Derivation of a Cropping System Transfer Function for Weed Management: Part 2 – Microwave Weed Management

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Abstract: System behaviour is described by transfer functions, which relate the system's output to one or more input parameters. This paper derives the transfer function for crop yield potential as a function of applied microwave energy for control of weeds. The resulting transfer function reveals that microwave weed control and soil treatment can increase normalized crop yield potential above the ideal weed free potential. It also revealed that there was an ongoing yield advantage associated with a once off microwave soil treatment to deplete the weed seed bank.

Keywords: System analysis, weeds, microwave, herbicide resistance, crop ecology.

1. INTRODUCTION

Good weed management is based on controlling the viable weed seed bank in the soil. A study by Chauhan *et al*. [1] found that in a no-till cropping systems, approximately 65% of the viable weed seed bank is found in the top 1cm of soil and 90% of the viable seed bank is in the top 5cm of soil [2]. Burnside *et al*. [3] reported that viable weed seeds in the soil can be reduced by 95% after five years of consistent herbicide management; however, Kremer [4] pointed out that in spite of achieving good weed control over several years, weed infestations will recur quickly in succeeding years if intensive weed management is discontinued or interrupted. These efforts to deplete the soil seed bank are also hindered by the growing list of herbicide-resistant weed biotypes.

Herbicide resistance in many weed species is becoming wide spread [5] and multiple herbicide resistances in several weed species has been widely reported [6]. Some studies have demonstrated that competition from weeds can reduce the expected yield of crops by between 35% and 55% [7, 8]. In time, herbicide resistant weeds may ultimately result in more significant yield reductions and grain contamination.

The International Agency for Research on Cancer (IARC), which is part of the World Health Organisation (WHO), has concluded that glyphosate is probably carcinogenic to humans [9]. 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 exposure to herbicides and pesticides [10-15].

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19th century [16], while interest in the effect of high frequency waves on plant material began in the 1920s [16]. Many of the earlier experiments on plant material focused on the effect of radio frequencies (RF) on seeds [16]. In many cases, short exposure resulted in increased germination and vigour of the emerging seedlings [17-19]; however, long exposure usually resulted in seed and plant death [16, 20].

Davis *et al*. [21, 22] were among the first to study the lethal effect of microwave heating on seeds. They treated seeds, with and without any soil, in a microwave oven and showed that seed damage was mostly influenced by a combination of seed moisture content and the energy absorbed per seed. Other findings from this study suggested that both the specific mass and specific volume of the seeds were strongly related to a seed's susceptibility to damage by microwave fields [22]. These finding may be associated with the radar cross section [23] of the seeds, with larger seeds intercepting more microwave energy.

In a theoretical argument, based on the dielectric and density properties of seeds and soils, Nelson [24] demonstrated that using microwaves to selectively heat seeds in the soil "*cannot be expected*." He concluded that seed susceptibility to damage from microwave treatment is a purely thermal effect, resulting from soil heating and thermal conduction into the seeds. Nelson's final conclusion was that microwave soil treatment was unviable because of its high energy requirements; however these studies ignored the effects of herbicide resistant weeds on crop yields.

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This paper presents a theoretical model for crop yield potential, as a function of microwave treatment energy, based on previous research into the effect of microwave treatment on weed plants, weed seeds, and the growth and yield of crops that have been grown in microwave treated soil.

2. MICROWAVE WEED CONTROL

Extensive experiments, which have been reported elsewhere [25], have shown that microwave treatment using a 2kW, continuous wave, 2.45GHz industrial microwave source and a pyramidal horn antenna with an aperture of 110mm by 55mm (Figure **1**), at a range of 18cm from the soil surface, resulted in 100% mortality of broad-leafed plants after 4 to 5 seconds of treatment. Earlier experiments using a modified domestic microwave oven (Figure **2**) with a measured average output power of 163W [26] resulted in 100% mortality of prickly paddy melon (*Cucumis myriocarpus*) [27] and fleabane (*Conyza bonariensis*) [28] within about 20 seconds of treatment.

Figure 1: Trailer mounted four by 2kW microwave system to treat weeds and soil.

Figure 2: Modified microwave oven with a waveguide and horn antenna arrangement to treat weeds and soil [Source: 20].

A recently completed pot trial [29], which treated annual ryegrass (*Lolium rigidum*) seedlings using the 2kW trailer mounted system, achieved only 85% to 90% ryegrass plant mortality after 5 seconds of treatment. It is unclear why the mortality rate was not higher; however it is noted that the shoot apical meristem of grasses is located at the base of the plant [30] as opposed to the tips of the plant as in broad-leafed species. This may influence the susceptibility of grasses to microwave treatment.

