Recent work on microwave-based weed control for cropping systems

Graham Brodie, Eloise Hollins and John Woods-Casey
Melbourne School of Land and Environment, The University of Melbourne, Dookie Campus, Nalinga Road, Dookie, Victoria 3647, Australia
(grahamb@unimelb.edu.au)

Summary Herbicide resistance motivates ongoing searches for new technologies that are compatible with no-till farming practices. Microwave weed management has been intermittently studied for over forty years. This paper presents the results of three recent small-scale but interlinked experiments involving microwave treatment of annual ryegrass (*Lolium rigidum* Gaud.) plants, ryegrass seeds in the soil, and early growth of a subsequently planted wheat (*Triticum aestivum* L.) crop. Microwave treatment kills annual ryegrass plants and seeds, but it also enhances the early vigour of wheat plants.

Keywords Microwave, weeds, soil.

INTRODUCTION

Herbicide resistance in many weed species is becoming wide spread (Heap 1997) and multiple herbicide resistances in several economically important weed species has also been widely reported (Owen *et al.* 2007). Selection pressure for herbicide resistance depends on the initial efficacy of the herbicide to remove susceptible individuals from the population, leaving only the resistant individuals to reproduce and the adoption of a single herbicide over a long period of time to sustain this selection pressure.

Work by Thornby and Walker (2009) predicted that resistance to glyphosate could develop in 15 years under continuous herbicide treatments. Herbicide rotations can forestall the development of a resistant population; however several weed species have developed resistance to several herbicide groups (Owen *et al*. 2007).

Crop ecology models have been developed to assess the impact of herbicide resistance on crop yield (Brodie 2014). In a scenario that is similar to the scenarios modelled by Thornby and Walker (2009), the crop ecology models predict that the cumulative crop yield loss over a 20 year period, due to residual weed competition after herbicide management has been implemented, could be the equivalent of 4 times the crop yield from a single ideal season (Figure 1).

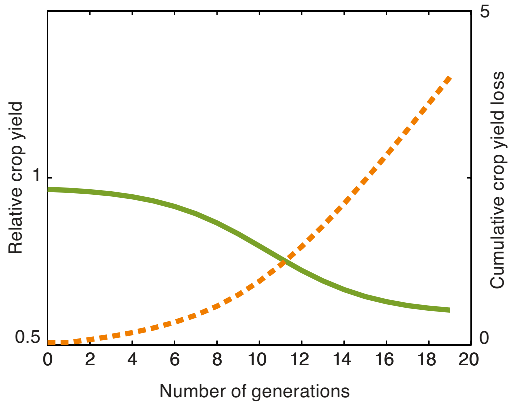

Figure 1. Crop yield (solid green line), relative to an ideal crop and cumulative crop yield loss (dotted orange line) as a function of number of weed generations.

Microwave weed control 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 1920s (Ark and Parry 1940).

Davis *et al.* (1971 and 1973) 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.

In a theoretical argument based on the dielectric and density properties of seeds and soils, Nelson (1996) demonstrated that selectively heating weed seeds in the soil using microwaves is not possible. He concluded that seed susceptibility to damage from microwave treatment is a purely thermal effect, resulting from soil heating and thermal conduction from the soil into the seeds.

Nelson's final conclusion was that microwave soil treatment was unviable because of its energy requirements; however his studies only considered seed treatment in soil, did not account for herbicide resistance, and did not assess the effect of microwave soil treatment on subsequent crop development. This paper assesses the effect of microwave treatment on annual ryegrass (*Lolium rigidum*) plants, ryegrass seeds in the soil, and early growth of a subsequently planted wheat (*Triticum aestivum*) crop.

MATERIALS AND METHODS

This study was conducted as a sequence of small, interrelated theoretical analyses of the microwave equipment and experiments. The experiments were conducted as pot trials using a four by 2 kW trailer mounted microwave system equipped with horn antennae for microwave energy application. Horn antennae are hollow pyramidal structures that guide and project the microwave energy onto the soil. Soil for all three experiments was harvested from the top 2 cm of one of the regularly cropped paddocks of the Dookie Campus of the University of Melbourne.

Because the direct measurement of microwave field strength near a horn antenna is very hazardous to personnel and equipment, a theoretical analysis of estimated field power density was undertaken. This analysis used four different analytical techniques: the derivation of a simplified antenna radiation model assuming a uniformly illuminated antenna aperture; development of a Finite-Difference Time-Domain simulation of the microwave fields from a horn antenna; a numerical integration of the antenna radiation fields; and assuming a spherical wave propagating from the antenna aperture. These separate estimates of microwave field strength were averaged to give an estimate of average applied microwave energy during the subsequent experiments.

Experiment 1 Annual ryegrass plants were grown in pots from seed over 9 weeks. Each of the 90 pots was allocated 20 seeds. The seeds were randomly placed on the soil surface and topped with a shallow covering of soil. Initially, the seeds were watered in with 500 mL of water per pot. Over the growing period, pots were watered with 100 mL of water every 3 days to ensure the soil remained moist.

