An assessment of microwave soil pasteurization for killing seeds and weeds

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Abstract

Microwave heating has been applied to various agricultural problems and products since the 1960s. Interest in soil pasteurization as an alternative method of weed control has been proposed for some time. Soil pasteurization requires the projection of microwave energy into the soil using an antenna. The pyramidal horn is probably the easiest microwave antenna to fabricate. This paper explores the use of a pyramidal horn antenna as a microwave applicator for soil pasteurization, with a particular focus on suppression of seed germination and control of already established weed infestations.

A laboratory system, energized from the magnetron of a modified microwave oven operating at 2.45 GHz, with a waveguide and pyramidal horn was developed for these experiments. Calibration of the microwave oven revealed that 205 ± 10 Watts of microwave power was delivered from the horn antenna. The H-plane temperature distribution within the soil has the maximum temperature about 3 cm below the surface along the centre line of the horn antenna, which proved to be effective at killing *Malva parviflora* seedlings and wheat seeds to a depth of about 6 cm.

Introduction

Over the past 40 years, microwave heating has frequently been proposed as an alternative method of controlling soil-borne pests such as weed seeds, insects, nematodes and pathogens (Nelson 1996). In particular, treatment of soils as a method of weed control (i.e. killing the weed seed bank) has been proposed for some time (Nelson 2003). Barker and Craker (1991) demonstrated that treatment of soil, containing 'Ogle' oats (*Avena sativa* L.) and an undefined number of naturalized weed seeds, in a microwave oven prevented seed germination when the soil temperature rose above 80°C. Other experiments (Brodie *et al.* 2007) have demonstrated that microwave treatment of soil significantly reduced wheat seed germination when the soil temperature rose above 65°C. These trials also demonstrated that microwaves interact with the soil rather than with the seeds and that heat must transfer from the soil to the seeds if germination is to be suppressed.

In situ soil pasteurization requires the projection of microwave energy into the soil. Aperture antennas, such as horns and dishes, are commonly used in communication systems to project microwave energy into open space; therefore it follows that an aperture antenna could be an effective device for projecting microwave energy into soil. The pyramidal horn is probably the easiest aperture antenna to fabricate. This paper explores the use of a pyramidal horn antenna as a microwave applicator for soil pasteurization, with a particular focus on suppressing seed germination and controlling already established weed infestations.

The pyramidal horn antenna

Horn antennas are very popular for microwave communication systems (Connor 1989). The antenna acts as an impedance transformer, which gradually matches the intrinsic impedance of the feeding waveguide to that of the open space in front of the horn (Connor 1989). The basic form of the horn antenna is shown in Figure 1.

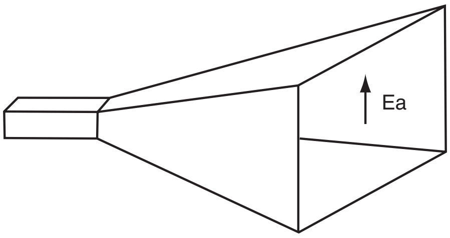

Figure 1. A typical horn antenna showing the orientation of the electrical field component of the microwave energy in the antenna's aperture.

The vertical plane of the horn antenna is usually referred to as the E-plane, because of the orientation of the electrical field (or E-field) in the antenna's aperture. The horizontal plane is referred to as the H-plane, because of the orientation of the magnetic field (or H-field) of the microwave energy.

The electric field distribution in the aperture of a horn antenna, fed from a wave-guide propagating in the TE_{10} mode, is described by:

$$\vec{E} = E_o \cos\left(\frac{\pi}{a}x\right) \cdot \hat{y} \ (\mathrm{V\ m^{-1}}) \qquad (1)$$

It is easy to show that, in a material medium such as soil, the electric field strength of applied microwave energy will decrease exponentially with distance from the source (Singh and Heldman 1993, Van Remmen *et al.* 1996, Torgovnikov 1993). Therefore the average field strength at a distance z below the soil surface is:

$$\vec{E} = E_o \cos\left(\frac{\pi}{a}x\right) \cdot e^{-\alpha z} \cdot \hat{y} \ (\mathrm{V\ m^{-1}}) \qquad (2)$$

where:

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)} \ (\mathrm{m^{-1}}) \quad (3)$$

Based on earlier work (Brodie 2005) the expected temperature distribution in the soil is calculated using Equation 4.

