Microwave Weed and Soil Treatment in Agricultural Systems

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Abstract: Weeds are the major hindrance in crop production, costing approximately AU$4 billion annually in Australian gain production systems, in 2006. Herbicide resistance is also becoming a global issue; therefore, there is a growing need for alternative weed control methods. Several thermal and non-thermal methods are possible. The thermal method of microwave weed management has been explored for some time. This paper provides a brief summary of the research associated with this technique.

Keywords: Weed, soil, microwave, herbicide resistance, crop production.

1. INTRODUCTION

Weeds are the major hindrance in crop production. They compete for light, space, nutrients, moisture and CO_2, significantly declining crop yields. Modern no-till cropping depends on herbicides for weed management. Herbicides are classified by their mode of action, as outlined in Table **1**.

In Australian agriculture, the total estimated direct cost of weed management and loss in crop productivity, due to weeds, was estimated, in 2006, to be about AU$4 billion annually [1]. Similarly, in 1995, Pimentel [2] estimated the indirect costs of chemical pest management to be approximately US$5.8 billion annually in the United States. Scaling this indirect expenditure to the Australian population, and accounting for some inflation in costs over time, currently yields about AU$0.5 billion annually. In terms of present costs, the combined direct and indirect costs of chemical weed management for Australian broad acre cropping is estimated to be approximately AU$6.2 billion annually (≈AU$280 ha^{-1} across the cropping area of the country).

1.1. The Growing Threat to Herbicide Use

Harper [4] predicted the development of herbicide resistance over 60 years ago; suggesting that the development of resistance is an inevitable consequence of reliance on chemicals for weed control [5]. Globally, there are now over 400 weed species that have developed resistance to 160 herbicides from the various chemical groups (Table **1**) and annually 9 new weed biotypes are reported as becoming herbicide resistant [6]. For example, Bagavathiannan *et al*, [7] reported glyphosate resistance in barnyard grass (*Echinochloa crus-galli L.*) in 2011, while ryegrass (*Lolium rigidum*), in Australia, has developed resistance to multiple chemical groups [8]. Thornby and Walker [9], determined, by simulation and field observations, that continuous use of glyphosate induced resistance in barnyard grass (*Echinochloa colona*) within 15 years.

The International Agency for Research on Cancer (IARC), which is part of the World Health Organisation (WHO), has also concluded that glyphosate is probably carcinogenic to humans [10]. This announcement has generated considerable debate in the media, concerning the use of herbicides. Other authors have also highlighted the potential hazard to human health of long term exposure to herbicides and pesticides [11-16]. This almost led to glyphosate being banned in the European Union; however, it was reregistered for agricultural applications.

1.2. Understanding Crop Response to Herbicide Weed Management

System analyses often shed useful light on the impact of change on agricultural production. A system transfer function, which relates crop yield potential to herbicide application, has been derived [17]:

$$Y = Y_o \left\{ 1 - \frac{W_a B}{100\left\{G + \frac{W_a B}{A_w}\right\}} + aH^2 - bH \right\} \qquad (1)$$

Where,

$$W_a = I.\left[W\left(1-N-D_o\right) - E_m + I_m\right], G = e^{ct}\left[1 + e^{-\left(\frac{t-t_o}{d}\right)}\right],$$

$$B = .\left[1 - S.e^{\frac{-ag^2}{2}} + S.e^{\frac{-ag^2}{2} - \lambda H}\right].$$

The sensitivity of yield potential to time can be deduced by differentiating this transfer function with respect to the number of weed generations (g):

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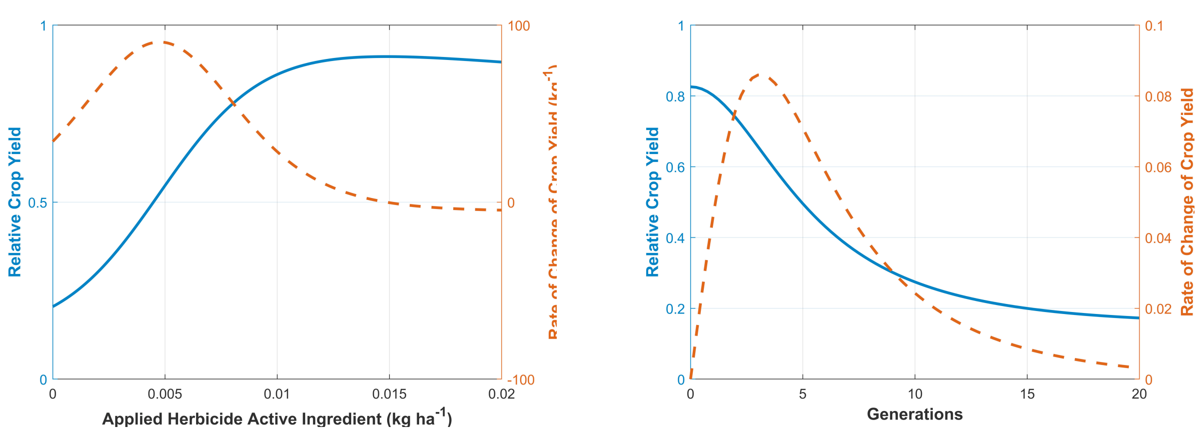
Table 1: Herbicide Group Classification by Mode of Action (Modified from: [3])

Chemical Family	Mode of Action
Group 1	Inhibitors of acetyl CoA carboxylase ACCase. These chemicals block an enzyme called ACCase. This enzyme helps the formation of lipids in the roots of grass plants. Without lipids, susceptible weeds die.
Group 2	ALS/AHAS inhibitors. These chemicals block the normal function of an enzyme called acetolactate (ALS) actohydroxyacid synthase (AHAS). This enzyme is essential in amino acid (protein) synthesis. Without proteins, plants starve to death.
Group 3	Microtubule assembly inhibitors. These chemicals inhibit the cell division in roots.
Group 4	Synthetic auxins. These chemicals disrupt plant cell growth in the newly forming stems and leaves; they affect protein synthesis and normal cell division, leading to malformed growth and tumors.
Group 5	Photosynthetic inhibitors at Photosystem II, Site A. These chemicals interfere with photosynthesis and disrupt plant growth, ultimately leading to death.
Group 6	Photosynthetic inhibitors at Photosystem II, Site II.
Group 7	Photosynthetic inhibitors at Photosystem II, Site B.
Group 8	Lipid synthesis inhibitors (not ACCase inhibition). These chemicals inhibit the cell division and elongation in the seedling shoots before they emerge above ground.
Group 9	Inhibitors of EPSP synthesis. These chemicals inhibit the amino-acid synthesis.
Group 10	Inhibitors of glutamine synthetase
Group 11	These chemicals inhibit the carotenoids biosynthesis.
Group 13	Inhibits DOXP, which is needed in plant metabolism.
Group 14	Inhibits an enzyme of chlorophyll and heme biosynthesis
Group 15	Inhibitors of cell growth and division
Group 19	Auxin transport inhibitor allowing buildup in the meristem area
Group 20	Inhibits actively dividing merestems in roots and shoots as well as seed germination
Group 22	Cell membrane disrupters. Chemicals that disrupt the internal cell membrane and prevent the cells from manufacturing food.
Group 27	Inhibits plant pigment biosynthesis and photosynthesis

