Electromagnetic Radiation for Plant Protection

Jacques LEWANDOWSKI

1 Introduction

This chapter describes techniques of plant protection using electromagnetic (EM) waves. EM protection depends on the nature of the interaction between EM waves and the target plants, soil, devastating insects and diseases. The examination of each factor affecting this interaction is thus essential since it will set up the limits and possibilities of applications for these EM techniques. First, we will describe the main characteristics of EM waves; then we will analyse their interaction with plants, the soil and the insects.

2 Some Notions about the EM Wave-Matter Interaction

2.1 The EM Spectrum

All EM waves have the same structure (Fig. 1): they consist of an electric field E and a magnetic field H vibrating in phase and perpendicular to the direction of propagation of the wave (Bonn and Rochon, 1992). EM waves differ by their frequency (f) or their wavelength (λ) which are connected by the following expression:

$$\lambda = c / f, \quad (1)$$

where c - 3 x 10^8 ms^{-1} is the speed of EM waves in vacuum. The EM spectrum is divided in eight spectral bands (Bonn and Rochon, 1992) illustrated in Fig. 2. Starting with the longer wavelengths, one finds audio waves, radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma rays. The wavelength range is very wide, extending from the very long audio waves (some thousands of km and more) to the very short gamma rays (10^{-12} m).

There is no single source able to emit the entire EM spectrum. Specific sources are available for each of the eight spectral bands. Audio and radio waves are obtained with a ferro or piezoelectric transducer. Microwaves are emitted by a magnetron or a klys-

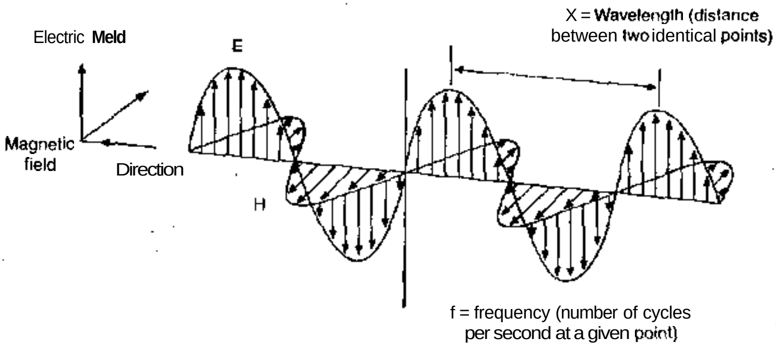


Fig. 1. The electromagnetic wave (After Bonn and Rochon 1992).

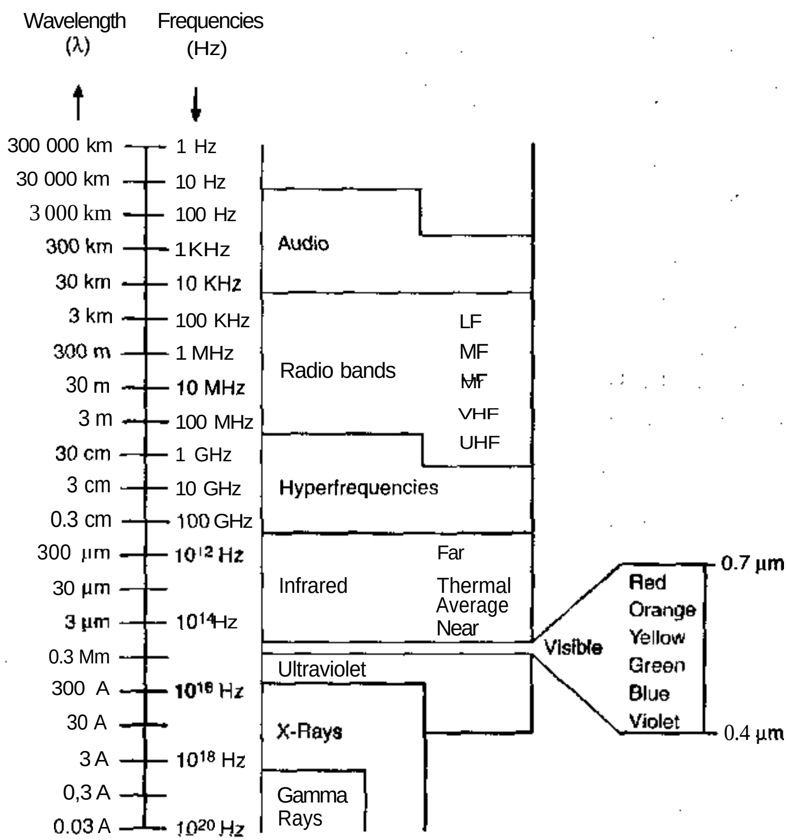


Fig. 2. The electromagnetic spectrum. (After Bonn and Rochon 1992). The eight spectral bunds are illustrated. Note the great range in terms of frequency and wavelength.

tron. IR is emitted by an incandescent object. An electric light bulb emits visible radiation. UV is radiated with deuterium or mercury vapour lamps. X-rays are emitted when electrons collide on a metal plate. Gamma rays are emitted by radioactive elements. From a purely practical aspect, one can recognise that small wavelengths are in general more difficult to obtain, require complex hardware and are often more expensive. Therefore, gamma ray or X-ray equipment generally requires a higher investment than IR or radio wave experiments. This financial aspect will have to be considered when selecting an EM wave.