Determining the electric field strength

The microwave's electric field strength must be determined before Equation 4 can be solved. Modelling of microwave fields requires the solution of Maxwell's electromagnetic equations in three dimensions when complex boundary conditions are imposed onto the system. Several techniques can be employed to solve Maxwell's equations, including numerical techniques such as the Finite Difference Time Domain (FDTD) technique, proposed by Yee (1966). The FDTD method is a simple and elegant way to transform the differential form of Maxwell's equations into difference equations. Yee used an electric field grid, as shown in Figure 2, which was offset both spatially and temporally from a magnetic field grid to calculate the present field distribution throughout the computational domain in terms of the past field distribution.

$$T = \frac{s\pi f \varepsilon_o \varepsilon'' \tau^2}{4k\alpha^2} \cdot E_o^2 \cdot \left(e^{4\gamma\alpha^2 t} - 1\right) \cdot \left[e^{-2\alpha z} + \left(\frac{h}{k} + 2\alpha\right) z \cdot e^{\frac{-z^2}{4\gamma t}}\right] \cdot Cos\left(\frac{\pi}{a}x\right)$$

Equation 4.

Equations 5 and 6 are the basic forms of the difference equations used in the FDTD algorithm.

In this case the equations calculate the electric and magnetic fields in the x direction. Similar equations are required to calculate Ey, Ez, Hy and Hz.

These equations are used in a leap-frog scheme to incrementally march the electric and magnetic fields forward in time; therefore this numerical technique is a simulation of the microwave field rather than a direct solution of the field equations in space and time.

A Finite-Difference Time-Domain model of the experimental apparatus was developed to simulate the distribution of microwave fields inside the pyramidal horn and soil samples. This was used to calculate the mean electric field strength at the surface of the soil. This calculated electrical field strength, and other data shown in Table 1, were used to predict the H-plane temperature distribution through the soil sample using Equation 4. The expected temperature distribution is shown in Figure 3. The E-plane temperature distribution is expected to be uniform across the full height of the horn's aperture because the electric field distribution is also uniform in this plane.

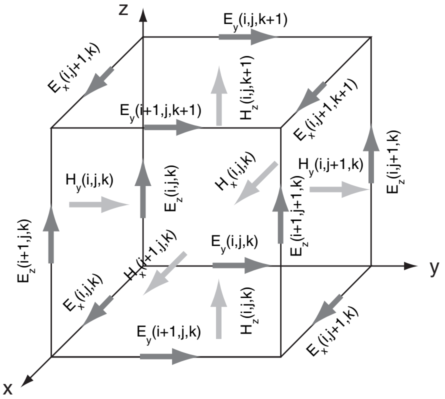

Figure 2. Single cell from the computational space used to compute Maxwell's equations using FDTD techniques.

Table 1. Data used in modelling temperature distribution in the soil.

Parameter	Value	Units
ε*	7.69 + j 1.20^A	
ρ	1150	kg m^{-1}
k	7.8^B	W m^{-1} K^{-1}
C	1130	J kg^{-1} K^{-1}
h	25	W m^{-1} K^{-1}

^{A}Dielectric data from von Hippel (1954).
^{B}The thermal conductivity of the soil was increased by a factor of 8 to account for simultaneous heat and moisture movement through the material (Brodie 2006).

$$E_x^{n+1}(i,j,k) = E_x^{n}(i,j,k) + \frac{\Delta t}{\varepsilon}\left[\frac{H_z^{n+1/2}(i,j+1,k) - H_z^{n+1/2}(i,j,k)}{\Delta y} - \frac{H_y^{n+1/2}(i,j,k+1) - H_y^{n+1/2}(i,j,k)}{\Delta z}\right]$$

Equation 5.

$$H_x^{n+1/2}(i,j,k) = H_x^{n-1/2}(i,j,k) + \frac{\Delta t}{\mu}\left[\frac{E_y^{n}(i,j,k+1) - E_y^{n}(i,j,k)}{\Delta z} - \frac{E_z^{n}(i,j+1,k) - E_z^{n}(i,j,k)}{\Delta y}\right]$$

Equation 6.

A laboratory system, energized from the magnetron of a modified microwave oven operating at 2.45 GHz, was developed for these experiments. The basic prototype is illustrated in Figure 4.

This arrangement used an 86 × 43 mm rectangular wave-guide to channel microwaves from the oven's magnetron, through the normal oven cavity, to an antenna outside the oven. A pyramidal horn with aperture dimensions of 180 × 90 mm and a length of 180 mm was attached to the wave-guide. The wave-guide ensures that the microwave energy did not enter the oven cavity. This arrangement also allows the oven's timing circuitry to control the activity of the magnetron.

