Understanding the Energy Requirements for Microwave Weed and Soil Treatment

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Abstract: Crop yield gaps, due to abiotic and biotic stresses undermine efforts to secure food for the world. Weeds are a significant biotic stress in cropping systems and can reduce productivity by 35 % to 55 % in some cases. Herbicide resistance is a compounding effect to control weeds. Non-chemical methods are being considered, especially thermal treatments, which are compatible with zero-till systems. Microwave weed and soil treatment has been shown to control weeds, weed seeds and pathogens in cropping systems. This paper explores the thermal efficiency of several thermal weed control systems, with an emphasis on microwave systems.

Keywords: Weed treatment, soil pasteurisation, thermal treatment, energy efficiency, microwave.

INTRODUCTION

Crop yield gaps significantly affect agricultural sustainability and food security. Crop yield gaps are differences between optimal yield potential and actual crop yield [1]. Biotic (weeds and pathogens) and abiotic stresses (drought, heat, salinity, flooding), which are ubiquitous in agricultural production systems [2], are hindering attempts to bridge crop yield gaps.

Among biotic stresses, some crop ecology studies have demonstrated that competition from weeds can reduce the potential yield of some crops by 35 % to 55 % [3]. Cousens [4] described the relationship between crop yield loss and weed density by the hyperbolic equation:

$$Y = Y_o \left[1 - \frac{I \cdot R}{100\left(e^{ct} + \frac{I \cdot R}{A_w} \right)} \right] \tag{1}$$

Brodie [5] extended this work to include other parameters, such as seed bank dynamics, the presence of a resistant portion of the weed population, and the timing of seedling emergence compared with crop emergence:

$$Y = Y_o \left\{ 1 - \frac{I \cdot [W(1-N-D_o) - E_m + I_m] \cdot \left[1 - S_o \cdot e\frac{-ag^2}{2} + S_o \cdot e\frac{-ag^2}{2} - \lambda H \right]}{100\left\{ e^{ct}\left[1 + e^{-\left(\frac{t-t_o}{d}\right)} \right] + \frac{I \cdot [W(1-N-D_o) - E_m + I_m] \cdot \left[1 - S_o \cdot e\frac{-ag^2}{2} + S_o \cdot e\frac{-ag^2}{2} - \lambda H \right]}{A_w} \right\}} + aH^2 - bH \right\} \tag{2}$$

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Figure **1** shows a typical crop yield response to herbicide application.

Modern no-till cropping depends on herbicides for weed management; therefore herbicide applications are an important system input [5]. Zero-tillage and reduced tillage have been used since ancient times, simply because man does not have the muscle force to till any significant area of land by hand [6]; however, domestication of animals and mechanisation have allowed for more extensive tillage practices to be developed.

The plough was developed very early in history and the use of the plough is often mentioned in ancient literature, including the Bible. One of the best-known biblical citations is from Isaiah chapter 2 v. 4: "*they shall beat their swords into plough shares*" [6]. Tillage can reduce weed burdens in cropping systems; however, some research has shown that even small disturbances of the soil can result in significant seedling recruitment from the soil weed seed bank [7]. Tillage also degrades soil structure making the soil very susceptible to erosion in hot dry climates [6]. The invention in 1955 of Paraquat, which is a quick acting and non-selective herbicide, provided a non-tillage solution for weed control, which was compatible with zero-tillage crop production [6].

HERBICIDE RESISTANCE

The specter of herbicide resistance was first highlighted by Harper [8] more than 60 years ago. Globally, there are now over 400 weed species that have developed resistance to various herbicides and annually 9 new weed biotypes are reported as being herbicide resistant [9-11]. According to Neve [12], between 2001–2005 about 12 % of papers published in

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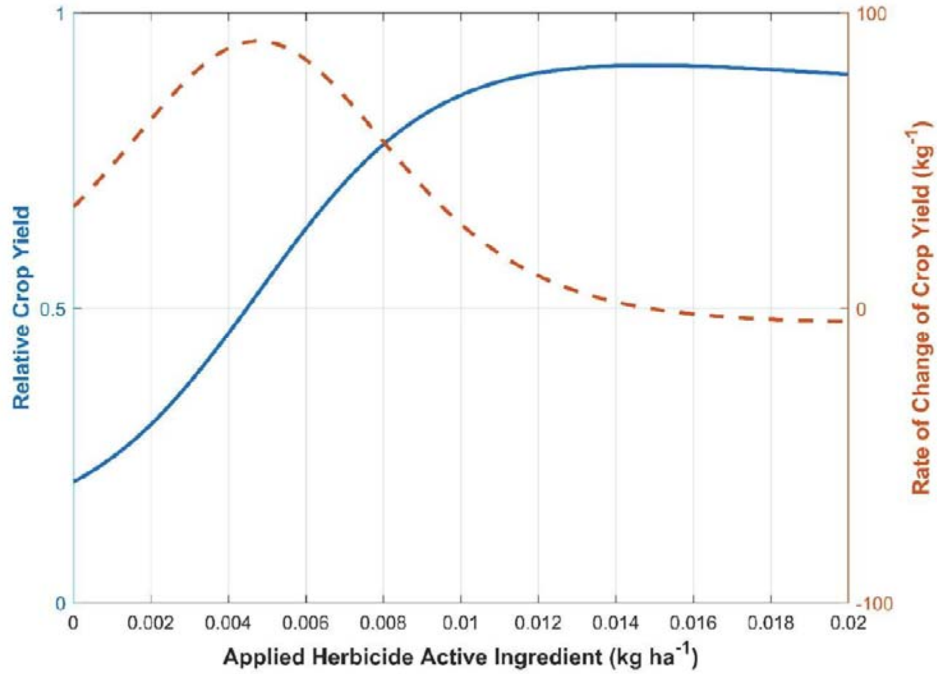


Figure 1: Crop yield response as a function of herbicide active ingredient application rate.

the journal *Weed Research* reported studies on herbicide resistant; therefore, herbicide resistance has become a significant issue. With few exceptions, one or more of three general mechanisms confers herbicide resistance: an altered herbicide target enzyme; enhanced herbicide metabolism; or reduced herbicide translocation [12].

