6 A Brief History of Microwave Weed Control Research

6.1 Introduction

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19th century (Ark & Parry, 1940), while interest in the effect of high frequency waves on plant material began in the 1920s (Ark & Parry, 1940). Many of the earlier experiments on plant material focused on the effect of radio frequencies (RFs) on seeds (Ark & Parry, 1940). In many cases, short exposure resulted in increased germination and vigour of the emerging seedlings (Nelson, Ballard, Stetson, & Buchwald, 1976; Nelson & Stetson, 1985; Tran, 1979); however, long exposure usually resulted in seed death (Ark & Parry, 1940; Bebawi et al., 2007; Brodie et al., 2009).

Davis et al. (1971; 1973) were among the first to study the lethal effect of microwave heating on seeds. They developed a set of prototypes, called “Zappers”, which they tested in the field for their Company and federal and state researchers. Their final prototype, designated Zapper III, underwent tests to provide the data necessary for the construction of the first semi-commercial prototype. In October 1971, the Company purchased all proprietary rights to a discovery made at Texas A&M University concerning the toxic effects of microwaves on plants Davis et al. (1971; 1973).

6.2 Pioneering Work

The discovery was the result of the efforts by Drs Merkle, Wayland, and Davis, who were originally professors in the Soil and Crop Sciences, Physics, and Range Science Departments, respectively, of Texas A&M University. The Company’s first field prototype was named Zapper I. Zapper I was used in a cooperative testing program with US federal and state agricultural research agencies and with growers in Texas, California, Florida, New Mexico, Washington, Idaho, Nebraska, Arkansas, North Carolina, Georgia and Michigan. The Zapper I test program proved that microwaves could safely treat soil and be an effective herbicide. In addition, microwaves also proved to be toxic to nematodes, certain fungi, and to soil-borne insect pests. Further, the phenomenon of growth stimulation was first observed in plants which germinated in treated soil (Davis, 1974).

Following the initial Zapper I program, the Company built a second prototype, the Zapper III (Figure 6.1), which was used to determine the cost of Zapper treatments required to destroy various types of weed seeds under different soil conditions. The Zapper III program also experimented with different equipment configurations to determine the most efficient system design for commercial use (Davis, 1974). Both systems operated at a frequency of 2.45 GHz.
A meta-study of published data (Menges & Wayland, 1974; Wayland, Merkle, Davis, Menges, & Robinson, 1975) reveals that microwave treatment of emerged weed plants, of eleven species, can be described by equations of the form (Figure 6.2):

\[ S = a \cdot \text{erfc}[b(\Psi - c)] \] (6.1)

When the weed species are separated into categories of broad leafed and grasses, it appears that grasses require slightly more microwave energy to achieve treatment efficacy, compared with broad leafed plants (Figure 6.3).

It also became apparent that microwave treatment of the soil could inactivate weed seeds at various depths (Menges & Wayland, 1974; Wayland et al., 1975). The efficacy of the treatment depended on the soil type, the seed burial depth, the microwave treatment energy density and whether the soil had been irrigated prior to treatment (Figure 6.4). Irrigation prior to treatment resulted in shallower microwave heating; therefore, seed which were buried deeper in the soil profile were less affected by the microwave heating (Menges & Wayland, 1974; Wayland et al., 1975). The consensus from this data is that 300 – 500 J cm\(^{-2}\) of microwave energy density at the soil surface, can control weeds and their seeds in the top 4 – 6 cm of soil. This is equivalent to between 30 and 50 GJ ha\(^{-1}\) of microwave energy, making microwave treatment a little more energy expensive than steam treatment (see Chapter 4).

It is unclear, from the available literature, why this promising technology did not become more widely available as a commercial system. It is apparent that the ideas generated by this early work interest persisted into the 1990’s, because Nelson (1996) used a theoretical argument to dismiss microwave soil treatment as a viable prospect for weed management. The high energy input required to achieve good weed and seed control was certainly a strong argument against the adoption of this technology.
Figure 6.2: Response of 11 species of weed to microwave energy (Sources: Menges & Wayland, 1974; Wayland et al., 1975).