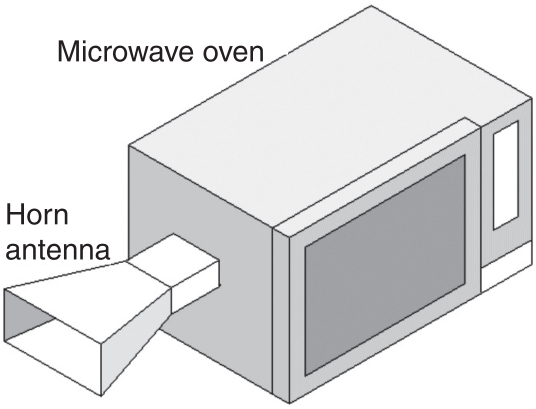

Figure 4. Single antenna laboratory prototype system based on a modified microwave oven.

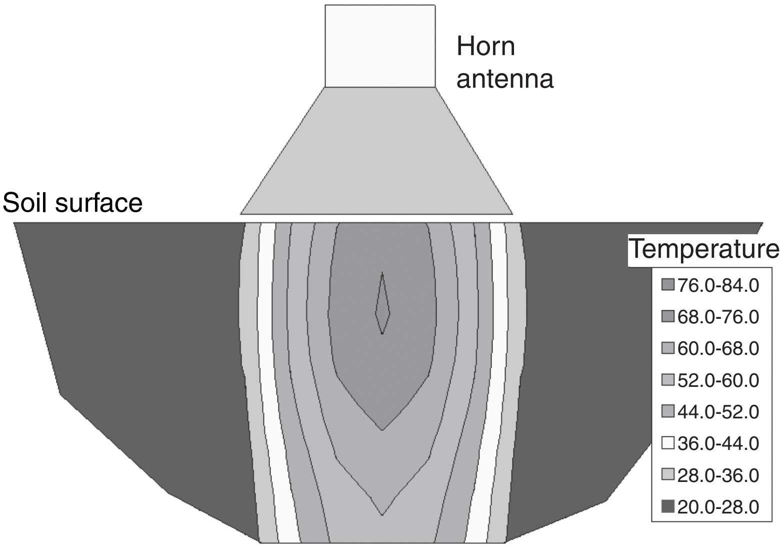

Figure 3. Theoretical temperature distribution in the H-plane of the pyramidal horn assuming 0.63 kW.h m^{-2} of applied microwave energy.

The deliverable power from a microwave system depends on many parameters including the impedance match between all the components of the wave-guide system. In this case, no attempt to match the impedance along the wave-guide was made, so it was important to determine the delivered microwave power so that energy and economic analyses could be conducted.

The deliverable microwave power can be determined using two samples of water. One acts as a control to determine the energy balance associated with the ambient conditions, while the other is heated by the microwave system. The deliverable power can then be calculated from the combination of sensible and latent heat observed in the two samples using Equation 7.

Method

Three separate but inter-related experiments were conducted to:

1. Validate the expected temperature distribution in the soil during microwave treatment using a pyramidal horn antenna;
2. Determine the ability of microwave soil pasteurization to kill wheat seeds at various depths in the soil profile; and
3. Demonstrate the ability of microwave soil pasteurization to kill established *Malva parviflora* L. weed plants in the field.

Wheat (*Triticum aestivum* L.) was chosen because its dielectric properties at microwave frequencies are well documented (ASAE 1994) and for its ability to germinate readily.

Experiment 1

The soil used in these experiments was gathered from the top 3 cm of a 4 m^2 area of paddock 6 of the Dookie campus of the University of Melbourne, and is a dark brown, medium clay with a pH of 6.87 in water and an electrical conductivity of approximately 1.03 dS m^{-1}. The soil was crushed, mixed thoroughly, and passed through a 2 mm sieve to ensure homogeneity and uniform response to the microwave fields, and air-dried to constant weight. Samples of approximately 2.3 kg were used for each of the experiments.

Soil samples were placed into a 20 × 20 cm plastic dish filled to a depth of 5 cm. Temperatures were measured using sixteen 120°C thermometers placed into the soil in the arrangement shown in Figure 5. Samples were heated using the experimental prototype for either 120 seconds or 150 seconds at full power. Thermometers were inserted into the soil immediately after heating was completed. Each heating experiment was repeated three times.

Experiment 2

For each treatment, 2.5 cm of soil was placed into the bottom of twelve 20 × 20 × 10 cm plastic dishes. Ten randomly selected wheat seeds were placed into envelopes created by folding a piece of filter paper in half and these were placed along the centre line at 3 cm, 6 cm and 10 cm from one end of the plastic dishes. A further 2.5 cm of soil was placed over the seed envelopes.