It was assumed that the susceptibility of weeds and their seeds to microwave damage has a normally distributed frequency distribution $\left(f\left(\psi|\mu,\sigma\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\psi-\mu)^2}{2\sigma^2}} \right)$, where ψ is the applied microwave energy (J cm^{-2}), μ is the mean energy needed to destroy 50% of the plants or seeds and σ is the standard deviation of susceptibility; therefore the total plant or seed mortality can be determined using the Gaussian error function $\left(erf\left(\frac{(\Psi-\mu)}{\sqrt{2}\sigma}\right) = \frac{2}{\sqrt{\pi}} \int_0^{\Psi} e^{-\frac{(t-\mu)^2}{2\sigma^2}} .dt \right)$, and seed or plant survival can be described by the complementary Gaussian error function $\left(erfc\left(\frac{(\psi-\mu)}{\sqrt{2}\sigma}\right) = \frac{2}{\sqrt{\pi}} \int_{\psi}^{\infty} e^{-\frac{(t-\mu)^2}{2\sigma^2}} .dt \right)$.

In the case of plant experiments, the data was fitted to a dose response curve of the form:

$$S = a\,.erfc\left[b\left(\psi - c\right)\right] \tag{1}$$

Where S = the survival rate for plants (a normalised fraction of the test population); and a, b, and c are constants to be experimentally determined for each species.

From these curves it is possible to estimate the LD_{50} for each weed species based on:

$$LD_{50} = \frac{erfc^{-1}\left(\frac{0.5}{a}\right)}{b} + c \tag{2}$$

Data from earlier experiments [27, 28] with fleabane (*Conyza bonariensis*) reveals that a simple model can describe the survival response (Figure **3**):

$$Survival = 0.49 erfc\left[0.049\left(\Psi - 67.97\right)\right] \tag{3}$$

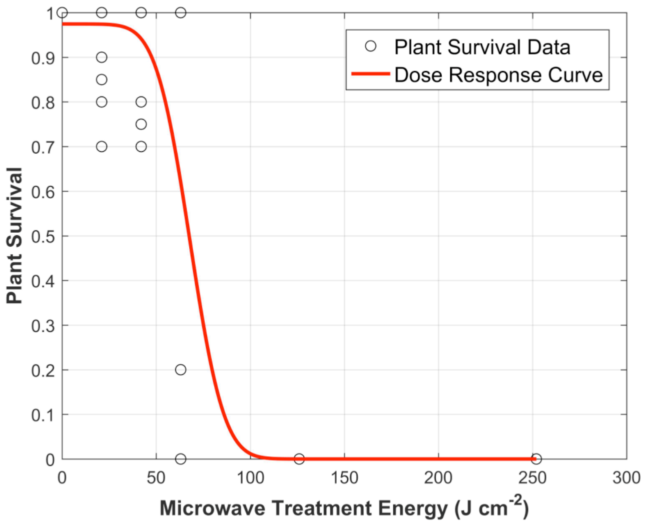

Figure 3: Combined fleabane survival response as a function of applied microwave energy [Data from: 27, 28].

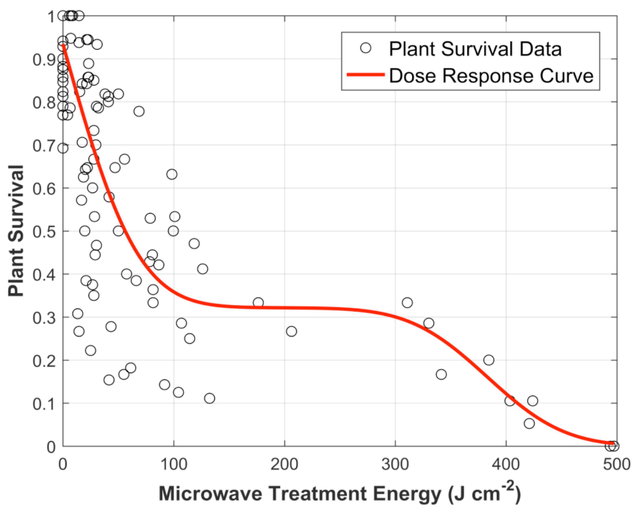

Figure 4: Annual ryegrass survival response as a function of applied microwave energy [Data from: 25, 29].

Data from Hollins' recent experiment [29], in which she treated annual ryegrass plants using the 2kW microwave system, has been regressed against the estimated energy density (Figure **4**) to reveal that a double logistic function can be used to model the response:

$$Survival = 0.61 \cdot erfc\left[0.013(\Psi - 0.0)\right] + 0.16 \cdot erfc\left[0.013(\Psi - 383.0)\right] \quad (4)$$

Microwave treatment of ryegrass seeds in the top 2cm of soil is also effective; however the amount of time (and therefore energy) required is much higher than for growing plants [26, 31]. It is noted that seeds in moist soil are much more susceptible to microwave treatment [26, 31] than seeds in dry soil. The survival of ryegrass seeds in dry soil, exposed to microwave energy, can be described by:

$$Survival = 0.31 erfc\left[0.046\left(\Psi e^{-0.097 d_s} - 2000\right)\right] \quad (5)$$

While for moist seeds in moist soil (Figure **5**) the relationship is:

$$Survival = 0.42 erfc\left[0.01\left(\Psi e^{-0.089 d_s} - 561.3\right)\right] \quad (6)$$

