Effect of microwave radiation on seed mortality of rubber vine (*Cryptostegia grandiflora* R.Br.), parthenium (*Parthenium hysterophorous* L.) and bellyache bush (*Jatropha gossypiifolia* L.)

F.F. Bebawi[A,D], **A.P. Cooper**[B], **G.I. Brodie**[B], **B.A. Madigan**[A], **J.S. Vitelli**[A,D], **K.J. Worsley**[C] and **K.M. Davis**[A]
[A] Tropical Weeds Research Centre, Queensland Department of Primary Industries and Fisheries, Charters Towers, Queensland 4820, Australia.
[B] Dookie Campus, University of Melbourne, Victoria 3647, Australia.
[C] Parks and Landscaping, Thuringowa City Council, Kirwan, Queensland 4817, Australia.
[D] CRC for Australian Weed Management.

Abstract

A trial was undertaken to evaluate the effect of microwaves on seed mortality of three weed species. Seeds of rubber vine (*Cryptostegia grandiflora* R.Br.), parthenium (*Parthenium hysterophorous* L.) and bellyache bush (*Jatropha gossypiifolia* L.) were buried at six depths (0, 2.5, 5, 10, 20 and 40 cm) in coarse sand maintained at one of two moisture levels, oven dry or wet (field capacity), and then subjected to one of five microwave radiation durations of (0, 2, 4, 8 and 16 min).

Significant interactions between soil moisture level, microwave radiation duration, seed burial depth and species were detected for mortality of seeds of all three species. Maximum seed mortality of rubber vine (88%), parthenium (67%) and bellyache bush (94%) occurred in wet soil irradiated for 16 min. Maximum seed mortality of rubber vine and bellyache bush seeds occurred in seeds buried at 2.5 cm depth whereas that of parthenium occurred in seeds buried at 10 cm depth. Maximum soil temperatures of 114.1 and 87.5°C in dry and wet soil respectively occurred at 2.5 cm depth following 16 min irradiation. Irrespective of the greater soil temperatures recorded in dry soil, irradiating seeds in wet soil generally increased seed mortality 2.9-fold compared with dry soil. Moisture content of wet soil averaged 5.7% compared with 0.1% for dry soil.

Results suggest that microwave radiation has the potential to kill seeds located in the soil seed bank. However, many factors, including weed species susceptibility, determine the effectiveness of microwave radiation on buried seeds. Microwave radiation may be an alternative to conventional methods at rapidly depleting soil seed banks in the field, particularly in relatively wet soils that contain long lived weed seeds.

Keywords: microwave radiation, seed mortality, rubber vine (*Cryptostegia grandiflora*), parthenium (*Parthenium hysterophorous*), bellyache bush (*Jatropha gossypiifolia*), burial depth, soil moisture.

Introduction

Invasive species such as rubber vine (*Cryptostegia grandiflora* R.Br.), parthenium (*Parthenium hysterophorous* L.) and bellyache bush (*Jatropha gossypiifolia* L.) can have a significant impact on animals, humans and the environment (Csurhes 1999, Parsons and Cuthbertson 2001, Bebawi *et al*. 2002). Weeds impact on livestock production by interfering with grazing practices, lowering forage yield and quality, increasing management costs and poisoning livestock (McGavin 1969, Adkins *et al*. 2000, Parsons and Cuthbertson 2001). In addition, weeds may reduce recreational land values and ecosystem structural diversity, and can cause dermatitis and other allergic reactions in humans and domestic animals (McGavin 1969, Chippendale and Panetta 1994, Adkins *et al*. 2000, Parsons and Cuthbertson 2001).

The great majority of weed control tactics, including chemical, mechanical, biological and fire, target the adult stage of plant development (Vitelli 2000, Vitelli and Pitt 2006). However, weed seeds initiate most weed invasions in grazing paddocks and are the primary source of persistent weed infestations in agricultural fields (Cousens and Mortimer 1995). Yet there is relatively little information on the value of managing weed seed banks.

Management of seed banks of rubber vine, parthenium and bellyache bush has been a major target of research in developing effective integrated weed management strategies (Grice 1996, Navie *et al*. 1998, Bebawi and Campbell 2002a). The soil seed bank of bellyache bush and parthenium has been estimated at 380 and 44 600 seeds m^{-2} respectively, with most seeds found in the top 5 cm (Bebawi and Campbell 2002b, Chamberlain and Gittens 2004, Navie *et al*. 2004). No estimates have been made of the size of the soil seed banks of rubber vine (Brown *et al*. 1996). Control techniques that deplete seed banks are critical to weed management, particularly in weed species that have long-lived seeds. The longevity of rubber vine, bellyache bush and parthenium seeds is estimated at two years, four years, and up to six years respectively (Navie *et al*. 1998, Bebawi *et al*. 2003, F. Bebawi – unpublished data, Chamberlain and Gittens 2004).

Interest in non-conventional control techniques such as electricity applied to the soil to control seeds (Fogelberg 2000), soil steaming (Peruzzi *et al*. 2004), lasers to cut weeds (Heisel *et al*. 2002) and the use of microwave radiation (Brodie *et al*. 2007a,b, Moore *et al*. 2006, Sartorato *et al*. 2006) for weed control have recently been gathering momentum. Microwave technology, now widely used in industry for drying purposes, monitoring moisture content and wood disinfestations, has become more readily available and less expensive (Sartorato *et al.* 2006).

