground following flexible metal strip electrodes and advanced electronic control, claim to be able to kill newly emerged seedlings (Koch *et al.*, 2020a; Koch *et al.*, 2020b). Zasso weeders are also being used on hard surfaces, such as roads and pavements in urban areas which have very low densities of weeds between various substrates, e.g., tarmac and paving stones, which is a comparable scenario to false seedbeds.

9.4.7. Repeat treatments

For difficult to kill weeds, the use of repeat / multiple treatments may achieve control. Plants require sunlight to get the energy they need to grow, and depriving them of that light, by repeatedly defoliating them will exhaust their energy and/or nutrient reserves resulting in death (unless they are parasitic). The number and frequency of repeat treatments will vary significantly and depend on a range of factors including: the amount of unharmed biomass remaining after treatment. How much the plants have to regrow before they can start photosynthesising again. The compensation point where photosynthesis is exceeding energy consumption in the plant as a whole. The time of year, e.g., summer vs. winter and therefore how much the plants would be growing without treatment, e.g., many temperate plants are dormant over winter, so are unable to grow during winter months. Commercial suppliers of flame, steam and other non-electrical thermal weeders have been known to demonstrate their machines just as the treated plants are about to go dormant and thus claim many months of control, which had the same treatment been undertaken in spring would of resulted in treated plants regrowing in a few weeks even days. Experiments much thus be setup under realistic conditions, and non-independent results scrutinised for improper methods.

9.5. Foliar biomass

Electrothermal weeding works by directly heating plant tissues, so if it is not contacting any plants, then it is not using any energy, apart from the internal machinery losses (Chapter 15). This means that the more plant biomass that electrothermal weeders treat, the more energy will be required to heat the biomass, and therefore the more fuel will be used and the higher the cost. This also means that because there is an upper limit on the amount of energy that can be supplied to an electrical weeder, e.g., there is a maximum power output from a tractor and the designed output of the weeder, the more biomass that is exposed to electricity the slower the weeding operation will have be to heat all the biomass to lethal temperature. The aim with electrothermal should therefore be to heat as little biomass as possible to minimise energy use, with some provisos.

As discussed above, for most plants, the destruction of the hypocotyl zone and meristems at the base of herbaceous species, is key to effectively killing most plants. Destruction of the plant tissues above-hypocotyl zone shoots is therefore of no benefit if the hypocotyl zone is destroyed. Consequently where there is a large amount of foliar biomass it may more effective and efficient to directly target the hypocotyl zone. In larger plants, e.g., a sapling, this would involve applying the electrode just above the hypocotyl zone, potentially around the full circumference of the stem / trunk to ensure the cambium and phloem are destroyed around the full girth, thus fully girdling the stem. For herbaceous (pasture) species directly targeting the hypocotyl of individual plants is practically more difficult. One approach would be to remove as much of the shoots as possible using alternative approaches, e.g., mowing, thus exposing the leaf and stem bases which can then be targeted with the electrode.

However, mowing may not be more energy efficient than electrothermal treating the whole plant, as mowing also uses energy, often considerable energy (Chapter 16) and (Coleman *et al.*, 2019, 2020), .

In all instances the plant biomass needs to be at a level that the electrical weeder can effectively treat. If biomass is excessive and electrical treatment fails to achieve weed control, this should not be considered a failure of the weeder, rather it is a failure to use the weeder in an appropriate way (section 1.3 and Chapter 11).

The key message is that critical analysis needs to be given to how, where and what the electrode contacts to minimise energy use and maximise efficacy.

9.6. Pre-harvest crop desiccation

Crop.Zone (section 11.6) has had a significant focus on pre-crop desiccation, including potatoes (*Solanum tuberosum*), grains (cereals) and seed crops. There is no know independent research on using EMW of any kind for desiccation, so this is an analysis of the use of electrothermal for desiccation based on general electrothermal theory and public statements by Crop.Zone and farmers using it for desiccation. It also gives a practical demonstration of the information presented above on the interaction of electrothermal and plant morphology.

Potatoes and grain & seed are have very different morphologies (Chapter 8) and location of the harvested portion so make a valuable comparison. For potatoes the harvested portion of the crop is the underground tubers, which are attached to several large fleshy underground stem(s) by thin-ish stolons, at varying distances from its stem. Above ground there are multiple fleshy stems with large soft leaves, called ‘haulm’, between 30 cm to nearly a meter high, with a high wet weight biomass, (Figure 14).

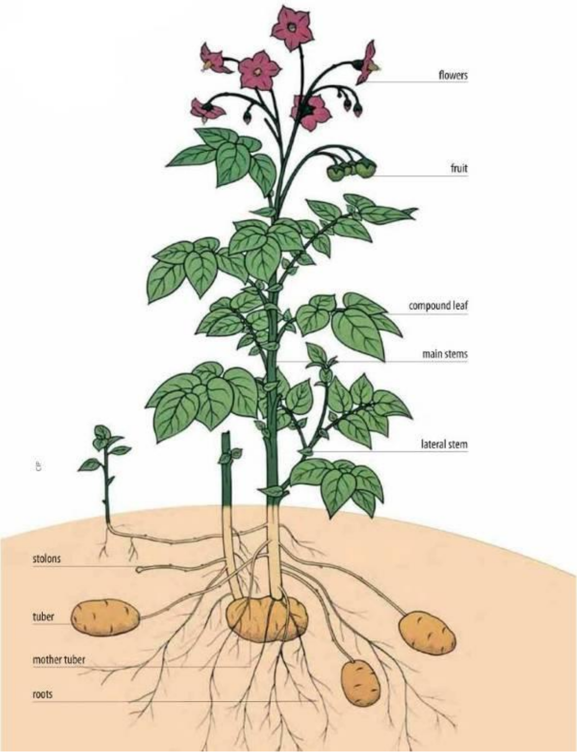

Figure 14. Structure and morphology of the potato plant. Image FAO https://www.fao.org/3/i0500e/i0500e02.pdf

For grain and seed crops, the harvested portion is the seeds and grain which are situated on the top of the plant, either right at the end of the stem as in the ear of wheat, or as an open branched inflorescence. All seed heads are connected to a single stem. While cereals can tiller (produce multiple stems from one plant) each tiller is morphologically an independent plant, i.e., it is not connected to the other tillers (section 9.4.5.3).

9.6.1. Potato desiccation

Successful desiccation of potatoes requires complete termination of all the above ground foliage without getting so much electricity into the tubers that it damages them. The challenge with terminating all the foliage is that it has a large wet biomass, so there is a large weight of material, with a high water content that must be heated up. Water has a high specific heat capacity[17] so takes a lot of energy (joules) to heat up. The thick fleshy aboveground stems continue into the soil for up to 30 cm before they transition into true roots (Figure 14). The stems therefore have the potential to conduct electricity under ground and transfer it into the tubers. However, as the tubers are connected to the underground true stems by thinner stolons, these have the potential to act as a fuse (section 9.4.3) being destroyed by the electricity before it can reach the tuber. This will depend on the length of the stolon / how close the tubers are to the main underground true stem. To achieve good desiccation with minimal tuber damage, having electrodes that can flatten down the haulm, and thus contact a large area of the foliage, along with using double or multiple electrodes (section 8.5). Also creating the electrical circuit mostly or entirely through the haulm, rather than down the stems and into the soil is likely to improve efficiency and minimise the risk of tuber damage (Chapter 7). Having advanced electronic control systems that can manage the power flow though the small areas of foliage so they are heated just enough to terminate them without extra heating will also improve energy efficiency and therefore treatment speeds.

9.6.2. Grain and seed desiccation

Grain and seed create a quite different challenge. At least some of the seed is likely to be directly exposed to the electrical currents / contact the electrode, so if too much power is used their quality and germination could be affected, to the point they are worthless. What is required is to sufficiently disrupt or destroy the vascular system in the stem in and below the grain and seed bearing areas, such that it no longer translocates water, allowing the seed and grain heads to dry out. Beneficial factors include: that grains and seeds are round (some are completely spherical), they will already be lowering their water (moisture) content as they are maturing, and have a small vascular attachment to the plant, so they will likely be less likely to be exposed to and be susceptible to the electricity. Cereals have a long thin stem, which is readily damaged by electrothermal treatment, so disrupting the vascular system. Negative factors are that too much electricity could cause the stem to disintegrate, making harvest difficult or impossible. Seed bearing plants, being dicotyledons, typically have thicker stems, potentially over a centimetre in diameter in species such as oil seed rape (*Brassica napus* sub species *napus*). This will require more electrical energy to damage sufficiently. In compensation the seeds are typically distributed through a large inflorescence, meaning only a few will directly contact the electrodes and be at risk of harm. Placing the electrodes so they contact the lower parts of the stem and travel up the stem means that the stem will be electrocuted first, and then continue to be electrocuted as it travels along / up the stem, with the seeds exposed last. Again having two electrodes (positive, and negative) touching the same stem, rather than using an electrical earth would keep the electricity within the stem, maximising damage while minimising the risk to non-targets. Having the electrodes sufficiently far apart that they cannot bridge the seed bearing area would further reduce the risk of seed and grain damage. Just having the electrodes contact the top of the plant likely to be less effective.