$$\frac{\partial Y}{\partial g} = Y_o \left\{ \frac{W_a \cdot G \cdot A_w{}^2 \cdot S \cdot a \cdot g \cdot \left(e^{\frac{-a g^2}{2}} - e^{\frac{-a g^2}{2} - \lambda H} \right)}{100\{G A_w + W_a \cdot B\}^2} \right\} \quad (2)$$

Using published data for the various parameters in equations (1) and (2), this transfer function predicts that significant herbicide resistance will occur within 15 generations (b) Figure **1**(**b**) when a single herbicide treatment strategy is adopted. This agrees with the work of Thorn by and Walker [9]. Therefore, sensible herbicide rotations or alternative weed control methods are needed. Alternative weed control methods include: tillage; natural chemicals; thermal treatment, such as flaming, steam, infrared radiation, hot water, or microwave treatment.



(**a**) (**b**)

Figure 1: Normalised crop yield (blue line) and rate of change of crop yield (orange line) as a function of (a) herbicide application in a single season, and (**b**) number of seasons (generations of weeds), based on Equations (1) and (2).

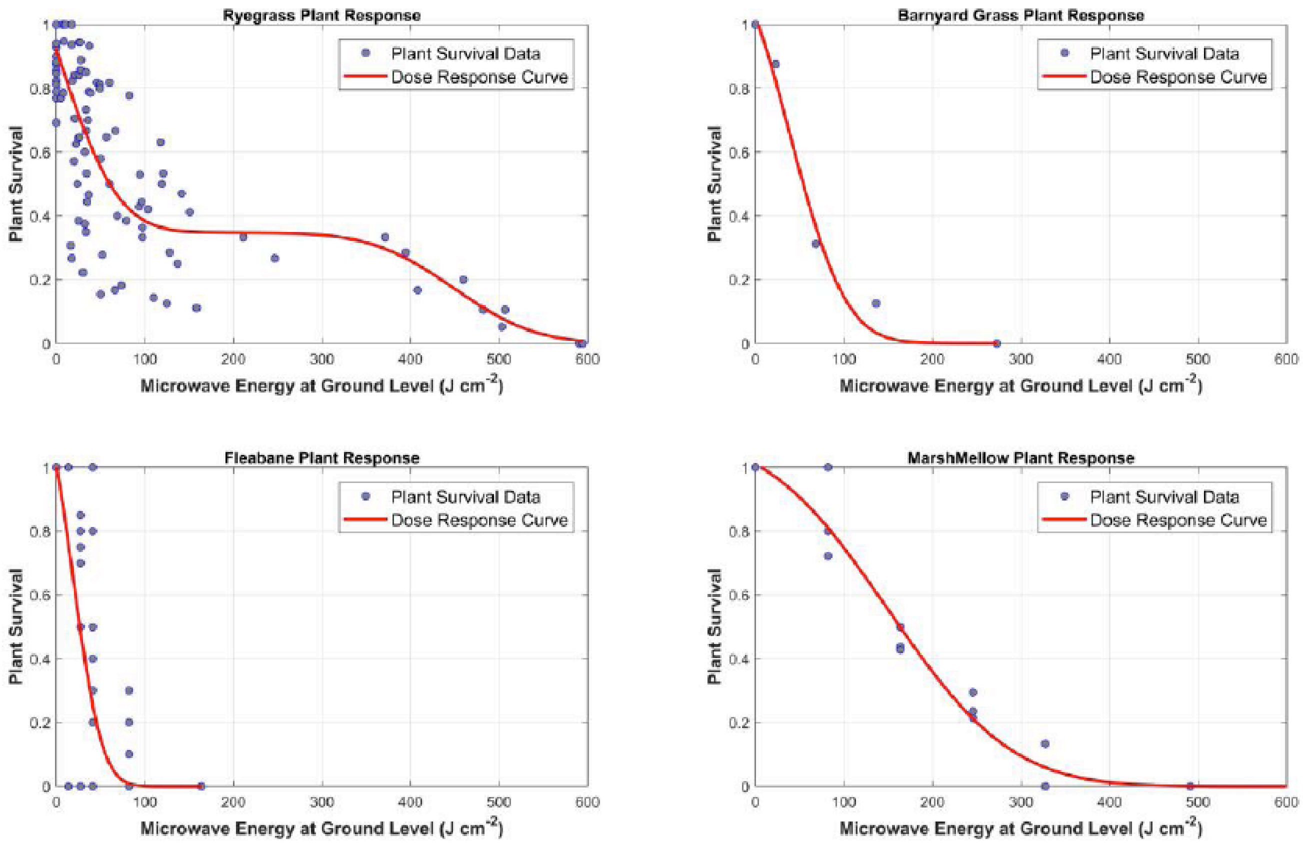


Figure 2: Dose response curves for microwave treatment of four species of weed plant using a horn antenna.

1.3. Radio Frequency and Microwave Weed Studies

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19th century [18], while interest in the effect of high frequency waves on plant material began in the 1920s [18]. Davis *et al*. [19, 20] were among the first to study the lethal effect of microwave heating on seeds. They showed that seed damage was mostly influenced by a combination of seed moisture content, specific mass, and specific volume [20]. Menges and Wayland [21] reported that microwave soil treatment (360 J cm^{-2}) significantly inhibited weed establishment and caused less crop injury (18% for microwave treatment) than residual methazole herbicide application (85%). Menges and Wayland used onions as their test crop. Although they used several new herbicides for selective weed control in onions, only methazole controlled London rocket in the experiment; however, it was also very damaging to the onion crop as well [21].