Development of herbicide resistance in a population can be very quick. Field experiments, conducted by Beckie and Reboud [13], demonstrated that almost 100 % of the seed bank of field pennycress (*Thlaspi arvense*), growing in wheat crops, showed acetolactate synthase [ALS] inhibitor herbicide resistance, within only four years. Resistance to Weed Science Society of America's (WSSA) Group 5 (photosystem II inhibitor) herbicides was first reported in 1970; this was followed by WSSA Group 2 (acetolactate synthase [ALS] inhibitor) herbicide resistance in 1982; and in 1996 with WSSA Group 9 (enzyme 5-enolpyruvylshikimate 3-phosphate synthase-inhibitor) herbicides [11]. For each of these herbicide groups, it took some additional time before a major agronomic impact in most crop systems was recognised [2], and most other herbicide groups now have weed biotypes, which exhibit resistance(s) in many economically important weed species [11].

There is a growing need for non-chemical weed control options. This paper considers thermal weed and soil treatment techniques, with a focus on microwave weed and soil treatment.

THERMAL WEED MANAGEMENT

Denaturing of plant cell components starts with long term exposure to temperatures of about 40°C. The fatal impacts of high temperatures on plants have been studied in detail for over a century [14]. An empirical relationship between lethal temperature and temperature holding time has been developed by Lepeschkin [15]:

$$T = 79.8 - 12.8 \cdot \log_{10} Z \qquad (3)$$

Similar lethal temperature and holding time relationships exist for most other organisms, such as nematodes, fungi, and weed seeds [16-18]. Therefore, various heat sources can be used to manage weeds and other pests.

Thermal weed control (i.e. flaming, steam and radiation) applies heat directly to the weed, which quickly raises the temperature of the moisture in the plants' cells. The rapid expansion of this moisture causes the cell structure to rupture, preventing nutrients and water from entering the stalk and leaves [19]. Thermodynamics predicts that energy, in the form of heat, moves along the temperature gradient until all spatial coordinates reach equilibrium.

Thermophysical properties of plant leaves, presented by Jayalakshmy and Philip [20], indicate that the mean specific heat is 1884.7 J kg^{-1} K^{-1}. Equation (3)

Table 1: Treatment Requirements and Efficacy Associated with Various Thermal Weed Control Methods [Treatment Data Drawn from: 25]

Treatment Strategy	Mean Single Dose (kg gas ha^{-1})	Equivalent Energy Density per Dose ($J\ cm^{-2}$)	Approximate Thermal Efficiency of a single dose (%)	Number of doses per year	Total Dose (kg gas ha^{-1})	Overall Equivalent Energy Density ($J\ cm^{-2}$)	Level of Weed Control Provided (%)
Flame	150	77.4	8.6	5	750	387	87
Hot air	335	172.7	3.9	5.5	1843	950	94
Steam	163	84.1	7.9	5.5	897	463	85
Hot water	312	161.0	4.1	3	936	483	96

suggests that plant materials need to be heated above 90 °C for 12 s for effective plant death. Field data from several experiments [21-23] indicate that the fresh weight of weeds common to wheat, canola and rice crops in southern Australia was about 13 g. If the initial plant temperature is about 20 °C, then it will require approximately 1.7 kJ $plant^{-1}$ to heat the entire plant to the necessary lethal temperature.

Flame weeding is a commonly applied thermal weed control method used in vegetable, row cropping and root cropping systems [24] and in urban weed management [25]. Several kinds of equipment have been developed for flame weeding, such as tractor-mounted flamers and hand-pushed or handheld devices for weeding around obstacles and for private households. Flaming controls a wide range of weed species [26], some of which are tolerant or resistant towards herbicides. In experiments conducted by Gourd [19], flaming provided 72% and 80 % control of ryegrass and volunteer alfalfa, respectively. Both kochia (*Kochia scoparia* (L.) Roth) and netseed lambsquarter (*Chenopodium berlandieri*) were also controlled at 65 %.

Based on the thermal value of propane (LPG) gas, which is 51.6 MJ kg^{-1} [27], 100 % thermal efficiency flaming would require at least 0.33 g $plant^{-1}$ of propane to provide the 1.7 kJ $plant^{-1}$ needed to kill a weed. Data from Rask and Kristoffersen [25] states that the mean weed cover in their untreated plots was approximately 39 plants m^{-2}. This requires approximately 66.3 kJ m^{-2} of applied thermal energy for effective weed control; therefore, the minimum dose of propane needed to control weeds would be 1.29 g m^{-2}, or 12.9 kg ha^{-1}.

Rask and Kristoffersen [25] found that 150 kg ha^{-1} of propane was needed to adequately control weed infestations on the surfaces they were studying, implying an 8.6 % thermal efficiency for the flaming system, depending on the size of the weeds in their study. Their study revealed that five treatments were needed through the year to properly suppress the weed population, which may have been due to incomplete control, recruitment from the seed bank and immigration of seeds from outside of the study area. Therefore, they required 750 kg of propane ha^{-1} for annual weed suppression in their study area.