These two examples thus highlight the potential complexity of crop desiccation using electrical weeders. Desiccation of one crop may thus have quite different requirements to another crop.

---

[17] https://en.wikipedia.org/wiki/Specific_heat_capacity

9.7. Reducing seed viability

In complete contrast to using electrothermal for crop desiccation where it is critical that the crop's seeds and grain are not negatively affected, Schreier *et al.*, (2022) studied reducing weed seed viability on the plant through electrothermal treatment. A Weed Zapper (section 11.5) was used to treat a range of weed species, at a range of grow stages up to seed set, in the absence of crop plants. The horizontal bar electrode was positioned 30 cm from the ground which means for most of the weeds it would have been in contact a considerable duration as it travelled along the weed stem. Seed viability was reduced between 54% to 80% depending on species, indicating that there is a species effect. The species effect could be due to a number of factors including morphology of the seedhead and thus how much of the seeds were exposed to electricity.

This highlights that there is potentially quite a small window between effectively desiccating crops and significantly harming the harvested product. Electrothermal weeder design and operating principles are considered likely to be crucial in this respect. Achieving sufficient control over the properties of the electricity produced in older electrical designs such as the Weed Zapper to achieve desiccation without crop seed / grain damage is likely to be challenging. Newer electronically controlled designs such as Crop.Zone are considered likely to be essential.

9.8. Evolved resistance

One of, if not the, most important issue facing herbicides is evolved resistance. This raises the question if plants could become resistant to EWM.

There are two types of herbicide resistance, target site and non-target site resistance (Ghanizadeh *et al.*, 2023). Target site is where there is a mutation in a gene that codes for a particular protein or other biochemical that a particular herbicide chemistry targets - as in the example of glyphosate interfering with amino acid synthesis (section 9.1). Non-target side resistance is much broader, e.g., mutations may increase the rate at which a herbicide is denatured, or moved to vacuoles in cells where it can do no harm. These all involved changes to a plants biochemistry. From single nucleotide that codes for a single amino acid in a protein in target site resistance, to much larger changes across multiple genes in non-target site resistance.

In comparison electrothermal causes physical harm plants, from denaturing proteins, through to destroying cells, to complete destruction of entire plant parts, e.g., a bulb. It is very difficult to see how plant can evolve resistance to such complete and wholesale forms of damage, so, it is considered impossible for plants to evolve resistance to electrothermal treatment itself. It could be possible for plants to evolve to avoid electrodes, e.g., becoming shorter than the crop so weeders that till crop overtopping weeds are no longer effective. This would require that use of a single approach to be the main, if not only, form of managing that weed species. All recommendations around herbicide resistance management are to increase the diversity of weed management approaches, within an IWM system (section 1.3). Thus if used as part of a diverse IWM the risk of weeds evolving resistance to electrothermal is considered low.

As electrobiological mode of action(s) has not been determined it would be premature to make a statement about the ability of weeds to develop target site resistance. The same comments regarding non-target site that applies to electrothermal are considered to equally apply to electrobiological.

9.9. Electrobiological and plant morphology and growth

It is hypothesized that electrobiological weeding may interact with plant morphology and growth differently to electrothermal. This is because the power (watts) of electrobiological is vastly lower than electrothermal so it will not destroy plant tissues, e.g., leaf petioles, that prevent high voltage electricity reaching the critical plant parts (e.g., meristems) and the long duration treatment times potentially allowing the electricity to spread throughout the plant, even deep underground. This is considered particularly important for hard to kill plants with extensive underground organs which they can regenerate from. Research is required to address these knowledge gaps.

Chapter 10. Environmental conditions

10.1. Key points

- Environmental conditions can have significant impacts on the effectiveness of EWM;
- Soil texture, which also affects soil organic matter and moisture (soil water content) impact the conductivity of soil and thus EWM effectiveness;
- However, poor conductivity may be an advantage when electricity is required to penetrate deeper into the root system / underground organs to kill these structures where they have the ability to dedifferentiate and regenerate;
- Rain and wet plants are generally considered incompatible with safe and effective electrothermal weeding;
- In comparison, EWM is unlikely to be affected by wind unless it blows plants away from the electrodes. This contrasts with herbicides that are clearly affected by wind speed;
- Dry conditions on the other hand are a potential fire risk, where this is a non-issue for herbicides applied by spraying.

The effectiveness of electrothermal weeders is affected by a range of environmental conditions. It is unknown how they would affect short duration electrobiological weeders. There is limited research on the interactions of environmental conditions of EWM efficacy as a whole, and while a number of review papers make statements about environmental conditions, the amount of original research found is very limited, so the area is in need of considerably more research.

10.2. Soil texture

Soil texture (also called type) is the proportion of sand, silt and clay that compose the mineral fraction of soil. Sand and silt are chemically and electrically inert small particles of rock. Clay is a range of hydrous aluminium phyllosilicate minerals, some of which carry electrical charges. Different soil textures consequently have different electrical properties, including conductivity / resistance, which can impact the effectiveness of EMW. Generally sandy soils have the poorest conductivity while clays have the best.

Soil texture impacts other aspects of soil properties, such as moisture and organic matter (see below) which also affects conductivity so can also impact the effectiveness of EWM. Sandy soils have lower moisture holding capacity and organic matter both of which are likely to result in lower conductivity, reinforcing their inherent lower conductivity. Clays have the highest moisture holding capacity and organic matter boosting their inherent conductivity.

Soil texture can be highly variable, even within single fields, requiring electrical weeders to be able to adapt to the varying electrical properties of the different textures.

10.3. Soil moisture

Soil moisture can affect EWM in multiple ways.

10.3.1. Soil conductivity

Soil moisture (water) content can have a significant impact on the conductivity / resistance of soils, with moister soils being better conductors. Moisture and texture interact, as different textures hold different amounts of water, with sands holding the least and clays the most, as noted above. Better soil conductivity reduces loss of electricity in the soil so improving efficiency, but, where underground organs need to be killed lower conductivity can be beneficial in keeping the electricity within the plant further underground (section 10.3.4).

10.3.2. Plant moisture content - turgor

Soil moisture also affects plant turgor, with turgor reducing as soil moisture approaches permanent wilting point. Plant turgor could impact the effectiveness of EWM. Schreier *et al.* (2022) found a significant correlation between plant moisture content and weed control across a range of weeds with higher moisture resulting in lower kill. This is the only know research studying this effect, so more research is required. As discussed in section 9.5 the more water there is in a plant the more water there is to heat and therefore the more energy required.

10.3.3. Post treatment recovery

Soil moisture may also affect plants ability to recover post treatment. For most forms of mechanical weeding hot dry conditions increase weed mortality due to post-treatment desiccation compared with cool wet conditions. There is potential for plants not killed outright by EWM may have greater mortality in hot dry conditions than cool wet ones. There may also be interaction with the size and morphology of treated plants (Chapter 8) with soil moisture leading to differing plant recovery and survival depending on plant size.

10.3.4. Affect on extent of electricity penetration through roots / underground organs

Soil moisture may also affect the depth / distance that electricity can penetrate plant roots /underground organs. Theoretically, as plant roots are inherently moist, and once intial resistance is overcome, the roots are potentially a path of lower resistance than the soil (section 5.4.6). How soon the electricity leaves the roots will depend on the conductivity of the soil. In a highly conductive soil, it would be expected that the electricity will rapidly exit the root system through multiple paths close to the soil surface. Where the soil has poor conductivity, or even has high resistance, e.g., a dry very sandy soil, then the electricity may penetrate deep into the root / underground, where soil would be expected to be moister and exit via a more limited number of paths. There is limited research that confirms this analysis. Vigoureux (1981) found that control of sugar beet (*Beta vulgaris* sub species *vulgaris* (var. *saccharifera*)) bolters increased in dry conditions. Beets (including beetroot) are swollen hypocotyls (section 9.4.1.2) not swollen roots as is commonly understood[18], so they may be a special case due to the Achilles' heal nature of the hypocotyl (section 9.4.1.2). Lati *et al.* (2021) found that redroot amaranth (*Amaranthus retroflexus*) was controlled better in moist soils than dry, but, as this was conducted in pots, the translation to field conditions is not clear as the performance of electrothermal weeders in pots is known to be higher than in the field (Diprose & Benson, 1984a).

In very poorly conductive soils, e.g., very dry, the benefit of deeper penetration by the electricity may be cancelled by the high resistance of the soil dissipating large amounts of electrical energy as it returns to the weeders earth.

The depth of penetration by electricity of roots and/or underground organs is irrelevant if the electricity has destroyed the hypocotyl and the plant is unable to regenerate from underground tissues (section 9.4.1.2).

10.4. Soil organic matter, pH and plant available nutrients

Soil organic matter, pH and plant available nutrients are known to effect the electrical conductivity of soils (Brady & Weil, 2008). Electrical conductivity is used to measure soil nutrient content (Brady & Weil, 2008). However there is no know research studying the how different organic matter, pH and/or nutrient levels impact field use of conductivity as that impacts the high voltages used in EWM.