Wayland, Merkle, Davis, Menges and Robinson [22] also demonstrated that microwaves can be very effectively used for post emergence weed control. In their experiments, single rows of Japanese millet (*Echinochloa frumentacea (Roxb.) W.F. Wight*), London rocket (*Sisymbrium irio L.*), annual sunflower (*Helianthus annuus L.*), ridgeseed euphorbia (*Euphorbia glytosperma* (Engelm.)) and redroot pigweed (*Amaranthus retroflexus* L.) were seeded into prepared beds. Microwave treatments were applied 21 days after planting, when the Japanese millet, London rocket, annual sunflower, ridgeseed euphorbia and redroot pigweed were at 0.2, 1, 2, and 10 cm in height, respectively. They found that acceptable control (91 % mortality) was achieved using 183 J cm^{-2} of microwave energy.

In a review of microwave soil treatment for weed seed deactivation, Nelson [23] estimated that the cost of microwave treatment would be about US$850 per acre (US$2,100 ha^{-1}). He concluded that this was an unreasonable cost for weed control [23]; however, since Nelson's paper was written, the agricultural industry has become acutely aware of herbicide resistance and the high indirect costs of herbicide use; therefore, microwave weed management strategies are again under consideration. This paper summarises some of the important findings from a decade long research programme that has explored the application of microwave energy as a potential weed control strategy.

2. POTENTIAL MICROWAVE APPLICATION STRATEGIES

Microwave energy can be applied to emerged weeds or to the soil prior to sowing. Many pot experiments and small field trials have been undertaken to evaluate the performance of both strategies.

2.1. Plant Treatment

If plant and seed responses to microwave treatment are assumed to be normally distributed, a simple plant survival function (S) relating survival to microwave treatment energy, can be derived by integrating the Gaussian Normal Distribution function:

$$S = a \cdot \mathrm{erfc}[b(\Psi - c)] \quad (3)$$

Some examples of these dose response curves, which indicate the portion of the population that survive a given energy dose, are shown in Figure **2** [24-26] and the associated response parameters from equation (3) are summarised in Table **2**. Comparison of various species survival curves indicate that some species are more susceptible to microwave treatment than others. Estimated lethal dose for 50% (LD_{50}) and 90% (LD_{90}) of the weed population can be determined by rearranging equation (3):

$$LD_{50} = \frac{erfc^{-1}\left(\frac{0.5}{a}\right)}{b} + c \quad (4)$$

$$LD_{90} = \frac{erfc^{-1}\left(\frac{0.1}{a}\right)}{b} + c \quad (5)$$

The LD_{50} and LD_{90} microwave energy levels, for each species, are also reported in Table **2**.

The exception to these basic relationships was ryegrass, which exhibited a double Gaussian response of the form:

$$S = a \cdot \mathrm{erfc}[b(\Psi - c)] + d \cdot \mathrm{erfc}[e(\Psi - f)] \quad (6)$$

2.2. Soil Treatment

Microwave field absorption, and therefore the rate of soil heating, depend entirely on the dielectric properties of the soil. These properties change significantly with soil composition, moisture content and soil structure (density). As the microwave field propagates into the soil, energy is transferred to the soil in the form of heat; therefore, the microwave field density is attenuated in accordance with:

$$\Psi = \Psi_o \cdot e^{-2cd} \quad (7)$$

The relationships between applied microwave energy and seed survival at different depths have also been derived [26]:

$$S = a \cdot \mathrm{erfc}\left[b \cdot \left(\Psi \cdot e^{-2cd} - f\right)\right] \quad (8)$$

In this case the LD_{50} and LD_{90} can be determined; however, it is dependent on how deep the seeds are buried in the soil:

$$LD_{50} = \left[\frac{erfc^{-1}\left(\frac{0.5}{a}\right)}{b} + f\right] \cdot e^{2cd} \quad (9)$$

Table 2: Equation Coefficients, Goodness of fit (R^2), LD_{50}, and LD_{90} for Weed Plant Survival as a Function of Microwave Energy Applied to the Soil Surface

Species	Coefficients						R^2	LD_{50} (J cm^{-2})	LD_{90} (J cm^{-2})
	a	b	c	d	e	f			
Annual Ryegrass	0.576	0.013	1.24E-07	0.174	0.01	448.4	0.72	60	480
Barnyard grass	0.54	0.02	44.7	__	__	__	0.98	48	91
Barley Grass	0.56	0.022	40.92	__	__	__	0.99	45	84
Brome Grass	0.58	0.012	65.19	__	__	__	0.98	76	148
Feather top Rhodes Grass	0.5	0.045	41.02	__	__	__	0.99	41	61
Fleabane	0.52	0.04	37.57	__	__	__	0.99	39	61
Marshmallow	0.55	0.0064	150.1	__	__	__	0.98	163	297
Paddy Mellon	0.52	0.047	33.92	__	__	__	0.99	35	53
Wild Oats	0.54	0.024	41.23	__	__	__	0.97	44	80
Wild Radish	0.52	0.017	64.53	__	__	__	0.99	67	118

$$LD_{90} = \left[\frac{erfc^{-1}\left(\frac{0.1}{a}\right)}{b} + \mathrm{f}\right] \cdot e^{2cd} \qquad (10)$$

Because sand is predominantly silicon dioxide, which is almost transparent to microwave energy, it requires the most energy to heat. Therefore, it is regarded as the “worst case” scenario for soil heating. Some examples of fitting dose rate curves to measured data for sand are shown in Figure **3** [21, 24, 26, 27].

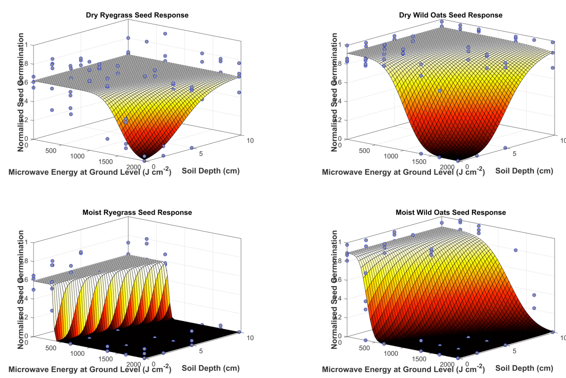


Figure 3: Dose responses of ryegrass and wild oats seeds as a function of soil moisture, microwave energy at ground level, and burial depth in soil.