In addition to flaming, Rask and Kristoffersen [25] also considered hot air, steam and hot water to control the weeds on their test sites. A meta-analysis of their results is presented in Table **1**. Based on this meta-analysis, flame weeding appears to be the most efficient of these options.

MICROWAVE WEED CONTROL

Davis, Wayland and Merkle [28], [29] were among the first to study the lethal effect of microwave heating on seeds. They developed a set of prototypes called "Zappers", which they tested in the field for their Company and federal and state researchers. Following the initial Zapper I program, the company built a second and third prototype, the Zapper III. The Zapper III was used to determine the cost of treatments required to destroy various types of weeds. Their final prototype, designated Zapper III, underwent tests to provide the data necessary for the construction of the first semi-commercial prototype. In October 1971, the company purchased all proprietary rights to a discovery made at Texas A&M University concerning the toxic effects of microwaves on plants.

All of the Zapper systems operated at a frequency of 2.45 GHz. A meta-study of published data [30, 31] reveals that when the weed species are separated into categories of broad leafed weeds and grasses, grasses require more microwave energy to achieve treatment efficacy, compared with broad leafed plants. In both cases, good post-emergent weed control was achieved when 300 J cm^{-2} of microwave energy was applied.

Figure 2: 3-D models of a comb type slow-wave applicator operating at 2.45 GHz (above) top view and (below) bottom view showing the comb.

The Zapper, developed by Wayland, Merkle, Davis, Menges and Robinson [31], utilised the equivalent of a horn antenna to apply the microwave energy to the weeds. The horn antenna has been widely used by other researchers for weed treatment [32-34]. While a horn antenna is a simple and effective applicator for weed control, antennas are designed to radiate energy long distances into space. This is not necessarily the most effective way to treat weeds.

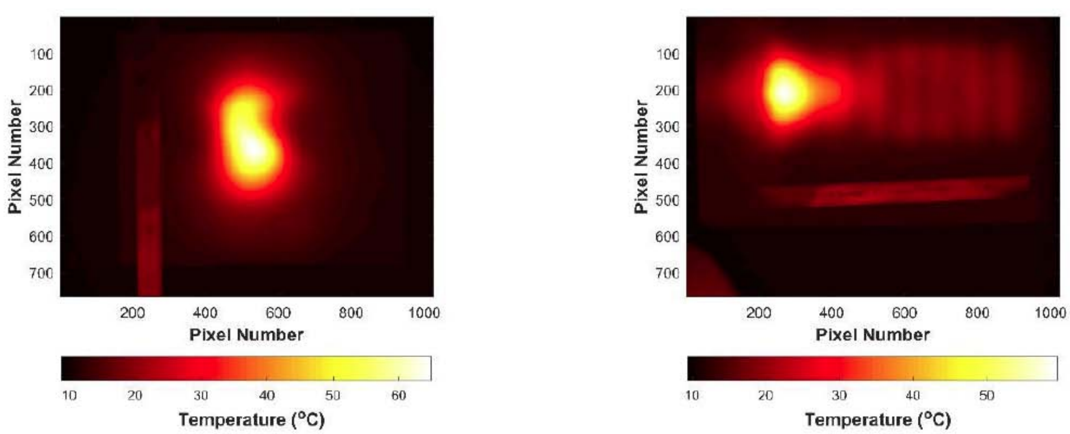
THE SLOW-WAVE APPLICATOR

Brodie, Torkovnikov and Farrell [35] have developed a new microwave applicator, based on a slow-wave structure (Figure **2**), to apply microwave energy for weed destruction in a better way. Slow-wave structures are non-radiating open transmission lines that have been used as charged particle accelerators and travelling wave tubes for more than half a century [36]. By their nature, slow-wave applicators confine the electromagnetic field distribution so that it does not radiate but remains very close to the surface of the slow-wave structure.

The main idea of slow-wave propagation is that in periodic resonant cavities, such as a comb-like structure, the group velocity of the electromagnetic wave is decreased proportionally to the fineness of the cavity. Consequently, the intensity of the propagating field is increased to conserve the energy flux [37]; therefore, the field strength at the surface of the slow-wave structure is very high.

A very high field intensity enables slow-wave structures to be used for heating thin dielectric materials [38, 39]; however, they are not commonly used for heating applications and have never been used for weed and soil treatment before.

In a simple experiment, the new slow-wave applicator was compared with a horn antenna by applying the same total microwave energy (32 kJ) to sheets of dry plywood. A thermal camera was used to capture images of the thermal footprint from each applicator, with a 300 mm steel ruler in the image (Figure **3**). From these images, it was determined that the energy density created by the horn antenna was



(a) (b)

Figure 3: Thermal footprints of (**a**) a Horn antenna with a 11 cm by 5.5 cm aperture, and (**b**) a slow-wave applicator.

approximately 750 J cm^{-2}. The Slow-wave applicator generated an energy density of approximately 94 J cm^{-2}. Therefore, by achieving similar temperatures with 12.5 % of the microwave energy density of a horn antenna, the slow-wave applicator is a good choice for weed and top soil treatment.

To further test the efficacy of the slow-wave applicator for weed and plant treatment, another very simple experiment was undertaken during early summer. When connected to a 2.0 kW, 2.45 GHz, microwave source, the slow-wave applicator took approximately two minutes to treat approximately 2 m^2 of kikuyu grass (*Pennisetum clandestinum*). The results of this simple test are shown in Figure **4**. The microwave energy density during these treatments was approximately 24 J cm^{-2}.