Each spectral band, from the audio waves to the gamma rays, may have a potential application in plant protection. Several modes of action can take place: some waves interact directly with the plant; others affect the insects selectively; others penetrate deeply into the ground and heat it. The type of interaction between the EM wave and the matter essentially relies on two factors: (1) the frequency of the wave and (2) the penetration depth of the wave in the medium. We will now describe the importance of these two factors in order to better determine the potential of EM waves in plant protection.

2.2 The Frequency or the Role of the Photon

An EM wave carries energy, but this energy is not emitted continuously. It is actually emitted in the form of small indivisible quantities (called photons) individually transporting an energy E_{ph} proportional to the frequency (Hecht 1987)

$$E_{ph} = h\,f = h\,c\,/\,\lambda\,, \qquad (2)$$

where $h = 0.66 \times 10^{-33}$ Js is Planck's constant. The concept of photons is fundamental because EM waves interact individually with matter through their photons. Because Planck's constant is very small, the energy of the photon is significant only for very small wavelengths. In other words, an EM wave with a small wavelength has a greater potential effect on matter.

For extremely small wavelengths — such as gamma rays, X-rays, UV and sometimes visible light — a photon has enough energy to extract an electron from the atom. In that case, the atom is ionised and the radiation is said to be ionising. If the extracted electron belongs to a molecule, ionisation will destroy a chemical bond. If the electron is part of a gene of a biological cell, the genetic code may be modified. One can thus predict that ionising radiations — small wavelengths like gamma rays, X-rays or UV — will interact deeply within the atomic or electronic structure of the matter components and, consequently, on the chemical or genetic integrity of the living organisms.

Photons of EM with longer wavelengths, i.e. visible light, IR, microwaves, radio and audio waves, do not have enough energy to extract an electron. These radiations are therefore known as non-ionising. In this case, the EM wave will nevertheless ac[illegible] the matter through its electric field oscillating at the frequency of EM wave. T[illegible] ged particles inside the matter will start to vibrate at the same frequency [illegible] be extracted from their chemical bonds. The resulting internal friction leads to a release of heat directly inside the matter. The matter is heated at the exact place where the EM is absorbed. Thus, non-ionising EM waves — long wavelengths like visible light, IR, microwaves, radio and audio waves — will produce vibrations of the matter components and heat the medium.

The EM wave frequency is therefore a fundamental characteristic which determines how the EM wave interacts with the medium, be it a plant, an insect or the ground. These interactions may range from generation of heat to breaking chemical links and possibly to atomic or genetic changes.

The energy delivered by the EM wave plays a different role since it determines the number of existing photons. This energy is proportional to the number of interactions involved: a larger energy level increases the number of interactions and allows a greater physical modification of the medium. On the other hand, if the EM wave frequency has no effect on a particular medium, increasing its energy will have no effect.

2.3 Penetration of EM Waves in Matter

For an EM wave to interact, it must penetrate and propagate inside the medium. The power P of an EM wave is defined as the energy carried per unit of time. When an EM wave of power P is incident on a medium, i.e. a plant, an insect or the soil, a fraction P_r is reflected at the interface and the remaining power P_t is transmitted inside the medium. The incident power can be expressed as follows:

$$P_r + P_t = P \tag{3}$$

Only the power P_t transmitted through the interface will interact with the medium since the reflected wave does not penetrate inside it. Introducing the reflectance $R = P_r / P$ and transmittance $T = P_t / P$, the preceding equation becomes

$$R + T = 1 \tag{4}$$

which is satisfied for any wavelength of the incident radiation. The coefficients R and T depend on the wavelength. Their variation with wavelength defines the spectral signature of the material. Figure 3 illustrates the spectral reflectance $R(\lambda)$ typical of lemon tree leaf.

The transmitted EM wave is gradually absorbed by the medium as soon as it penetrates. After a distance x of propagation, the remaining power $P_t(x)$ decreases according to the exponential law (Hecht 1989):

$$P_t(x) = P_t \exp(-\alpha x) \tag{5}$$

where α is the absorption coefficient of the medium expressed in m^{-1}. A more convenient measurement of the EM wave absorption in the medium is the penetration depth D defined by

$$D = 1 / \alpha. \tag{6}$$

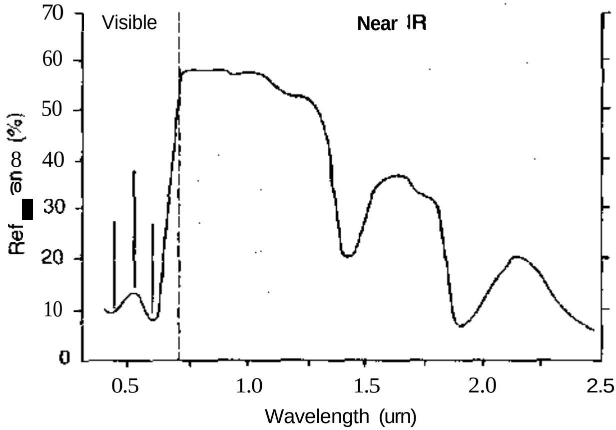


Fig. 3. Reflectance spectrum of a leaf of lemon tree. (After Gausman **1985) The higher** reflectance **of green** (0.55 μm) **explains the** colour **of the leaf. Leaves** show a very **high reflectance in near IR.**

This penetration depth plays a significant role for EM techniques since it indicates the distance along which the EM wave/matter interaction takes place. If D is very small, the interaction will take place close to the surface or within the surface layers. If D is large, the EM wave will penetrate deeply and the interaction will not be efficient because of the extremely weak absorption. An EM wave can thus penetrate more or less deeply in the medium. The penetration depth depends on the dielectric properties of material and the frequency of the EM wave.

