Microwave Weed and Soil Treatment in Agricultural Systems

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Introduction

Weeds are the major hindrance in crop production. They compete for light, space, nutrients, moisture and CO_2, and significantly decline crop yields all over the world. In Australian agricultural industries, the total estimated direct cost of weed management and loss in crop productivity due to weeds, was estimated to be about AU$4 billion annually (DAFF 2006). Additionally, Pimentel (1995) has 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, yields about AU$0.5 billion annually. In terms of Present Costs, the combined direct and indirect costs of chemical weed management for Australia may be approximately AU$6.2 billion annually (~AU$280 ha^{-1} across the cropping area of the country).

The growing threat to herbicide use

Harper (1956) predicted the development of herbicide resistance over 60 years ago; suggesting that the development of resistance is an inevitable consequence of reliance on chemistry for weed control (Menalled, *et al.* 2016). Globally, there are now over 400 weed species that have developed resistance to 160 herbicides and annually 9 new weed biotypes are reported as becoming herbicide resistant (Heap 2016).

The nomenclate used in this study is listed in Appendix A. The system transfer function presented by Eq. (B1) in Appendix B relates crop yield potential to herbicide application (Brodie 2014). The sensitivity of yield potential to time can be deduced by differentiating this transfer function with respect to the number of weed generations (g) as shown in Eq. (B5). Using published data for the various parameters, this transfer function predicts that significant herbicide resistance will occur within 15 generations (Figs. 1a, b)). This was verified by Thornby and Walker (2009), who determined, by both simulation and field observations, that continuous use of glyphosate induced resistance in barnyard grass (*Echinochloa colona*) within 15 years. Therefore, alternatives to herbicide weed control are needed.

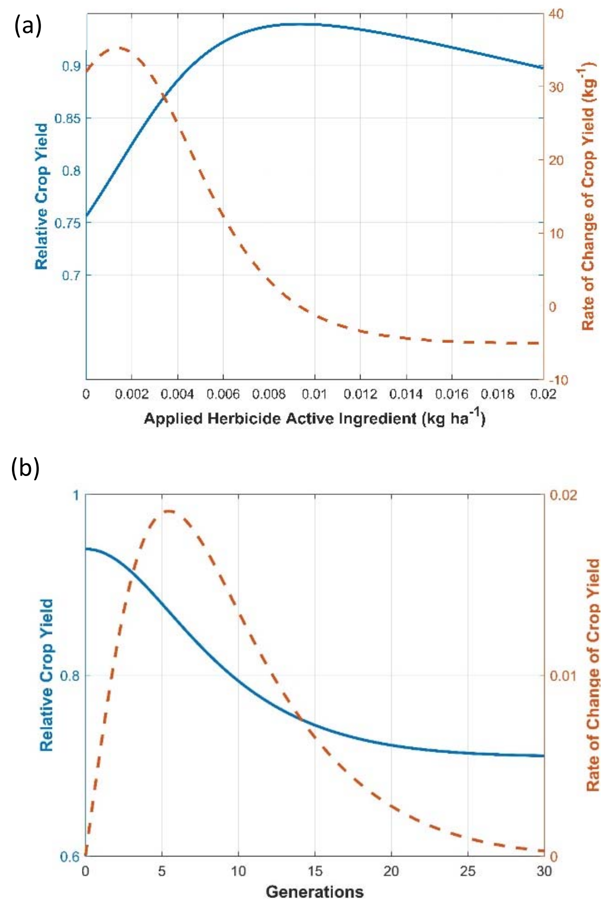

Figure 1: Normalised crop yield (blue line) and rate of change of crop yield (orange line) as a function of (a) herbicide application in a single season, and (b) number of seasons (generations of weeds), based on Eq. (B1).

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 (Ark and Parry 1940), while interest in the effect of high frequency waves on plant material began in the 1920's. Davis et al. (1971, 1973) 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 (Davis 1973). Menges and Wayland (1974) reported that microwave soil treatment (360 J cm^{-2}) significantly inhibited weed establishment and caused less crop injury (18% for microwave treatment) than residual herbicide application (85%).