Three samples of the above ground grass biomass were collected from 30 cm by 10 cm quadrats and weighed to determine that the above ground biomass of the kikuyu grass was approximately 1.5 kg m^{-2}. Based on the mean specific heat of 1884.7 J kg^{-1} K^{-1} for fresh plant material, the minimum heat energy required to treat the grass should be approximately 19.5 J cm^{-2}. Therefore, the thermal efficiency of the slow-wave microwave weed treatment system is approximately 81 %.

This weed treatment efficacy, for the slow-wave system, is attributable to the transformation of the incoming microwave field into a spatially confined travelling wave, propagating across the surface of the slow-wave structure at a phase velocity that is slower than the normal speed of light (hence the name of the structure). The field confinement, and therefore intensification of the microwave energy on the surface of the slow-wave structure, is due to the structure's geometry. The comb like structure acts as an electromagnetic transmission line with multiple shunted stubs that manipulate the transmission line's impedance at the surface of the comb's teeth.

It is sensible to cover the slow-wave structure with a cover to protect it from moisture and abrasion. This cover will have dielectric properties of its own, which will affect the microwave field distribution. The microwave's field distribution, as a function of distance from the surface of a slow-wave structure with a dielectric cover plate, is:

$$E = E_o e^{-\tau 2 \cdot z} \quad (4)$$

Where

$$\tau_2 = -k^2 \Psi_\tau \frac{\kappa_1'}{2\tau_1} + \sqrt{\left(k^2 \Psi_\tau \frac{\kappa_1'}{2\tau_1}\right)^2 + \tau_1^2 + k^2 \kappa_1'} \quad (5)$$

And

$$\tau_1 = \sqrt{\tau_2^2 + k^2(\kappa_2' - \kappa_1')} \quad (6)$$

It is apparent from equations (5) and (6) that τ_2 depends on the value of τ_1; however, because of the impedance transforming effect of the dielectric cover, τ_1 also depends on τ_2; therefore, this problem needs to be solved iteratively. This problem usually converges very quickly.

Figure 4: Patches of kikuyu grass treated with Slow-wave applicator connected to a 2.0 kW, 2.45 GHz microwave source – 2 minutes to treat approximately 2 m^2 (Note: this image was captured approximately 24 hours after treatment).

While thermal treatment, and particularly microwave treatment, can kill weed plants, recruitment from the soil seed bank will quickly replace killed weeds. Thermal treatment of the soil can deplete the soil seed bank and therefore reduce ongoing weed infestations.

SOIL SEED BANK TREATMENT

Several thermal systems are capable of heating soil to temperatures which are lethal to seeds. Some commonly explored systems include solarisation [40], soil surface flaming [40], steam treatment [41-44] and microwave soil treatment [28, 31, 45, 46].

Solarisation

Hoyle, McElroy and Rose [40] found that solarisation was a very effective method of weed control. Data presented in DeVay, Stapleton and Elmore [47] demonstrates that six weeks of solarisation can reduce the weed burden by 29 % to 54 %. They found that solarisation, followed by mulching with plastic, can reduce the weed burden by 99 %.

Soil solarisation is initiated by covering the soil with a clear film for a period of 4 to 6 weeks [48]. The best season to practice solarization is summer. Soil moisture is also a critical variable in soil solarization since the transfer of heat to weed seeds, and plants and micro-organisms in soil is greatly increased by moisture. Soil solarization is a hydrothermal process and its success depends on moisture for maximum heat transfer [47].

Four major challenges affect solarisation as a weed control strategy: the defuse nature of solar energy (approximately 1,000 W m^{-2} for a surface that is perpendicular to the sun's rays), which leads to long soil treatment times (usually several weeks); the thermal efficiency of solar collection, which diminishes rapidly with increasing temperature differentials between the heated surface and the ambient environment; the potential environmental issue of plastic disposal after the treatment process; and the challenge of trying to treat the soil to a reasonable depth.

The thermal efficiency of a solar collection system is defined by:

$$\eta = \tau_c \alpha_a - \frac{U}{IA_c}(T_s - T_a) - \frac{\sigma}{1}(T_s^4 - T_a^4) \tag{7}$$

It can be demonstrated that the temperature response of soil to a sinusoidally fluctuating surface temperature can be described by [49]:

$$T(z,t) = T_o + \Delta T e^{-\sqrt{\frac{\omega}{2\gamma}}Z}\left[\cos\left(\omega t - \sqrt{\frac{\omega}{2\gamma}}Z\right)\right] \tag{8}$$

The skin depth is the depth at which the temperature fluctuation is $\frac{1}{e}$ of the surface fluctuation. From equation (8), the skin depth of the soil is:

$$z_o = \sqrt{\frac{2\gamma}{\omega}} \tag{9}$$

From data for several soil types, presented by Oyeyemia, Sanuade, Oladunjoye, Aizebeokhai, Olaojo, Fatoba, Olofinnade, Ayara and Oladapo [50], the mean thermal diffusivity for moist soils is 6.7 x 10^{-7} m^2 s^{-1}. The angular velocity of the earth on its axis is 7.27 x 10^{-5} Rad s^{-1}; therefore, the skin depth of a moist soil is about 0.136 m.

Data, presented by DeVay, Stapleton and Elmore [47], shows that soil temperatures under transparent plastic are between 5 and 13 °C higher through the day than in uncovered soil and that the highest temperature differences are near the soil surface with the temperature difference diminishing with soil depth, as would be expected from equation (8).