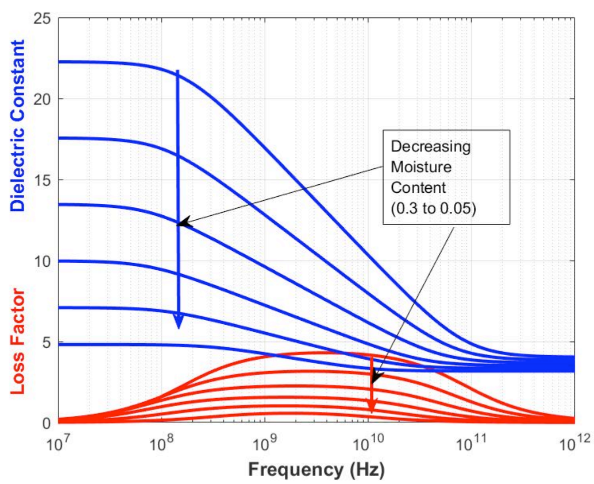


Figure 4: Dielectric properties (blue = dielectric constant and red = loss factor) for clay soil as a function of frequency and soil moisture.

As is evident from the dose responses shown in Figure **3**, higher soil moisture results in better seed deactivation. This is related to the dielectric properties of soil, although the relationship is complex. For example, higher moisture content gives rise to higher dielectric properties (Figure **4**) and therefore more surface energy reflection and field attenuation in the soil, compared with dry soil. This results in less total energy entering the soil, but faster soil heating in the top layers of the soil.

Soil structure also affects the soil’s response to electromagnetic fields, with clay soils having a dielectric response that has a broader band of frequencies (Figure **4**) than sand (Figure **5**); however, moist sand has a higher dielectric loss factor (Figure **5**) than clay (Figure **4**), at the same moisture content. Despite this, at important ISM frequencies (i.e. 860 to 960 MHz and 2450 MHz), the dielectric constant of sand is higher than that of clay and the dielectric loss of sand is lower than that of clay, at all moisture levels (Figure **6**).

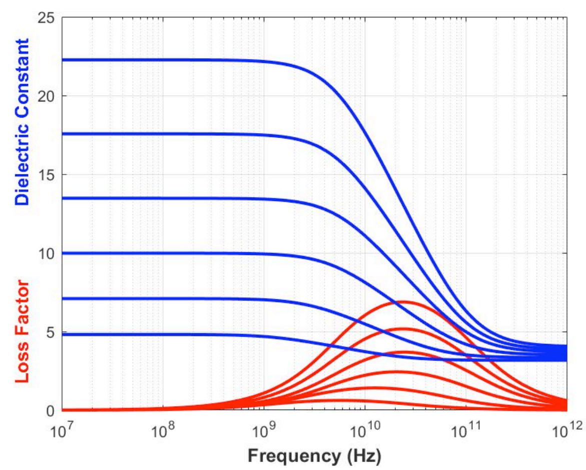


Figure 5: Dielectric properties (blue = dielectric constant and red = loss factor) for sandy soil as a function of frequency and soil moisture.

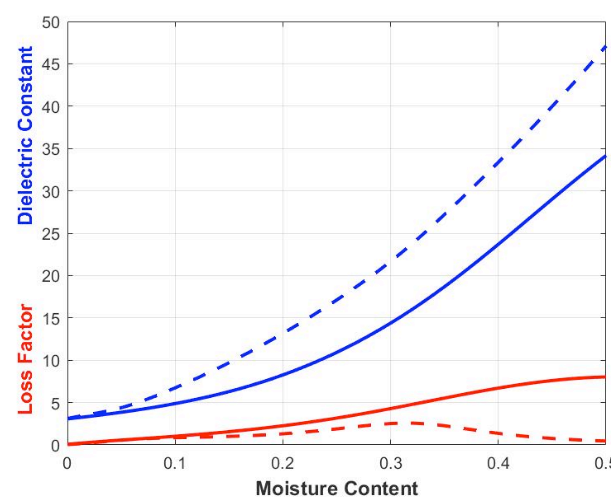


Figure 6: Dielectric properties of a sand (dotted) and clay (solid) as a function of soil moisture, at 2.45 GHz (Data from: [28]).

Applying equation (8) to the work done by Menges and Wayland [21], reported earlier, reveals that the

Table 3: Equation Coefficients, and Goodness of fit (R^2) for Weed Seed Survival as a Function of Microwave Energy Applied to the Sand Surface, Seed Burial Depth, and Soil Moisture Status [Source: 21, 24, 26, 27]

Species	Sand Moisture													
	Dry					LD_{50}* (J cm^{-2})	LD_{90}* (J cm^{-2})	Wet					LD_{50}* (J cm^{-2})	LD_{90}* (J cm^{-2})
	a	b	c	f	R^2			a	b	c	f	R^2		
Annual Ryegrass	0.31	0.0033	0.06	1521	0.52	1339	1737	0.30	0.0456	0.07	355.40	0.91	341	371
Bellyache bush	0.50	0.0020	0.08	664.5	0.90	666	1117	0.56	0.0033	0.15	255.8	0.87	287	546
Parthenium	0.55	0.0011	0.22	762.8	0.79	842	1614	0.97	0.0012	0.08	0.0001	0.73	375	940
Perrenial Ryegrass	0.41	0.0027	0.06	1400	0.78	1330	1708	0.43	0.0148	0.13	240.5	0.94	232	299
Rubber vine	0.49	0.0020	0.03	936.6	0.58	1386	310	0.61	0.0015	0.03	406.00	0.86	513	1046
Wild Oats	0.46	0.0028	0.12	1006	0.76	981	1326	0.45	0.0074	0.12	346.8	0.84	334	465
Wild Radish ¥	-	-	-	-	-	-	-	0.16	0.1083	0.12	74.25	0.72	65	78
Menges and Wayland [21] ¥	0.3392	0.028	0.104	109.8	0.63	94	137	0.349	0.0588	0.28	84.51	0.69	79	99

LD_{50} and LD_{90} values represent the soil surface energy doses needed to kill 50% and 90% of the seeds at 2 cm burial depth, respectively. These values are much lower than the values derived for sand (Table **3**), but are like the values for Wild Radish in Table **3**, because these experiments were conducted in moist clay soil rather than sand.