In a review of microwave soil treatment for weed seed deactivation, Nelson (1996) 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 (Nelson 1996); 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.

Potential microwave application strategies

Microwave energy can be applied to already growing weeds or to the soil prior to crop planting. Many pot experiments have been undertaken to evaluate the performance of both strategies.

Plant treatment

A simple plant survival function *S* for microwave treatment can be derived by integrating the Gaussian normal distribution function,

$$S = a \cdot \mathrm{erfc}\left[b\left(\Psi - c\right)\right], \qquad (1)$$

where all the parameters used in this study are defined in Appendix A at the end of the article. Some examples of these survival curves are shown in Figure 2 (Brodie, et al. 2007b, Brodie, et al. 2012, Brodie and Hollins 2015).

Soil treatment

The relationships between applied microwave energy and seed survival have also been derived,

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

Some examples of the fitting of these curves to measured data are shown in Figure 3 (Brodie, *et al.* 2007a, Brodie, *et al.* 2007b, Brodie, *et al.* 2007c, Brodie, *et al.* 2009, Brodie and Hollins 2015).

Taking to the field

An experimental microwave trailer has been developed (Figure 4) 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.

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 5) when the trailer was moved over the grass at between 700 and 900 m hr^{-1}. 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 4 days, the treated strips were quite evident (Figure 6), with 100 % mortality along almost all the treated strips.

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. The trailer can also be used to treat soil with a high dose of microwave energy. In this case, treatment of up to 120 s 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.

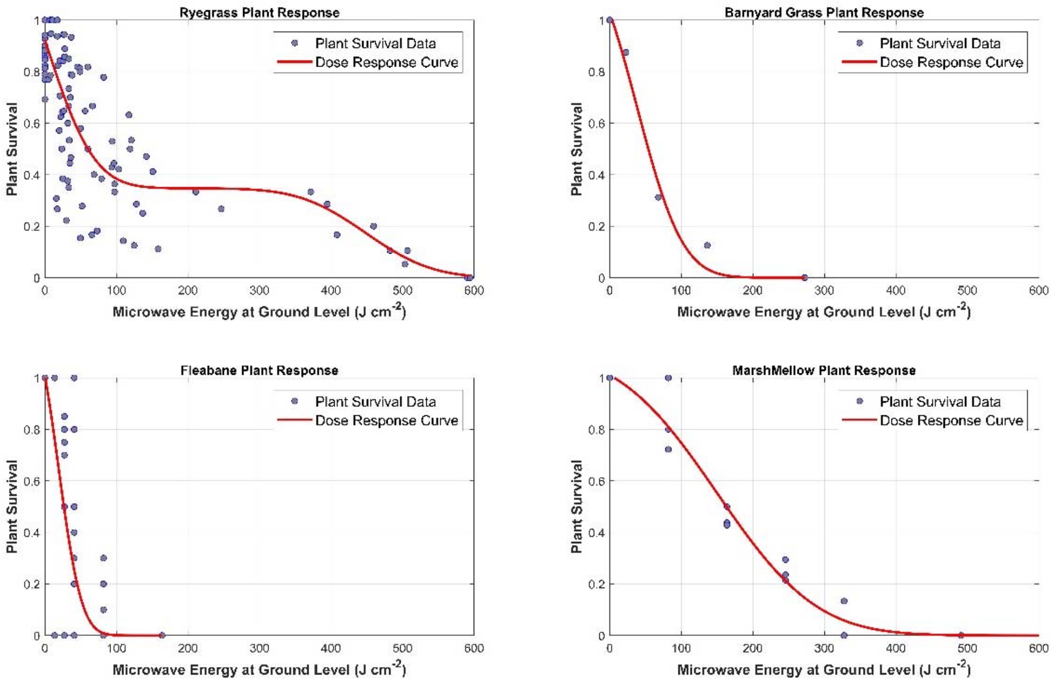

Figure 2: Dose response curves for microwave treatment of four species of weed plant using a horn antenna.