3 Use of Electromagnetic Waves

The interactions between EM energy and biological organisms are a very complex subject due to the great diversity of living organisms and the physical phenomena at play. Each living organism reacts differently to radiation. EM wave/matter interaction depends on the photon energy, ranging from atomic changes to the break of chemical or genetic links and possibly to the generation of heat. EM waves can also penetrate more or less deeply in the medium, going from surface interactions to very deep penetrations. An advantage of EM techniques over traditional chemical processes is that, in theory, they do not leave any toxic residue.

3.1 Combination of the Various Factors

For an EM wave to be effective in plant protection, several factors must be satisfied simultaneously: (1) the EM wave must eradicate the target without damaging the sur-

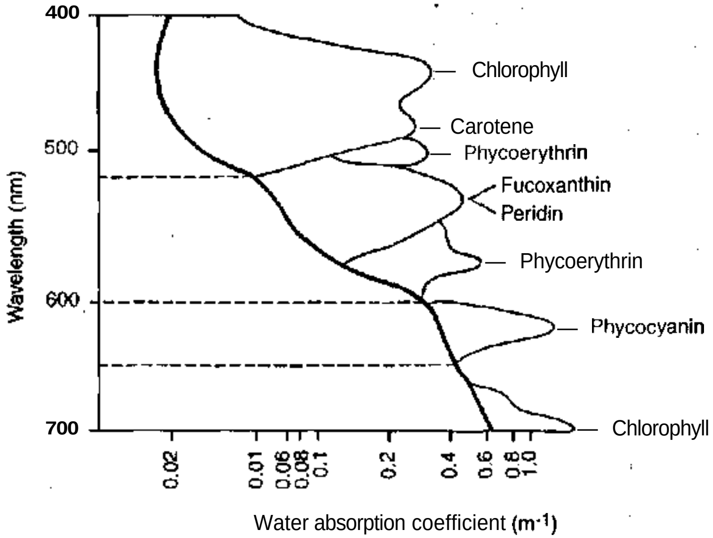


Fig. 4. Absorption coefficients of water and certain pigments associated with biological activity. (After Bonn and Rochon 1992) Minimum absorption of water is around 0.45 mm where the penetration depth is D = 1 / 0.02 = 50 m. Chlorophyll shows absorption peaks at 0.42 and 0.70 µm.

rounding medium, (2) it must penetrate the ground or the plant to reach the target, (3) the radiation source must be reasonable in terms of cost and ease of use, and (4) the energy should not have harmful side effects.

X-rays penetrate deeply in plants and are absorbed by insects. UV rays and IR are absorbed at the surface and microwaves have very different penetration depths and that depends on the nature of the material and its moisture content. For visible light, the absorption coefficients for the principal plant biological components and for water are illustrated in Fig. 4 (Bonn and Rochon 1992).

Figure 5 summarises the properties of EM waves in relation to the media found in plant protection, i.e. soils, plants and insects. The mode of interaction (ionising or non- ionising), the penetration depths in the medium (ground, plant or insect) and the facility of use of the radiation source are illustrated for each of the eight spectral bands. Figure 5 shows that radio waves penetrate a substrate very deeply and are thus practically ineffective in plant protection. In contrast, X-rays and gamma rays may kill insects inside a substrate like food, while UV rays will kill them only on the surface. On each side of visible light, the waves which offer the best compromise for penetration are X-rays and microwaves. The first acts at the chemical bond level, and the second overheats the medium.

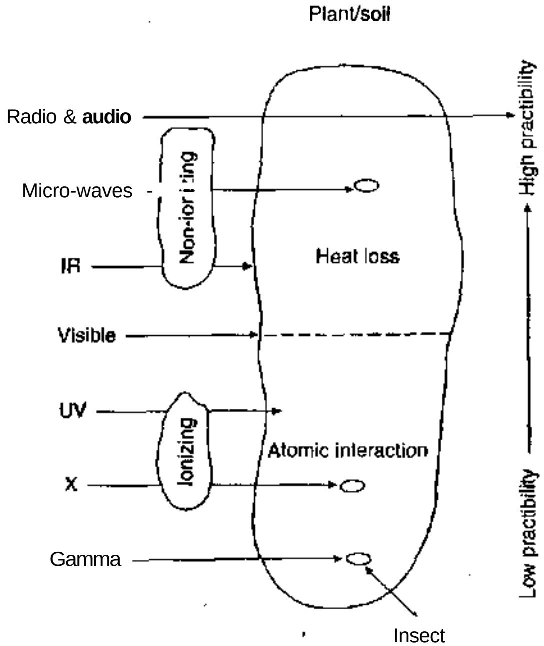


Fig. S. Combination of the various factors for EM techniques in plant protection. EM waves are illustrated by their ionising or non-ionising behaviour, their penetration depth inside the plant or the ground, and their ease of use (not very practical to very practical). Notice that the extreme spectral bands (gamma rays, X-rays and UV, microwaves and radio waves) penetrate well inside the plant, whereas the intermediate bands (visible and 1R) are absorbed at the surface. Ionising radiations interact at the atomic level, whereas non-ionising radiation tend to heat the medium. On a practical level, short wavelengths require expensive equipment that is difficult to set up.