The filter paper was used to allow easier retrieval of the seeds from the soil. These envelopes were stood vertically in the soil. Because the thickness of the filter paper was very small in comparison with the wavelength of the microwave radiation, it was assumed that there would be little interference with the propagation of the microwaves through the soil caused by the filter paper.

The twelve dishes were randomly allocated between:

1. No microwave treatment,
2. Microwave treatment from the side closest to the 3 cm deep seeds for 120 s and,
3. Microwave treatment from the side closest to the 3 cm deep seeds for 150 s.

The experimental arrangement of the soil and antenna was similar to that shown in Figure 5. The microwave energy was projected into the soil samples from the side, rather than from above, to allow easier set up of the experiment using the prototype described above. Radiation hazards were reduced by having metal shielding between the operator and the samples. A radiation meter was used to indicate radiation hazard potential during the experimental runs.

All wheat seeds were retrieved from the soil after one hour, laid out on moist cotton wool and filter paper and left for five days to germinate. Germination percentages were calculated from average germination in each set of ten seeds. Results were analysed using a two factor analysis of variance, with the factors being burial depth and applied energy. Least significant differences were calculated to determine differences between the means of each treatment.

Experiment 3

Marshmallow is a weed of wasteland, cultivation and degraded pastures throughout Australia. A field trial was conducted at a residential site in Benalla (Location 36°32'S, 145°59'E) where seedling marshmallow plants of three to five leaf development stage dominated, as can be seen in Figure 6. The trial site was approximately

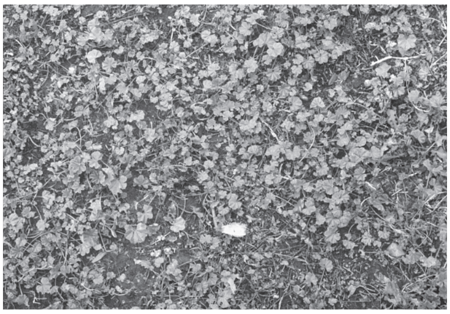

Figure 6. Seedling marshmallow at the experimental site.

$$P = \frac{\left\{ \left(4.18\Delta T_m + \frac{2260\Delta m_m}{m_m} \right) - \left(4.18\Delta T_c + \frac{2260\Delta m_c}{m_c} \right) \right\} m_m}{t_h}$$

Equation 7.

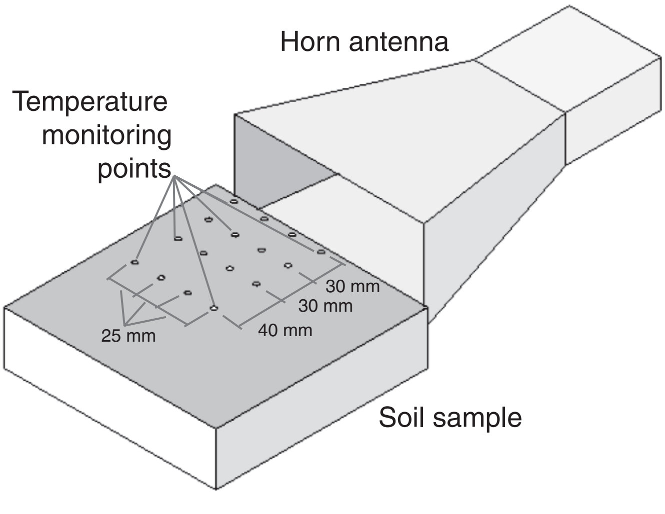

Figure 5. Schematic of thermometer placement during temperature measurement experiment.

5 × 6 m. Average plant numbers, determined by counts within four randomly allocated 0.25 m^2 quadrats, were approximately 260 plants m^{-2}.

The experiment was conducted between 18th and 24th of July, 2005. On 16th of July the trial site received approximately 25 mm of rainfall over 24 hours, which thoroughly saturated the soil. This rainfall event was followed by nine days of fine weather.

On July 18th, 1 m long strips of weed-infested ground were treated using the microwave prototype for 30, 60, 90, 120, 180, and 300 seconds of microwave heating for each segment of the treatment strip. The prototype was mounted on a carriage arrangement so that the horn antenna was pointing vertically into the soil and suspended about 2 cm above the soil surface. Untreated strips were also interspersed among the treatments to act as a control for the experiment. Each treatment was replicated three times in a random block design.

A buffer of 300 mm was left between treatments strips to minimize cross-treatment effects. Plant assessments were made five days after treatment and percentage survival rates were calculated by counting both living and dead plants along the treatment strips. Treatment strips were re-assessed after six weeks to determine whether there has been any recruitment of marshmallow. Mean survival rates were plotted against applied microwave energy in order to determine a microwave dose response curve for marshmallow.