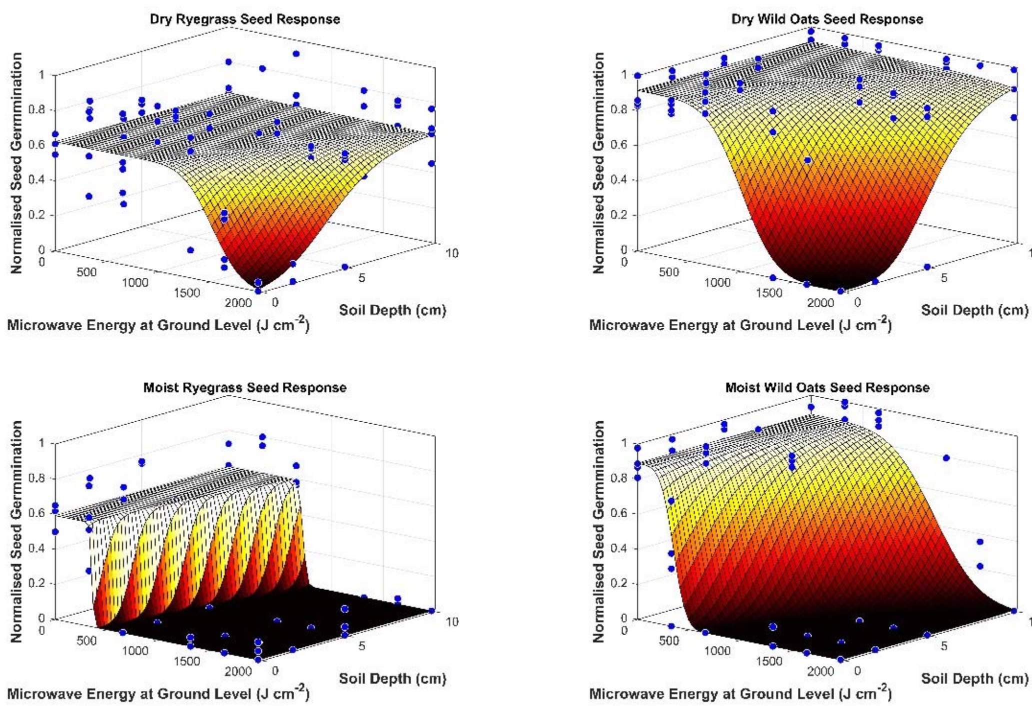

Figure 3: Dose responses of ryegrass and wild oats seeds as a function of soil moisture, microwave energy at ground level, and burial depth in soil.

Figure 4: A 4x2 kW microwave trailer prototype in the field.

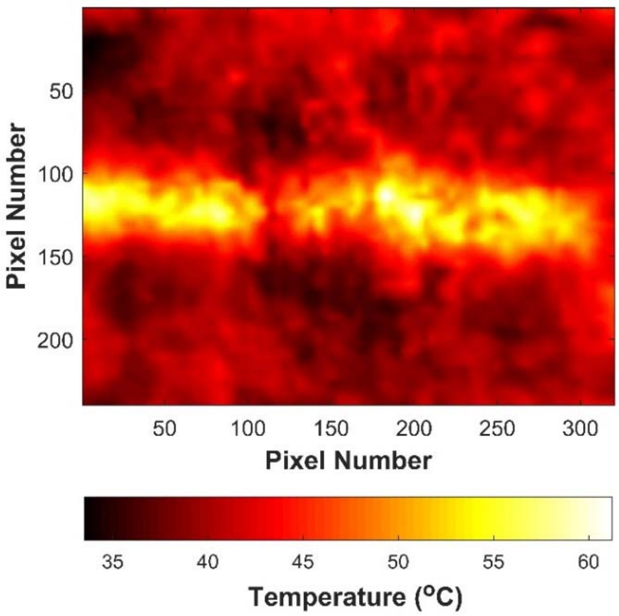

Figure 5: Thermal image of treated strip of kikuyu grass, captured with a FLIR C2 thermal camera.