---

[18] https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:164505-1/general-information

10.5. Soil management

How soils are managed can affect soil organic matter, moisture, pH plant available nutrients and density (compaction), which in turn may affect electrical conductivity. These management effects can be very small scale, for example between the herbicide strip under perennial crops and the pasture in the tractor alleyway (interrow). Such situations could be valuable for researching the impacts of these soil conditions on EWM.

10.6. Rainfall and external plant water films

External water films on plants (wet plants) are likely to result in the electrical current travelling down the water films rather than through the plant (Diprose, M. pers. comm.). Treating wet plants is therefore likely to result in lower or no plant kill. However, Crop.Zone are using a water based salt solution to reduce the initial high electrical resistance of the plants, which would appear to contradict the issue of water films short circuiting plants. However the Crop.Zone system is applying a small amount of salt solution to the top of the plants, which contrasts when the whole plant surface is wet. However, there is no independent research into the use of salt solutions in EWM so the function of the salt solution cannot be verified. Clearly another area where research is required.

It is generally considered unsafe to use EWM, especially electrothermal, when it is raining due to the potential for the high voltage electricity to find alternative circuits that are dangerous, e.g., over / though the weeding machinery, tractors, etc. (section 14.3).

10.7. Wind impacts and comparison with herbicide application windows

There is no known research looking at the impact of wind on EWM. It is suggested that unless conditions are so windy that the plants to be treated are being blown away from the electrodes, EWM should be mostly unaffected by wind speed. Again, research is required.

This lack of wind impact contrasts with herbicides which cannot be applied when it is too windy due to drift and the herbicide ending up on non-target areas or insufficient wind in some situations. This is considered to be an important additional advantage for EWM in locations where herbicide spraying is often prohibited by wind speed, i.e., that EWM can be conducted in windy conditions that would prevent herbicide spraying. In contrast, herbicides can be applied in dry conditions that would preclude the use of EWM due to fire risk (section 14.2). Thus, as discussed in section 15.7 for different thermal weeders, EWM and herbicides are complimentary for some environmental application conditions, meaning when the situation prohibit the use of one technology the other can still be used.

10.8. Dry conditions

As discussed in section 14.2, electrothermal is a fire risk and should not be used in dry conditions where fires could start.

Chapter 11. Electrothermal companies and machines

11.1. Key points

- There are currently five companies making electrothermal weeders. In chronological order of founding:
    - Lasco Inc. lightningweeder.com;
    - Zasso Group AG zasso.com;
    - Rootwave - Ubiqutek Ltd. rootwave.com;
    - The Weed Zapper - Old School Manufacturing, LLC theweedzapper.com;
    - Crop.Zone GmbH crop.zone.
- There are also two robotic weeders using electrothermal to individually kill weeds.

This section gives a brief summary of the EWM companies and machines they produce. It is only a brief summary because: There is a large amount of information about the companies and their machines on the internet, including the company's websites, YouTube, agricultural media, research organisations, etc. There is (very) rapid development of new machines and applications, information about EWM machines and companies thus quickly becomes out of date. There are also issues of copyright of images and videos, commercial sensitivities around the details of the weeders designs, and very limited technical information publically provided by the companies, which limits what can be presented here. Thus it is assumed that the reader can find the information about the companies and their weeders they want themselves. Slaven *et al*., (2023) also provides a comprehensive list of weeders available at the time of writing.

11.2. Lasco Inc.

Lasco (lightningweeder.com) first produced the 'Lightning Weeder' in the 1970s (Kautman & Schaffner, 1979) taking out a patent in 1975 (Pluenneke & Dykes, 1975). A considerable amount of research of a wide range of weeder designs was undertaken (section Chapter 3). However, only the Lightning Weeder is still produced. It is designed for killing weeds taller than the crop using a horizontal electrode spanning several meters.

11.3. Zasso Group AG

Zasso (zasso.com) was founded by Satoru Narita as Sayyou in 1992 in Botucatu Brazil[19]. It undertook extensive development over the next two decades. In 2016 the company renamed to Zasso Group AG, it moved its head office to Switzerland, and opened manufacturing site in Germany as Zasso GmbH (which is 100% owned by Zasso Group AG). In 2020 CNH Industrial[20] acquired a minority stake in Zasso Group AG[21].

Zasso initially produced a contiguous weeder (Merfield, 2023b) that kills surface vegetation using thin, flexible metal strips that follow the ground contour. They now offer an increasing range of machines all based on the flexible metal strip system for a wide range of annual cropping systems, urban areas including road corridors and hard to reach areas with a weeder unit on a hydraulic arm, perennial cropping systems (fruit, nuts, vines) as well as crop desiccation, a self-propelled pedestrian controlled weeders plus a hand-held spot weeder.

---

[19] https://zasso.com/about/ and https://zasso.pwdev.de/category/history-timeline/

[20] https://en.wikipedia.org/wiki/CNH_Industrial

[21] https://media.cnhindustrial.com/EMEA/cnh-industrial/cnh-industrial-acquires-a-minority-stake-in-zasso-group-ag/s/cd9fa2f1-cabc-4633-be07-48d085583815

11.4. Rootwave - Ubiqutek Ltd

Rootwave (rootwave.com) started out as Ubiqutek Ltd. in 2012[22] founded by Dr Mike (Michael) Diprose and his sons Andrew and Robert. Dr Mike Diprose undertook a wide range of research in the 1970s and 1980s on EWM in the UK (Diprose *et al.*, 1978; Diprose *et al.*, 1980a; Diprose *et al.*, 1980b; Diprose & Benson, 1984b, 1984a; Diprose *et al.*, 1985; Diprose & Mattsson, 1993; Diprose *et al.*, 2009). Rootwave initially developed a hand applied weeder the 'RootWave Pro' based on a generator and transformer carried on a farm truck or side by side. More recently they have developed a perennial crop weeder using a flexible electrode system and are also developing an annual rowcrop weeder. They have also developed and patented very high frequency - 18 kilohertz (kHz) - systems which is safer than mains frequency of 50 hz (see section 5.4.2.1) and is also claimed to be much more energy efficient[23]. They also license their technology to other companies.

11.5. The Weed Zapper - Old School Manufacturing, LLC

The Weed Zapper (theweedzapper.com) - Old School Manufacturing, LLC was established in 2015 in the USA by two brothers Michael and Benjamin Kroeger, with experience in both farming and electrical engineering[24][25]. Their machine is similar to the Lasco Lightning Weeder being a horizontal bar electrode designed for killing crop overtopping weeds. There are a range of different machine widths from 4.5 to 12 m[26].

11.6. Crop.Zone GmbH

Crop.Zone (crop.zone) was registered in 2019 in Germany. In 2020 it started a collaboration with Nufarm[27] (a global crop protection and seed technology company[28]). In 2022 Crop.Zone also joined the John Deere Startup Collaborator program[29]. Crop.Zone developed an electrode system based on multiple, short (~ 50 cm) horizontal bars, underneath a modular, ground following, hood. Crop.Zone initially focused on crop desiccation, initially potato (*Solanum tuberosum*) and more recently cereals and oilseeds. It is also claimed to be used for pre-planting and pre-emergence weeding. The weeder is combined with a proprietary water based salt spray, applied to the plants just before electrocution to improve the electrical conductivity of the crop (section 9.2), in turn to improve energy efficiency. The field machine was initially 9 and 12 m wide with a 24 m machine added in 2023.

11.7. Robotic weeders using electrothermal

Robotic weeding is currently advancing very rapidly (Merfield, 2023a). The latest generation of robots (Level 3) identify individual weeds plants and then separately kills them, using tools such as lasers, focused blue light and electrothermal (Merfield, 2023a). Currently two companies are known to have robotic weeders using electrothermal: the Small Robot Company's (smallrobotco.com) 'Dick' robot and BH Frontier Solutions Inc.'s (bhfsolution.com) 'Agrobot' robot. There is very little publically information available about the EWM systems on these robots. It is suggested that short duration electrobiological systems (Chapter 6) would be particularly valuable for robotic weeders due to their very low power consumption.

---

[22] https://find-and-update.company-information.service.gov.uk/company/08148525

[23] https://rootwave.com/high-frequency-electricity-gives-better-weed-control-with-lower-energy-use/?avia-element-paging=3

[24] https://theweedzapper.com/about/

[25] https://patents.justia.com/assignee/old-school-manufacturing-llc

[26] https://theweedzapper.com/the-weed-zapper/pricing/

[27] https://nufarm.com/announcements/nufarm-and-crop-zone-announce-collaboration-to-bring-alternative-weed-control-to-major-european-markets/

[28] https://nufarm.com/

[29] https://crop.zone/en/news/john-deere-wird-neuer-partner-von-crop-zone/

Chapter 12. It is no longer possible to draw broad conclusions about EWM from testing single machines

12.1. Key points

- Even if it was possible in the past to make general statements about EWM as a whole from studying the performance of one electrical weeder, due to the increasing complexity, sophistication and diversity of machines this is no longer possible;
- Making comparisons or extrapolating between, electrothermal and electrobiological is considered mostly invalid. It makes as much sense as doing the same for contact and systemic herbicides;
- It is proposed that research would be better aimed at working on the fundamental mode of action of different types of weeder / forms of electricity and how they interact with plant morphology and environmental variables;
- On-farm performance weeder performance can be evaluated by farmers outside the constraints of peer reviewed research.