Figure 6.3: Response of grasses (blue) and broad-leafed weeds (red) to microwave energy (Sources: Menges & Wayland, 1974; Wayland et al., 1975).
Despite this, then there has been ongoing research interest in microwave soil treatment and weed management. Table 6.1 lists a subset of the papers that have been published on these and related topics. The consensus from these studies is that: microwave treatment can kill plants; moderate microwave treatment can break dormancy in some hard-seeded species; and high energy microwave treatment can kill seeds in the soil.

**Figure 6.4:** Response weed seeds in the soil to microwave energy, as a function of applied energy density, burial depth and irrigation status (Sources: Menges & Wayland, 1974; Wayland et al., 1975).
Table 6.1: Literature addressing the application of microwave technology to seed and weed treatment.

| Paper Title                                                                 | Reference                                                                 |
|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Douglas-fir tree seed germination enhancement using microwave energy       | (Jolly & Tate, 1971)                                                      |
| Microwave processing of tree seeds                                       | (Kashyap & Lewis, 1974)                                                  |
| Increasing legume seed-germination by VHF and microwave dielectric heating | (Nelson et al., 1976)                                                    |
| Effects of low-level microwave radiation on germination and growth rate in corn seeds | (Bigu-Del-Blanco, Bristow, & Romero-Sierra, 1977)                        |
| Effects of Microwave Energy on the Strophiole, Seed Coat and Germination of Acacia Seeds | (Tran, 1979)                                                             |
| The effect of microwave-energy on germination and dormancy of wild oat seeds | (Lal & Reed, 1980)                                                       |
| The Effect of Externally Applied Electrostatic Fields, Microwave Radiation and Electric Currents on Plants and Other Organisms, with Special Reference to Weed Control | (Diprose, Benson, & Willis, 1984)                                         |
| Control of field weeds by microwave radiation                             | (Vela-Múzquiz, 1984)                                                     |
| Effect of microwave irradiation on germination and initial growth of mustard seeds | (Rao, Chakravarthy, & Panda, 1989)                                       |
| Inhibition of weed seed germination by microwaves                         | (Barker & Craker, 1991)                                                  |
| A possibility of correction of vital processes in plant cell with microwave radiation | (Petrov, Moisheva, & Morozova, 1991)                                     |
| Microwave irradiation of seeds and selected fungal spores                 | (Cavalcante & Muchovej, 1993)                                            |
| Response surface models to describe the effects and phytotoxic thresholds of microwave treatments on barley seed germination and vigour | (Stephenson, Kushalappa, Raghavan, & Mather, 1996)                        |
| Energy Efficient Soil Disinfestation by Microwaves                         | (Mavrogianopoulos, Frangoudakis, & Pandelakis, 2000)                     |
| Microwave effects on germination and growth of radish \(Raphanus sativus L.\) seedlings | (Scialabba & Tamburello, 2002)                                           |
| Report on the Development of Microwave System for Sterilisation of Weed Seeds: Stage I – Feasibility | (Advanced Manufacturing Technologies, 2003)                              |
| Design, construction and preliminary tests of a microwave prototype for weed control | (Zanche, Amista, Baldoin, Beria, & Giubbolini, 2003)                     |
| Thermal effects of microwave energy in agricultural soil radiation         | (Velazquez-Marti & Gracia-Lopez, 2004)                                   |
| Influence of low-frequency and microwave electromagnetic fields on seeds   | (Kalinin, Boshkova, Panchenko, & Kolomiichuk, 2005)                      |
| An improved microwave weed killer                                          | (Vidmar, 2005)                                                           |
The long-standing interest in applying microwave technology to weed and soil treatment has resulted in many attempts to capture the intellectual property through various patents (Tab. 6.2). It is evident that some of these are the same invention; however, they have been patented in different parts of the world. Patents have included two main methods of soil treatment: in-situ treatment systems that do not disturb the soil (Clark & Kissell, 2003; Haller, 2002; Joines, 2009); and tunnel treatment systems which use some mechanical method to remove the top soil, pass it through a microwave treatment chamber or tunnel and then return the soil to its original position after treatment (Wall, 2009). The in-situ treatment systems use various antenna systems or multi-mode cavities (somewhat like half of a microwave oven that is open to the soil) to apply the microwave energy (For example: Clark & Kissell, 2003; Haller, 2002). Several of these patents claim to control other crop pests as well as weeds and their seeds in the soil (Grigorov, 2003; Haller, 2002; Joines, 2009). There are also several companies that have developed microwave based weed management technologies, but have chosen not to apply for a patent to protect their inventions. There will be others that the authors are not aware of. Some of these
companies have developed mature technologies; however most have systems that are in the developmental stage.