Several experiments have been conducted to evaluate the effectiveness of microwave radiation on soil for the control of weed seeds, soil borne pests and pathogens, including fungi, nematodes and some bacteria (Davis *et al*. 1973, Menges and Wayland 1974, Barker and Craker 1991, Nelson 1996, Moore *et al*. 2006, Brodie *et al*. 2007b). Control of weed seed germination is the most promising application of microwave technology for soils (Nelson 1996). The aim of the present study was to evaluate the effect of microwaves on seed mortality of three weed species (rubber vine, parthenium and bellyache bush) buried at different soil depths.

Material and methods

Microwave oven characteristics

A microwave oven (Sanyo Electric Co., 800 W, size 46 × 31 × 28 cm) was modified by Dr. Graham Brodie, School of Resource Management, University of Melbourne, Victoria, for use in this study. A rectangular (86 ×43 mm) wave-guide channelled the microwaves from the oven's 2.4 GHz magnetron to a pyramidal horn antenna outside of the oven (Figure 1). The horn (aperture dimensions of 180 × 90 mm and a length of 180 mm) was attached to the wave-guide via a 90° elbow. The activity of the magnetron was still controlled by the oven's timing circuitry.

Pyramidal horn antennas have been used to project microwave radiation into soil (Sartorato *et al*. 2006). Based on earlier work by Brodie (2006), the temperature distribution in the soil, generated by a pyramidal horn antenna in the H-plane, would be similar to that shown in Figure 2. Depending on the soil's moisture content, textural properties and mineral content, the peak temperature should occur in the top 5 cm of the soil (Brodie 2006), producing temperatures of up to 84°C for a 630 W microwave.

The deliverable power from a microwave system depends on many parameters, including the impedance match between all the components of the wave-guide. As there was no attempt to match the impedance along the wave-guide in this case, the deliverable microwave power was determined using two samples of water (Brodie 2006). One water sample acted as a control while the other was heated by the microwave system. The deliverable power was calculated from the combination of sensible and latent heat observed in the two samples using the following equation:

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

(Equation 1)

where P is the microwave power (W), ΔT_m is the change in temperature (°C) of the microwave treated water sample, Δm_m is the change in mass of the microwave treated sample (g), m_m is the initial mass of the microwave treated sample (g), ΔT_c is the change in temperature (°C) of the control water sample, Δm_c is the change in mass of the control sample (g), m_c is the initial mass of the control sample (g) and t_h is the heating time (sec).

Experimental design

An experiment was undertaken to determine whether microwave radiation has any effect on viability of rubber vine, parthenium and bellyache bush seeds buried at several soil depths in sand at two moisture levels. The experiment was conducted in March 2006 at the Tropical Weeds Research Centre, Queensland Department of Primary Industries and Fisheries, Charters Towers, Queensland.

Parthenium seeds were of the central Queensland biotype (Chamberlain *et al*. 2000, Navie 2006) and both bellyache bush and rubber vine seeds were collected from the vicinity of Charters Towers, North Queensland. Seed weights and seed size (total surface area) of rubber vine, parthenium and bellyache bush were 12.5, 0.38, and 80 mg and 9.5, 1.1 and 22.3 mm^2 respectively (F. Bebawi unpublished data).

The experiment was factorial and involved two soil moisture levels and five microwave radiation durations in a randomized complete block design with four replicates, split for six depths and split again for three weed species. Factor A was assigned to the main plots and included the two soil moisture levels: oven dry soil and field capacity (wet soil). Factor B was assigned to the sub-plots and consisted of the five microwave radiation durations (0, 2, 4, 8 and 16 minutes). The plots were then split for six soil seed burial depths (0, 2.5, 5, 10, 20 and 40 cm) and split again for the seeds of the three weed species (rubber vine, parthenium and bellyache bush).

Twenty randomly selected seeds were obtained by subsampling from bulk samples of unscarified fresh seed (approximately four weeks old) of rubber vine, parthenium and bellyache bush. Rubber vine and bellyache bush seeds were placed in 70% shade rating perforated shade cloth bags (4 × 4 × 0.5 cm; approximately 1.1 × 2.4 mm mesh size) while parthenium seeds were placed in polyester gauze (4 × 4 × 0.5 cm; 0.60 × 0.25 mm mesh size) due to their small size. This ensured that seed retrieval was simplified while maximizing soil/seed contact. Different coloured bags were assigned to seeds of the three different species for identification purposes. Coarse river sand (sieved through a 2 mm wire mesh) was placed in plywood boxes (12 × 20 × 40 cm) that were perforated at the base (8 mm diameter perforation) to allow free drainage of water. Blotting paper was placed at the base of the plywood boxes to prevent soil loss and allow free drainage. One bag of each of the three species was randomly placed at each designated soil depth. The boxes also contained lateral holes at each soil depth that allowed the insertion of thermocouples for the determination of soil temperature. The internal dimensions of each box fitted neatly under the pyramidal horn.