Steam Treatment

The diminishing effect of soil surface temperature with depth suggests injecting heat into the soil. This can be achieved in several ways, such as distributing hot air or steam through hollow tines or perforated tubes; however, steam treatment is a commonly applied option. About 95% of the heat for treating a soil mix comes from condensing water vapor out of the aerated steam. The rest of the heat comes from cooling the air-water vapor mixture [51].

Many studies have demonstrated that 100 % weed seed mortality can be achieved at soil temperatures between 80 °C and 100 °C [47, 52, 53]. From an engineering design perspective, the energy needed to raise the top 13.6 cm of soil, which is the same as the skin depth for solarisation, by 70 °C can be determined from the average bulk density of soils (about 1230 kg m^{-3} - from [42]) and the average thermal capacity of moist soils (about 1.3 kJ kg^{-1} K^{-1} – from [50]). This equates to applying 15.2 MJ m^{-2} at the soil surface or 1.5 kJ cm^{-2}. To heat the soil to a depth of 6 cm, it requires 88.2 J cm^{-2} of heat energy.

Gay, Piccarolo, Ricauda Aimonino and Tortia [42] applied 0.6 kg h^{-1} of super-heated steam, at 120 °C, to soil in 40 by 40 by 40 cm plastic boxes. Their applicator used a 20 by 20 cm hood to contain the steam during application at the soil surface and the steam generator consisted of a 8.5 kW electric boiler, capable of delivering 4 kg hr^{-1} of steam with a 1.6 kW electrical super heater to raise the steam temperature above boiling point before application to the soil. Their system also allowed for steam injection below the soil surface for some of their experiments. Injection resulted in more uniform soil heating.

Using the thermal properties of water (i.e. specific heat of liquid water = 4.187 kJ kg^{-1} K^{-1}; specific heat of water vapour = 1.996 kJ kg^{-1} K^{-1}; and heat of vaporisation = 2260 kJ kg^{-1}), it requires approximately 2.9 kW of power to boil 4 kg of water in one hour; therefore, the thermal efficiency of the steam generator used in the study by Gay, Piccarolo, Ricauda Aimonino and Tortia [42] is 34 %.

When Gay, Piccarolo, Ricauda Aimonino and Tortia [42] applied steam only to the soil's surface, the temperature in the soil rose from 15 °C to 100 °C in most of the top centre volume of the soil samples (approximately 20 by 20 by 6 cm) after 15 minutes of steam heating. This implies that 0.15 kg of super-heated steam was applied to the soil. Using a bulk density for the soils of 1230 kg m^{-3}, as reported by the authors [42], and a soil thermal capacity of 1.3 kJ kg^{-1} K^{-1} (from [50]), the required energy to achieve a 85 °C temperature change in the top 6 cm of soil is 326.2 kJ. The embodied heat in 0.15 kg of super-heated steam, using the standard thermal properties of water, is 398 kJ. Allowing for the thermal efficiency of the steam generator, the equivalent surface energy application for this steam treatment is approximately 2.9 kJ cm^{-2}; therefore, compared with the theoretical soil treatment energy density needed to heat the soil to a depth of 6 cm is 88.2 J cm^{-2}, the steam treatment system used by Gay, Piccarolo, Ricauda Aimonino and Tortia [42] has an overall thermal efficiency of approximately 3 %.

In another simple experiment (unpublished), 140 kg of moist clay-loam soil (60 % of field capacity) was treated in a 29 kW commercial steam injection treatment system for 90 minutes to reach a temperature of 90 °C. This represents an energy investment of 1.1 MJ kg^{-1}. The required energy for increasing the soil temperature by 75 °C is 97.5 kJ kg^{-1}; therefore, the thermal efficiency of the commercial steam injection system is about 8.8 %.

When plastic pots with 2.9 kg of the same soil were heated in a domestic microwave with a microwave power rating of 900 W (approximately 2.25 kW of electrical power), it required 150 s of treatment to reach 90 °C. This equates to 116.4 kJ kg^{-1}; therefore, the thermal efficiency of the microwave system is about 83.8 %.

Microwave Soil Treatment for Weed Seed Control

Menges and Wayland [30] determined that 100 % seed mortality of redroot pigweed, in the top 2.5 cm of soil, could be achieved with the application of 180 J cm^{-2} of microwave energy at 2.45 GHz frequency. Application of 360 J cm^{-2} of microwave energy provided 100 % seed mortality to a depth of 7.5 cm. Similar control of a variety of weed seeds, to a depth of 10 cm in many cases, has been observed by Brodie *et al*. [52-56], using a prototype design based around a domestic microwave oven feeding into a horn antenna. A summary of some results is illustrated in Table **2**. Both Menges and Wayland [30] and Brodie found that moisture in the soil assisted in microwave weed seed control.

Based on the heat required to raise the soil to 90 °C in the top 10 cm, the minimum energy density at the surface will be approximately 147 J cm^{-2}; therefore, the microwave system used in the experiments outlined in Table **2** has an efficiency of approximately 40 %. Allowing for electrical efficiencies in converting electrical energy into microwave energy, the overall efficiency of the microwave system used in these experiments was about 28 %. A purpose designed commercial microwave system should be able to achieve better efficiencies than are illustrated in these results.

To help understand the longer term efficacy of microwave treatment to deplete the weed seed bank, a simple field experiment was established where a 1 m^2 plot in a weedy drainage channel was treated with approximately 400 J cm^{-2} of microwave energy and monitored for weed control over time. From the image sequence in Figure **5**, it is apparent that weed emergence in the centre of the treated plot has been controlled for over 470 days; however, there has been encroachment onto the treated plot from the edges.