Once plants were well established, each pot was placed under the microwave antenna for treatment durations of 0, 2, 5, 10, 30 and 120 seconds, with 15 replicate pots per treatment. After treatment, pots received 100 mL of water every 3 days for a total of 10 more days to encourage recovery and growth of ryegrass plants. After this time, the number of surviving plants was recorded. A non-linear regression was used to determine a dose-response curve for microwave treatment.

Experiment 2 Thirty pots were filled with soil and received 500 mL of water to reach a consistent moisture level. Pots were left overnight. Twenty-five ryegrass seeds each were placed at depths of 0, 2, 5, 10 and 20 cm within each pot.

Each pot was placed under the microwave antenna for treatment durations of 0, 2, 5, 10, 30 and 120 seconds, with 5 replicate pots in each treatment. Pots were left to return to ambient temperature. Each layer of seeds was removed and placed into individual bags for each depth. In order to promote germination, seeds were placed between layers of moistened paper towel, within a small, open plastic bag and kept in a warm, dark place. The paper towel was remoistened each day. After 10 days, the total number of germinated seeds was recorded to determine the percentage of germination following microwave treatment. A cubic spline surface regression was used to determine a dose response curve that included both microwave treatment energy and soil depth.

Experiment 3 Twenty five pots were filled with soil. Each pot was placed under the microwave antenna for treatment durations of 0, 30, 70 and 120 seconds, with 5 replicate pots in each treatment. Pots were left to return to ambient temperature. Ten wheat seeds were planted in each pot and the pots were placed in a climate controlled growth chamber to maintain consistent growing conditions for the wheat. The chamber was set to provide 14 hours of light each day at a temperature of 25°C.

Plant height was measured regularly and after 23 days from sowing, all plants were harvested, separated into roots and shoots and dried in an oven to determine dry matter. Data from this experiment was tested for normality and analysed using analysis of variance.

RESULTS

All four antenna analysis techniques for estimating the microwave field strength from the horn antenna showed that the normalised field intensity dissipates very rapidly with distance from the antenna (Figure 2). The estimated energy density at the soil surface for these experiments was estimated to be 0.8 J cm^{-2} s^{-1}.

Experiment 1 Data revealed that a moderate level of microwave treatment (approximately 6 J cm^{-2}) killed up to 90 % of ryegrass plants; however a much higher level of treatment (approximately 75 J cm^{-2}) was needed to kill all plants (Figure 3).

Experiment 2 Data revealed that seed survival in the top 5 cm of soil was significantly reduced when the applied microwave energy was greater than 90 J cm^{-2} (Figure 4); however seeds that were buried deeper in the soil were unaffected by microwave treatment. Less microwave energy had no effect on seed survival either.

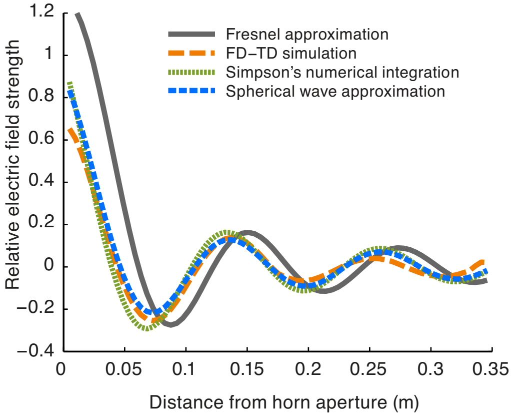

Figure 2. Estimated relative microwave field strength as a function of distance from the aperture of a horn antenna.

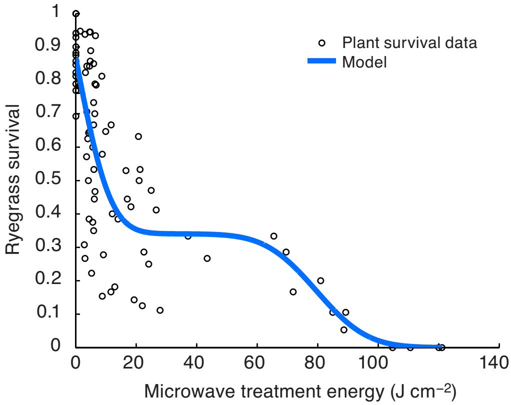

Figure 3. Ryegrass plant survival as a function of applied microwave energy.

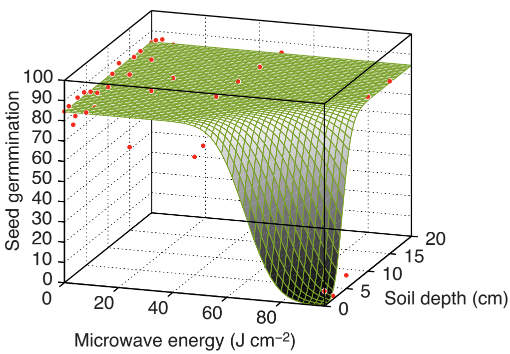

Figure 4. A spline regression surface of ryegrass seed survival as a function of both applied microwave energy and burial depth.