With growing interest in EWM there is growing amount of research studying the performance of electrical weeders. This frequently has the aim of discovering what the broad capabilities of electrical weeders are based on the performance of one machine, often based on real-world (i.e., real farming situations) senarios. It is suggested that while that may have been valid when most weeders had similar designs, that assumption is no longer considered to be correct due to the increasing divergence between basic electrical weeders and more advanced electronic controlled weeders (Chapter 8). To use a herbicide analogy, it is impossible to extrapolate the performance of all herbicides based on the performance of one selective systemic herbicide. Likewise it is no longer possible to extrapolate the performance of EWM from single machines or one experimental setup. This is particularly true of comparing electrothermal with electrobiological: it is like comparing broadleaf selective with grass selective herbicides, it does not make sense. However, there are many instances where this form of statement appears in regards to EWM. It is therefore considered critical that electrical weeders are considered in the same way as herbicides, that, the full details of the electrical weeder are given — its ‘mode of action’ — and that the weeder is appropriate for the kind of weed control that aims to be achieved. Only machines with the same mode of action should be compared.

Likewise it is vital to test electrical weeders in the correct way. Another herbicide analogy, no one would consider the application of a broadleaf selective herbicide to grasses a failure if it failed to kill the grasses, rather it would be viewed as a failure of the applicator to understand how the herbicide worked. However, comparable errors are increasingly being made with testing of electrical weeders, where they are being used in situations for which they are not suited.

Further, it is argued that there are often complex treatment interactions e.g., plant morphology × plant size × treatment technique (duration, voltage, amperage, etc. constant electrical state vs. on-the-fly electronic adjustment) × electrode design. Varying one of these could well change the outcome, potentially significantly. Thus the same as for herbicides, where no one would extrapolate the results from a specific real-world herbicide experiment / situation (e.g., crop species, weed species, exact herbicide product / formulation, water rate, application method, weather, etc.,) to all of herbicides, it is no longer considered possible to extrapolate from specific real-world EWM experiments / situation, to all of EWM.

It is suggested what is required for EWM is the herbicide equivalent of understanding the biochemical mode of action, e.g., glyphosate acts by inhibiting the plant enzyme 5-enolpyruvylshikimate-3-phosphate synthase. This requires laboratory, glasshouse and field based research to determine the fundamentals of how electricity interacts with plants, both electrophysical and particularly electrobiological so truly generalisable knowledge can be developed which can inform current usage and the next generations of electrical weeders.

Chapter 13. Impacts on soil biology

13.1. Key points

- A common concern about electrothermal, and thermal weeding as a whole, is negative impacts on soil biology;
- Research shows no or limited statistically significant effects, both positive and negative, however, statistically significant results are often biologically non-significant;
- It is suggested that this concern is misplaced, many other farm activities, e.g., leaving soil bare, tilling / cultivating are far more harmful to soil;
- The biggest negative impact of EWM, and both physical and chemical weed management as a whole, is that their primary purpose — the elimination of non-crop plants — is by far the largest cause of negative soil health impacts due to the large reduction in plant biomass and diversity that results.

A common concern about electrothermal, and thermal weeding as a whole, is negative impacts on soil biology. There is a small number of papers (peer and non-peer reviewed) studying the impacts of electrothermal.

Ruf *et al.*, (2023) compared a 72 kW Zasso Xpower system (electrothermal) with a chisel plough (mechanical) or glyphosate (herbicide) applied to a grass and clover pasture on: the effectiveness of pasture kill, hot water extractable carbon (HWEC) (a surrogate measure of microbial biomass) and earthworm biomass. There was no immediate effect on earthworms but two weeks post treatment there was a significant drop in earthworms in the tillage treatment. Six months post treatment both mechanical and electrothermal had statistically significantly lower worm biomass than the herbicide and control, although the absolute biomass differences were not biologically large. Likewise while the electrothermal treatment had significantly higher HWEC the biological differences were not large.

Schild *et al.*, (2017) in a non-peer reviewed report undertaken for Zasso found results on soil biology were found to be inconclusive in terms of impacts on earthworms as soil texture, temperature and moisture content were confounding factors. In very moist soils they suggested the impacts could be significant. Similarly for microbial biomass the causes where differences were found were unclear and the indirect impact of increased nutrient availability and dead biomass providing improved conditions for microbial growth could not be determined.

In another non-peer reviewed report Borger & Slaven (2022) using a 36 kW Zasso system with a 55 cm wide applicator applied at 1.4 kph with zero to three applications found it had no effect on the root crop pathogen *Rhizoctonia solani*. It was hypothesised that as the *R. solani* was in direct root contact with the treated plants, if direct negative impacts of electrothermal on soil biology were to occur, this would be the best-case scenario to see an effect. That no effect was seen led them to suggest that direct negative impacts on wider soil biology were unlikely.

Löbmann *et al.*, (2022) using a Zasso weeder in a vineyard compared the impact of electrical treatments with mechanical weeding on earthworms and epigeic arthropods (‘insects’ that live on the soil surface). They found no impact on earthworms though the data had high standard errors (the data were noisy). No statistically or biological significant differences were also found for epigeic arthropods.

Tatnell *et al.*, (2020) as part of a study developing the RootWave perennial crop weeder, measured the soil microbial activity by CO_2 burst test, one hour and one week post treatment. There was no difference one hour post treatment, indicating no immediate impact on soil microbes, but there was a week later with higher CO_2 from the treated plots, which it was suggested was due to microbes feeding on the killed plant roots.

There are no known studies of the impacts of foliar flame and steam weeding on soil biology. Intrarow soil thermal weeding (Merfield, 2013a) has been clearly shown to have negative impacts (Elsgaard, 2010; Elsgaard *et al.*, 2010).

It is suggested that the concern about negative impacts of thermal weeding on soil biology and health are misplaced. While there are no studies looking at the temperature increase of soil around plants electrothermal treated plants, practical experience with flame and steam weeders has found that the soil surface (< 1 cm deep) is warmed by a few tens of decrees Celsius, such that that a hand can be placed on the soil directly after treatment and it feels warm, not uncomfortably hot. In comparison, bare soil on a hot summers day can be too hot to touch, so bare soil will be much hotter for a much greater period of time due to heating by the sun than from flame and steam weeding. In addition electrothermal weeders heat plants directly while flame and steam weeders mostly heat non plant targets (Chapter 15) thus electrical weeders would be expected to discharge much less energy into the soil, so should not heat it anywhere to the same amount.

Further tillage is well known to have large negative impacts on soil biology (Kladivko, 2001). With the revolution in soil organic matter formation from plant root exudates it is clear that the largest negative impact on soil biology by weed management is the removal of plant biomass and diversity (Cotrufo *et al.*, 2022). This means that the fundamental aim of physical and chemical weed management — killing weeds — i.e., reducing plant diversity and biomass, is likely to have the largest negative impact of EWM on soil biology (Curtin *et al.*, 2015) compared with the direct impacts of weed treatments, e.g., direct effect of herbicide chemistry, heat and electricity on soil biology. The largest negative impact of EWM is therefore if it is used as a straight substitute for herbicides with the objective of eliminating all non-crop vegetation. Thus as discussed in section 1.5, from an agro/ecological weed perspective, EWM should only be used to manage / eliminate vegetation that is causing significant harm (Merfield, 2022) and the aim of weed management should move to agroecological approaches such as intercropping, which increases plant diversity and biomass while still maintaining crop productivity and quality.

Chapter 14. Health and safety

14.1. Key points

- EWM, and electrothermal in particular uses inherently dangerous forms of electricity;
- All commercial machines have undergone extensive safety testing, either under American or European standards;
- Thus when used correctly they are no more hazardous than other weed management technologies, e.g., herbicides, machinery;
- Electrothermal is a clear fire risk and must not be used in dry conditions, at least without suitable fire fighting equipment;
- Currently electrical weeders cannot be used in the rain and performance may be considerably reduced if plants are wet;
- Step potential is a risk for some weeders and suitable protective equipment is required.

A key, if not the biggest concern many people have about EWM, particularly electrothermal, is if the machinery is dangerous. High voltage electricity (1,000-15,000 V), particularly at mains electricity's 50 Hertz as used in some electrothermal weeders, is a clear safety hazard. While some of the new machines designs use forms of electricity that are lower risk, e.g., very high Hertz, they are still hazardous due to the amount of energy they produce. Machinery therefore includes a range of safety features, such as:

- Machines are designed with protection systems to keep users and other people and animals near them, safe;
- Extensive user instructions and protocols on machine use;
- Protective covers over the electrodes;
- Barriers to stop people and animals being able to reach / touch the electrodes;
- Tractor drivers seat switches so the driver must be sat in the tractor for the machine to operate;
- Various warning signs and flashing lights;
- Use of dielectric (insulated (yellow)) wellington boots, and other insulated / protective clothing.