CROP RESPONSES TO MICROWAVE TREATED SOIL

Fully replicated pot and field plot experiments have been undertaken over an extended period by the authors to better understand the impact of pre-sowing microwave soil treatment on crop growth [57]. Experiments were undertaken with wheat (*Triticum spp.*) [58], rice (*Oryza sativa*) [21], maize (*Zea mays*), canola (*Brassica napus*) [59], processing tomatoes and strawberry runners. The crops were planted within 1 – 3 hours of the microwave treatment, once the soil had returned to ambient temperature. Pre-sowing microwave soil treatment was found to have significant beneficial effects on subsequent crop growth [57]. The increases in crop yield, compared with hand weeded

Table 2: Effect of Microwave Energy on Germination Percentage of Various Seeds as a Function of Seed Depth, Microwave Energy and Soil Moisture [Data from 53]

Weed Species	Soil Condition	Microwave Energy (J cm^{-2})																			
		0				92				185				370				462			
		Soil Depth (cm)				Soil Depth (cm)				Soil Depth (cm)				Soil Depth (cm)				Soil Depth (cm)			
		0	2	5	10	0	2	5	10	0	2	5	10	0	2	5	10	0	2	5	10
Annual Ryegrass	Oven Dry Soil	0.6	0.75	0.63	0.72	0.59	0.55	0.66	0.47	0.6	0.72	0.58	0.71	0.6	0.46	0.63	0.55	0.26	0.28	0.58	0.69
	Soil (20 % Moisture)	0.57	0.63	0.65	0.59	0.57	0.63	0.42	0.67	0	0	0	0.58	0.01	0	0	0	0	0	0	0.01
Perennial Ryegrass	Oven Dry Soil	0.84	0.84	0.84	0.84	0.83	0.8	0.81	0.75	0.83	0.8	0.78	0.81	0.61	0.5	0.85	0.88	0.26	0.28	0.58	0.69
	Soil (20 % Moisture)	0.85	0.85	0.85	0.85	0.11	0.34	0.79	0.86	0	0	0	0.84	0	0	0	0	0	0	0	0
Wild Oats	Oven Dry Soil	0.88	0.89	0.91	0.91	0.86	0.93	0.92	0.92	0.91	0.93	0.86	0.93	0.44	0.16	0.8	0.93	0	0	0.76	0.92
	Soil (20 % Moisture)	0.89	0.88	0.91	0.87	0.36	0.86	0.86	0.97	0	0	0.06	0.7	0.03	0	0	0.2	0	0	0	0.15
LSD (P = 0.05)																					0.17

Note: the LSD is the Least Significant Different, which indicates the least difference between treatment means that can be regarded as statistically different from each other with a confidence of 95 %.

pots or field plots, ranged between 18 % and 92 %. This suggests that the crop yield responses in these pot and field trials is due to factors beyond weed competition.

Noling and Ferris [60] demonstrated that nematodes can reduce alfalfa yields by more than 70 percent. Similarly, fungi can significantly reducing crop yield potential [61, 62]. The impact of soil borne pathogens can be described by [57]:

$$Y = Y_o\left[1 - a(1 - e^{-fN})\right] \quad (10)$$

If the pathogen population is resource limited, as are most natural populations, then the pathogen population can be described by [57]:

$$N = \frac{K}{2}\left[1 + tanh\left(\frac{r \cdot^{\circ} D}{2} + tanh^{-1}\left(\frac{2 \cdot No}{K} - 1\right)\right)\right] \quad (11)$$

Ferriss [62] demonstrated that microwave soil heating can eliminate Pythium and Fusarium species as well as all nematodes, except *Heterodera glycines*. Rahi and Rich [63] also demonstrated that microwave soil heating can effectively control nematodes. Cooper and Brodie [55] and Brodie, Grixti, Hollins, Cooper, Li and Cole [64] and Khan, Jurburg, He, Brodie and Gupta [65] demonstrated that microwave soil treatment significantly diminished bacterial populations at similar treatment levels needed to kill weed seeds in the soil; however, Vela, Wu and Smith [66] showed that nitrifying bacteria were resilient to very high microwave treatments (> 40,000 J cm^{-2}).

From equations (10) and (11), if a crop requiring 1500 growing degree days to mature is exposed to an initial *Meloidogyne hapla* nematode population of 1085 individuals kg^{-1} of soil, the yield potential would be 0.3 at the end of crop maturation; however, if the crop was exposed to an initial population of only 4 individuals kg^{-1} of soil because of some pre-sowing soil sanitation strategy, the crop yield potential would be approximately 0.7. Therefore, pre-sowing soil sanitation could provide a crop yield increase (compared with untreated soil) of: $\frac{(0.7 - 0.3)}{0.3} \times 100 = 133\%$ [64]. This reduction in pathogenic organisms in the soil may explain the significant increases in crop yield observed when a crop is planted into microwave treated soil.