6.4 Conclusion

It is clear from the number of papers, patents and other evidence that the basic principle of microwave weed management is of considerable interest and is well understood. Several system designs have been developed and protected; however, there is still scope to develop novel microwave applicator designs that better couple the microwave energy into the soil and weed plants. There is also opportunity to develop and implement better energy control systems that could reduce the energy required to achieve effective soil and weed treatment and automate the weed management process.

On the more cautionary side, in a theoretical argument based on the dielectric and physical properties of seeds and soils, Nelson (1996) demonstrated that using microwaves to selectively heat seeds in the soil “cannot be expected.” He stated that seed susceptibility to damage from microwave treatment is a purely thermal effect, resulting from soil heating and thermal conduction into the seeds. He concluded that microwave weed management was not viable; however, his arguments ignored any effects of herbicide resistance on crop yields.

Table 6.2: Patents which address or are associated with microwave weed and soil treatment.

| Publication Number | Priority Date | Filing Date | Date of Publication | Title |
|--------------------|---------------|-------------|---------------------|-------|
| EP 0413847 A1      | 17/10/1986    | 24/08/1989  | 27/02/1991          | Microwave/steam sterilizer. |
| US4861956 A        | 17/10/1986    | 29/08/1989  |                     |       |
| WO1991002548 A1    | 24/08/1989    | 7/03/1991   |                     |       |
| US5287818 A        | 11/05/1993    | 11/05/1993  | 22/02/1994          | Method for killing soil pathogens with microwave energy |
| US5141059 A        | 27/02/1991    | 27/02/1991  | 25/08/1992          | Method and apparatus for controlling agricultural pests in soil |
| CA2299301 A1       | 16/08/1996    | 15/08/1996  | 26/02/1998          | Method and device for weed control |
| DE69625089 D1      | 16/08/1996    | 9/01/2003   |                     |       |
| DE69625089 T2      | 16/08/1996    | 4/09/2003   |                     |       |
| EP0928134 A1       | 16/08/1996    | 14/07/1999  |                     |       |
| EP0928134 B1       | 16/08/1996    | 27/11/2002  |                     |       |
| US6237278 B1       | 16/08/1996    | 29/05/2001  |                     |       |
| WO1998/007314 A1   | 20/02/1995    | 16/08/1996  | 26/02/1998          |       |
Table 6.2: Patents which address or are associated with microwave weed and soil treatment.