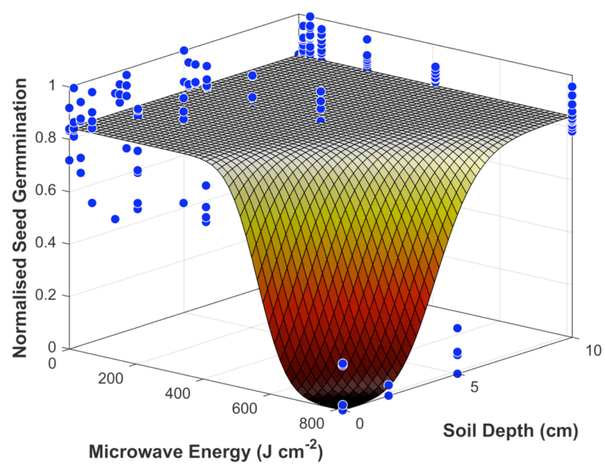

Figure 5: Ryegrass survival response as a function of applied microwave energy [Data from: 25].

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

Figure 6: Comparison of wheat and canola plant growth as a function of microwave treatment energy: (**a**) wheat and (**b**) canola (Note: In each image, control on the left though to highest microwave treatment on the right).

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

Figure 7: Comparison of (**a**) potted rice plant growth as a function of microwave soil treatment energy (Control on the left and highest microwave treatment on the right) and (**b**) sub-sampled rice plants (highest microwave treated soil on left and control on right).

3. EFFECT OF MICROWAVE SOIL TREATMENT ON SUBSEQUENT CROP GROWTH AND YIELD

It has also been demonstrated elsewhere [32] that plant maturation rate, plant height (Figure **6**), plant/tiller density (Figure **7**), and mean yield (Figure **8** and Table **1**) all increased significantly in response to the level of applied microwave energy. As an example, the relationship between rice yield and applied microwave energy can be described by:

$$Y = Y_o \left\{1.29 + 0.29 \cdot erf\left[0.0067\left(\Psi - 284.6\right)\right]\right\} \quad (7)$$

Where Y_o is the mean yield of hand weeded control pots.

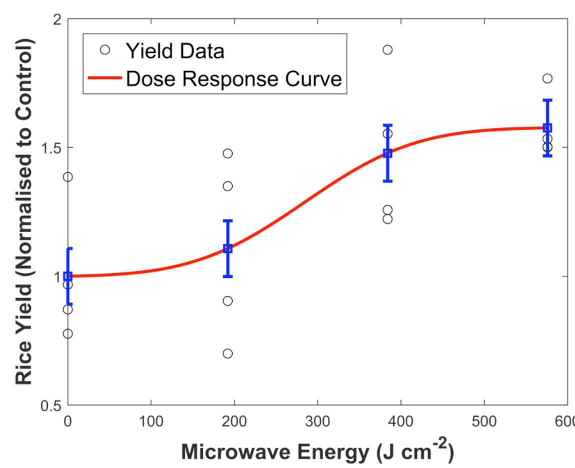

Figure 8: Normalised mean rice yield per pot as a function of applied microwave energy (Error bars represent Least Significant Differences P = 0.05).

4. DERIVATION OF CROP SYSTEM TRANSFER FUNCTION FOR MICROWAVE WEED MANAGEMENT

As pointed out in a previous paper [33], equation (8) approximates the crop yield potential in response to weed infestation and herbicide application. This model also attempts to account for herbicide resistance within the weed population and the potential toxicity of the herbicide to the crop itself.

Table 1: Effect of Microwave Soil Treatment on Crop Yield and Maturation Rate (Source for Wheat and Canola Data: [32])

Microwave Treatment ($J\ cm^{-2}$)	Un-Weeded Control	Hand Weeded Control	168	384	576	LSD (P = 0.05)	Change from Control
Canola Dry Pod Yield ($g\ pot^{-1}$)	0.27^a	0.56^a	0.36^a	1.25^b	1.95^c	0.55	550%
Days to Flowering - Canola	71.4^a	67.6^{ab}	70.2^a	63.2^b	61^b	7.1	14.6%
Wheat Dry Grain Yield ($g\ pot^{-1}$)	0.66^a	0.67^a	0.68^a	0.75^a	1.25^b	0.30	90%
Rice Dry Grain Yield ($g\ pot^{-1}$)	40.00^a	41.3^a	43.25^a	59.00^{ab}	64.00^b	18.90	60%

Note: entries with different superscripts across the rows are statistically different from one another (Also note: pots used in rice experiment were larger than for other crops – hence higher yield per pot.).

$$Y = Y_o \left[1 - \frac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{100 \left(e^{ct} \left[1 + e^{-\left(\frac{t - t_o}{d}\right)} \right] \left[1 + p_o \left(e^{sg} - 1 \right) \right] + \frac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{A_w} \right)} + aH^2 - bH \right] \quad (8)$$

Where I is the percentage yield loss as the weed density tends towards zero (= 0.38 [34]), W is the viable seed bank, 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), D_o is a fraction of the seed population developing dormancy (Note: this is expressed as a fraction of the initial seed bank population W_o, E_m is the seed emigration out of the area of interest, I_m is the seed immigration into the area of interest, p_o is the initial portion of the weed population that is resistant to herbicides, s is the selection pressure for herbicide resistance in the system, g is the number of weed generations in the study period, c is the rate at which I approaches zero as time approaches ∞(= 0.017 [34]), t is the time difference between crop emergence and weed emergence, t_o is the time for 50% germination of the viable seed bank, d is the slope of the seed bank recruitment curve at to, λ is the efficacy of the herbicide killing action, H is the herbicide dose, and Aw is the percentage yield loss as weed density approaches ∞ (= 38.0 [34]).