A viable crop yield response model for microwave weed and soil treatment has also been developed by

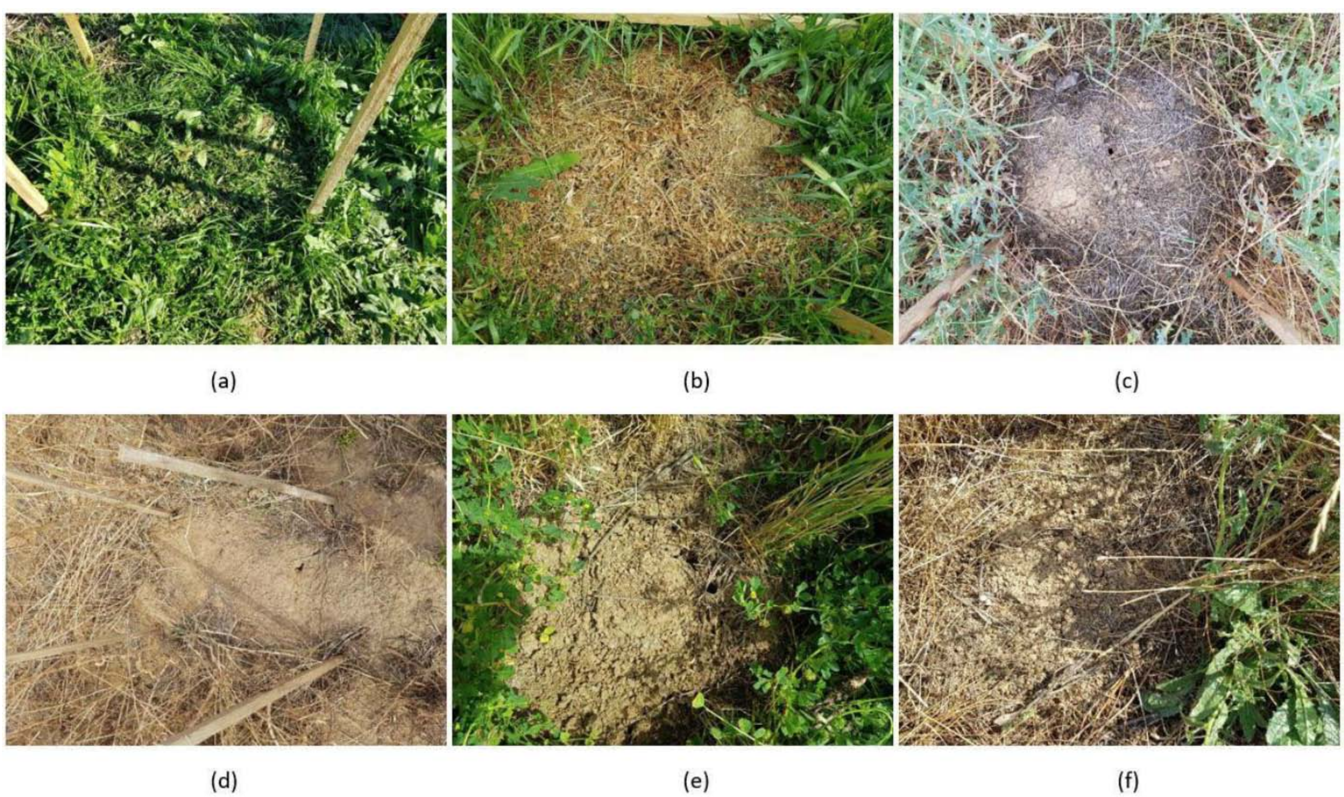


Figure 5: Image sequence of test plot treated with approximately 400 J cm^{-2} of microwave energy. The sequence is (**a**) immediately after treatment, (**b**) 18 days after treatment, (**c**) 88 days after treatment, (**d**) 220 days after treatment, (**e**) 400 days after treatment and (**f**) 470 days after treatment.

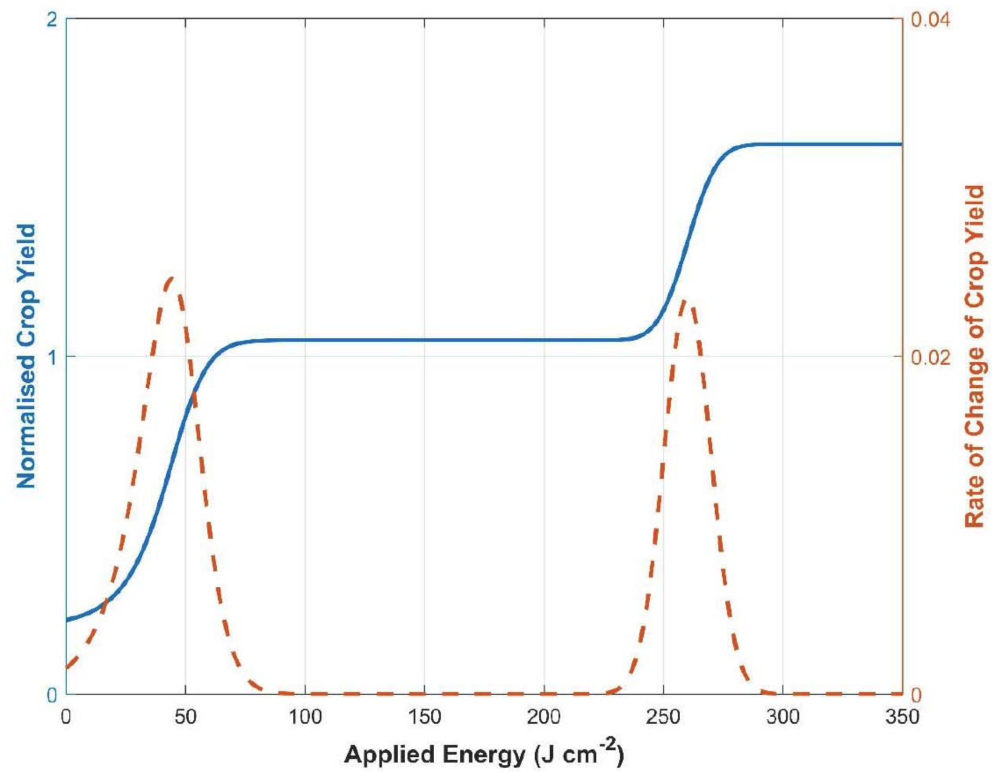


Figure 6: Crop yield response in a typical cropping system in response to increasing microwave energy application.