Safety features such as these ensure the weeders are compliant with the health and safety legislation of the countries the machines are being sold / operating in. If an electrical weeder is compliant with legislative requirements it is safe if used as directed.

In comparison, many of alternative tools to electrical weeders and other farm equipment are also hazardous, even dangerous if not used correctly and with proper health and safety protocols, e.g., line trimmers, chainsaws, tractor mounted mechanical weeders and tillage tools, especially if they are powered from the tractors PTO. Thus when used correctly electrothermal weeders are considered no greater hazard than other machinery used for similar purposes.

As electrobiological weeders operated at much lower power, and forms of electricity that are much less dangerous than 50 Hz, they are considered to be a much lower to almost zero hazard risk. However, some may still be able to cause pain, e.g., similar to an electric fence. Such designs will also need appropriate protection systems and be used correctly.

14.2. Fire risk

Electrothermal weeders can generate sparks which along with the direct heating of vegetation can ignite dry vegetation causing a fire (Diprose & Benson, 1984b). There is again limited research on this issue. Borger & Slaven (2022) studied the impact of operation speed, type of residue and residue biomass and found that speed and type of residue effected fire risk but not amount of biomass. They concluded that EWM could not be used on sites with dry residue in summer.

14.3. Rain and wet conditions

As noted in section 10.5 it is not considered safe to use EWM, particularly electrothermal, in wet conditions and especially when there is precipitation.

14.4. Step potential

‘Step potential’ is a form of ‘earth potential rise’[30] which is where a large current flows to earth through an earth grid impedance. The potential is highest at the point where current enters the ground, and declines with distance from the source. Step potential or ‘step voltage’ is the voltage difference between the feet of someone, or animals, standing on the ground. If the step potential is large enough electricity can flow up the leg(s) closest to the current source and down the other leg(s). If the step potential is sufficiently large this can injure or even kill.

Electrothermal weeders have the ability to create step potential that could be hazardous, particularly as the distance between the electrode and earth increases. Where step potential is a risk, the use of dielectric (insulated, yellow) wellington boots is recommended by manufacturers along with a range of other safety measures.

---

[30] https://en.wikipedia.org/wiki/Earth_potential_rise

Chapter 15. Comparison of electrical weed management with other thermal weeders

15.1. Key points

- The key difference between electrothermal and other foliar thermal weeders is that electrothermal heats plants directly, while the others heat plants indirectly. This makes electrothermal orders of magnitude more efficient than other thermal weeders;
- Electrothermal has in many cases a systemic mode of action while other foliar weeders only have a contact action;
- Electrothermal cannot operate when there is a fire risk while steam, hot water and foam can;
- Electrothermal also cannot operate in wet conditions, while flame, steam, hot water and foam can;
- Thermal weeders, along with herbicides have complimentary weeding conditions - such that when one weeder cannot operate, another can. This considerably widens the environmental conditions under which weeding can be undertaken. This is at the cost of increase capital expenditure on extra weeding machinery.

The key difference between electrothermal and other foliar thermal weeders such as flame, hot water, hot foam and steam is that electrothermal heats plants directly, while the others heat plants indirectly.

Soil thermal weeders (Merfield, 2013b, 2013a) are excluded from this analysis as they have a completely different aim and mode of action compared to foliar applied thermal weeding.

15.2. Energy efficiency

In an electrothermal weeder when the electricity is applied to a plant, the initially high electrical resistance of the plant causes the electrical energy to be converted into heat energy inside the plant, thus the plant is heated directly. Some energy is also lost on the return path through the soil, but as soil is generally a reasonable to good conductor, and has a large bulk for the electricity to travel through, these losses are comparatively small. If the electrothermal weeder is not touching any plants, so the electrical circuit is not completed, then no electricity is used, so the power consumed by the weeder is only that used to maintain a steady state: colloquially ‘tick-over’. In comparison when a large amount of plant biomass is being heated the power requirements are very high. For example, research in the 1970s in the United Kingdom controlling sugar beet bolters using a 54 kW, 6 m wide electrothermal weeder powered by a 75 kW tractor, the tractor would stall if too many bolters were contacted at the same time (Diprose *et al.*, 1985; Diprose pers. comm.)

In comparison flame weeders use heated air to transfer heat into plants. As air is a very good insulator / poor conductor of heat and has a very low energy density, it is one of the least efficient means of transferring heat. Infrared flame weeders use red-hot ceramic plates to create infrared radiation that then heats the plants. Steam weeders also heat the air, but, it is principally the latent heat of condensation of the steam that transfers most of the energy. In comparison hot water and foam weeders transfer the heat via liquid phase water. In all of these approaches, the heat is generated by burning a fuel, e.g., diesel or LPG (liquefied petroleum gas), to create a flame which then heats the transfer medium, i.e., air, water or ceramic plate, which is then used to heat the weeds, thus the plant is heated indirectly. This typically means that the weeders run continually at full power, regardless if weeds are present or not which is one reason why they are inefficient. Further as weeds typically make up only a small proportion of the materials that are heated, which are mostly the soil surface and the air (atmosphere) their efficiency can be very low, often less than

1% (Merfield, 2006). Electrical weeders are therefore much more energy efficient than other thermal weeders. See Chapter 16 for comparison of energy use with herbicides and other mechanical weeding techniques.

15.3. Systemic vs. contact herbicide effects

All non-electrical thermal weeders (flame, steam, hot water, foam) can only target and kill above ground vegetation. As discussed in Chapter 11, due to the large amount of soil and its high specific heat, non-electrical thermal weeders only cause a small amount of soil heating, and that is confined to the surface (<1 cm). It is thus impossible for such weeders to achieve a systemic kill, i.e., kill the roots and other underground organs. They are thus comparable to a contact herbicide not a systemic herbicide.

15.4. Post-crop emergence selective weeding

That non-electrical thermal weeders are comparable to contact herbicides means they can be used for post-crop emergence selective thermal weeding (Dastgheib *et al.*, 2010). This is used from soon after emergence for about a month on crops with a morphology that makes them resistant to the thermal weeders (Chapter 8) while the weeds are susceptible. Electrothermal could not be used as the systemic effect would kill the young crop plants.

There could be other situations where a contact rather than a systemic effect is required meaning only non-electrical thermal weeders would be suitable.

It is noted that Level 3 robotic weeders (Merfield, 2023a) (some of which use EWM, section 11.7) are an alternative to post-crop emergence selective thermal weeding based on complete defoliation.

15.5. Fire risk

EWM, especially electrothermal is a fire risk in dry conditions (section 14.2). This limits the conditions they can be used in. In comparison steam, hot water and hot foam weeders are not a fire risk, indeed, due to the presence of water they could extinguish smouldering vegetation and very small fires. These weeders can therefore be used in dry conditions that prohibit the use of electrical weeders. Flame weeders are a very high fire risk as they will set light to any material that is capable of burning.

Crop.Zone's use of a salt based spray in conjunction with it's electrical weeder raises the question if this has any impact on the fire risk of this system. The salt spray is likely to have two effects, (i) the presence of water, even if in small amounts, should reduce the risk of vegetation catching fire, and, (ii) if the salt solution reduces the resistance of the plants to electricity entering this may reduce the risk of sparks. There is very little independent research studying fire risk of electrical weeders as a whole and no known study into the fire risk of the Crop.Zone system.

15.6. Wet conditions

Currently EWM is not considered safe to use when it is raining, and can loose efficacy when plants have surface moisture (section 14.3). Flame, steam, hot water and hot foam, can be used in the rain and on wet plants, though efficacy may be slightly reduced due to the extra water on the plants that has to be heated up.

15.7. Weeder complementarity for different environmental application conditions

Due to the ability to work in dissimilar environmental conditions (e.g., dry, raining, as discussed above) EWM, flame, steam, hot water and foam are considered complimentary, in that were conditions preclude one machine, another could still be used. This also applies to herbicides as discussed in section 10.7. Complementarity of environmental operating conditions broadens the times that weeding can be undertaken, potentially increasing the overall effectiveness and flexibility of on-farm weed management systems, i.e., an integrated weed management (IWM) / many little hammers approach (section 1.5). However, this comes at the cost of increased capital expenditure on the different types of machines.

Chapter 16. Comparative energy consumption

16.1. Key points

- Electrothermal currently has among the lowest energy use on a lifecycle analysis of all weed management technologies, lower than herbicides, tillage / cultivation and particularly other thermal weeders.

Electrothermal weeders use between 10 and 100 Mj/ha while the other thermal weeders use between 1,000 and 10,000 Mj/ha, and herbicides (total energy of both production and application) between 150 and 700 Mj/ha (Figure 15), (Kaufman & Schaffner, 1982; Coleman *et al.*, 2019, 2020; Bloomer *et al.*, 2022). Electrothermal weeders therefore use orders of magnitude less energy (fuel) efficient than flame, infrared and steam weeders, and even less than herbicides (Figure 15).