3. CROP RESPONSE TO MICROWAVE SOIL TREATMENT

Several pot trials, using wheat, canola, and rice, have been conducted. Various doses of microwave energy (0, 80, 160, and 320 J cm^{-2}) were applied to the soil in the pots, using a horn antenna and a 2 kW microwave source, operating at 2.45 GHz. These experiments used either five or ten replicates of each treatment.

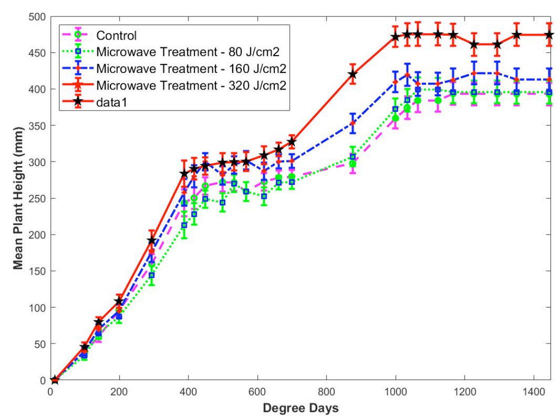


Figure 7: Mean wheat plant height as a function of time since planting and microwave soil treatment energy (error bars represent LSD for P = 0.05) [Modified from: 28].

Figure 8: Representative examples of wheat and canola plant growth as a function of microwave treatment energy (Control on the left and highest treatment on the right).

Table 4: Summary of Crop Responses to Microwave Soil Treatment [Modified from: 28, 32, 33]

	Control	Hand Weeded	Microwave Treatment (J cm^{-2})			LSD (P = 0.05)	Change from Hand Weeded/Control
			80	160	320		
Glass house Experiments							
Canola Pod Yield (g pot^{-1})	0.27^a	0.56^a	0.36^a	1.25^b	1.95^c	0.55	248 %
Wheat Grain Yield (g pot^{-1})	0.66^a	0.67^a	0.68^a	0.75^a	1.25^b	0.3	87 %
Rice Grain Yield (g pot^{-1})	40.0^a	41.3^a	43.3^a	59.0^{ab}	64.0^b	18.9	55 %
Maize (g pot^{-1})	5.3^a	6.6^a	__	10.3^{ab}	12.8^b	4.8	92 %
Field *Experiments*							
Rice (t ha^{-1}) – Dookie Year 1 (2015/2016)	7.5^a	__	__	__	10.1^b	2.0	35 %
Rice (t ha^{-1}) – Dookie Year 2 – (2016/2017) - cold affected	2.1^a	__	__	__	3.9^b	1.3	84 %
Rice (t ha^{-1}) – Old Coree – (2016/2017)	7.7^a	__	__	__	9.1^b	1.2	19 %
Wheat (t ha^{-1})	5.7^a	6.6^{ab}	__	__	7.8^b	1.4	39 %
Tomato (t ha^{-1})	64.1^a	65.2^a	__	__	89.6^b	24.7	37 %

After the soil had cooled to ambient temperatures, crop seeds were planted into the treated soil and grown to maturity in a glass house, located at Dookie Campus of the University of Melbourne (145°42' E, 36°23' S). Plant maturation rate, mean plant height (Figure **7** and **8**), plant/tiller density, and mean yield per pot (Table **4**) all increased significantly as the level of applied microwave energy increased. For example, 320 J cm^{-2} of applied microwave energy increased the yield of canola, wheat and rice by 248%, 86.6% and 55%, respectively, compared with the hand weeded control (Table **4**). Figure **9** illustrates the response of rice yield to microwave soil treatment energy.

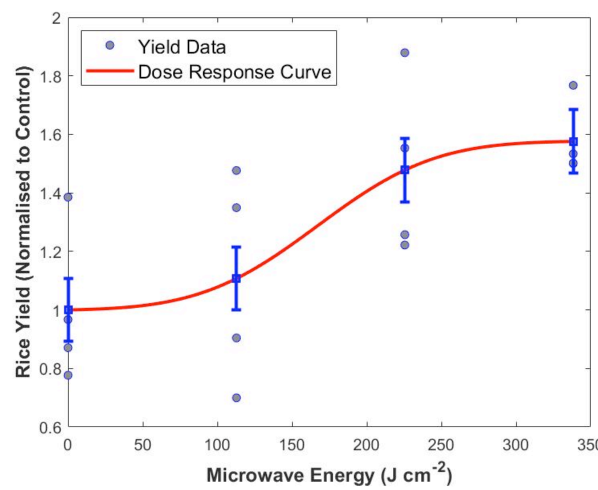


Figure 9: Normalised rice yield as a function of microwave treatment.

Figure 10: Four by 2 kW microwave trailer prototype in the field.

4. TAKING TO THE FIELD

An experimental microwave trailer has been developed (Figure **10**) to slowly move over the soil during experiments. It has four independently controlled, 2 kW microwave generators operating at 2.45 GHz. The trailer is powered from two on-board 7 kVA, 3 phase electrical generators. The microwave energy is channelled to the ground *via* waveguides and horn antennae.

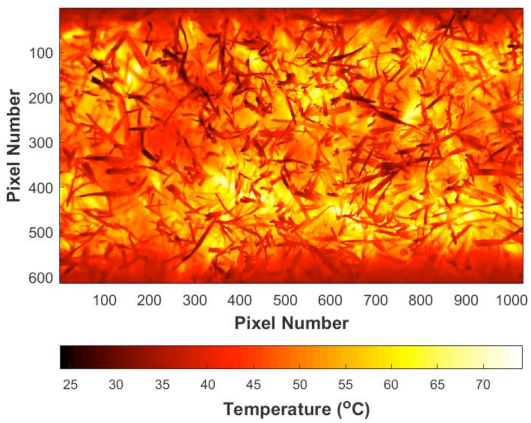


Figure 11: Thermal image of treated strip of kikuyu grass, captured with a FLIR T1024 thermal camera.

The trailer can be used to treat emerged weeds and grasses. For example, thermal images revealed that kikuyu grass (*Pennisetum clandestinum*) achieved a temperature of 61°C (Figure **11**) when the trailer was moved over the grass at about 720 m hr^{-1} with the aperture of the horn antenna being within 1.0 cm of the soil surface. There was audible crackling of the grass as the antennae moved along the strip, indicating that micro-steam explosions were occurring in the grass stems, due to rapid microwave heating. After four days, the treated strips were quite evident (Figure **12**), with 100% mortality along almost all the treated strips.

Figure 12: Image of treated strips of kikuyu grass, taken 4 days after treatment.