3.2 The Terrestrial EM Environment

Plants, insects and soil are subjected daily to illumination by the sun. It is therefore important to be aware of the spectral characteristics of sun rays incident on Earth (Fig. 6). Solar radiation has the following properties:

- 44% of the emitted energy is in the visible band (0.4 to 0.8 µm). Visible photons have sufficient energy to initiate the phenomenon of photosynthesis, activate the retinal receivers or affect photographic films through the photochemical effect.
- UV-B rays (0.28 to 0.32 µm) are partially absorbed by the ozone layer. Many researchers simulated the impact of a ozone layer reduction on vegetation and agriculture (Flint et al. 1996) because UV-B rays have a major influence on the biochemical behaviour of plants.
- Solar radiation in the microwave band (I mm to 10 cm) is negligible.

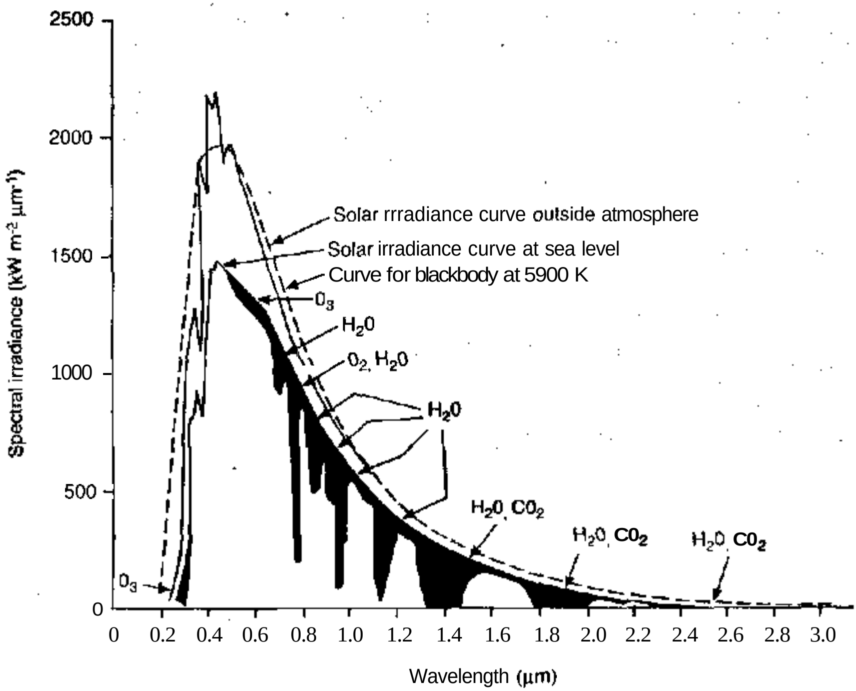


Fig. 6. Solar spectral illumination. (After Bonn and Rochon 1992). Solar illumination at sea level is significant in the visible band but not negligible in near-IR (0.70 to 2.50 µm) and in UV.

Box 1. Ionising Radiation

There is ionisation when an atom loses one or more electrons. An atom can be ionised by a radiation whose photon has sufficient energy, such as X-rays, UV or even visible light. The energy of ionisation required to extract an electron depends on the atom in question: it is different for each species. The effect of the ionising radiation on a living organism can be very complex. If the extracted electron belongs to a molecule, ionisation involves the destruction of a chemical bond. If this molecule belongs to a gene inside the core of a cell, its genetic code can be modified. Ionising radiation includes UV rays (bronzing and sunstroke), X-rays (radioscopy) and gamma rays (radioactive materials). UVs are used in microbiology to control and produce organisms with faded physiological characteristics. X-rays and gamma rays are used for microbiological sterilisation. These very penetrating radiations can produce ionisation in biological tissues, causing severe consequences if permitted doses are exceeded. In the food industry, ionising radiations are used to kill insects on fruits and many spices (black pepper, coriander, ginger and marjoram).

- Solar radiation is extremely variable (latitude, hour of the day, orientation of the leaves or plants) and depends strongly on the cloud cover (Schulzowà 1996).
We will describe separately each of the eight spectral bands, starting with short wavelength ionising radiation and mention some interesting EM applications for plant protection.

3.3 Gamma **Rays** (X Lower than 0.3 A)

Gamma ray photons are so energetic that they interact at the electronic and atomic level of matter. They offer the advantage of being selective. They are absorbed by the insects while penetrating deeply inside food material. The potential of application for gamma rays is therefore considerable in the food industry. Irradiation increases the storage time (Thayer 1985) because it destroys the harmful organisms inside the food. In 1963, the United States Department of Agriculture (USDA) authorised the use of gamma rays for irradiation of corn and com flour (Van Kooij 1982). Gamma rays are also used to eliminate insects from spices such as black pepper, coriander, ginger and marjoram. However, some observers mentioned that the taste of these spices changed after irradiation (Thayer 1985). Nevertheless, gamma rays remain of little use because of the high cost of equipment and the precautions necessary for the protection of personnel. It should also be noted that gamma rays are dissipated over short distances in the atmosphere.

3.4 **X-Rays** (0.3 to 300 A)

Like gamma rays, X-rays are used for post-harvest processing to selectively kill insects (or to make them sterile) without interacting with the surrounding medium. Banks (1976) reports a great variability of the results on the lethal doses of radiation for various insects. As for gamma rays, production of X-rays is not very effective and is expensive: their use remains therefore relatively limited.