Two soil moisture levels were used. The dry soil was obtained by placing the sieved sand in 12 cm plastic pots in a drying oven (80°C). The pots were weighed daily until the weight remained constant. Soil field capacity of the wet soil treatment was determined after the bags of seed were placed in the plywood boxes and the boxes were topped with dry soil. A known quantity of water was then gradually added from a measuring cylinder onto the dry soil until the water freely drained from the perforated base of the plywood boxes. The excess drained water was collected in a plastic container, measured and subtracted from the total quantity of water used, thus giving the field capacity of the soil. The volume of soil placed in each plywood box was approximately 6600 mL, which required 3.21 ± 0.04 L of water to reach field capacity. Prior to the microwave radiation treatment the soil moisture content of the dry and wet soil was also determined for the six soil depth treatments. Five replicates of soil samples from control boxes were weighed, then oven-dried (80°C for 24 h). Dry weights were then recorded and gravimetric soil moisture (dry basis) calculated. Seeds of the three species may have imbibed water in the wet soil treatments for approximately one hour before microwave irradiation was applied.

Boxes were randomly selected and then placed so the top of the box was 1 cm directly under the horn antenna of the microwave. Microwave radiation was then applied for one of five durations (0, 2, 4, 8 and 16 minutes). Immediately after radiation application, type K steel encased thermocouples hooked to a data logger (Data Electronics Pty Ltd) were placed into predrilled holes at each soil depth to measure duration of resident soil temperature. This was done for one plywood box of each microwave irradiation treatment. The soil temperature in the box exposed to

Figure 1. Prototype microwave oven soil pasteurizer and wooden boxes used.

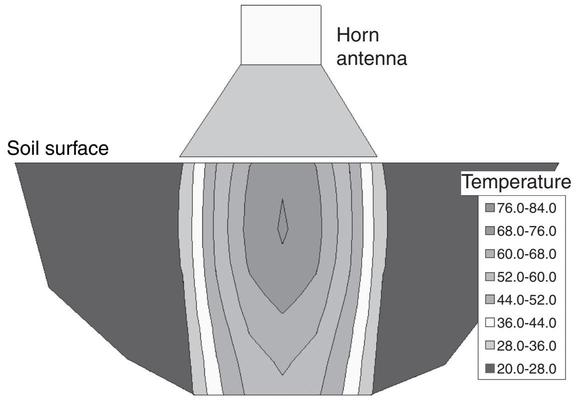

Figure 2. The temperature distribution, in the H (horizontal)-plane of the pyramidal horn, assuming 0.63 kW.h m^{-2} of applied microwave energy.

0 min radiation was assumed to be at ambient temperature. Soil temperature readings were recorded at 0, 5, 10, 15, 30, 60, 90, 120, 150, 180 and 240 min or until ambient laboratory temperature was reached. Four thermocouples recorded the ambient temperature of the laboratory.

After the soil had cooled to ambient temperature, the bags containing seeds were washed under tap water to remove attached sand particles. All seeds were extracted and placed in 9 cm Petri dishes lined with moistened filter paper. Petri dishes were randomly stacked in a germination cabinet set at a 30/20°C 12 h light/dark cycle. The Petri dishes were examined daily for any seed germination and distilled water was added as needed to maintain moisture. Germinated seeds were identified by radicle emergence (approximately equal to the length of the seed) and removed. After two weeks, any seeds that did not germinate were tested for seed viability using incubation in tetrazolium salt (Moore 1985). Seeds were placed in compartmentalized 10 cm square Petri dishes filled with 3 mL of 1% triphenyl tetrazolium chloride per compartment and kept in complete darkness for up to five days at 30°C. Seeds that showed pink embryos when cut longitudinally with a sharp scalpel were considered viable.

Total viable seeds were defined as those that germinated following exposure to microwave radiation plus any ungerminated seeds identified as viable following tetrazolium testing. Seed viability for each experimental unit was expressed as a percentage of the viability of control treatments for each species. Seed mortality percentage was then calculated. For mortality and soil moisture content, analysis of variance was performed on arcsine-transformed data that were later back-transformed. Fisher's protected l.s.d. test was used to identify differences between treatments. Statistical evaluation of species sensitivity to microwave radiation was performed by regression analysis using the regression coefficient 'b' in a Finlay and Wilkinson (1963) style analysis, regressing each species mean on overall species mean. In such an analysis a regression coefficient value of 1.0 indicates average sensitivity whereas values <1.0 indicate low sensitivity and values >1.0 indicate high sensitivity.

Results and discussion

Microwave oven characteristics

Based on equation 1 calculations, the deliverable power of the microwave system used in this study was 74% lower (205.8 ± 10.0 watts) than the nominated microwave power of the unmodified oven (800 W).

Soil temperature and moisture

On average, maximum soil temperatures recorded in dry soil post microwave irradiation were greater by 10% than those in wet soil (Table 1 and 2). In a review and assessment of microwave energy for soil treatment to control pests, Nelson (1996) found that as soil moisture increased, penetration depth into the soil was reduced. In the present study soil temperatures at 16 min irradiation were relatively higher in dry soil at 20 cm (46°C) and 40 cm (42°C) depth compared with 20 cm (32°C) and 40 cm (26°C) depth in wet soil (Table 1 and 2). Maximum soil temperatures of 114.1°C in dry soil and 87.5°C in wet soil were recorded at the 16 min duration and seed burial depth of 2.5 cm (Table 1 and 2). Both dry and wet soil temperatures across all soil depths were above

Table 1. Wet soil temperatures (°C) post-microwave irradiation for 2, 4, 8 and 16 min associated with seed burial depth.