It is important to note that the treatment strips are very clearly defined in the grass; therefore, with auto-steering technology, microwave treatment can be used to control weeds between crop rows, without damaging the crop.

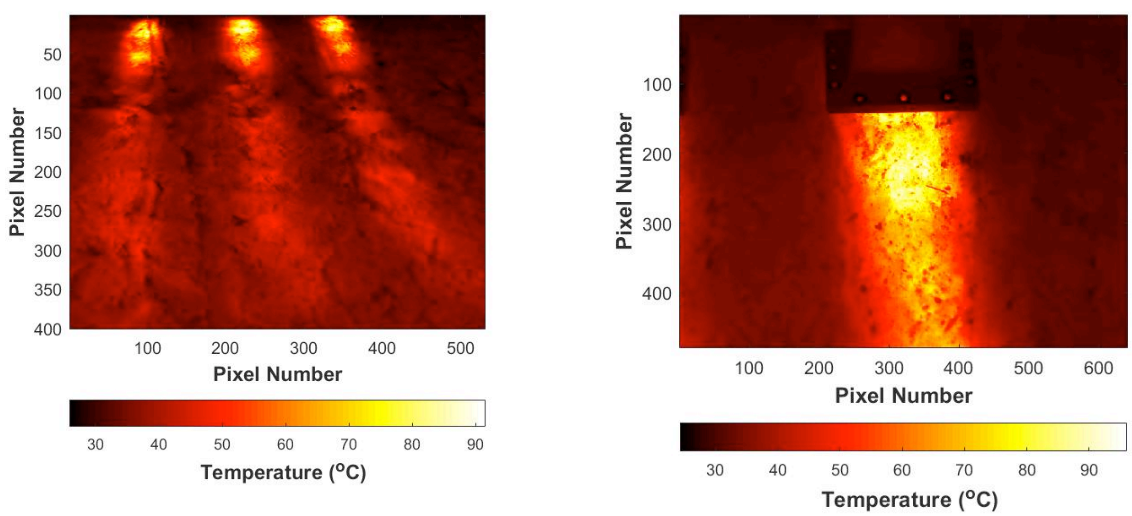


Figure 13: Thermal images of the soil surface during microwave treatment using the prototype trailer, captured with a FLIR T640 thermal camera.

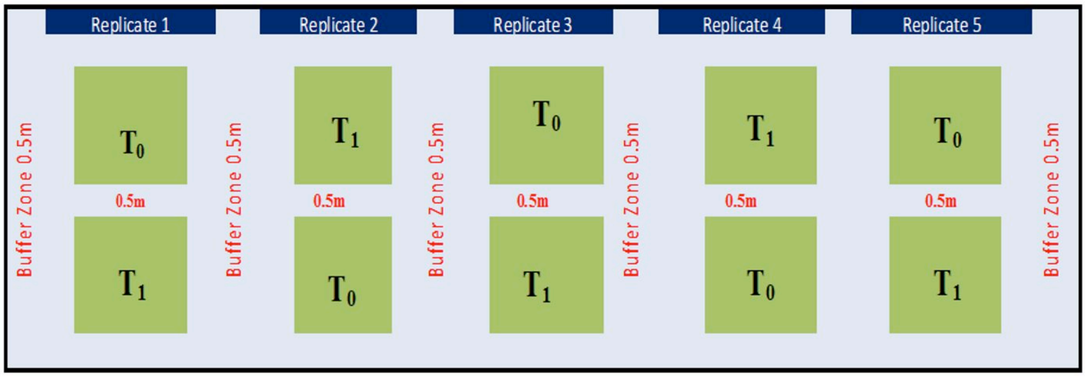


Figure 14: Experimental layout of the all microwave field experiments: untreated control (T_0) and MW treated (T_1) [Source: 32].

The trailer can also be used to treat soil with a high dose of microwave energy. In this case, treatment of up to 120s duration occurs while the trailer is stationary. The trailer is then moved forward by about 8 to 10 cm, depending on the dimensions of the horn antennae, and treatment is done again in the next small section of soil. Complete soil coverage was achieved by performing two passes over the treated plots, with the second pass being offset from the first to cover the inter-row strip. Figure **13** shows thermal images of the soil surface during microwave treatment, in preparation for planting a rice crop.

4.1. Effect of Microwave Soil Treatment on Subsequent Crop Performance

It has been demonstrated that when the soil is treated in this manner, weed seeds, nematodes, soil bacteria, and fungi, such as *Fusarium oxysporum* and *Sclerotium rolfsii*, are significantly reduced in number [30-32]. Microwave pre-treatment of the soil, prior to crop planting has been shown to significantly reduce weed emergence, enhance crop vigour, and increase final yield potential in both glasshouse and field conditions [33, 34]. All field experiments were laid out according to Figure **14**. A summary of all glass house and field yield data, from the microwave experiments, is shown in Table **4**.

4.2. Effect of Microwave Soil Treatment on Soil Biota

Speir *et al*. [35] demonstrated that fungi are more susceptible to microwave soil treatment than bacteria. This has been verified by other researchers [36-38]. Microwave induced "heat shock" activation of bacterial and fungal spores has also been observed [37]. Vela *et al*. [37] also demonstrated that soil bacteria, bacterial spores, actinobacteria, fungi, nitrogen-fixing bacteria, and nitrifying bacteria were all resistant to over 40,000 J cm^{-2} of microwave energy applied to the soil surface. Experimental analyses of the soil biota data revealed that microwave treatment significantly reduced the number of soil bacteria (Table **5**) but did not completely sterilize the soil; however, bacterial numbers significantly increased after a month (Table **6**) and ended significantly higher than at the start of the experiment. Fungi and nematodes are also significantly affected, but soil protozoa seem to be unaffected [32, 38].