3.5 **UV Rays** (300 A with 0.4 **µm)**

UV rays are also ionising radiations, but their penetration depth is very small and the interaction with materials occurs at the surface. These radiations typically penetrate to depths of approximately 100 µm. Thus, the targets (e.g. insects and bacteria) must be exposed directly to the UV radiation. The UV band is divided into three spectral subbands:

- UV-A (0.32 to 0.40 µm) corresponds to energy photons having minor effects in plant protection. UV-A wavelength 0,365 µm was used, however, to kill some insects **(Stuben 1973).**

- UV-B (0.28 to 0.32 µm) is the most commonly band used because photons are sufficiently energetic to attack the plant morphology by causing damage to the cells and modifying their genetic constitution (Culotta 1994). This is due (o the UV-B absorption by macromolecules such as nucleic acids, proteins and pigments. Even if UV-B rays constitute a small portion of solar radiation, they are sufficiently energetic to create a range of biological effects. For example, UV-B was used to sterilise insect eggs (Krieg 1975) and to decrease the impact of the post-harvest diseases of certain plants (Arul et al. 1996, see Chap. 10).
- UV-C (1 < 0.28 µm) are the most energetic and their effects are even more detrimental on plants and microorganisms (Baden et al. 1996).

In laboratories, UV lamps reproduce solar radiation to grow plants (Olszyk et al. 1996). Fig. 7 shows that it is possible to rather accurately reproduce solar radiation between 0.29 and 0.30 µm, whereas radiation from 0.30 to 0.31 µm is inadequately reproduced in laboratories. Covers filtering the solar radiation can modify the spectral composition of the light incident on plants and gave interesting results in inhibiting grey rot in a greenhouse environment (Nicot et al. 1996, see Chap. 9).

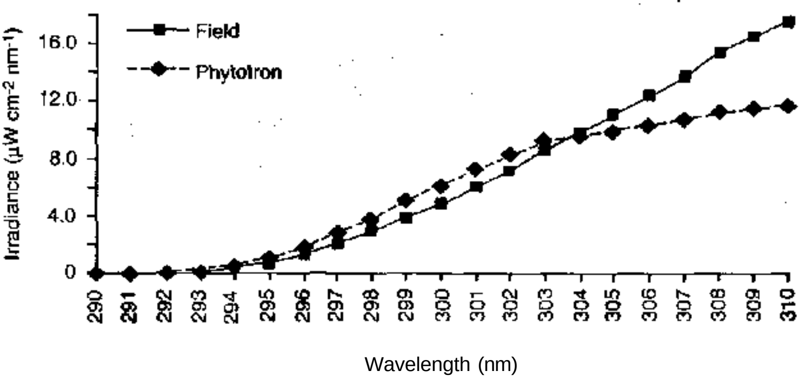


Fig. 7. Compared UV-B illuminations for sun and laboratory lamps (Olszyk et al. 1996). The solid line (field) corresponds to the UV solar spectral illumination (see Fig. 6). The reproduction of laboratory illumination (plant laboratory) is reliable up to 300 nm.

3.6 Visible and Near IR (0.4 to 2.5 µm)

Visible light (0.4 to 0.8 µm) and near IR (0.8 to 2.5 Jim) have the advantage of offering a source of natural radiation available everyday. In this spectral band, the radiation can sometimes extract an electron, sometimes make the molecules of the medium vibrate. The non-ionising wavelengths are used to dry food, like fish or grapes. The ionising effect is the power house of plant photosynthesis (Fig. 4).

Box 2. Non-Ionising Radiation

Photons from low frequency EM radiation — visible light, IR, microwaves and radio waves — do not have enough energy to extract an electron or modify the chemical bond. For these non-ionising radiations, the electric field of the EM wave makes the charged particles vibrate within the matter, without dissociating them from their chemical bond. Internal friction, at the frequency of the EM wave, leads to energy dissipation in the matter. A very great number of photons of weak energy act together to heat the material. The principal effect of radio waves, microwaves and IR on living organisms is internal generation of heat. The choice of EM wave frequency depends on the object to be treated, the depth, the percentage of moisture, etc. The role of water is especially significant: microwave radiation agitates the molecules of water and fat of the insects, increasing the temperature to the lethal point. Thus, a heterogeneous mixture of matter, like insects and plants, subjected to a microwave radiation will experience a different heating for each component of the mixture.
IR waves, microwaves and radio waves produce a great quantity of heat whereas visible light is used to dry many foods, like fish or grapes. Microwaves are especially used in the food industry to thaw frozen products or for cooking.

3.7 Medium and Thermal IR (2.5 to 14 µm)

Medium and thermal IR possess photons that are only able to initiate vibrations and rotations of the molecules. IR rays are absorbed at the surface and are principally used for cooking. Thermal IR has been used to detect the presence of insects in food (Bruce et al. 1982) but failed to kill them. IR sources are relatively affordable and easy to set up. However, few applications of thermal IR have been reported in plant protection.