Burial depth (cm)	Irradiation duration (min)	Ambient temp. (°C)	Time after heating (min)									Maximum temp. (°C)
			0	5	10	15	30	60	90	120	150	
0	2	24.7	45.9	39.5	35.5	33.2						45.9
	4	24.7	50.8	42.9	40.1	37.5	33.8	31.0				50.8
	8	24.6	60.7	44.6	43.7	40.9	36.9	33.9	32.2	30.8	29.9	60.7
	16	24.7	66.1	58.8	54.2	50.9	47.4	38.6	34.5	31.6		66.1
2.5	2	24.8	50.4	43.1	38.4	35.2						50.4
	4	24.9	60.4	47.4	43.8	40.7	35.6	31.8				60.4
	8	24.8	76.0	63.0	54.7	47.9	41.7	37.1	34.7	33.0	31.4	76.0
	16	24.8	87.5	70.3	63.6	59.0	55.3	43.2	37.5	34.3		87.5
5	2	24.7	40.7	38.3	35.9	34.1						40.7
	4	24.7	56.6	48.5	44.9	41.9	36.8	32.8				56.6
	8	24.6	73.8	65.5	58.2	51.5	44.9	39.9	37.0	35.0	33.3	73.8
	16	24.7	87.3	71.7	65.5	60.8	57.2	45.1	39.9	36.0		87.3
10	2	24.8	32.2	31.3	30.9	30.5						32.2
	4	24.9	36.9	37.6	37.2	36.5	34.8	32.7				37.6
	8	24.8	50.4	51.1	49.5	46.8	43.2	39.8	37.5	35.8	34.4	51.1
	16	24.8	66.1	60.0	56.9	54.2	52.6	43.9	40.1	36.9		66.1
20	2	24.7	27.5	27.4	27.5	27.5						27.5
	4	24.7	28.1	28.3	28.4	28.5	29.0	29.7				28.5
	8	24.6	29.9	30.2	30.4	30.8	31.5	32.0	32.1	32.2	32.2	32.2
	16	24.7	28.9	29.5	29.8	30.2	30.7	31.2	31.7	31.3		31.7
40	2	24.8	30.1	30.3	30.5	30.5						30.5
	4	24.9	30.8	31.2	31.3	31.2	31.0	30.5				31.3
	8	24.8	29.3	29.4	29.4	29.5	29.7	29.8	29.5	29.6	29.4	29.8
	16	24.8	25.7	25.8	25.9	25.9	26.1	25.6	25.7	25.8		26.1

ambient temperature following irradiation (Table 1 and 2). However, it is interesting to note that raised soil temperatures (dwelling heat/resident heat) recorded in dry soil post microwave irradiation persisted longer before reaching ambient temperature, compared with wet soil (Table 1 and 2). The dry soil temperature (dwelling heat/resident heat) post microwave irradiation at 2.5 cm depth at 16 min irradiation persisted approximately for 4 h before reaching ambient temperature compared with 2.5 h in wet soil (Table 1 and 2). Our results suggest that the microwave generated heat not only penetrated deeper in dry soil but also persisted longer compared with wet soil. Brodie *et al*. (2007a) also found that dry soil retained more heat than wet soil.

Significant interactions (P = 0.05) between soil moisture level and soil depth were detected for soil moisture content (Table 3). Soil moisture content of the dry and wet soil averaged 0.1 ± 0.0% and 5.7 ± 0.4% respectively. Maximum soil moisture content peaked at 40 cm depth in both dry and wet soil and was 2.5 times greater at 40 cm depth in the wet soil than it was at the 0 cm depth (Figure 3).

Seed mortality

Significant interactions (P = 0.05) between soil moisture content, microwave radiation durations, seed burial depths and species were detected for seed mortality (Table 4). Irrespective of soil moisture content, maximum seed mortality of the three species was achieved at 16 min microwave irradiation (Table 5). However, seed mortality of the three species was 2.9-fold greater in wet soil compared with dry soil despite the lower temperatures and shorter duration of residual heat generated in wet soils. Vela-Múzquiz (1984) showed that dry weed seeds were more resilient to microwave treatment than imbibed seeds; however the time allowed for the seeds to imbibe did influence the susceptibility of the seeds (Vela-Múzquiz 1984). Other workers (Davis *et al*. 1973, Menges and Wayland 1974) also found that hydrated weed seeds were more susceptible to

Table 3. Degrees of freedom and mean squares for the variance in soil moisture associated with main effects and interactions.

Source of variance	df	Mean squares	Observed ‘F’	Tabulated ‘F’ (P = 0.05)
Replicates	4	0.8	1.0	6.39
Soil moisture (SM)	1	478.2	597.8*	7.71
Residual	4	0.8	–	–
Soil depth (SD)	5	9.8	19.6*	2.45
SM × SD	5	9.7	19.4*	2.45
Residual	40	0.5	–	–
Total	59	–	–	–

* Statistically significant at P = 0.05.

Table 2. Dry soil temperatures (°C) post-microwave irradiation for 2, 4, 8 and 16 min associated with seed burial depth.