| Publication Number | Priority Date | Filing Date | Date of Publication | Title |
|--------------------|---------------|-------------|---------------------|-------|
| DE 19850195 A1     | 22/10/1998    | 22/10/1999 | 4/05/2000           | Method and device for killing wood-destroying animals |
| DE 59915075 D1     | 22/10/1998    | 22/10/1999 | 1/02/2007           | Procede et dispositif pour exterminer des parasites animaux dans le bois |
| EP 1158853 A1      | 22/10/1999    | 5/12/2001  |                     | Verfahren und vorrichtung zum abtöten von tierischen schädlingen in holz |
| WO2000/024247 A1   | 22/10/1999    | 4/05/2000  |                     | Microwave energy applicator |
| CA2372471A1        | 4/04/2000     | 3/04/2001  | 18/10/2001          | Method and system for exterminating pests, weeds and pathogens |
| CA2372471C         | 3/04/2001     | 11/12/2007 |                     | Procede et systeme d'extermination d'animaux nuisibles, de plantes nuisibles et d'agents pathogenes |
| DE60014392D1       | 3/04/2001     | 1/12/2005  |                     | Verfahren und system zur vernichtung von ungeziefer, unkraut und pathogenen |
| DE60014392T2       | 3/04/2001     | 27/07/2006 |                     | Microwave disinestation system for biological pests |
| EP1272032A1        | 3/04/2001     | 8/01/2003  |                     | Système de désinfection à micro-ondes pour lutte biologique |
| EP1272032B1        | 3/04/2001     | 26/10/2005 |                     | Mikrowellendes Infektionsystem für biologische Schädlingsbekämpfung |
| US20030037582A1    | 3/04/2001     | 27/02/2003 |                     | Method and apparatus [device] for controlling pests found in the ground, in particular termites |
| US6647661B2        | 3/04/2001     | 18/11/2003 |                     | Procede et dispositif pour lutter contre les animaux nuisibles vivant dans le sol, en particulier les termites |
| WO2001/076362 A1   | 3/04/2001     | 18/10/2001 |                     | Verfahren und Vorrichtung zur Bekämpfung von im Erdboden hausenden Schädlingen, insbesondere Termiten |
| US 6401637 B1      | 8/01/2001     | 15/06/2001 | 11/06/2002          | Microwave disinestation system for biological pests |
| US 20020090268     | 15/06/2001    | 11/07/2002 |                     | Système de désinfection à micro-ondes pour lutte biologique |
| EP 1224863 A2      | 15/11/2001    | 15/11/2001 | 24/07/2002          | Microwave disinestation system for biological pests |
| EP 1224863 A3      | 15/11/2001    | 21/09/2005 |                     | Système de désinfection à micro-ondes pour lutte biologique |
| US20040009092A1    | 15/07/2002    | 15/01/2004 |                     | Microwave disinestation system for biological pests |
| CA 2483749 A1      | 28/03/2002    | 27/03/2003 | 9/10/2003           | Method and apparatus [device] for controlling pests found in the ground, in particular termites |
| CN 1642414 A       | 27/03/2003    | 20/07/2005 |                     | Procede et dispositif pour lutter contre les animaux nuisibles vivant dans le sol, en particulier les termites |
| DE 10213983 C1     | 28/03/2002    | 13/11/2003 |                     | Verfahren und Vorrichtung zur Bekämpfung von im Erdboden hausenden Schädlingen, insbesondere Termiten |
| EP 1487263 A1      | 27/03/2003    | 22/12/2004 |                     | Microwave disinestation system for biological pests |
| US 20050039379 A1  | 27/09/2004    | 24/02/2005 |                     | Système de désinfection à micro-ondes pour lutte biologique |
| WO2003/081999 A1   | 27/03/2003    | 9/10/2003  |                     | Microwave disinestation system for biological pests |
### Table 6.2: Patents which address or are associated with microwave weed and soil treatment.

| Publication Number | Priority Date | Filing Date | Date of Publication | Title |
|--------------------|---------------|-------------|---------------------|-------|
| US20030215354 A1   | 17/05/2002    | 16/09/2002  | 20/11/2003          | Systems and methods for in situ soil sterilization, insect extermination and weed killing. |
| WO2003/099004 A2   | 4/10/2002     | 4/12/2003   |                     |       |
| WO2003/099004 A3   | 4/10/2002     | 17/06/2004  |                     |       |
| US20060186115A1    | 11/01/2005    | 11/01/2006  | 24/08/2006          | Microwave system and method for controlling the sterilization and infestation of crop soils. |
| US20090232602A1    | 22/09/2009    | 17/09/2009  |                     |       |
| US7601936B2        |               | 13/10/2009  |                     |       |
| US201220091123A1   |               | 19/04/2012  |                     |       |
| US20080149625A1    | 25/10/2006    | 25/10/2006  | 26/06/2008          | Device for soil sterilization, insect extermination, and weed killing using microwave energy. |
| US7560673B2        |               | 25/10/2006  | 14/07/2009          |       |
| WO2008057215A2     | 24/10/2007    | 15/05/2008  |                     | A device and method for soil sterilization, insect extermination, and weed killing using microwave energy. |
| WO2008057215A3     | 24/10/2007    | 24/07/2008  |                     |       |
| US 20130212928A1   | 17/02/2012    | 13/02/2013  | 22/08/2013          | Apparatus for using microwave energy for insect and pest control and methods thereof. |
| US 20150101239A1   | 18/12/2014    | 16/04/2015  |                     |       |
| US 8943744 B2      | 13/02/2013    | 3/02/2015   |                     |       |
| WO2013/123089 A1   | 13/02/2013    | 22/08/2013  |                     |       |

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