Several of these experiments were repeated in different soils from the Dookie Campus of the university of Melbourne, with similar results. The combined response of bacteria from all these experiments is shown in Figure **15**. The response surface of the combined bacterial experiments can be described by:

$$S = 0.3016.erfc\left(0.0025\left(\psi.e^{-0.022D} - 0.034\right)\right) + 0.22.erfc\left(0.00029\left(\psi.e^{-0.022D} - 0.53\right)\right) \quad (11)$$

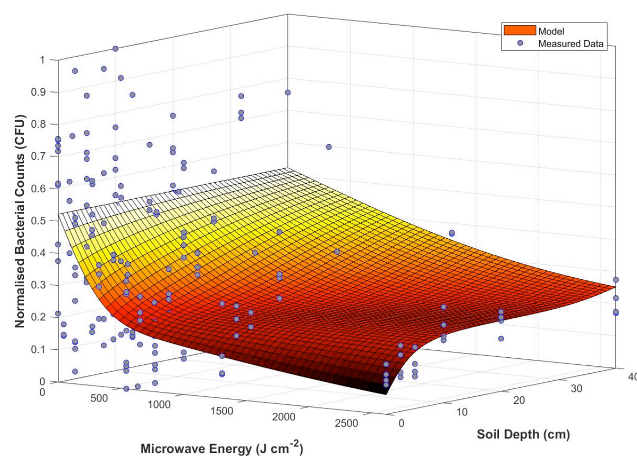


Figure 15: Combined response of bacteria to microwave treatment, as a function of applied energy density and soil depth [Sources of some data: 31, 37].

This wide variability of bacterial susceptibility to microwave treatment is apparent from other literature as well. In a review by Shamis, Croft, Taube, Crawford and Ivanova [39], they refer to microwave radiation (at 45°C and a frequency of 18 GHz) being used to sterilise transplant biomaterial of pathogenic bacteria (*E. coli* and *S. aureus*) without compromising tissue functionality and durability of the transplant materials. According to their study, fatality in the bacteria was achieved at 45°C.

On the other hand, Vela, Wu and Smith [37] found that nitrifying bacteria were resistant to 40,000 J cm^{-2} of microwave energy, at 2.45 GHz applied in a modified microwave oven cavity, when the soil temperature was in excess of 80°C. Bacterial cells form the highest C:N ratio of soil biota. Killing the cells through the microwave treatment provides extra nutrients for the remaining bacteria leading to an increase in their populations during the period following the treatment. High nitrogen availability in microwave treated soil was observed in all the pot and plot experiments reported earlier. This increased nitrogen availability contributes to better plant growth and final yield for crops that were planted into the treated soil.

5. POTENTIAL CROP YIELD RESPONSE TO MICROWAVE TREATMENT

Using the same basic derivation, that was used to develop the herbicide transfer function response in equation (1), but substituting parameters for microwave weed and soil treatment instead of the herbicide efficacy components of equation (1), provides the relationship between crop yield potential and applied microwave energy:

$$Y = Y_o \left\{ \begin{matrix} 1 - \dfrac{W_a \cdot \{a \cdot erfc\,[b(\Psi - g)] + e \cdot erfc\,[f(\Psi - k)]\}}{100\left\{G + \dfrac{W_a \cdot \{a \cdot erfc\,[b(\Psi - g)] + e \cdot erfc\,[f(\Psi - k)]\}}{A_W}\right\}} + l \\ + m \cdot erf[n(\Psi - q)] \end{matrix} \right\} \quad (12)$$

Differentiating equation (12) with respect to Ψ determines the sensitivity of crop yield to microwave weed treatments:

$$\begin{aligned} \frac{dY}{d\psi} = {} & Y_o \frac{W_a \cdot \left\{ \frac{2ab}{\sqrt{\pi}} .e^{-\left[b^2(\psi-g)^2\right]} + \frac{2ef}{\sqrt{\pi}} .e^{-\left[f^2(\psi-k)^2\right]} \right\}}{100\left\{ G + \frac{W_a \cdot \left\{ a.erfc\left[b(\psi-g)\right] + e.erfc\left[f(\psi-k)\right]\right\}}{A_w} \right\}} \\ & - Y_o \frac{W_a^{\,2}.\left\{a.erfc\left[b(\psi-g)\right] + e.erfc\left[f(\psi-k)\right]\right\}.\left\{ \frac{2ab}{\sqrt{\pi}} .e^{-\left[b^2(\psi-g)^2\right]} + \frac{2ef}{\sqrt{\pi}} .e^{-\left[f^2(\psi-k)^2\right]} \right\}}{100^2\left\{ G + \frac{W_a \cdot \left\{ a.erfc\left[b(\psi-g)\right] + e.erfc\left[f(\psi-k)\right]\right\}}{A_w} \right\}} \\ & + Y_o \frac{2mn}{\sqrt{\pi}} .e^{-\left[n^2(\psi-q)^2\right]} \end{aligned} \quad (13)$$

Figure **16** shows the potential crop yield response, as a function of applied microwave energy. This model implies that an improvement in normalized crop yield potential, above unity, may be possible, due to the enhanced crop yield in microwave treated soil. Unlike residual chemical options, microwave soil treatment is a purely thermal effect [23], therefore the treated site is accessible as soon as the soil cools. (Table **5** and **6**)

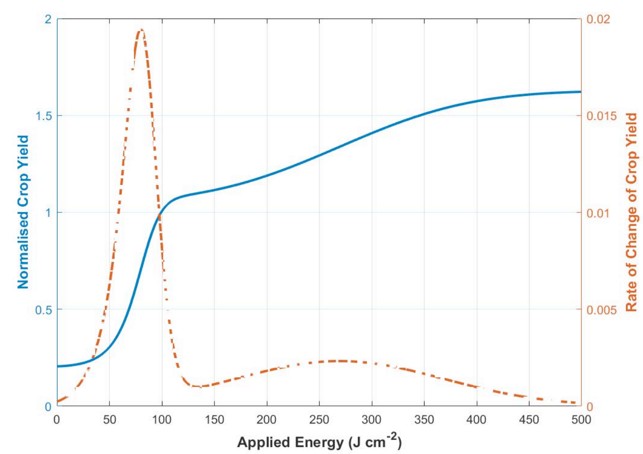


Figure 16: Relative crop yield as a function of applied microwave energy, based on the derived microwave response model in equations (12) and (13).