Weed competition in any season depends on the recruitment rate from the viable weed seed bank. The weed seed bank at the start of any cropping cycle, in simplified terms, can be understood as the sum of the dormant seed bank and the seed set from survivors of the previous season's weed management strategies; therefore an iterative approach to weed studies must be adopted [35, 36]. This can be approximated by:

$$W_i = \frac{\left[W_{i-1}\left(1 - N_{i-1} + D_b\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg_{i-1}}\right) e^{-\lambda H} + p_o e^{sg_{i-1}} \right] \cdot S_s}{1 + e^{-\left(\frac{t - t_o}{d}\right)}} + D_o W_{i-1} \quad (9)$$

Where S_s is the viable seed set from the surviving weed population, i is the counter for the current season, i–1 indicates the previous season, and D_b is the 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).

Selection pressure for genetic traits depends on the initial efficacy of the herbicide to remove susceptible individuals from the population, leaving only the resistant individuals to reproduce. The adoption of a single herbicide over a long period of time sustains this selection pressure. Assuming an initially small resistant population (p_o = 1×10^{-8}), an average seed set of 700 seeds per weed plant, a slightly positive selection coefficient of 0.0001 for herbicide resistance [37], and other key herbicide data published by Bosnić and Swanton [34] and Yin *et al*. [38], equations (8) and (9) predict the same 15 year period to develop herbicide resistance as predicted by Thorn by and Walker [39]. Herbicide rotations can forestall the development of a resistant population; however several weed species have developed resistance to multiple herbicide groups [6].

Using the same basic derivation, that was used to develop the herbicide transfer function response in equation (8), but substituting parameterised versions of the microwave weed response indicated by equations (3) to (7) instead of the herbicide efficacy components of equation (8), provides the relationship between crop yield potential and applied microwave energy:

$$Y = Y_o \left[1 - \frac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \begin{Bmatrix} a \cdot erfc\left[b\left(\Psi - g\right) \right] \\ + e \cdot erfc\left[f\left(\Psi - k\right) \right] \end{Bmatrix}}{100 \left(e^{ct} \left[1 + e^{-\left(\frac{t - t_o}{d}\right)} \right] + \frac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \begin{Bmatrix} a \cdot erfc\left[b\left(\Psi - g\right) \right] \\ + e \cdot erfc\left[f\left(\Psi - k\right) \right] \end{Bmatrix}}{A_w} \right)} + l + m \cdot erf\left[n\left(\Psi - q\right) \right] \right] \quad (10)$$

Table 2: Summary of Experimentally Derived Coefficients for Microwave Weed Management Using a Horn Antenna Applicator for Different Weed Species to be Use in Equation (10) (Source of Data: [25, 27-29, 40])

Species	Coefficients						R^2	LD_{50} ($J\ cm^{-2}$)
	a	b	g	e	f	k		
Annual Ryegrass (*Lolium rigidum*)	0.61	0.013	0	0.16	0.013	383	0.73	63
Barley Grass *(Hordeum vulgare)*	0.517	0.005	242.7	0			0.97	249
Barnyard Grass *(Echinochloa crus-galli)*	0.792	0.005	48.09	0			0.98	116
Brome Grass *(Bromus spp.)*	0.495	0.006	282.1	0			0.98	281
Fleabane (*Conyza bonariensis*)	0.528	0.019	71.97	0			0.97	74
Marshmallow (*Malva parviflora*)	0.553	0.006	176	0			0.98	190
Paddy Mellon (*Cucumis myriocarpus)*	0.5	0.12	64.49	0			0.83	64
Wild Oats (*Avena sativ)*	0.51	0.009	164.3	0			0.98	166
Wild Radish (*Raphanus raphanistrum)*	0.52	0.009	149.1	0			0.91	152

Where a, b, g, e, f, and k are constants from equations (1) to (4), which have all been experimentally determined for different weed species (Table **2**). The parameters I, m, n and q are associated with the yield response described in equation (7).