Complete soil coverage was achieved by performing two passes over the plot, with the second pass being offset from the first to cover the inter-row strip. Figure 7 shows thermal images of the soil surface during microwave treatment, in preparation for planting a rice crop.

It has been demonstrated that when the soil is treated in this manner, weed seeds, nematodes, soil bacteria, and pathogenic fungi, such as *Fusarium oxysporum* and *Sclerotium rolfsii*, are significantly reduced in number (Ferriss 1984, Rahi and Rich 2008, Brodie, *et al.* 2015). 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 (Khan, *et al.* 2016, Khan, *et al.* 2017a).

Figure 6: Image of four treated strips of kikuyu grass, taken (a) 4 days after treatment, and (b) 20 days after treatment on two different experimental sites.

In independent field experiments, where rice and wheat were planted into microwave treated soil, there were significant reductions in weed emergence and significant increases in crop yield (Table 1, Table 2 Figure 8,). Similar results have been found for processing tomatoes (Table 3). Processing tomato production routinely uses soil fumigants to manage weeds and pathogens, so microwave soil treatment was also compared to this industry standard practice.

All field experiments were laid out according to Figure 9. There is also evidence that the crop yield improvement due to microwave soil treatment persists for at least two seasons without further treatment (Khan, *et al.* 2017b).

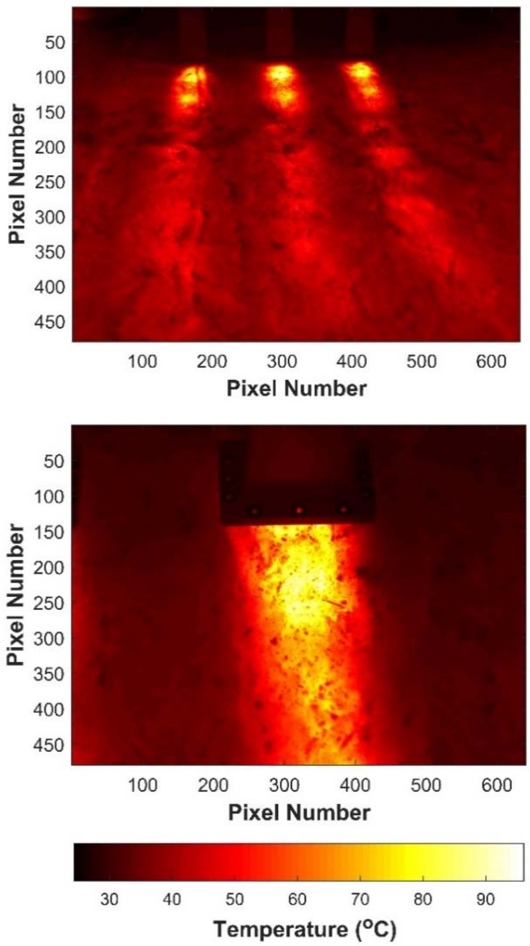

Figure 7: Thermal images of the soil surface during microwave treatment using the prototype trailer, captured with a FLIR T640 thermal camera.

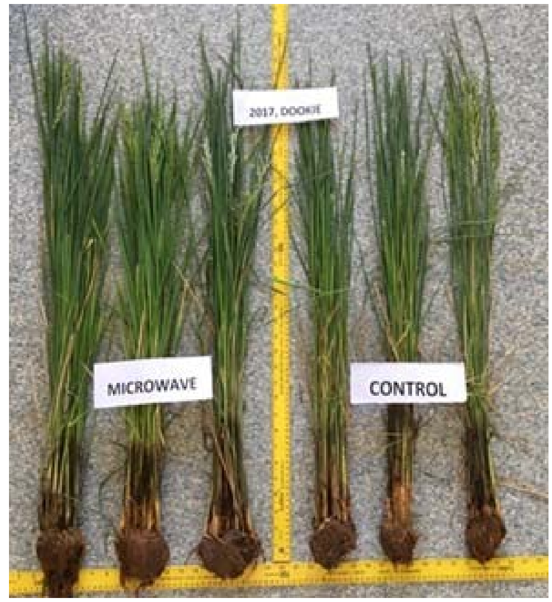

Figure 8: Comparison of randomly sampled rice plants grown in the microwave treated plots (left) with rice plants grown in the control plots (right).