Table 5: Soil Bacterial Numbers Shortly after Microwave Treatment (Entries in the Table with Different Superscripts are Significantly Different to one Another) [Source: 31]

Soil Depth (cm)	Estimated Microwave Treatment (J cm^{-2})			
	0	80	160	320
0	6.20^{a}	5.57^{a}	4.73^{ab}	1.78^{c}
5	3.78^{abc}	4.71^{ab}	4.23^{ab}	1.18^{c}
10	4.06^{ab}	2.93^{bc}	3.87^{abc}	1.74^{c}
LSD (P = 0.05)				2.60

Table 6: Soil Bacterial Numbers as a Function of Microwave Treatment, Soil Depth and Recovery Time after Treatment (Entries in the Table with different Superscripts are Significantly Different to one another) [Source: 31]

Soil Depth (cm)	Time from Microwave Treatment (Days)	Estimated Microwave Treatment ($J\ cm^{-2}$)			
		0	80	160	320
0	1	6.20[d]	5.57[d]	4.73[d]	1.78[d]
	31	18.90[c]	38.48[a]	38.25[a]	19.67[c]
5	1	3.78[d]	4.71[d]	4.23[d]	1.18[d]
	31	18.73[c]	24.28[bc]	29.95[b]	28.22[b]
10	1	4.06[d]	2.93[d]	3.87[d]	1.74[d]
	31	16.93[c]	26.13[bc]	28.90[b]	18.00[c]
LSD (P = 0.05)					7.30

6. A PRELIMINARY ECONOMIC EVALUATION

In the grass based experiment shown earlier (Figure **11** and Figure **12**), 100 % control of kikuyu grass was achieved with a travel speed of about 720 m h^{-1}. The applicator treats a strip about 150 mm wide and there are four microwave generators on the trailer; therefore, it can treat an area of 432 $m^2\ hr^{-1}$. The 7 kW electrical generators on the trailer have a specific fuel consumption of 2.0 L hr^{-1}; therefore, with two electrical generators on the trailer, the fuel consumption is about 4.0 L, or 9.3×10^{-3} L m^{-2}. Assuming a fuel price of AU$0.70 L^{-1} for land holders, the cost of treatment is about AU$0.0065 m^{-2}. The trailer prototype is set up to demonstrate inter-row weed treatment in a crop. In this configuration, the costs of treatment are about AU$64.80 ha^{-1}.

A larger system, run from the PTO of a tractor could potentially perform better than the trailer prototype.

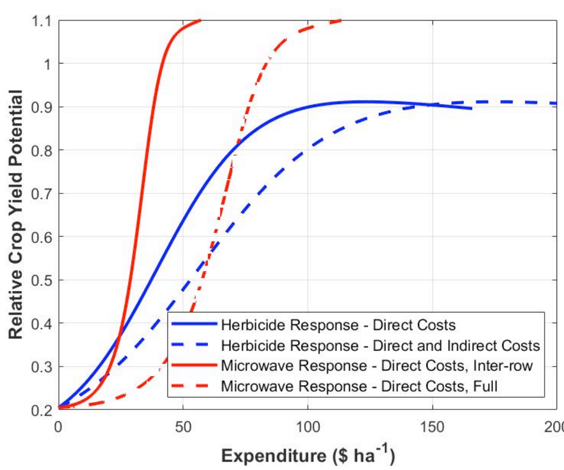


Figure 17: Indicative comparison of crop yield potential for microwave and herbicide based weed management systems, using the microwave energy to knock down weed plants.

Figure **17** compares microwave weed management to herbicide weed management, assuming a larger prototype system and engine performance based on data from Durković and Damjanović [40]. Because optimal travel speed and performance on the trailer system needs to be clarified, the data in Figure **17** should be regarded as indicative only; however, for inter-row weed control in crops, it appears that microwave weed management may be comparable in expenditure to herbicide weed management.

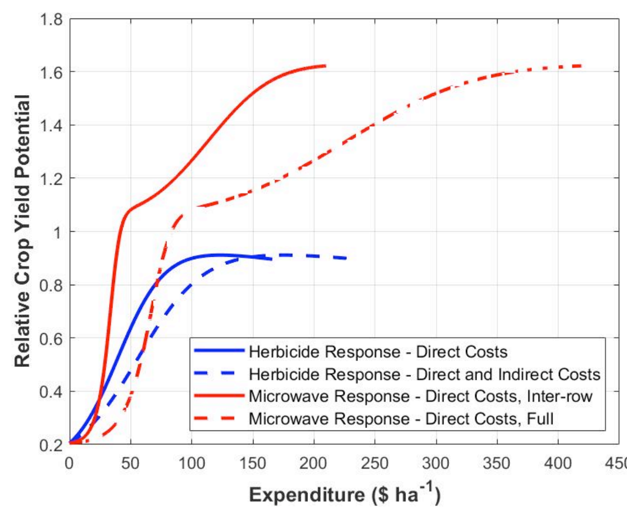


Figure 18: Indicative crop yield response to microwave soil treatment based on microwave soil treatment.

As pointed out earlier, microwave soil treatment has many secondary benefits and can be regarded as a soil fumigation treatment. Figure **18** shows indicative crop responses to expenditure on microwave soil treatment.

7. FUTURE DIRECTION

The next phases of this research include: devising a more efficient applicator for microwave weed and soil treatment, which is now subject to provisional patents; evaluating the acceptability of this technology by the agricultural industry and wider community, which has been positive so far; and developing more robust and powerful field prototypes for nation-wide testing and evaluation. If these are acceptable to the industry, commercialization of the technology will begin.

CONCLUSION

Microwave energy kills weeds and their seeds in the soil. Soil treatment has some secondary benefits for crop growth; however, it also requires considerably more energy than treating emerged weeds. Weed plant treatment is comparable to knock-down herbicide treatment, while microwave soil treatment is comparable to soil fumigation, which is routinely practiced in some agricultural enterprises, like tomato and strawberry production.

NOMENCLATURE

Ψ	Microwave field density (J cm^{-2}).
a	Is the selection pressure for herbicide resistance.
a, b, c, f and k	Are constants for equations to be experimentally determined for each species.
A_w	Is the percentage yield loss as weed density approaches (= 38.0 [Source: 41]).
c	Is the speed of light (m s^{-1}) or the rate at which I approaches zero as t approaches (= 0.017 [40]).
d	Is the slope of the seed bank recruitment curve at t_o or depth of seed in soil (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_m	Seed immigration from the area of interest.
g	Is the generational number.
H	Is the herbicide's active ingredient dose (kg ha^{-1}).
I	Is the percentage yield loss as the weed density tends towards zero (= 0.38 [40]).
Im	Seed immigration into the area of interest.
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).
S_o	Is the initial frequency of plants in the population that are susceptible to herbicide treatment.
S_s	Viable seed set per plant from surviving volunteers in the weed population.
t	Is the time difference between crop emergence and weed emergence.
t_o	Is the time for 50 % germination of the viable seed bank.
W	Is the viable seed bank.
Y_o	Is the theoretical yield with no weed infestations.
λ	Is the efficacy of the herbicide killing action.

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