Differentiating equation (10) with respect to Ψ determines the sensitivity of crop yield to microwave weed treatments:

$$\frac{dY}{d\Psi}=\frac{Y_o I\cdot\left[W\left(1-N-D_o\right)-E_m+I_m\right]\left\{\frac{2ab}{\sqrt{\pi}}\cdot e^{\left[-b^2(\Psi-g)^2\right]}+\frac{2erf}{\sqrt{\pi}}\cdot e^{\left[-f^2(\Psi-k)^2\right]}\right\}}{100\left(e^{ct}\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]+\frac{I\cdot\left[W\left(1-N-D_o\right)-E_m+I_m\right]}{\frac{\left\{a\cdot erfc\left[b\left(\Psi-g\right)\right]+e\cdot erfc\left[f\left(\Psi-k\right)\right]\right\}}{A_w}}\right)}$$
$$-\frac{Y_o I^2\cdot\left[W\left(1-N-D_o\right)-E_m+I_m\right]^2\left\{a\cdot erfc\left[b\left(\Psi-g\right)\right]+e\cdot erfc\left[f\left(\Psi-k\right)\right]\right\}\left\{\frac{2ab}{\sqrt{\pi}}\cdot e^{\left[-b^2(\Psi-g)^2\right]}+\frac{2ef}{\sqrt{\pi}}\cdot e^{\left[-f^2(\Psi-k)^2\right]}\right\}}{100^2\left(e^{ct}\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]+\frac{I\cdot\left[W\left(1-N-D_o\right)-E_m+I_m\right]}{\frac{\left\{a\cdot erfc\left[b\left(\Psi-g\right)\right]+e\cdot erfc\left[f\left(\Psi-k\right)\right]\right\}}{A_w}}\right)^2}$$
$$+Y_o\frac{2mn}{\sqrt{\pi}}\cdot e^{\left[-n^2(\Psi-q)^2\right]} \qquad (11)$$

5. METHOD

Equations (8) to (11) were coded into a simple cropping system model using the MatLab (version 2015b) software platform. Using data published by Bosnić and Swanton [34] and Yin *et al*. [38] for some of the crop and weed parameters and assuming: an average seed set of 700 seeds per weed plant; and a seed mortality rate of 10% each year, the system transfer function was used to analyse crop yield potential as a function of applied microwave energy. The parameters for microwave treatment are taken from equations (4), (6), and (7).

One possible scenario for using microwave energy in a broad acre cropping system is as a once off microwave soil treatment to deplete the weed seed bank, followed by a resumption of herbicide weed control. This can be modelled using equations (8) and (9), but assuming different numbers of weed seeds at the start of the time based analysis. It has been shown that microwave soil treatment can destroy seeds in the top 5cm of soil [25, 31]. It is also apparent that 90% of the viable weed seed bank in zero-till systems can be found in the top 5cm of soil [2]; therefore the impact of a once off microwave soil treatment can be estimated by comparing the time based crop response from a conventional herbicide regime with another analysis with an initial seed bank population of 10% of the original analysis.

6. RESULTS AND DISCUSSION

Figure **9** shows the potential crop yield response to microwave-based weed control, as a function of applied microwave energy. This model implies that an improvement in normalised crop yield potential, above unity, may be possible, due to the enhanced crop yield in microwave treated soil. It is also important to understand that microwave soil treatment has the potential to deactivate the dormant weed seed bank in the upper layers of soil. It is unclear how the depletion of the soil seed bank may affect the longer term potential of microwave weed control. Residual chemicals can provide some seedbank depletion; however chemical soil treatment often requires a delay before the treated site can be accessed or used. Unlike residual chemical options, microwave soil treatment is a purely thermal effect [24], therefore the treated site is accessible as soon as the soil cools.

The mathematical system transfer function presented in this paper is useful for assessing the potential of using microwave weed management strategies as a tool for managing herbicide resistant weed populations.

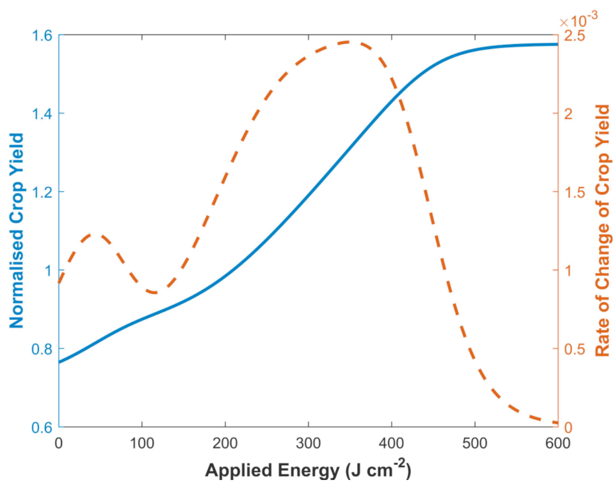

Figure 9: Relative rice crop yield as a function of applied microwave energy, based on the derived microwave response model in equations (10) and (11).

Figure **10** shows the 15 year crop response (i.e. 15 annual generations of weeds) to ongoing herbicide weed management, assuming an initial weed seed bank density of 500seeds m^{-2}, an initially small resistant population ($p_o = 1 \times 10^{-8}$), an average seed set of 700seeds per weed plant, a slightly positive selection coefficient of 0.0001 for herbicide resistance [37], and other key herbicide data published by Bosnić and Swanton [34] and Yin *et al*. [38]. Figure **11** shows the 15 year crop response to the same ongoing herbicide weed management, except that the initial weed seed bank density is reduced to 50 seeds m^{-2} to account for a once off microwave soil treatment. The difference in crop yield potential and soil seed bank growth is shown in Figure **12**.