Burial depth (cm)	Irradiation duration (min)	Ambient temp. (°C)	Time after heating (min)											Maximum temp. (°C)
			0	5	10	15	30	60	90	120	150	180	240	
0	2	24.7	40.2	37.9	35.7	35.3	35.0	33.8						40.2
	4	24.7	52.5	45.7	42.6	40.5	38.7	34.2						52.5
	8	24.6	69.8	56.7	53.0	49.8	44.7	38.7	37.3	35.6	35.1	34.4	33.4	69.8
	16	24.7	91.3	78.5	70.5	64.3	60.6	47.1	39.3	34.4	31.9	30.7	30.3	91.3
2.5	2	24.8	41.4	39.6	38.9	38.1	37.5	35.5						41.4
	4	24.9	51.7	46.8	44.2	42.1	40.3	35.2						51.7
	8	24.8	66.7	58.6	56.1	53.8	47.9	41.5	38.9	37.1	36.1	35.2	33.9	66.7
	16	24.8	114.1	103.7	92.4	84.4	78.3	57.8	46.4	41.4	37.2	35.0	33.0	114.1
5	2	24.7	43.4	41.9	41.3	40.3	39.6	37.1						43.4
	4	24.7	43.5	41.9	41.2	40.5	39.8	36.2						43.5
	8	24.6	71.9	65.4	63.2	60.5	54.7	47.1	43.1	40.4	38.7	37.3	35.3	71.9
	16	24.7	108.1	101.8	94.0	88.0	83.1	64.3	51.9	46.0	40.7	37.8	34.8	108.1
10	2	24.8	37.5	36.4	36.3	36.2	36.2	35.4						37.5
	4	24.9	37.2	37.0	36.8	36.7	36.5	35.4						37.2
	8	24.8	53.9	53.8	53.6	53.3	50.5	46.9	44.6	41.8	40.2	38.6	36.4	53.9
	16	24.8	61.9	62.5	62.7	62.3	61.8	56.7	50.5	46.4	42.1	39.3	36.2	61.9
20	2	24.7	34.6	34.5	34.5	34.4	34.4	33.9						34.6
	4	24.7	36.9	35.8	35.3	35.0	34.6	33.4						36.9
	8	24.6	45.2	45.3	45.2	45.0	44.1	42.2	40.6	39.3	38.5	37.4	35.9	45.2
	16	24.7	45.5	45.2	45.0	44.9	44.7	43.1	40.9	39.5	37.5	36.2	34.5	45.5
40	2	24.8	32.5	32.5	32.3	31.0	31.0	31.0						32.5
	4	24.9	33.7	33.2	33.1	33.0	33.0	32.3						33.7
	8	24.8	39.7	38.7	37.1	35.5	32.2	32.3	32.1	32.8	31.1	31.0	30.9	39.7
	16	24.8	42.2	42.2	41.6	40.6	39.2	39.0	38.4	37.6	34.6	32.9	31.1	42.2

microwave radiation than non-hydrated seeds. In the present study, seeds of the three species may have imbibed water in the wet soil treatments for approximately one hour before microwave radiation was applied. Such imbibitions may have made these seeds more susceptible to microwave radiation. Future studies should consider factors such as seed moisture content which may play a role in seed mortality of microwave irradiated seeds.

The soil temperatures at which maximum seed mortality occurred varied between species in wet soil. Maximum seed mortality in wet soil averaged 88 and 93% at 2.5 cm depth at a maximum soil temperature of 87.5°C for rubber vine and bellyache bush and averaged 67% at 10 cm depth at a maximum temperature of 66.1°C for parthenium, compared with the control (Table 1 and 5). The lethal temperature range recorded in wet soil agrees in principle with that of Nelson (1996) and Barker and Craker (1991), who worked on other weeds. Barker and Craker (1991) investigated the use of microwave heating in soils of varying moisture content (10-280 g water kg^{-1} of soil) to kill 'Ogle' oats (*Avena sativa* L.) and an undefined number of weeds. When the soil temperature was raised to 75°C there was a sharp decline in both oat seed and weed seed germination. When the soil temperature was raised above 80°C, seed germination in all species was totally inhibited (Barker and Craker 1991). Their results demonstrated that a seed's susceptibility to microwave treatment is entirely temperature dependent. Recently, Moore *et al*. (2006) studied the effects of 0, 10, 20, 40 and 60 sec microwave irradiation on dry and soaked intact and scarified seeds of gorse (*Ulex europaeus* L.) in Petri dishes. They found that high doses of microwave radiation killed gorse seeds whereas relatively low levels of microwave radiation killed scarified and soaked gorse seed. Apparently, this research has not been extended to seeds occurring in soil. More recently, Brodie *et al*. (2007b) found that both microwave energy and burial depth profoundly reduced the germination potential of wheat seeds (*Triticum aestivum* L.) from 80% to 10%.

Maximum seed mortality in dry soil invariably occurred at 2.5 cm depth for all three species, contrary to what was observed in wet soil (Table 5). Maximum seed mortality in dry soil averaged 65, 33 and 54% for rubber vine, parthenium and bellyache bush respectively and also occurred at 16 min microwave irradiation at a maximum soil temperature of 114.1°C (Table 2 and 5). A comparison of kill rates in wet and dry soil suggests that maximum seed mortality for these species was not purely a thermal effect but a combination of substrate effect (soil moisture effect) and a depth effect, contrary to the conclusions of Nelson (1996) and Barker and Craker (1991) who suggest that microwave treatment is entirely temperature dependent.