Using the same basic derivation, that was used to develop the herbicide transfer function response in Appendix B, but substituting parameters for microwave weed and soil treatment instead of the herbicide efficacy components of Eq. (B1), provides the relationship between crop yield potential and applied microwave energy in Eq. (B7).

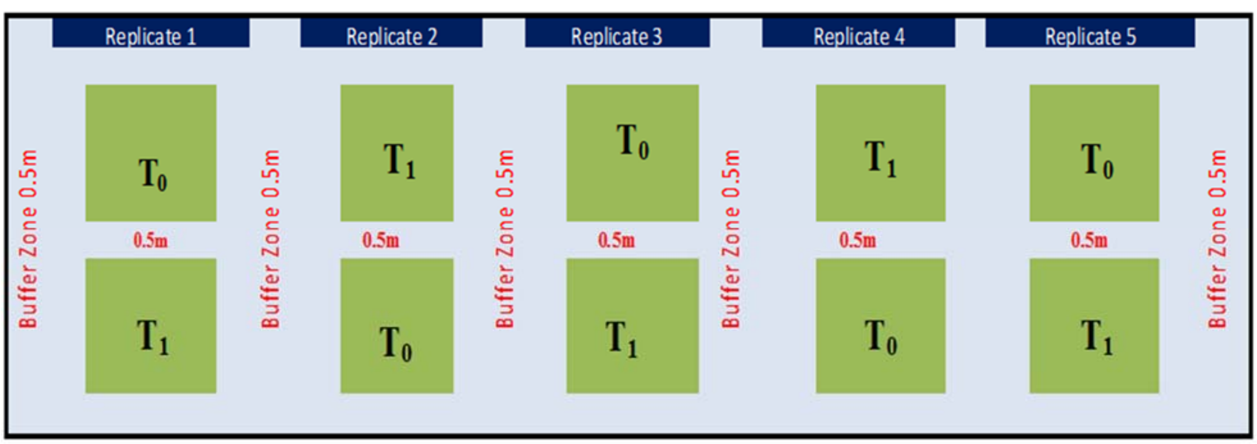

Figure 9: Experimental layout of the all microwave field experiments: untreated control (T0) and MW treated (T1).

Table 1: Assessment of key crop growth parameters for rice crop experiment

	Treatment		$LSD_{5\%}$	% Change from control
	Microwave	Control		
Fresh weight[a] (g quadrate^{-1})	416.8	225.5	116.3	85%
Dry weight[a] (g quadrate^{-1})	91.3	50.8	26.1	80%
Tiller density[a] (Tillers quadrate^{-1})	104.0	61.5	32.2	69%
Weed density (plants plot^{-1})	7.5	44.3	28.4	-83%
Chlorophyll content	42.3	43.6	4.5	-3%
Leaf area index	4.0	2.6	2.0	56%
Gain yield (t ha^{-1})	9.0	6.7	1.7	34%

[a] at panicle formation stage

Table 2: Summary of data from wheat field trial

	Treatment		$LSD_{5\%}$	% Change from control
	Microwave	Control		
Weed density at tillering (Plants plot^{-1})	27.0	72.3	26.1	-63%
Tiller density (Tillers quadrate^{-1})	96.8	67.0	29.5	44%
Weed dry wt at tillering (g quadrate^{-1})	5.3	55.3	37.5	-90%
Crop dry matter at tillering (g quadrate^{-1})	112.3	89.8	20.3	25%
Weed dry weight at harvest (kg m^{-2})	0.08	0.23	0.1	-65%
Crop dry matter at harvest (kg m^{-2})	2.04	1.52	0.47	34%
Grain yield (t ha^{-1})	7.97	5.66	2.1	41%