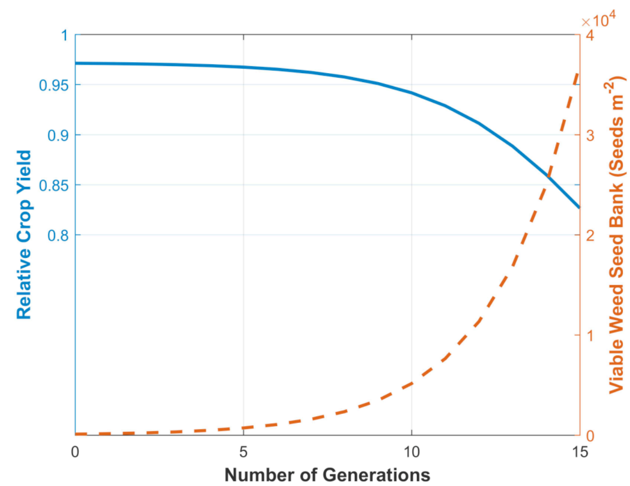

Figure 11: Modelling the generational impact of herbicide resistant weeds on potential crop yield assuming a 90% depletion of the weed seed bank by a once off microwave soil treatment.

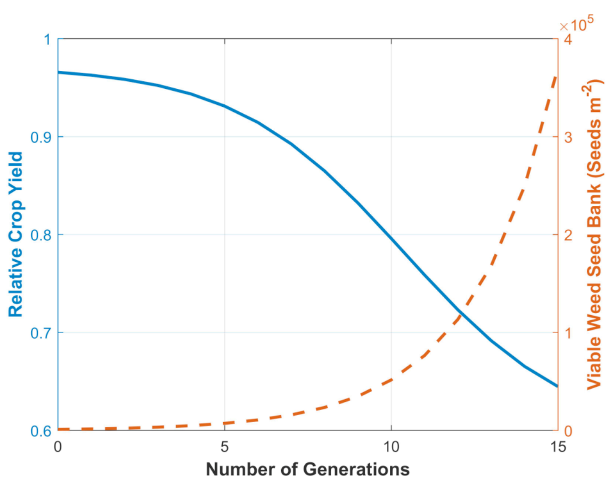

Figure 10: Modelling the generational impact of herbicide resistant weeds on potential crop yield under continuous herbicide weed management, based on equations (8) and (9).

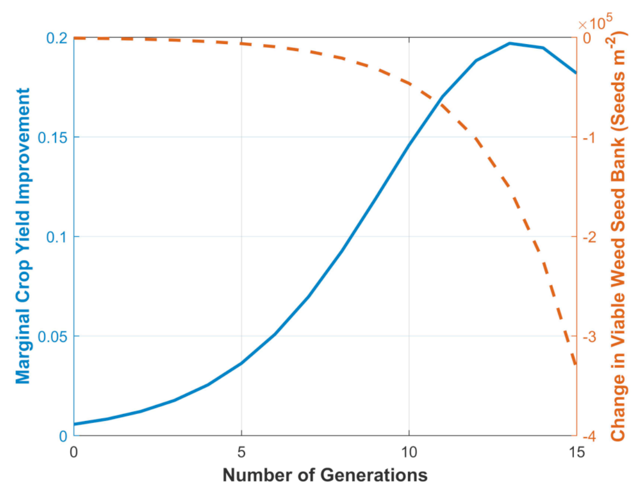

Figure 12: Difference in crop yield potential and cumulative soil seed bank between the scenarios depicted in Figures **10** and **11**.

The cumulative yield advantage over the 15 year simulation, offered by a once off microwave soil treatment to deplete the weed seed bank, is equivalent to 1.5 full crops. When this is coupled with the 55% increase in crop yield potential (See Figures **8** and **9**) in a single season due to microwave soil treatment, the full advantage of a once off microwave soil treatment in a cropping system may be equivalent to 2.05 additional crops. Another advantage of depleting the initial soil weed seed bank is that the seed bank grows at a significantly slower rate than would otherwise occur.

It is also apparent from Figure **12** that the crop yield advantage has a limited life time and that after 15 years the difference in crop yield potential begins to decline. This suggests that a periodic application of microwave soil treatment to "restart" the conventional herbicide strategy may be a viable option.

For low yielding, low value crops, the expenditure needed to treat the soil with microwave energy may not be justified; however for higher yielding, high value horticultural or rice crops, this expenditure may be more than balanced by the additional value derived by the yield advantage provided by a once off microwave treatment.

All modelling exercises are only indicative. The true value of microwave weed and soil treatment, if there is one, will only become evident as field experience with the technology over many years is gained; however these models provide motivation to develop the technology to the point where field experience can be gained.

CONCLUSION

This paper has developed a cropping system transfer function relating microwave application energy to potential crop yield. The resulting transfer function reveals the microwave weed and soil treatment has the potential to increase normalised crop yield potential above unity, resulting in significant increases in production potential. It also suggests that a once off microwave soil treatment to deplete the weed seed bank may offer long term yield advantages under conventional herbicide weed management scenarios.