Brodie [67]. The yield potential can be described by:

$$Y = Y_o \left\{ \begin{array}{l} 1 - \dfrac{I \cdot [W(1-N-D_o) - E_m + I_m] \\ \{a \cdot erfc[b(\Psi - g)] + e \cdot erfc[j(\Psi - k)]\}}{100 \left\{ \begin{array}{l} e^{ct}\left[1 + e^{-\left(\frac{t-t_o}{d}\right)}\right] \\ + \dfrac{I \cdot [W(1-N-D_o) - E_m + I_m]\{a \cdot erfc[b(\Psi - g)] + e \cdot erfc[j(\Psi - k)]\}}{A_w} \end{array} \right\}} \\ +1 + m \cdot erf[n(\psi - q)] \end{array} \right\} \quad (12)$$

The form of equation (12) is illustrated in Figure **6**, where the first peak is associated with emerged weed removal from the cropping area and the second peak is associated with depletion of soil borne weed seeds and pathogens.

CONCLUSIONS

Heating weeds, weed seeds, and soil pathogens above their lethal temperatures for sufficient time achieves good weed and pathogen control. The amount of energy needed to kill emerged weeds is relatively small because the mass of plant material being heated is not huge; however, treatment of weed

Table 3: Nomenclature Used in this Paper

η	**Thermal efficiency of a solar collection system**
Ψ_τ	$\Psi_\tau = \dfrac{1 - \dfrac{\kappa'_1 \cdot \kappa \cdot \tan(kd)}{\tau_1} \cdot \tanh(\tau_1 b)}{\dfrac{\kappa'_1 \cdot \kappa \cdot \tan(kd)}{\tau_1} \cdot \tanh(\tau_1 b)}$
°D	Is the degree days which are suitable for the growth of the pest or pathogen
a	Is the maximum crop yield loss due to soil borne pathogens
a, b, g, e, f, k, l, m, n and q	Are parameters associated with weed competition and crop yield responses in the yield potential equations. These are determined by experimental outcomes.
A_c	Area of the covered soil (m^2)
A_w	Is the percentage yield loss as weed density approaches ∞ (= 38.0 [68])

(Table 3). Continued.

η	**Thermal efficiency of a solar collection system**
b	Is the thickness of the dielectric plate covering the slow-wave structure (m)
c	Is the speed of light (m s^{-1}) or the rate at which I approaches zero as t approaches ∞ (= 0.017 [68])
d	Is the slope of the seed bank recruitment curve at t_o
d	Is the depth of the teeth of the slow-wave structure (m)
D_b	Fraction of the seed population from previous seasons breaking dormancy (Note: this is expressed as a fraction of the initial seed bank population W_o)
D_o	Fraction of the seed population developing dormancy (Note: this is expressed as a fraction of the initial seed bank population W_o)
E	Is the strength of the microwave field (V m^{-1})
E_m	Seed emigration from the area of interest
E_o	Is the strength of the microwave field at the surface of the slow-wave structure (V m^{-1})
f	Is a population sensitivity parameter for the crop (i.e. damage rate)
g	Is the generational number
H	Is the herbicide dose
I	Is the percentage yield loss as the weed density tends towards zero (= 0.38 [68])
I	Solar insolation onto the soil surface (W m^{-2})
Im	Seed immigration into the area of interest
k	Is the wave number of the microwave field
K	Is the carrying capacity of the pest or pathogenic population
N	Is the natural death rate for the whole population (Note: this is expressed as a fraction of the initial seed bank population W_o)
N	Is the pest or pathogen population number
N_o	Is the starting population for pathogenic organisms in the crop
p_o	Is the initial frequency of herbicide resistant plants
r	Is the base population growth rate of the pest or pathogen
s	Is the selection pressure for herbicide resistance
S_s	Viable seed set per plant from surviving volunteers in the weed population
T	Temperature (°C)
t	Is the time difference between crop emergence and weed emergence
T_a	Ambient temperature (°C)
t_o	Is the time for 50 % germination of the viable seed bank
T_o	Is the mean surface temperature (°C)
T_s	Solarised soil temperature (°C)
U	Thermal conductivity of the plastic film covering the solarised soil (W m^{-2} $°C^{-1}$)
W	Is the viable seed bank
Y_o	Is the theoretical yield with no weed infestations
Z	Lethal temperature holding time, in minutes (Levitt, 1980)
z	Is the depth of soil (m)
ΔT	Is the amplitude of the temperature fluctuation (°C)
α_a	The solar absorption coefficient of the solarised soil
γ	Is the thermal diffusivity of the soil (m^2 s^{-1})
κ_1'	Is the dielectric constant of the material adjacent to the slow-wave structure
κ'	Is the dielectric constant of the plants/soil being treated by the slow wave structure
λ	Is the efficacy of the herbicide killing action
σ	Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4})
τ_c	The optical transmission coefficient of the plastic film covering the solarised soil
ω	Is the angular velocity of the sinusoidal temperature fluctuation (Rad s^{-1})

seeds and soil borne pathogens requires heating of the bulk soil, which requires far more thermal energy because of the much larger mass of soil to be heated. Weed and soil heating can be achieved by using several techniques, including solarisation, hot air or flaming techniques, steam treatment, or microwave heating. This paper has demonstrated that microwave heating has a higher thermal efficiency than other techniques and should therefore be considered as a viable thermal weed and pathogen control mechanism.

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