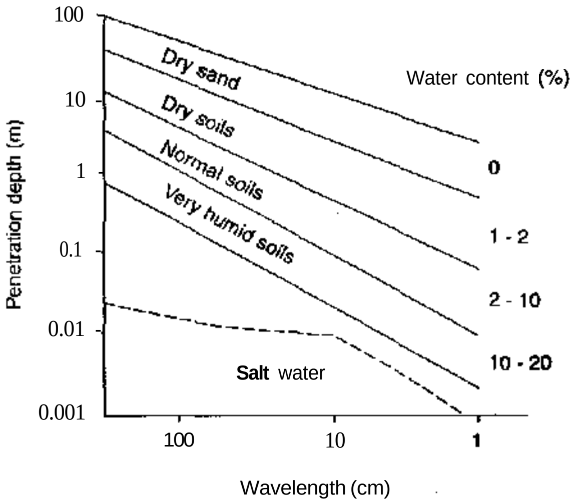
3.8 Microwaves (1 mm to 10 cm)

Microwaves cause molecules of the medium to oscillate and vibrate and part of the microwave radiation is thus transformed into heat. Thanks to their adequate penetration, microwaves are used in the food industry to thaw frozen products or for cooking. In EM applications, one can use microwaves to heat the soil and its organisms, increasing their temperature to lethal points. Each organism has a living temperature threshold (see Chap. 5). For human cells, destruction ocurs at about 40 °C, whereas a coleopteran of the rice flour dies at a final temperature ranging from 65 to 70 °C (Rosenberg and Bögl 1987).
Microwave frequencies cause the water molecule to vibrate within a very wide frequency band. Water plays a significant role because it is present everywhere in nature. The human body consists of approximately 70% of water; the majority of food

contains a significant proportion of water; and insects contain more water than the surrounding medium. For example, com in the storehouse has a water content between 14 and 16%, whereas the insects consist of 50 to 65% water. Due to the particular absorption of water at certain frequencies, microwaves penetrate deeper in dry soils (Ulaby et al. 1982). Microwaves from 2 to 12 GHz penetrate to depths from a few centimetres to a few metres, depending on the type of soil and its percentage of moisture (Fig. 8). Ideally, one would like to heat the unwanted insect selectively without heating the surrounding medium. Frequencies from 10 to 100 MHz offer the best advantage for selective heating. Insects absorb 3 to 3.5 times more *EM* energy than the surrounding medium (Nelson 1985; see Fig. 2 of Chap. 11). Unfortunately, even if the insect is selectively heated, the conduction of heat into the medium decreases the selectivity of this technique.
Microwave sources, including oscillators and waveguides, must emit a large EM power, consume a lot of electric power and are expensive. The costs of microwave techniques for insect control are definitely higher than those of chemical processes.

3.9 Radio and Audio Waves (λ Higher than 10 cm)

Because of their excessive penetration in the soil (Figure 8), radio waves offer few applications in plant protection, except for de-infestation of dry or dehydrated food products (Fleurat-Lessard, Chap. 11). On the other hand, these waves are used in geo-



Fig, 8. Penetration depths of microwaves and radio waves in various types of soil (Ulaby et al, 1982). Microwaves and radio waves are very sensitive to soil moisture and penetrate deeper in dry soils. For example, an EM wave of 10 cm wavelength can reach a 10 m depth in dry soil, hut penetrates only down to 5 cm in very wet soil.

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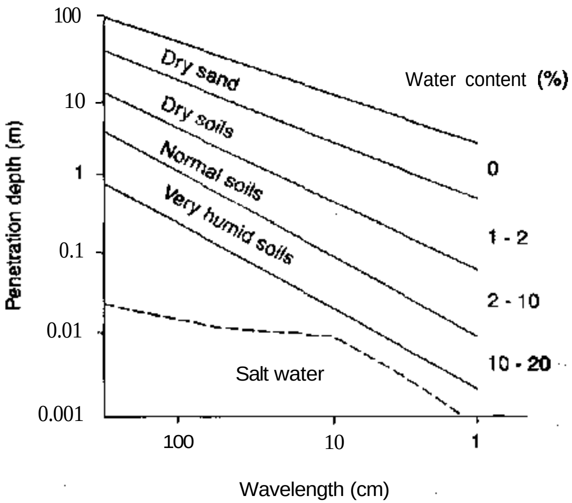

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logical prospecting because they allow the probing of deep underground layers (Fisher et al. 1994) and the detection of the presence of specific materials.

4. Conclusion

EM techniques are interesting alternatives to chemical methods because they offer the advantage of eliminating plant enemies without damaging the surrounding medium or leaving residues. Moreover, a study reported by the New York Times (1995) on chemical methods pointed out that insecticides and fungicides can spread thousands of kilometres from their place of origin and that some 10-year-old chemical pesticides still continue to affect the environment.
EM techniques have their limits and they may pose hazards. Indeed, it is rather easy to deteriorate the germinative faculty of seeds with an over-intense microwave exposure (Philbrick 1984) or to modify the immune system of certain mammals (Yang et al. 1983). So far there have been no reports of acquired tolerance to EM irradiation by plants or animals. Although adaptation to gamma rays seems very improbable, some form of tolerance to other EM waves is still possible. For practical applications, EM techniques seem more expensive than conventional methods. In spite of this additional cost, the use of EM waves for the control of crop pathogens does not rest solely on economic considerations, but also on the acceptance of these methods by society. Additional research on the interactions between EM waves and matter is necessary to discover all the potential applications and to enlarge the field of validity of EM techniques for plant protection.

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Electrical Weed Control: Theory and Applications

Clement VIGNEAULT and Diane L. BENOÎT

1 Introduction

The concept of using electrical energy to kill weeds was developed in the late 1800s and several patents have been registered in the United States since 1890. The most recent electrical weed control system consists of a tractor-driven device (Lasco Inc.) designed to destroy persistent weeds in row crops following conventional chemical treatment. The machine, called the Lasco LW5 Lightning Weeder, was manufactured in Vicksburg, Mississippi, and first appeared on the market in 1980 (Fig. I).