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REFERENCES

[1] Chauhan BS, Gill G and Preston C. Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (Lolium rigidum) seed bank Weed Science 2006; 54 (4): 669-676. http://dx.doi.org/10.1614/WS-05-184R.1

[2] Swanton CJ, Shrestha A, Knezevic SZ, Roy RC and Ball-Coelho BR. Influence of tillage type on vertical weed seedbank distribution in a sandy soil. Canadian Journal of Plant Science 2000; 80 (2): 455-457. http://dx.doi.org/10.4141/P99-020

[3] Burnside OC, Moomaw RS, Roeth FW, Wicks GA and Wilson RG. Weed seed demise in soil in weed-free corn (Zea mays) production across Nabraska. Weed Science 1986; 34 (2): 248-251.

[4] Kremer RJ. Management of Weed Seed Banks with Microorganisms. Ecological Applications, 1993; 3 (1): 42-52. http://dx.doi.org/10.2307/1941791

[5] Heap IM. The occurrence of herbicide-resistant weeds worldwide. Pesticide Science 1997; 51 (3): 235-243. http://dx.doi.org/10.1002/(SICI)1096-9063(199711)51:3<235::AID-PS649>3.0.CO;2-N

[6] Owen M, Walsh M, Llewellyn R and Powles S. Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (Lolium rigidum) populations. Australian Journal of Agricultural Research 2007; 58 (7): 711-718. http://dx.doi.org/10.1071/AR06283

[7] Mondani F, Golzardi F, Ahmadvand G, Ghorbani R and Moradi R. Influence of Weed Competition on Potato Growth, Production and Radiation Use Efficiency. Notulae Scientia Biologicae 2011; 3 (3): 42-52.

[8] Cathcart RJ and Swanton CJ. Nitrogen management will influence threshold values of green foxtail (Setaria viridis) in corn. Weed Science 2003; 51 (6): 975-986. http://dx.doi.org/10.1614/P2002-145

[9] Guyton KZ, Loomis D, Grosse Y, El Ghissassi F, Benbrahim-Tallaa L, Guha N, *et al.* Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. The Lancet Oncology 16(5): 490-491. http://dx.doi.org/10.1016/S1470-2045(15)70134-8

[10] Duke SO. Herbicide and pharmaceutical relationships. Weed Science 2010; 58 (3): 334-339. http://dx.doi.org/10.1614/WS-09-102.1

[11] Hernández AF, Parrón T, Tsatsakis AM, Requena M, Alarcón R and López-Guarnido O. Toxic effects of pesticide mixtures at a molecular level: Their relevance to human health. Toxicology (0).

[12] Mačkić S and Ahmetović N. Toxicological Profiles Of Highly Hazardous Herbicides With Special Reference To Carcinogenicity To Humans. Herbologia 2011; 12 (2): 55-60.

[13] Peighambarzadeh SZ, Safi S, Shahtaheri SJ, Javanbakht M and Forushani AR. Presence of Atrazine in the Biological Samples of Cattle and Its Consequence Adversity in Human Health. Iranian Journal of Public Health 2011; 40 (4): 112-121.

[14] Troudi A, Sefi M, Ben Amara I, Soudani N, Hakim A, Zeghal KM, *et al.* Oxidative damage in bone and erythrocytes of suckling rats exposed to 2,4-dichlorophenoxyacetic acid. Pesticide Biochemistry and Physiology 2012; 104(1): 19-27. http://dx.doi.org/10.1016/j.pestbp.2012.06.005

[15] Wickerham EL, Lozoff B, Shao J, Kaciroti N, Xia Y and Meeker JD. Reduced birth weight in relation to pesticide mixtures detected in cord blood of full-term infants. Environment International 2012; 47(0): 80-85. http://dx.doi.org/10.1016/j.envint.2012.06.007

[16] Ark PA and Parry W. Application of High-Frequency Electrostatic Fields in Agriculture. The Quarterly Review of Biology 1940; 15(2): 172-191. http://dx.doi.org/10.1086/394605

[17] Tran VN. Effects of Microwave Energy on the Strophiole, Seed Coat and Germination of Acacia Seeds. Australian Journal of Plant Physiology 1979; 6(3): 277-287.

[18] Tran VN and Cavanagh AK. Effects of microwave energy on Acacia longifolia. Journal of Microwave Power 1979; 14(1): 21-27.

[19] Nelson SO and Stetson LE. Germination responses of selected plant species to RF electrical seed treatment. Transactions of the ASAE 1985; 28(6): 2051-2058. http://dx.doi.org/10.13031/2013.32564

[20] Bebawi FF, Cooper AP, Brodie GI, Madigan BA, Vitelli JS, Worsley KJ, *et al*. Effect of microwave radiation on seed mortality of rubber vine (*Cryptostegia grandiflora* R.Br.), parthenium (*Parthenium hysterophorous* L.) and bellyache bush (*Jatropha gossypiifolia* L.). Plant Protection Quarterly 2007; 22(4): 136-142.