Table 3: Results of field trial for processing tomatoes

	Treatment			$LSD_{5\%}$	% Change from control	% Change from chemical Fumigant
	Microwave	Control	Chemical Fumigant			
Fruits per plant	187.30	106.40	149.25	43.93	76%	25%
Weeds per plot	0.50	3.00	2.50	1.71	-83%	-80%
Crop biomass (kg/plot)	35.94	25.32	25.22	9.75	42%	43%
Fruit yield (t/ha)	89.56	64.10	65.20	8.38	40%	37%

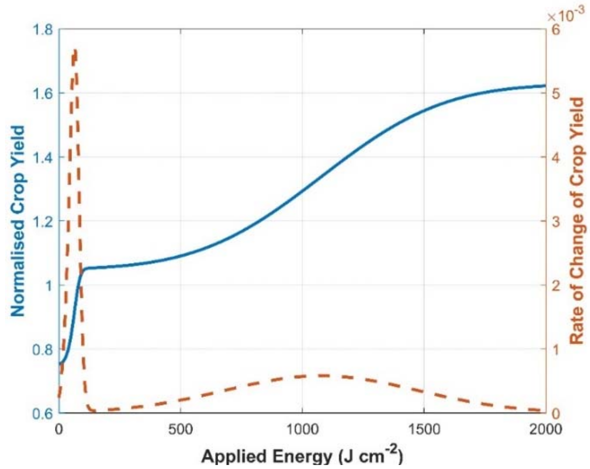

Figure 10: Relative crop yield as a function of applied microwave energy, based on the derived microwave response model in Eq. (B7).

Differentiating equation Eq. (B7) with respect to Ψ determines the sensitivity of crop yield to microwave weed treatments in Eq. (B11). Figure 10 shows the potential crop yield response, 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. Unlike residual chemical options, microwave soil treatment is a purely thermal effect (Nelson 1996), therefore the treated site is accessible as soon as the soil cools.

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, commercialisation will be explored.

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 weed plant treatment. 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 production.

For further reading

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Appendix A: Nomenclature

Ψ	Microwave field density (J cm^{-2})
a	Selection pressure for herbicide resistance
a-c, f, k	Constants experimentally determined for each species
A_w	Percentage yield loss
d	Slope of seed bank recruitment curve at t_o or depth of seed in soil (m)
D_b	Fraction of seed population from previous seasons breaking dormancy
D_o	Seed population fraction with dormancy
E_m	Seed emigration from the area of interest
g	The generational number
H	Herbicide active ingredient dose (kg ha^{-1})
ha	Hectare (10^4 m^2)
I	Percentage yield loss
Im	Seed immigration into the area of interest
N	Natural death rate for whole population
S_o	Initial frequency of plants in population susceptible to herbicide treatment
S_s	Viable seed set per plant from surviving volunteers in weed population
t	Time difference between crop emergence and weed emergence
t_o	50 % germination time of viable seed bank
W	Viable seed bank
Y_o	Theoretical yield with no weed infestation
λ	Efficacy of herbicide killing action

Appendix B: System equations (Brodie 2014)

The following system transfer function relates the crop yield potential to the herbicide application:

$$Y = Y_0\left\{1 - \frac{A_1(1-SA_2)}{A_3} + aH^2 - bH\right\}, \qquad \text{(B1)}$$

where

$$A_1 = I\left[W(1-N-D_0) - E_m + I_m\right], \qquad \text{(B2)}$$

$$A_2 = e^{-ag^2/2} - e^{-ag^2/2-\lambda H}, \qquad \text{(B3)}$$

$$A_3 = 100\left\{e^{ct}\left[1+e^{-\frac{t-t_o}{d}}\right] + \frac{A_1(1-SA_2)}{A_w}\right\} \qquad \text{(B4)}$$