Some environmentalists believe that using electricity is the ideal way to control early-emerging weeds. This approach leaves no chemical residues into the environment or food chain, and it does not disturb the soil surface or promote erosion.

An analysis of the annual operating costs of destroying weeds that are taller than the crop on a basis of 100 ha, showed that electrical weed control is on a par with a roller applicator, but is more expensive than a recirculating sprayer (Kaufman and Schaffner 1980). Three passes are recommended to ensure optimum weed control using the electrical method.

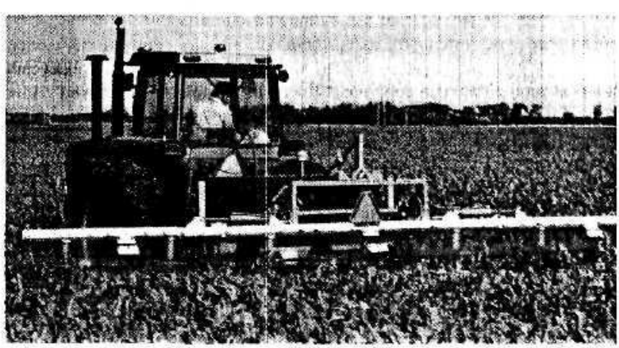

Fig. 1. Tractor-mounted electrical weed control machine, in operation.

The use of electricity to control small weeds in row crops was studied by Hackam (1985), and a machine similar to that manufactured by Lasco was developed for this purpose. The single electrode of the Lasco system was replaced with a series of small electrodes that could be placed closer to the soil surface between the crop rows. Deflectors and shields were used to prevent contact between the crop and the electrode. However, testing of this prototype revealed excess power consumption and mechanical failure of the generator drive train when the machine was operated in fields with high weed densities.

An analysis of the theoretical concepts of electrical weed suppression is essential in order to identify key parameters for machine design and use. This chapter reviews the theory of electrical weed control and present knowledge of the factors influencing the efficiency of the electrical method. It also compares the energy requirements of the electrical method with other weed control techniques.

2 Theory of Electrical Weed Control

When a high-voltage electrode touches a weed, electric current passes through the plant and is returned to the transformer via the soil by a ground contact device. Due to the electrical resistance of the plant, the electrical energy is converted to heat in accordance with Eq. (1).

$$E = \frac{V^2 T_c}{R_p} \quad (1)$$

The energy transmitted to a single plant (E) is directly related to the electrical resistance of the plant (Rp), the contact time (Tc) and the electrode voltage (V).

Plant death is caused primarily by the increase in temperature and vaporization of the water and other volatile liquids it contains. This results in a buildup of pressure within the cells, and subsequent rupture of the cell membranes (Diprose et al. 1980; Dykes 1980). In extreme cases, when an excess of energy is absorbed by the plant, localized hot spots occur and eventually the plant stem burns and ruptures. The severity of damage depends on the plant species, morphology, age and population density. The contact time and voltage can affect the extent of damage (Dykes 1980; Sanwald and Koch 1978).

2.1 Impact of the Morphology of the Target Species

In plants with an extensive root system, the electric current travels deep into the root system before being dissipated into the soil (Diprose et al. 1980; Drolet and Rioux 1983; Dykes 1980). Plants with large or specialized underground organs will suffer little root damage (Diprose et al. 1980; Drolet and Rioux 1983). Root damage is more severe under dry than under moist soil conditions (Diprose and Benson 1984; Dykes 1980; Vigoureux 1981). The rhizomes of quackgrass (*Agropyron repens* L. Beauv.) survive several electrical treatments (Diprose and Benson 1984). The use of electricity is ineffective in controlling common burdock (*Arctium minus* Hill Bernh.) in field-grown crops, because the lower branches are not touched by

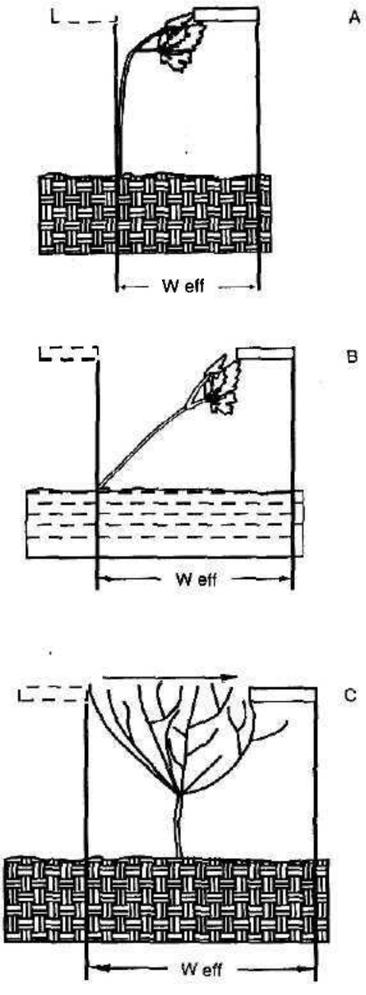

Fig. 2 A-C. Three possible scenarios to describe the maximum and minimum contact times. A Erect plant where only the foliage bends. B Erect plant where the entire plant bends at its base. C Bushy plants with multiple contacts. W_{eff} Effective electrode width.

the electrode (Drolet and Rioux 1983). Bull thistle [*Cirsium vulgare* (Savi) Tenore] and Canada thistle [*Cirsium arvense* (L.) Scop.] escaped destruction, with regrowth of shoots occurring from the undamaged root system.