Over all soil moisture conditions, the sensitivity of seed mortality to microwave radiation of the three species was bellyache bush > rubber vine > parthenium, with regression coefficients of 1.07, 0.97,

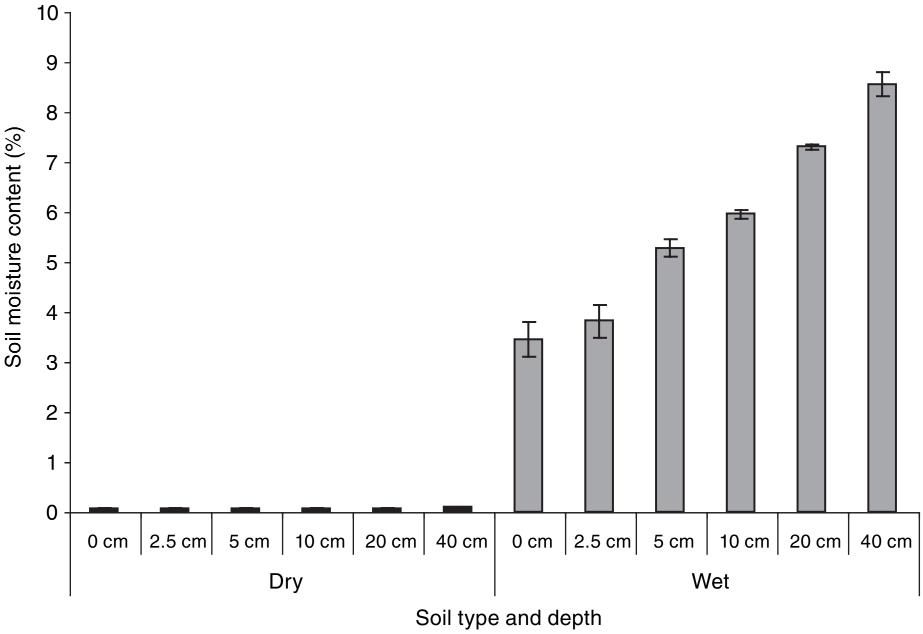

Figure 3. Soil moisture content of dry (permanent wilting point) and wet (field capacity) soil before microwave soil irradiation associated with soil depth. Vertical bars indicate the S.E. of the means.

Table 4. Degrees of freedom and mean squares for the variance in seed mortality of the three species associated with main effects and interactions.

Source of variation	df	Mean squares	Observed 'F'	Tabulated 'F' (P = 0.05)
Replicate stratum	3	95.1	0.31	2.96
Rep.Moisture.Microwave stratum				
Soil moisture (SM)	1	28714.3	94.1*	4.21
Microwave (M)	4	21954.8	149.0*	2.73
SM × M	4	5297.0	35.9*	2.73
Residual	27	147.3	1.2	
Rep.Moisture.Microwave.Depth stratum				
Depth (D)	5	9485.3	76.7*	2.27
SM × D	5	3777.9	30.5*	2.27
M × D	20	2129.6	17.2*	1.64
SM × M × D	20	997.1	8.1*	1.64
Residual	150	123.7	0.7	
Rep.Moisture.Microwave.Depth.Species stratum				
Species (S)	2	57.8	0.4	3.02
SM × S	2	902.1	5.4*	3.02
M × S	8	897.3	5.4*	1.96
D × S	10	133.4	0.8	1.85
SM × M × S	8	401.8	2.4*	1.96
SM × D × S	10	363.0	2.2*	1.85
M × D × S	40	285.2	1.7*	1.42
SM × M × D × S	40	271.2	1.6*	1.42
Residual	360	167.5		
Total	719			

* Statistically significant at P = 0.05.

Table 5. Seed mortality of rubber vine, parthenium and bellyache bush in dry and wet soil at 0 (control), 2, 4, 8 and 16 min irradiation at 0, 2.5, 5, 10, 20 and 40 cm burial depth. Values followed by the same letter(s) are not significantly different at P >0.05.