The sensitivity of yield potential to time can be deduced by differentiating Eq. (B1) with respect to the number of weed generations (*g*):

$$\frac{dY}{dg} = Y_0\left\{\frac{A_1 A_4 A_w Sa\cdot g\cdot A_2}{100\left\{A_4 + A_1(1-SA_2\right\}^2}\right\}, \qquad \text{(B5)}$$

where

$$A_4 = e^{ct}\left[1+e^{-(t-t_o)/d}\right]. \qquad \text{(B6)}$$

Using the same basic derivation, that was used to develop the herbicide transfer function response in Eq. (B1), but substituting parameters for microwave weed and soil treatment instead of the herbicide efficacy components provides the relationship between crop yield potential and applied microwave energy:

$$Y = Y_0\left\{1-\frac{A_1A_6}{A_7}-\frac{A_1A_5A_6}{A_7^2}+l+m\cdot\operatorname{erf}\left[n\left(\Psi-q\right)\right]\right\}, \qquad \text{(B7)}$$

where

$$A_5 = A_1\left\{a\cdot b\ \mathrm{e}^{-b^2(\Psi-g)^2}+e\cdot f\ \mathrm{e}^{-f^2(\Psi-k)^2}\right\}, \qquad \text{(B8)}$$

$$A_6 = a\cdot\operatorname{erfc}\left[b\left(\Psi-g\right)\right]+e\cdot\operatorname{erfc}\left[f\left(\Psi-k\right)\right], \qquad \text{(B9)}$$

$$A_7 = 100\left\{e^{ct}\left[1+e^{-\frac{t-t_o}{d}}\right]+\frac{A_1\left(1-sA_2\right)}{A_w}\right\} \qquad \text{(B10)}$$

Differentiating Eq. (B7) with respect to Ψ determines the sensitivity of crop yield to microwave weed treatments:

$$\frac{dY}{d\Psi}=\frac{2}{\sqrt{\pi}}Y_0\left\{\frac{A_1A_5}{A_7}-\frac{A_1A_5A_6}{A_7^2}+m\cdot n\cdot e^{-n^2\,(\Psi-q)^2}\right\} \qquad \text{(B11)}$$

About the Authors

Graham Brodie is an electrical engineer with the Faculty of Veterinary and Agricultural Sciences at the University of Melbourne. His research interests include: microwave heating of bio-materials; using microwaves for sensing and communication in agriculture and forestry; improving water use efficiency in agriculture; producing renewable energy on farms; on-farm animal waste management; and applications of Geographic Information System (GIS) and Remote Sensing technologies in agriculture and archaeology. He obtained his PhD from the University of Melbourne, Australia, in 2005. He has over 35 years of professional experience in industry and academia.

Dorin Gupta is a crop scientist working with the University of Melbourne with a research focus on improving the sustainability and efficiency of crop production systems (cereals and legumes) through optimum resource use, field experimentations, and molecular techniques for managing biotic (fungal) and abiotic (drought) stresses. Dr Gupta obtained her PhD degree from H.P. Agriculture University, Palampur, India, in 2003. She was awarded prestigious Vavilov Frankel Fellowship in 2008 by Bioversity International Rome funded by GRDC, Australia. She is passionate about taking on challenges for sustainable food production and security.

Muhammad Jamal Khan received the Master of Sciences (Honors) degree in Agronomy from Pir Mehr Ali Shah-Arid Agriculture University Rawalpindi, Punjab, Pakistan, in 2014. He started Doctor of Philosophy degree in Agriculture Sciences in the University of Melbourne, Victoria, Australia, in 2015. His research interests focus on microwave weed management and bio-stimulation effects of microwave energy on soil nutrients dynamic in cereals.

Sally Foletta grew up on a mixed enterprise family farm in North East Victoria. She obtained her Bachelor of Agricultural Science (Honours)/Bachelor of Commerce from the University of Melbourne in 2006. She then worked as an Agribusiness Analyst for the NAB, before returning to the University of Melbourne as a PhD student. She recently submitted her PhD and is currently a casual teaching and research staff member at the University of Melbourne and subject coordinator at North Melbourne Polytechnic.