One further strip was treated for 120 s of microwave heating. Three plants from this strip were randomly selected, harvested immediately after treatment and photographed. Three plants from one of the buffer areas were also randomly selected, harvested and photographed for comparative purposes.

Results and discussion

The calibration exercise revealed that the modified microwave system was delivering 205 ± 10 Watts of microwave power. Therefore heating times of 30, 60, 90, 120, 150, 180 and 300 seconds equate to microwave energy levels of 0.10, 0.20, 0.31, 0.41, 0.53, 0.62 and 1.24 kW.h m^{-2} respectively.

Using equations found in Metaxas and Meredith (1983) the measured output power was used to determine that the maximum electric field strength in the wave guide was approximately 10 910 V m^{-1}. This was used in the FDTD simulation to determine the electrical field distribution throughout the system. Figure 7 shows the FDTD simulation output in the H-plane for the horn antenna. From the FDTD analysis, it was determined that the maximum electric field strength in the aperture of the horn antenna was 4505 V m^{-1} while it was 1110 V m^{-1} just above the soil surface. This value of 1110 V m^{-1} was used in Equation 4 to calculate the predicted soil temperatures during microwave heating.

Experiment 1

Figure 8 compares the predicted and measured temperature distribution in the soil. The spatial distributions are very similar, suggesting that the mathematical model, developed earlier, will be useful for designing future microwave soil pasteurization systems. The H-plane heat distribution within the soil has its maximum temperature at about 3 cm below the surface of the soil along the centre line of the horn antenna.

Experiment 2

Figure 9 shows the temperature distribution along the centre line of the soil sample and the corresponding seed germination percentages. The complete seed germination results are shown in Table 2. It appears that temperature is the single parameter that influences wheat seed germination. This has also been found in other studies (Barker and Craker 1991, AMT 2003). Increasing the temperature from 66.5°C (0.41 kW.h m^{-2} of microwave energy) to 71.5°C

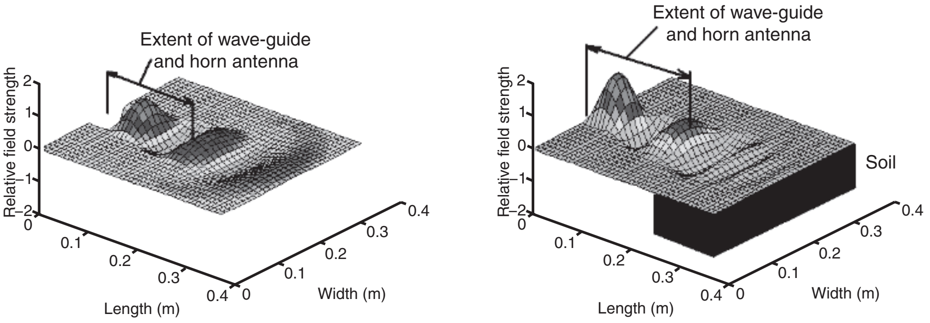

Figure 7. FDTD simulation of the microwave's electric field strength in the H-plane for the antenna projecting into empty space (left) and projecting into soil (right).