Irradiation duration (min)	Depth (cm)	Rubber vine Dry	Rubber vine Wet	Parthenium Dry	Parthenium Wet	Bellyache bush Dry	Bellyache bush Wet
		Seed mortality (%)					
Cont.	Cont.	0 t	0 t	0 t	0 t	0 t	0 t
2	0	5.5 opqrst	8.0 opqrst	15.2 mnopqrst	18.7 lmnopqr	13.8 mnopqrst	11.9 nopqrst
	2.5	0 t	6.3 opqrst	0 t	16.2 lmnopqrst	3.1 pqrst	11.3 nopqrst
	5	9.8 nopqrst	25.5 klmno	0.5 st	4.6 opqrst	3.8 pqrst	13.1 mnopqrst
	10	5.5 opqrst	7.1 opqrst	0.5 st	7.5 opqrst	6.3 opqrst	2.5 qrst
	20	3.0 pqrst	3.4 pqrst	2.2 rst	3.7 pqrst	2.5 qrst	1.9 rst
	40	0.9 st	3.4 pqrst	3.5 pqrst	3.3 pqrst	3.8 pqrst	5.6 opqrst
4	0	1.8 rst	17.5 lmnopqrs	4.2 pqrst	37.5 hijk	8.2 opqrst	12.5 nopqrst
	2.5	4.3 pqrst	1.7 rst	1.7 rst	57.1 efg	13.1 mnopqrst	11.3 nopqrst
	5	7.6 opqrst	26.7 klmn	7.2 opqrst	30.0 jklm	8.8 opqrst	7.5 opqrst
	10	4.3 pqrst	4.6 opqrst	8.2 opqrst	7.9 opqrst	8.8 opqrst	0.6 st
	20	0.9 st	1.3 st	4.7 opqrst	1.7 rst	1.3 st	1.9 rst
	40	0.9 st	1.3 st	3.5 pqrst	9.6 nopqrst	1.3 st	2.5 qrst
8	0	8.5 opqrst	38.0 hijk	7.2 opqrst	44.6 ghij	5.6 opqrst	62.5 def
	2.5	10.1 nopqrst	48.8 fghi	2.2 rst	69.6 cde	6.3 opqrst	76.3 bcd
	5	0.9 st	25.5 klmno	3.0 pqrst	64.6 def	12.5 nopqrst	70.0 cde
	10	3.9 pqrst	7.1 opqrst	5.7 opqrst	13.7 mnopqrst	20.0 lmnop	10.6 nopqrst
	20	0 t	4.2 pqrst	0 t	0.8 st	2.5 qrst	0.6 st
	40	1.8 rst	4.6 opqrst	6.4 opqrst	7.5 opqrst	7.5 opqrst	5.0 opqrst
16	0	19.6 lmnopq	55.5 efg	3.5 pqrst	54.6 efgh	9.4 nopqrst	65.0 def
	2.5	64.8 def	88.0 ab	33.2 ijkl	58.3 efg	53.8 efgh	93.8 a
	5	16.8 lmnopqrst	86.7 abc	13.9 mnopqrst	63.3 def	45.0 ghij	62.5 def
	10	13.5 mnopqrst	48.0 fghi	0.5 st	67.1 de	11.9 nopqrst	9.4 nopqrst
	20	5.5 opqrst	21.7 klmnop	6.0 opqrst	12.5 nopqrst	7.5 opqrst	3.1 pqrst
	40	14.3 mnopqrst	14.6 mnopqrst	14.7 mnopqrst	1.7 rst	4.8 opqrst	2.5 qrst

and 0.95 respectively. Differences in seed mass and surface area between the three species investigated in this study may help explain differences in kill rate. Wolf *et al.* (1993) 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. They indicated that the association between the volume of the seed and its susceptibility to microwave treatment may be linked to the larger 'radar cross-section' that bigger seeds present to propagating microwaves, thus their capacity to absorb electromagnetic energy.

Conclusion

Microwave irradiation was more effective in increasing seed mortality in wet compared with dry soil but efficacy varied with microwave radiation duration, soil depth and weed species. Seeds were generally more susceptible to microwave radiation at 16 min duration and at 2.5 cm depths. Bellyache bush was the most susceptible species, possibly due to its larger seed mass and size. The significant interactions in seed mortality observed in this study may be attributed to differences in soil moisture content, microwave radiation durations, soil depth and species. The study indicates that microwave irradiation may have potential, after further development, for use in integrated weed management, particularly in seed bank depletion of selected weeds, with efficacy depending on soil moisture level, species and seed depth and size.

Acknowledgments

The authors wish to thank the Queensland Department of Primary Industries and Fisheries, the University of Melbourne, and the CRC for Australian Weed Management for providing financial support. We also thank Dr Wayne Vogler (NRW), Dr Dane Panetta (NRW) and Ms Cathy Lockett (NRW) for reviewing the manuscript.

References

Adkins, S.W., Navie, S.C., McFadyen, R.E., Tomley, A., Dhileepan, K. and Chamberlain, J. (2000). Parthenium weed: the recent research effort. Proceedings of the 6th Queensland Weed Symposium, pp. 130-5. (Weed Society of Queensland, Brisbane, Queensland).

Barker, A.V. and Craker, L.E. (1991). Inhibition of weed seed germination by microwaves. *Agronomy Journal* 83, 302-5.

Bebawi, F.F. and Campbell, S.D. (2002a). Impact of fire on bellyache bush (*Jatropha gossypiifolia*) plant mortality and seedling recruitment. *Tropical Grasslands* 36, 129-37.

Bebawi, F.F. and Campbell, S.D. (2002b). Effects of fire on germination and viability of bellyache bush (*Jatropha gossypiifolia*). *Australian Journal of Experimental Agriculture* 42, 1063-9.

Bebawi, F.F., Campbell, S.D. and Stanley, T.D. (2002). Priority lists for weed research in the wet- and dry-tropics of north Queensland. *Plant Protection Quarterly* 17, 67-73.

Bebawi, F.F., Campbell, S.D. and Lindsay, A.M. (2003). Effects of burial and age on viability of rubber vine (*Cryptostegia grandiflora*) seeds. *Plant Protection Quarterly* 18, 120-5.

Brodie, G. (2006). Modeling microwave heating in blocks, cylinders and spheres. ASABE Paper No. 063006, St. Joseph, Mich., ASABE.

Brodie, G., Botta, C. and Woodworth, J. (2007a). Preliminary investigation into microwave soil pasteurization using wheat as a test species. *Plant Protection Quarterly* 22, 72-5.

Brodie, G., Hamilton, S. and Woodworth, J. (2007b). An assessment of microwave soil pasteurization for killing seeds and weeds. *Plant Protection Quarterly* 22, 143-9.