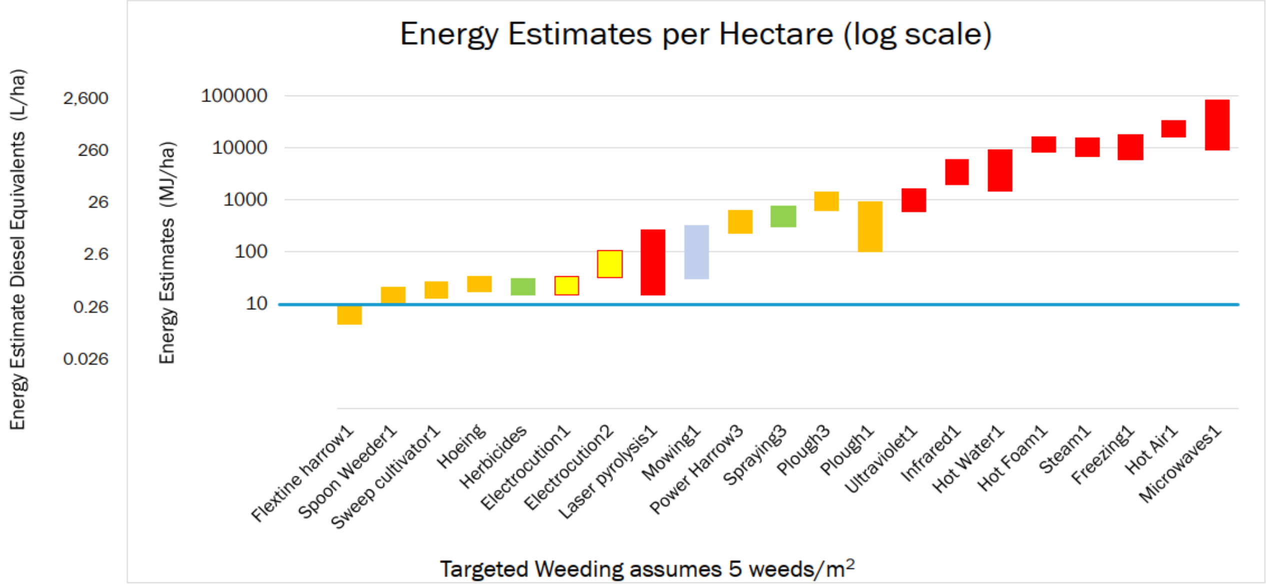

Figure 15. Weed control: relative energy requirements. From (Bloomer, 2023).

Electrobiological weeders, as they don't aim to heat plants up (section 6.2) use even less power and may use less than 10 MJ/ha (Bloomer *et al.*, 2022).

A key concern about thermal and non-chemical weeding as a whole is that they are more energy intensive than herbicides, which is problematic in the face of the climate crisis. Electrothermal, and particularly newer designs with high frequency electronic control are clearly using less energy than herbicides. Electrobiological research hints that considerably lower energy weed management may be possible. Concerns about the energy use for electrothermal are therefore considered misplaced, and consequently energy consumption should not be considered a barrier to EWM uptake.

Chapter 17. Conclusions

EWM is increasingly looking like a ‘get out of jail card’ for the post-herbicide era (Marshall, 2010). That said, the technology is still bleeding to cutting edge, with newer designs using highly complex electronics, so it is currently neither a simple or cheap technology. However with the potential of EMW is being increasingly demonstrated, and some of the worlds largest agricultural machinery and agrichemical companies investing in and partnering with EWM companies, it is expected that with increasing production volumes, ongoing research, the entry of new companies with new technologies and approaches, mean that effectiveness, efficiency and availability will increase while equipment prices will fall over time.

Electrobiological with its exceptionally low energy use is particularly exciting, but it is currently ‘just’ a research concept and some way from being a field-scale operation, let alone being commercialised.

This coupled with the agricultural robot revolution allowing individual plant management which in turn facilitates ecological weed management (Merfield, 2023a) could herald a true revolution in weed management.

Chapter 18. Acknowledgments

Dr Mike Diprose for photos, stimulating and informative conversations and fact checking this report.

Chapter 19. References

ADAS UK Ltd. (2014). *An economic assessment of electric weed control and comparable alternatives. PS2143*. Boxworth, Cambridgeshire. UK: ADAS UK Ltd https://randd.defra.gov.uk/ProjectDetails?ProjectId=18592

Adeux, G., Vierenw, E., Carlesi, S., Bàrberi, P., Munier-Jolain, N. & Cordeau, S. (2019). Mitigating crop yield losses through weed diversity. *Nature Sustainability, 2*(11), 1018-1026. doi:10.1038/s41893-019-0415-y https://www.nature.com/articles/s41893-019-0415-y

Bloomer, D. J. (2023). Alternative weed control methods Proceedings of the LandWISE 'Normal practice revisited", Havelock North, New Zealand

Bloomer, D. J., Harrington, K. C., Ghanizadeh, H. & James, T. K. (2022). Micro electric shocks control broadleaved and grass weeds. *Agronomy, 12*(9), 2039. doi:10.3390/agronomy12092039 https://www.mdpi.com/2073-4395/12/9/2039

Borger, C. & Slaven, M. (2022). *What is the best fit for electric weed control in Australia? 2022 Progress Report*. Perth, Australia: Department of Primary Industries and Regional Development Western Australia https://www.wineaustralia.com/getmedia/efd1a178-6100-43c6-8aec-80feff438a01/Public-Annual-Report-2023-What-is-the-best-fit-for-electric-weed.pdf

Brady, N. C. & Weil, R. R. (2008). *The nature and properties of soil* (14th ed.). Upper Saddle River, New Jersey: Pearson Education Inc.

Coleman, G. R. Y., Stead, A., Rigter, M. P., Xu, Z., Johnson, D., Brooker, G. M., Sukkarieh, S. & Walsh, M. J. (2019). Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. *Weed Technology, 33*(4), 633-650. doi:10.1017/wet.2019.32 https://www.cambridge.org/core/article/using-energy-requirements-to-compare-the-suitability-of-alternative-methods-for-broadcast-and-sitespecific-weed-control/CE8E572179F660512A09F5490094189E

Coleman, G. R. Y., Stead, A., Rigter, M. P., Xu, Z., Johnson, D., Brooker, G. M., Sukkarieh, S. & Walsh, M. J. (2020). Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control – CORRIGENDUM. *Weed Technology, 34*(1), 153-154. doi:10.1017/wet.2019.131 https://www.cambridge.org/core/article/using-energy-requirements-to-compare-the-suitability-of-alternative-methods-for-broadcast-and-sitespecific-weed-control-corrigendum/626A8AD86BD59D8A3FD969D0AED87245

Cotrufo, M. F., Lavallee, J. M. & Sparks, D. L. (2022). Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. In *Advances in Agronomy* (Vol. 172, pp. 1-66): Academic Press doi:10.1016/bs.agron.2021.11.002 https://www.sciencedirect.com/science/article/pii/S0065211321001048

Curtin, D., Fraser, P. M. & Beare, M. H. (2015). Loss of soil organic matter following cultivation of long-term pasture: effects on major exchangeable cations and cation exchange capacity. *Soil Research, 53*(4), 377-385. doi:10.1071/SR14173 https://www.publish.csiro.au/sr/SR14173

Dastgheib, F., Merfield, C. N. & Chamberlain, T. P. (2010). Post-emergence thermal weeding in onions (*Allium cepa*). *Agronomy New Zealand, 40*, 177-186. https://www.agronomysociety.org.nz/files/2010_16._Post-em_thermal_weeding_onion.pdf

de Andrade Coutinho Filho, S., Antenor Pomilio, J., Valverde, B. & Teruo Mendes de Souza, D. (2023). Weed inactivation device, *United States Patent and Trademark Office* (Vol. US11684060B2, pp. 17). USA: Zasso Group AG

de Rooy, S. C. (1992). *Improved efficiencies in flame weeding.* Lincoln University, Canterbury, New Zealand https://hdl.handle.net/10182/18

Diprose, M. F., Balls, R., Holland, R. E. B. & Bradwell, I. T. (2009). *Electrical weed control in the UK – the current situation.* http://baer.uni-ruse.bg/papers_v13/2009_v13_04.pdf

Diprose, M. F. & Benson, F. A. (1984a). The effect of externally applied electrostatic fields, microwave radiation and electric currents on plants and other organisms, with special reference to weed control. *Botanical Review, 50*(2), 171-223. doi:10.1007/BF02861092 https://link.springer.com/article/10.1007/BF02861092

Diprose, M. F. & Benson, F. A. (1984b). Electrical methods of killing plants. *Journal of Agricultural Engineering Research, 30*, 197-209. doi:10.1016/S0021-8634(84)80021-9 https://www.sciencedirect.com/science/article/abs/pii/S0021863484800219

Diprose, M. F., Benson, F. A. & Hackam, R. (1980a). Electrothermal control of weed beet and bolting sugar beet. *Weed Research, 20*(5), 311-322. doi:10.1111/j.1365-3180.1980.tb01625.x https://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.1980.tb01625.x