[21] Davis FS, Wayland JR and Merkle MG. Ultrahigh-Frequency Electromagnetic Fields for Weed Control: Phytotoxicity and Selectivity. Science 1971; 173(3996): 535-537. http://dx.doi.org/10.1126/science.173.3996.535

[22] Davis FS, Wayland JR and Merkle MG. Phytotoxicity of a UHF Electromagnetic Field. Nature 1973; 241(5387): 291-292. http://dx.doi.org/10.1038/241291a0

[23] Wolf WW, Vaughn CR, Harris R and Loper GM. Insect radar cross-section for aerial density measurement and target classification. Transactions of the American Society of Agricultural and Biological Engineers 1993; 36(3): 949-954. http://dx.doi.org/10.13031/2013.28420

[24] Nelson SO. A review and assessment of microwave energy for soil treatment to control pests. Transactions of the ASAE 1996; 39(1): 281-289. http://dx.doi.org/10.13031/2013.27508

[25] Brodie G and Hollins E. The Effect of Microwave Treatment on Ryegrass and Wild Radish Plants and Seeds. Global Journal of Agricultural Innovation, Research and Development 2015; 2(1): 16-24. http://dx.doi.org/10.15377/2409-9813.2015.02.01.2

[26] Brodie G, Harris G, Pasma L, Travers A, Leyson D, Lancaster C, *et al*. Microwave soil heating for controlling ryegrass seed germination. Transactions of the American Society of Agricultural and Biological Engineers 2009; 52(1): 295-302. http://dx.doi.org/10.13031/2013.25935

[27] Brodie G, Ryan C and Lancaster C. The effect of microwave radiation on Paddy Melon (Cucumis myriocarpus). International Journal of Agronomy 2012; 1-10. http://dx.doi.org/10.1155/2012/287608

[28] Brodie G, Ryan C and Lancaster C. Microwave technologies as part of an integrated weed management strategy: A Review. International Journal of Agronomy 2012; 1-14. http://dx.doi.org/10.1155/2012/636905

[29] Hollins E. Microwave Weed Control and the Soil Biota. Unpublished Thesis. Melbourne School of Land and Environment: University of Melbourne 2013.

[30] Pautler M, Tanaka W, Hirano HY and Jackson D. Grass Meristems I: Shoot Apical Meristem Maintenance, Axillary Meristem Determinacy and the Floral Transition. Plant and Cell Physiology 2013; 54(3): 302-312. http://dx.doi.org/10.1093/pcp/pct025

[31] Brodie G, Pasma L, Bennett H, Harris G and Woodworth J. Evaluation of microwave soil pasteurization for controlling germination of perennial ryegrass (*Lolium perenne*) seeds. Plant Protection Quarterly 2007; 22(4): 150-154.

[32] Brodie G, Bootes N and Reid G. Invited Paper. Plant growth and yield of wheat and canola in microwave treated soil. In: Proceedings to IMPI's 49th Microwave Power Symposium. San Diego, California, USA 2015; 40-41.

[33] Brodie G. Derivation of a Cropping System Transfer Function for Weed Management: Part 1 – Herbicide Weed Management. Global Journal of Agricultural Innovation, Research and Development 2014; 1(1): 11-16. http://dx.doi.org/10.15377/2409-9813.2014.01.01.2

[34] Bosnić AČ and Swanton CJ. Economic Decision Rules for Postemergence Herbicide Control of Barnyardgrass (Echinochloa crus-galli) in Corn (Zea mays). Weed Science 1997; 45(4): 557-563.

[35] Pekrun C, Lane PW and Lutman PJW. Modelling seedbank dynamics of volunteer oilseed rape (Brassica napus). Agricultural Systems 2005; 84(1): 1-20. http://dx.doi.org/10.1016/j.agsy.2004.06.007

[36] Bagavathiannan MV, Begg GS, Gulden RH and Van Acker RC. Modelling the Dynamics of Feral Alfalfa Populations and Its Management Implications. PLoS ONE 2012; 7(6): 1-10. http://dx.doi.org/10.1371/journal.pone.0039440

[37] Baucom RS and Mauricio R. Fitness costs and benefits of novel herbicide tolerance in a noxious weed. Proceedings of the National Academy of Sciences of the United States of America 2004; 101(36): 13386-13390. http://dx.doi.org/10.1073/pnas.0404306101

[38] Yin XL, Jiang L, Song NH and Yang H. Toxic Reactivity of Wheat (Triticum aestivum) Plants to Herbicide Isoproturon. Journal of Agricultural and Food Chemistry 2008; 56(12): 4825-4831. http://dx.doi.org/10.1021/jf800795v

[39] Thornby DF and Walker SR. Simulating the evolution of glyphosate resistance in grains farming in northern Australia. Annals Of Botany 2009; 104(4): 747-756. http://dx.doi.org/10.1093/aob/mcp152

[40] Brodie G, Hamilton S and Woodworth J. An assessment of microwave soil pasteurization for killing seeds and weeds. Plant Protection Quarterly 2007; 22(4): 143-149.

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