Brown, J.R., Grice, A.C., Vitelli, J., Lindsay, A.M., Campbell, S.D., Jeffrey, P.L., Keir, M. and Barker, M. (1996). Managing tropical woodlands to control exotic woody weeds. Final Report, MRC Project. CS209, CSIRO Tropical Agriculture, Aitkenvale, Queensland.

Chamberlain, J. and Gittens, A. (2004). 'Parthenium weed management – challenges, opportunities, and strategies'. (Queensland Department of Natural Resources, Mines and Energy, Brisbane, Queensland).

Chamberlain, J., Dearden, S.W., Leitch, A. and Moran, A. (2000). Parthenium weed – best management practice. (Department of Primary Industries, Brisbane, Queensland).

Chippendale, J.F. and Panetta, F.D. (1994). The cost of parthenium weed to the Queensland cattle industry. *Plant Protection Quarterly* 9, 73-6.

Cousens, R. and Mortimer, M. (1995). 'Dynamics of weed populations', pp. 332. (Cambridge University Press, UK).

Csurhes, S.M. (1999). 'Bellyache bush (*Jatropha gossypiifolia*) in Queensland – pest status review series – land protection.' (Queensland Department of Natural Resources, Brisbane, Queensland).

Davis, F.S., Wayland, J.R. and Merkle, M.G. (1973). Phytotoxicity of a UHF electromagnetic field. *Nature* 241, 291-2.

Finlay, K.W. and Wilkinson, G.N. (1963). The analysis of adaptation in a plant breeding programme. *Australian Journal of Applied Research* 14, 742-54.

Fogelberg, F. (2000). Electroporation – can we control weed seeds by use of electric pulses applied in soil? Proceedings 4th EWRS Workshop on physical weed control, Elspeet, The Netherlands, p. 50. (European Weed Research Society, http://www.ewrs.org/pwc/proceedings.htm).

Grice, A.C. (1996). Seed production, dispersal and germination in *Cryptostegia grandiflora* and *Ziziphus mauritiana*, two invasive shrubs in tropical woodlands of northern Australia. *Australian Journal of Ecology* 21, 324-31.

Heisel, T., Schou, J., Andreasen, C. and Christensen, S. (2002). Using laser to measure stem thickness and cut weed stems. *Weed Research* 42, 242-8.

McGavin, M.D. (1969). Rubber vine (*Cryptostegia grandiflora*) toxicity for ruminants. *Queensland Journal of Agriculture Animal Science* 26, 9-19.

Menges, R.M. and Wayland, J.R. (1974). UHF electromagnetic energy for weed control in vegetables. *Weed Science* 22, 584-90.

Moore, R.P. (1985). 'Handbook on tetrazolium testing'. (International Seed Testing Association, Zurich).

Moore, J., Sandiford, L., Austen, L. and Poulish, G. (2006). Controlling gorse seedbanks. Proceedings of the 15th Australian Weeds Conference – managing weeds in a changing climate,' eds. C. Preston, J.H. Watts and N.D. Crossman, pp. 283-6. (Weed Management Society of South Australia, Adelaide).

Navie, S. (2006). Parthenium weed (*Parthenium hysterophorous* L.) – seed biology of Australian biotypes. www.weeds.uq.edu.au/parthenium.htm

Navie, S.C., Panetta, F.D., McFadyen, R.E. and Adkins, S.W. (1998). Behaviour of buried and surface-sown seeds of *Parthenium hysterophorous*. *Weed Research* 38, 335-41.

Navie, S.C., Panetta, F.D., McFadyen, R.E. and Adkins, S.W. (2004). Germinable soil seedbanks of central Queensland rangelands invaded by the exotic weed *Parthenium hysterophorous* L. *Weed Biology and Management* 4, 154-67.

Nelson, S.O. (1996). A review and assessment of microwave energy for soil treatment to control pests. *Transactions of the American Society of Agricultural Engineers* 39, 281-9.

Parsons, W.T. and Cuthbertson, E.G. (2001). 'Noxious weeds of Australia'. (CSIRO Publishing, Collingwood, Victoria).

Peruzzi, A., Borelli, M., Mazzoncini, M., Raffaelli, M., Ginanni, M. and Barberi, P. (2004). Weed seeds control by steam and substances in exothermic reaction. Proceedings 6th EWRS Workshop on physical and cultural weed control, Lillehammer, Norway, pp. 155-65. (European Weed Research Society, http://www.ewrs.org/pwc/proceedings.htm).

Sartorato, I., Zanin, G., Baldoin, C. and De Zanche, C. (2006). Observations on the potential of microwaves for weed control. *Weed Research* 46, 1-9.

Vela-Múzquiz, R. (1984). Control of field weeds by microwave radiation. *Acta Horticulturae (ISHS)* 152, 201-8.

Vitelli, J.S. (2000). Options for effective weed management. *Tropical Grasslands* 34, 280-94.

Vitelli, J.S. and Pitt, J.L. (2006). Assessment of current weed control methods relevant to the management of the biodiversity of Australian rangelands. *The Rangeland Journal* 28, 37-46.

Wolf, W.W., Vaughn, C. R., Harris, R. and Loper, G.M. (1993). Insect radar cross-section for aerial density measurement and target classification. *Transactions of the American Society of Agricultural Engineers* 36, 949-54.