Diprose, M. F., Benson, F. A. & Turner, N. V. (1980b). The use of high voltage electricity for weed beet control Proceedings of the British Crop Protection Conference - Weeds, Brighton, UK, 545-548 doi: https://www.bcpc.org/wp-content/uploads/2022/05/BCPC-Weeds-Conference-1980-Vol-I-III-Contents.pdf

Diprose, M. F., Fletcher, R., Longden, P. C. & Champion, M. J. (1985). Use of electricity to control bolters in sugar beet (*Beta vulgaris* L.): a comparison of the electrothermal with chemical and mechanical cutting methods. *Weed Research, 25*(1), 53-60. doi:10.1111/j.1365-3180.1985.tb00617.x

Diprose, M. F., Hackam, R. & Benson, F. A. (1978). Weed control by high voltage electric shocks Proceedings of the British Crop Protection Conference - weeds, Brighton, UK, 443-450 doi:

Diprose, M. F. & Mattsson, B. (1993). Non-chemical weed control-trends in European practice-with special reference to electrical weed control. *Soil Science: Trends In Agricultural Science, 1*, 243-250. https://merfield.com/research/external/non-chemical-weed-control-trends-in-european-practice-with-special-reference-to-electrical-weed-control-1993-diprose-mattsson.pdf

Duke, S. O. & Powles, S. B. (2008). Glyphosate: a once-in-a-century herbicide. *Pest Management Science, 64*(4), 319-325. doi:10.1002/ps.1518 https://onlinelibrary.wiley.com/doi/10.1002/ps.1518

Eberius, M., Coutinho, S. & Vandenhirtz, D. (2018). Device for the electrocution of structures in the environment and use of said device, *World Patent Office* (Vol. WO2018050138A1, pp. 24)

Elsgaard, L. (2010). Dynamics of mineral nitrogen, water-soluble carbon and potential nitrification in band-steamed arable soil. *Biology and Fertility of Soils, 46*(8), 883-889. doi:10.1007/s00374-010-0486-4 http://rd.springer.com/article/10.1007/s00374-010-0486-4

Elsgaard, L., Jørgensen, M. H. & Elmholt, S. (2010). Effects of band-steaming on microbial activity and abundance in organic farming soil. *Agriculture, Ecosystems & Environment, 137*(3–4), 223-230. http://www.sciencedirect.com/science/article/pii/S0167880910000411

Ghanizadeh, H., Buddenhagen, C. E., Griffiths, A. G., Harrington, K. C. & Ngow, Z. (2023). Target-site and non-target site resistance mechanisms are associated with iodosulfuron resistance in *Lolium perenne* L. *New Zealand Journal of Agricultural Research, 67*(1), 40-53. doi:10.1080/00288233.2022.2153875 https://www.tandfonline.com/doi/abs/10.1080/00288233.2022.2153875

Gliessman, S. R. (2014). *Agroecology: The ecology of sustainable food systems, third edition*. Bosa Roca, USA: Taylor & Francis Group doi:10.1201/b17881 https://www.taylorfrancis.com/books/mono/10.1201/b17881/agroecology-stephen-gliessman

Harrington, K. C. & Ghanizadeh, H. (2017). Herbicide application using wiper applicators - A review. *Crop Protection, 102*, 56-62. doi:10.1016/j.cropro.2017.08.009 https://www.sciencedirect.com/science/article/pii/S0261219417302387

Healy, A. (1953). Control of docks. *New Zealand Journal of Science and Technology, Section A 34*, 473–475.

Heap, I. (2023). *The International Herbicide-Resistant Weed Database*. Retrieved October 15, 2023, www.weedscience.org

Holm, L. G. (1991). *The world's worst weeds: Distribution and biology*. Malabar, Florida, United States: Krieger Publishing Company

Ivanovich, B. V. & Viktorovich, Y. I. (2017). The determination of the most effective current type for electrical damage of plants. *Indian Journal of Science and Technology, 10*(1), 1-6. doi:10.17485/ijst/2017/v10i1/109974 https://indjst.org/articles/the-determination-of-the-most-effective-current-type-for-electrical-damage-of-plants

Jordan, N. & Vatovec, C. (2004). Agroecological benefits from weeds. In Inderjit (Ed.), *Weed Biology and Management* (pp. 137–158). Dordrecht, Netherlands: Springer doi:10.1007/978-94-017-0552-3 https://link.springer.com/book/10.1007/978-94-017-0552-3

Judaev, I. V. (2008). The definition of electro impulses used in weed control. *Journal of Agricultural Sciences, Belgrade, 53*(1), 37-44. doi:10.2298/JAS0801037J https://doiserbia.nb.rs/Article.aspx?ID=1450-81090801037J

Kaufman, K. R. & Schaffner, L. W. (1982). Energy and economics of electrical weed control. *Transactions of the ASAE, 25*(2), 297. doi:10.13031/2013.33523 http://elibrary.asabe.org/abstract.asp?aid=33523&t=3

Kautman, K. R. & Schaffner, L. W. (1979). Energy requirements and economic analysis of electrical weed control. *Sugarbeet Research and Extension Reports, 10*, 72-85. https://archive.sbreb.org/Research/weed/weed79/79p72.htm

Kladivko, E. J. (2001). Tillage systems and soil ecology. *Soil and Tillage Research, 61*(1), 61-76. doi:10.1016/S0167-1987(01)00179-9 https://www.sciencedirect.com/science/article/pii/S0167198701001799

Koch, M., Hermann, A., Ergas, B. & Risser, P. (2020a). Electrical weed control in sugar beet - A comparison of pre-emergence methods Proceedings of the Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und -bekämpfung, Braunschweig, Germany, 438–440 doi:10.5073/jka.2020.464.066 https://ojs.openagrar.de/index.php/JKA/article/view/14940

Koch, M., Tholen, T., Drießen, P. & Ergas, B. (2020b). The Electroherb™ Technology - A new technique supporting modern weed management Proceedings of the Proceedings of the 29th German workshop on questions of weed biology and control (Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und -bekämpfung), Braunschweig, Germany, 261-263 doi:10.5073/jka.2020.464.039 https://www.openagrar.de/receive/openagrar_mods_00056695

Lati, R. N., Rosenfeld, L., David, I. B. & Bechar, A. (2021). Power on! Low-energy electrophysical treatment is an effective new weed control approach. *Pest Management Science, 77*(9), 4138-4147. doi:10.1002/ps.6451 https://onlinelibrary.wiley.com/doi/abs/10.1002/ps.6451

Lee, H.-k., Baatarkhuu, D., Tuvshinjargal, D. & Jargalsaihan, A. (2018). Destruction of weeds using HV pulsed discharges. *Journal of Multidisciplinary Engineering Science Studies, 4*(11), 2277-2280. http://www.jmess.org/wp-content/uploads/2018/11/JMESSP13420444.pdf

Liebman, M. & Gallandt, E. R. (1997). Many little hammers: ecological management of crop-weed interactions. In L. E. Jackson (Ed.), *Ecology in Agriculture* (pp. 291–343). San Diego, CA: Academic Press doi:10.1016/B978-012378260-1/50010-5 https://www.sciencedirect.com/science/article/pii/B9780123782601500105

Liebman, M., Mohler, C. L. & Staver, C. P. (2001). *Ecological management of agricultural weeds*. Cambridge: Cambridge University Press doi:10.1017/CBO9780511541810 https://www.cambridge.org/core/books/ecological-management-of-agricultural-weeds/26FC8424411DCC504C1C36972B1C6462

Löbmann, A., Klauk, B., Lang, C., Petgen, M. & Petersen, J. (2022). Electrical weed control and its effect on soil organisms Proceedings of the Proceedings of the 30th German workshop on questions of weed biology and control (Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und -bekämpfung), Braunschweig, Germany, 277-282 doi:10.5073/20220124-064756 https://www.openagrar.de/receive/openagrar_mods_00077219

Marshall, E. J. P. (2010). Weed Research reaches volume 50! Looking back and looking forward. *Weed Research, 50*(1), 1-4. http://dx.doi.org/10.1111/j.1365-3180.2009.00760.x

Matsuda, Y., Kakutani, K. & Toyoda, H. (2023). Unattended electric weeder (UEW): A novel approach to control floor weeds in orchard nurseries. *Agronomy, 13*(7), 1954. doi:10.3390/agronomy13071954 https://www.mdpi.com/2073-4395/13/7/1954

Matsuda, Y., Shimizu, K., Sonoda, T. & Takikawa, Y. (2020a). Use of electric discharge for simultaneous control of weeds and houseflies emerging from soil. *Insects, 11*(12), 861. doi:10.3390/insects11120861 https://www.mdpi.com/2075-4450/11/12/861

Matsuda, Y., Takikawa, Y., Kakutani, K., Nonomura, T., Okada, K., Kusakari, S.-i. & Toyoda, H. (2020b). Use of pulsed arc discharge exposure to impede expansion of the invasive vine pueraria montana. *Agriculture, 10*(12), 600. doi:10.3390/agriculture10120600 https://www.mdpi.com/2077-0472/10/12/600