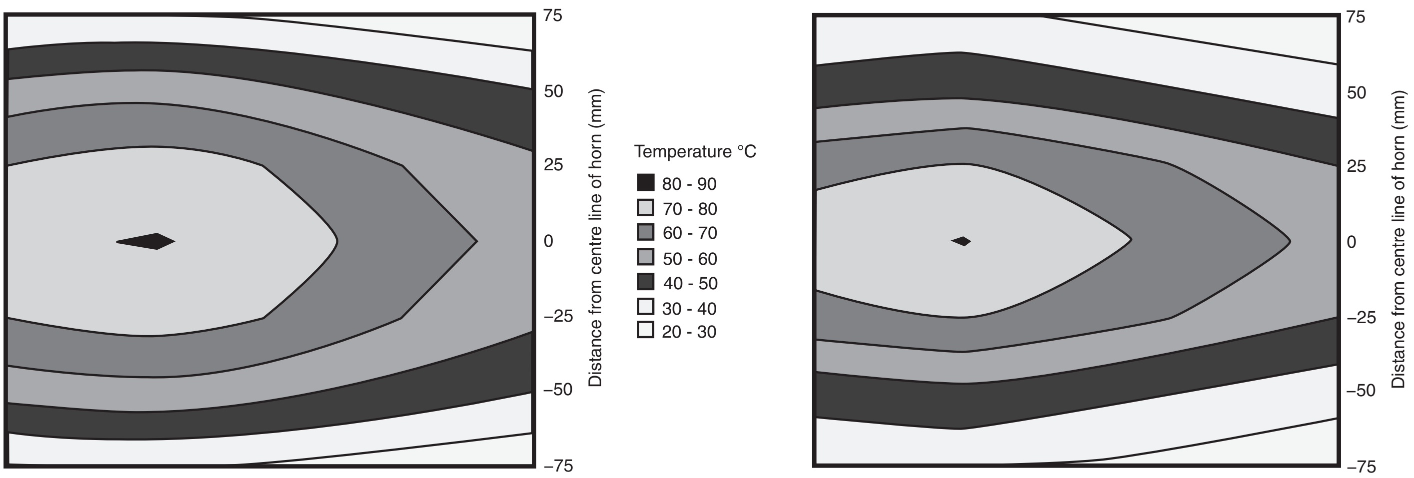

Figure 8. Comparison of predicted temperature profile on the left and the measured temperature profile on the right.

(0.53 kW.h m^{-2} of microwave energy) reduces the germination potential of wheat seeds from 80% to 10%.

Table 2 shows that both microwave energy and burial depth profoundly influence seed survival. This should be expected as microwave energy directly influences the soil temperature. On the other hand, the amount of soil above a seed tends to shield the seed from radiation exposure. Therefore seeds that are buried deeper in the soil profile will probably survive microwave treatment. This may be a problem where the soil is regularly disturbed because of tillage or natural mulching actions or movement of seed by ants and other invertebrates. If the soil remains undisturbed, these deeper seeds may not germinate and may eventually become unviable.

Experiment 3

Figure 10 shows the effect of microwave treatment on established *Malva parviflora* plants. Microwave heating wilted the leaves and may have also ruptured internal structures within the plants. Figure 11 shows the survival rate, five days after treatment. No regeneration of *Malva parviflora* was evident in the strips treated with 0.41 kW.h m^{-2} and above.

An empirical relationship between applied microwave energy (E_m) and plant survival was determined:

$$Survival = e^{-16.667 E_m^2} \qquad (8)$$

The coefficient of determination (r^2) comparing this empirical relationship with the observed data is 0.997.

The mathematical expression for a normal probability distribution is:

$$f(x) \propto e^{-ax^2} \qquad (9)$$

The empirical model, expressed in Equation 8, has the same basic form as the normal probability distribution; therefore it may represent the normal variability associated with the population response of the *Malva parviflora* to microwave heating. Natural resistance to many control treatments occurs when small numbers of resistant individuals survive the treatment and reproduce. This suggests that under treatment using microwave heating could lead to heat resistance within this population; therefore care must be exercised when applying microwave soil pasteurization to control weed populations.

Because the maximum temperature occurs about 3 cm below the soil surface, the pyramidal horn antenna was effective at killing deeper rooted weed species such as *Malva parviflora* and wheat seeds that were buried in the soil to a depth of about 6 cm. This is supported by Figures 9, 10 and 11 and the data in Table 2.

The deliverable energy required for effective microwave treatment was approximately 0.53 kW.h m^{-2}. Magnetron efficiency can vary considerably; however if