Experiment 3 Wheat plants that grew in soil that was treated by the highest and second highest levels of microwave energy grew faster (Figure 5) and produced approximately three times the biomass (Table 1) of the plants growing in untreated soils during the first 23 days after sowing.

Plants in these high energy level treatments were also more mature than those in the controls and the lower microwave energy treatment. Plants in the control treatments and the lowest microwave energy treatment were all at the multiple leaf, single stem stage of growth at 23 days after planting; however plants in the higher microwave energy treatments were all at the multiple tiller growth stage.

DISCUSSION

Microwave treatment kills annual ryegrass plants and seeds. Based on data in Figure 3, moderate levels of microwave treatment (about 6 J cm^{-2}) can kill about

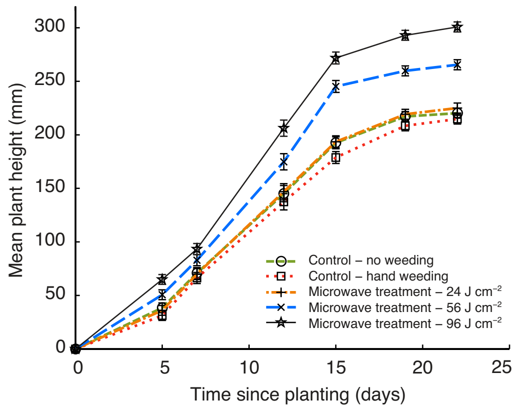

Figure 5. Wheat plant height as a function of time since sowing and microwave treatment (error bars represent LSD P = 0.05).

Table 1. Comparison of mean crop dry matter between treatments of Experiment 3.

Treatment	Stem DM (g pot^{-1})	Root DM (g pot^{-1})
Control I	0.9 [a]	1.3 [ab]
Control II	0.8 [a]	1.0 [a]
24 J cm^{-2}	0.9 [a]	1.1 [a]
56 J cm^{-2}	2.0 [ab]	2.2 [b]
96 J cm^{-2}	3.4 [b]	3.4 [c]
LSD (P = 0.05)	1.9	0.9

(Note: means with different superscripts in the same column are significantly different to one another).

80% of emerged ryegrass plants, while higher levels of energy (above 90 J cm^{-2}) will kill all ryegrass plants. This higher microwave treatment energy (above 90 J cm^{-2}) will also kill ryegrass seeds in the soil; however this is limited to the top 5 cm of the soil profile (Figure 4).

These higher microwave treatment energies also promote early vigour in subsequent crop plants (Figure 5). Therefore the combination of early vigour and removal of weed competition should significantly improve crop yield, when other limiting factors, such as water stress, are not involved (Figure 6).

In terms of cumulative potential crop yield, adopting microwave weed control technology may provide a net benefit due to long term recovery and improvements in crop yield above what might be expected from using herbicide treatment alone (Figure 7).

These experimental outcomes are very encouraging; however it is still unclear why microwave treatment may enhance early vigour in the subsequent crop. Some literature suggests that heating the soil may transform inherent soil nutrients, making them more available to the crop (Kitur and Frye 1983, Certini 2005). As yet, the effect on final crop yield has not been explored either. The effect of microwave treatment on soil biota is also unclear; therefore further research is required.

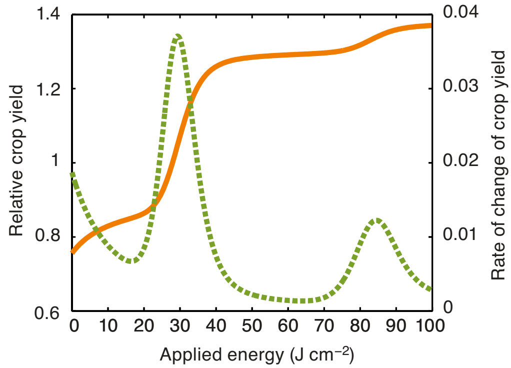

Figure 6. Crop yield potential (solid orange line) and rate of change of crop yield (dotted green line) as a function of microwave energy for weed control.

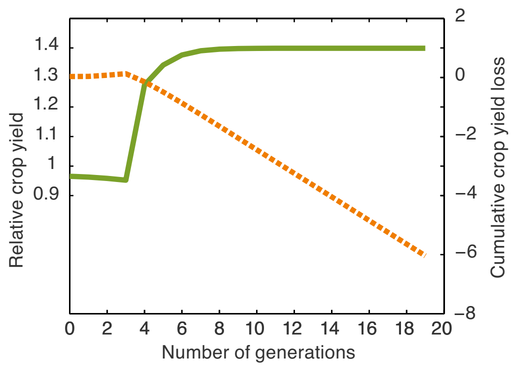

Figure 7. Comparison of crop yield potential (solid green line) and cumulative (dotted orange line) crop yield loss with microwave weed treatment.

ACKNOWLEDGMENTS

This research was supported by the Grains Research and Development Corporation and the Rural Industries Research and Development Corporation.

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