Matsuda, Y. & Toyoda, H. (2023). Target-size-dependent application of electrostatic techniques for pest management in greenhouses. *Agronomy, 13*(1), 125. doi:10.3390/agronomy13010125 https://www.mdpi.com/2073-4395/13/1/125

Merfield, C. N. (2006). *Organic F1 hybrid carrot seed (Daucus carota L.) production: the effect of crop density on seed yield and quality, thermal weeding and fungal pathogen management.* PhD Thesis, Lincoln University http://www.merfield.com/research/2006/phd/index.htm

Merfield, C. N. (2013a). *Expanding the potential of intrarow soil thermal weeding*. Lincoln: The BHU Future Farming Centre https://merfield.com/research/2013/expanding-the-potential-of-intrarow-soil-thermal-weeding-v2-2013-ffc.pdf

Merfield, C. N. (2013b). *Intrarow soil thermal weeding research report: The effect of soil texture and moisture content on soil structure after mixing and heating with steam*. Lincoln, New Zealand: The BHU Future Farming Centre https://merfield.com/research/2012/intrarow-soil-thermal-weeding-research-report--the-effect-of-soil-texture-and-moisture-content-on-soil-structure-after-mixing-and-heating-with-steam-2012-merfield-ffc.pdf

Merfield, C. N. (2015). False and stale seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment. *The Future Farming Centre Bulletin, 4*, 1-25. https://merfield.com/research/2015/false-and-stale-seedbeds--the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment-2015-ffc-merfield.pdf

Merfield, C. N. (2016). Back to the future - electrothermal, systemic, weedkiller. *The FFC Bulletin, 2016*(V1) http://www.bhu.org.nz/future-farming-centre/information/bulletin/2016-v1/back-to-the-future-electrothermal-systemic-weedkiller

Merfield, C. N. (2019). *Integrated weed management in arable crop systems*. Lincoln, New Zealand: Merfield Agronomy Ltd https://merfield.com/research/2019/integrated-weed-management-in-arable-crop-systems-2019-merfield.pdf

Merfield, C. N. (2022). Redefining weeds for the post-herbicide era. *Weed Research, 62*(4), 263-267. doi:10.1111/wre.12544 https://onlinelibrary.wiley.com/share/author/2XJPNXNTRBFMQHFVPMPI?target=10.1111/wre.12544

Merfield, C. N. (2023a). Could the dawn of Level 4 robotic weeders facilitate a revolution in ecological weed management? *Weed Research, 63*(2), 83-87. doi:10.1111/wre.12570 https://onlinelibrary.wiley.com/share/author/SDVNYVQKUI5IMKRZVPQD?target=10.1111/wre.12570

Merfield, C. N. (2023b). Integrated weed management in organic farming. In S. Chandran, M. R. Unni, S. Thomas & D. K. Meena (Eds.), *Organic farming: Global perspectives and methods. 2nd Edition* (pp. 31-110). Cambridge, MA, United States: Elsevier Science https://shop.elsevier.com/books/organic-farming/chandran/978-0-323-99145-2

Merfield, C. N., Hampton, J. G. & Wratten, S. D. (2009). A direct-fired steam weeder. *Weed Research, 49*(6), 553–556. doi:10.1111/j.1365-3180.2009.00733.x http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.2009.00733.x/full

Mizuno, A., Tenma, T. & Yamano, N. (1990). Destruction of weeds by pulsed high voltage discharges Proceedings of the Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting, Seattle, WA, USA, 720-727 vol.721 doi:10.1109/IAS.1990.152264 https://ieeexplore.ieee.org/document/152264

Naylor, R. E. L. (Ed.). (2002). *Weed management handbook. Ninth Edition*. Oxford, UK: Blackwell Science for British Crop Protection Council

Pluenneke, R. H. & Dykes, W. G. (1975). Method and apparatus for using electrical current to destroy grasses and weeds In U. S. P. Office (Ed.) (Vol. US3919806, pp. 9). USA: Lasco, Inc., Greenwood, Miss. https://patents.google.com/patent/US3919806A/en

Reed, J. (2009). *Desk Study: Electrical weed control in field vegetables. FV 346*. Bedford, UK: Silsoe Technology Ltd https://horticulture.ahdb.org.uk/fv-346-desk-study-for-electrical-weed-control-in-field-vegetables

Riemens, M., Sønderskov, M., Moonen, A.-C., Storkey, J. & Kudsk, P. (2022). An integrated weed management framework: A pan-European perspective. *European Journal of Agronomy, 133*, 126443. doi:10.1016/j.eja.2021.126443 https://www.sciencedirect.com/science/article/pii/S1161030121002148

Ruf, T., Oluwaroye, M., Leimbrock, L. & Emmerling, C. (2023). Field fodder conversion using electricity – Negative effects on earthworms and changes in labile carbon fractions. *Soil and Tillage Research, 232*, 105746. doi:10.1016/j.still.2023.105746 https://www.sciencedirect.com/science/article/pii/S0167198723001137

Schild, M., Dierauer, H. & Maurer, C. (2017). *Test Elektroherb: Wirksamkeit und einfluss auf bodenlebewesen (Test Elektroherb: Effectiveness and influence on soil organisms)*. Frick, Switerland: Forschungsinstitut für biologischen Landbau FiBL

Schreier, H., Bish, M. & Bradley, K. W. (2022). The impact of electrocution treatments on weed control and weed seed viability in soybean. *Weed Technology, 36*(4), 481-489, 489. doi:10.1017/wet.2022.56 https://www.bioone.org/journals/weed-technology/volume-36/issue-4/wet.2022.56/The-impact-of-electrocution-treatments-on-weed-control-and-weed/10.1017/wet.2022.56.full

Slaven, M. J. & Borger, C. (2022). Australian weed morphology and its potential impact on electric weed control application efficacy Proceedings of the 22nd Australasian Weeds Conference, Adelaide, SA, Australia, 305-306 doi: https://caws.org.nz/wp-content/uploads/2023/02/0207.pdf

Slaven, M. J., Koch, M. & Borger, C. P. D. (2023). Exploring the potential of electric weed control: A review. *Weed Science*, 1-19. doi:10.1017/wsc.2023.38 https://www.cambridge.org/core/article/exploring-the-potential-of-electric-weed-control-a-review/231EE50C385EF8962CDC46055C264237

Tatnell, L. (2021). *Electrical weed control of docks: Final report* Boxworth, UK: RSK & ADAS UK Ltd https://adas.co.uk/wp-content/uploads/2021/01/Electrical-Weed-Control-of-Docks-EIP-Report-FINAL.pdf

Tatnell, L., Osborn, S., Diprose, A. & Diprose, R. (2020). *Electrical weeding in bush and cane fruit. Project number: 104559*: ADAS UK Ltd. https://adas.co.uk/wp-content/uploads/2021/01/Electrical-weeding-in-bush-and-cane-fruit-FINAL.pdf

Toshpulatov, N. T. (2020). The mechanism of destruction of plant rhizomes under the influence of an electric pulse discharge. *IOP Conference Series: Earth and Environmental Science, 614*(1), 012115. doi:10.1088/1755-1315/614/1/012115 https://iopscience.iop.org/article/10.1088/1755-1315/614/1/012115

Toyoda, H. (2023). Electrostatic techniques for physically managing pathogens, insect pests, and weeds in field and greenhouse cropping systems. *Agronomy, 13*(12), 2855. doi:10.3390/agronomy13122855 https://www.mdpi.com/2073-4395/13/12/2855

Vigneault, C. & Benoît, D. L. (2001). Electrical weed control: Theory and applications. In C. Vincent, B. Panneton & F. Fleurat-Lessard (Eds.), *Physical control methods in plant protection* (pp. 174-188). Berlin, Germany: Springer-Verlag http://link.springer.com/chapter/10.1007%2F978-3-662-04584-8_12

Vigneault, C., Benoit, D. L. & McLaughlin, N. B. (1990). Energy aspects of weed electrocution. *Reviews of Weed Science, 5*, 15-26.

Vigoureux, A. (1981). Results of trials carried out in Belgium in 1980 about killing weed beets by electric discharge Proceedings of the Meded. Fac. Landbouwwet., Gent, Belgium, 163–172 doi: http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCALAGROLINEINRA82X0100723

Yudaev, I., Daus, Y., Kokurin, R., Prokofyev, P., Gamaga, V. & Armenyanov, N. (2019). Electro-impulse irreversible plant tissue damage as highly efficient agricultural technology. In V. Kharchenko & P. Vasant (Eds.), *Advanced agro-engineering technologies for rural business development* (pp. 396-430): IGI-Global doi:10.4018/978-1-5225-7573-3.ch015 https://www.igi-global.com/gateway/chapter/225693

Ziska, L. H. & Dukes, J. S. (2010). Benefits from weeds. In L. H. Ziska & J. S. Dukes (Eds.), *Weed Biology and Climate Change* (pp. 181-197). Ames, Iowa, USA: Blackwell Publishing Ltd doi:10.1002/9780470958674.ch10 https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470958674.ch10