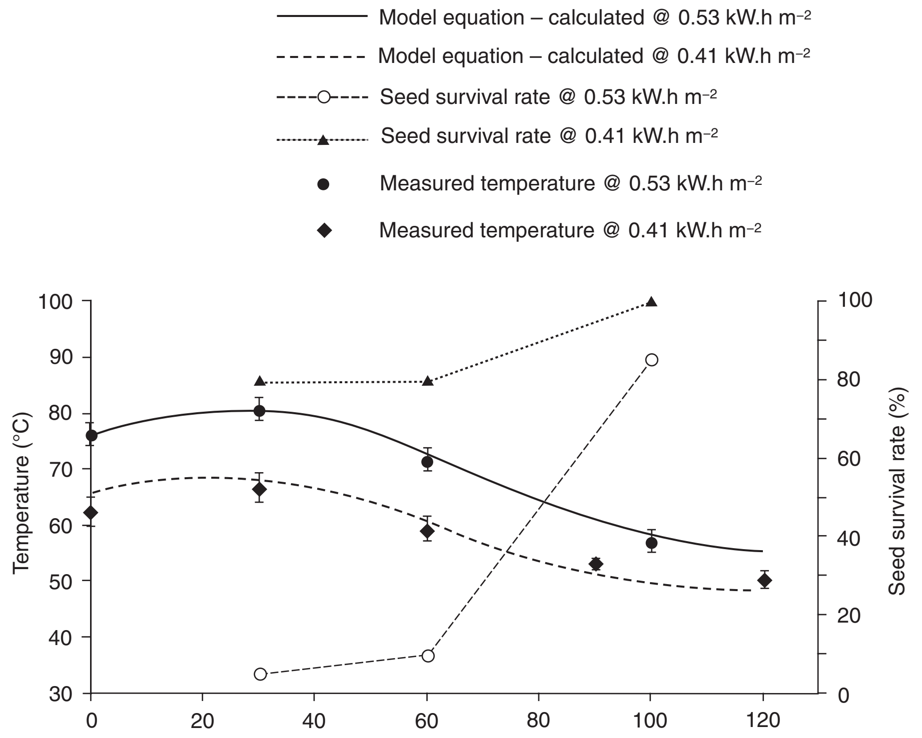

Figure 9. Comparison between theoretical and measured soil temperatures along the centre line of the soil sample and wheat seed survival rates for 0.41 kW-h/m² and 0.53 kW.h m^{-2}. (Error bars on the temperature data represents the standard error for the data points.).

Table 2. Mean wheat seedlings germinated per 10 seeds.

Microwave energy (kW.h m^{-2})	Burial depth 3 cm	Burial depth 6 cm	Burial depth 10 cm
0	10.0^a	10.0^a	10.0^a
0.41	8.0^b	8.0^b	10.0^a
0.53	0.5^c	1.0^c	8.5^b
LSD ($P < 0.05$)		1.35	

Note: Means in Table 2 with different superscripts are significantly different from each other.

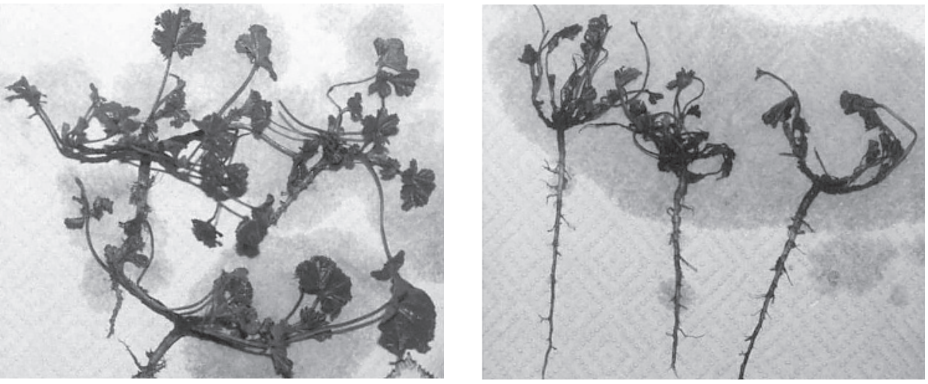

Figure 10. Comparing untreated *Malva parviflora* plants on the left with plants on the right that were treated with approximately 0.41 kW.h m^{-2} of microwave energy (Photograph taken within 10 minutes of microwave treatment).

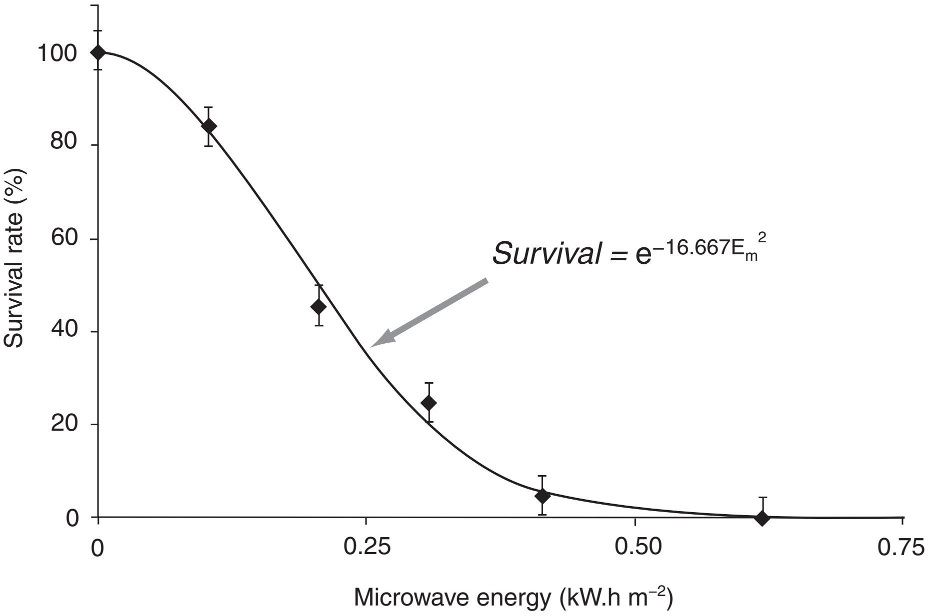

Figure 11. Average survival rate of *Malva parviflora* plants five days after microwave treatment (Error bars represent the LSD ($P < 0.05$) between treatments).

the efficiency is assumed to be about 70%, then the input energy required for effective microwave treatment would be approximately 0.76 kW.h m^{-2}. Assuming an energy tariff of between AU\$0.20 and AU\$0.30 per kW.h (Victoria Electricity 2005), the treatment costs are between AU\$0.15 m^{-2} and AU\$0.23 m^{-2}. If off-peak tariffs of AU\$0.03 per kW.h (Victoria Electricity 2005) can be used then the treatment costs will be approximately AU\$0.023 m^{-2} or AU\$230 ha^{-1}. This compares very favourably with some soil fumigant treatments. According to data presented by Sydorovych *et al.* (2004), the cost of soil fumigation using methyl bromide is US\$939.50 per acre (≈ AU\$2900 per hectare) for materials alone. Commercial development of these systems may be achieved by designing a system which mounts on the back of a tractor and has a generator that is powered by the power-take-off.

Many soil fumigants are being phased out by government regulatory bodies and microwave treatment of specific weeds could be an environmentally beneficial option. Microwave soil pasteurization may also be useful on small sites; in conjunction with precision farming technologies; or where large seed banks, environmental sensitivity or herbicide resistant weeds will result in significant on-going control costs. In the particular case of precision agriculture, it may be possible to treat strips adjacent to crop seed rows, rather than treating the entire paddock. This would reduce the cost per hectare considerably.

The use of sieved soil in the soil temperature and wheat seed treatment experiments is not what would be expected in most natural soil. Further field testing may be required to measure the impact of foreign bodies in the soil on the movement of microwaves through soil under field conditions. Other investigations that will be undertaken shortly include the effect of microwave soil pasteurization on other species of seeds; the effect microwave soil pasteurization on other soil biota; and the effect of increasing microwave power concentration on the treatment efficiency of the system.

Although wheat was the only seed tested in this experiment, literature suggests that other plant seeds can be killed by microwave soil pasteurization (Barker and Craker 1991, Nelson 2003).

Conclusion

Microwave soil pasteurization kills both established weed plants and wheat seeds buried in the soil to a depth of at least 6 cm. The maximum temperature occurs about 3 cm below the soil surface along the centre line of the H-plane of the pyramidal horn antenna.

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Nomenclature.

α	Microwave attenuation factor (m^{-1})
ε	Complex dielectric constant ($= \varepsilon' + j\,\varepsilon''$)
ε'	Dielectric constant of the material
ε''	Dielectric loss factor
μ	Magnetic permeability ($H\ m^{-1}$)
γ	Diffusion coefficient for simultaneous heat and moisture transport ($m^2\ s^{-1}$)
ρ	Material density ($kg\ m^{-3}$)
τ	Microwave transmission coefficient at the interface between the air and the material
a	Dimension of horn antenna aperture in the H-plane (m)
c	Speed of light in free space ($m\ s^{-1}$)
C	Thermal capacity of the material ($J\ kg^{-1}\ °C^{-1}$)
f	Frequency of the microwave energy (Hz)
h	Convective heat transfer coefficient at surface of a material ($W\ m^{-1}\ °C^{-1}$)
j	$\sqrt{-1}$
k	Thermal conductivity of material ($W\ m^{-1}\ °C^{-1}$)
s	Coupling constant for simultaneous heat and moisture movement
t	Time (s)
x	Distance form the centre line of the horn in the H-plane (m)
z	Distance below the surface of the heated material (m)
E_o	Electric field strength ($V\ m^{-1}$)
E_m	Microwave energy ($kW.h\ m^{-2}$)
$\hat{y}$	Unit vector in the vertical direction
ΔT_m	Change in temperature of a sample of water heated by the microwave system (°C)
ΔM_m	Change in mass of a sample of water heated by the microwave system (g)
m_m	Initial mass of a sample of water heated by the microwave system (g)
ΔT_c	Change in temperature of a control sample of water exposed to the same ambient conditions as the microwave system (°C)
Δm_c	Change in mass of a control sample of water exposed to the same ambient conditions as the microwave system (g)
m_c	Initial mass of a control sample of water exposed to the same ambient conditions as the microwave system (g)
t_h	Microwave heating time used in the calibration of the microwave system (s)