2.2 Impact of Electrode Contact Time

When an electrode passes over the weed population, individual weeds remain in contact with the electrode for a distance determined by the forward speed of the tractor. Diprose and Benson (1984) derived theoretical limits of contact for an upright plant by considering two extreme cases: (1) the plant remains upright and only bends at the point of contact; 2) the plant stays rigid but bends at the base (Fig. 2a,b). For very bushy plants, contact may begin before the leading edge of the electrode is positioned over the plant base and may cease after the trailing edge of the electrode has passed the base (Fig. 2c). The distance travelled by the electrode while maintaining contact with the plant is called the effective electrode width (W_{eff}). It is a function of electrode width, height of horizontal movement and plant geometry and rigidity.

The number of plants in contact with the electrode at any given time (n_c) is equal to the product of electrode length (L), effective width (W_{eff}) and weed density (D).

$$n_c = LW_{eff}D \tag{2}$$

2.3 Effect of Weed Density

Load resistance across the transformer (R_l) is equal to the sum of the parallel resistances (R_{pi}) created by n_c plants touching the electrode simultaneously, plus the resistance of the soil (R_s) [Eq. (3)]. Thus, the load resistance across the transformer is largely reduced by multiple contacts of weeds with the electrode.

$$R_l = \left[\sum_{i=1}^{n_c} \frac{1}{R_{pi}} \right]^{-1} + R_s \tag{3}$$

Plant resistance varies widely with species, morphology, age and lignin or cellulose content (Diprose and Benson 1984; Dykes 1980; Vigneault 1985). However, in a simplified case where all plants have the same resistance, Eq. (3) reduces to Eq. (4).

$$R_l = \frac{R_p}{n_c} + R_s \tag{4}$$

2.4 Importance of Generator Power

In the ideal case, where all plants have the same electrical resistance, and disregarding the energy losses due to the resistance of the transformer, the power produced by a generator is given by Eq. (5).

$$P = \frac{V^2}{R_1} = \frac{n_c V^2}{R_p + n_c R_s} \tag{5}$$

The following relationships can be deduced from Eq. (2) to (5).
The required generator power (P) increases as the number of weeds touching the electrode (n_c) increases, which is itself proportional to weed density (D).
As weed density increases, the electrical resistance of the plants becomes negligible compared to the soil resistance. As a result, generator power becomes a function of the soil resistance and the voltage applied. Eq. (5) can thus be replaced by Eq. (6). At high weed densities, a significant proportion of generator power is absorbed by the ground, leaving little energy for killing the weeds.

$$P = \frac{V^2}{R_s} \tag{6}$$

Generator power is independent of the forward speed of the tractor. Thus, unlike tillage operations, where power requirements are proportional to ground speed, power demands on the generator cannot be reduced simply by decreasing the forward speed of the tractor.

2.5 Operating Capacity of the Machine

A minimum threshold contact time (T_c) of about 0.2s is required for a lethal effect on young weeds under field conditions (Dykes 1980). This places an upper limit on the machine's forward speed (U), as a function of the effective electrode width (W_{eff}).

$$T_c = \frac{W_{eff}}{U} \leq 0.2s \qquad U \leq 5.0 W_{eff} \tag{7}$$

The electrode length (L) is, however, limited by the available generator power (P).

$$L = \frac{PT_c}{EDW_{eff}} \tag{8}$$

The operating capacity of the machine in terms of area treated per unit of time (Q) is a function of available generator power (P), energy transmitted to the plant (E) and density of the weed population (D).

$$Q = \frac{P}{ED} \qquad (9)$$

Most of the studies done so far have examined the effectiveness of electrical control of escaped weeds. One field trial investigated the use of electric currents to control weed beet and bolting beet growing in the rows of a sugar beet crop (*Beta vulgaris* L.). Before the electrical method can be applied, however, the weeds must be allowed to grow taller than the crop. In theory, a 5- to 10-cm difference in height between the crop plants and the weeds is necessary for adequate weed control and minimal crop damage. In practice, however, a minimum height differential of 10 to 20 cm is required (Lutman 1980).
Tests revealed that a single pass is sufficient to treat infestation densities of up to 2000 stems ha^{-1}. For weed densities of 2000 to 6000 stems ha^{-1}, two passes are generally required (Guiraud and Givelet 1981; Vigoureux 1981, 1982). Vigoureux (1981, 1982) obtained 98 to 99.9% control of bolting beet at infestation densities of between 100 and 5000 stems ha^{-1}. In contrast, only 24% weed control was achieved at densities exceeding 18000 stems ha^{-1}.

3 Energy Requirements

Knowledge of the electrical resistance of the soil and plants is helpful in understanding the factors affecting generator power requirements. The electrical resistance of plants varies widely among species, and the energy required for a lethal effect increases with increasing plant maturity.
When voltage is applied to a plant, the current begins to cause damage to the plant structures. As the level of damage increases, plant resistance decreases, allowing more current to flow through the plant (Diprose and Benson 1984; Diprose et al. 1980; Dykes 1980). This rise in current is not constant but occurs in two stages. The first stage is slow and linear, terminating at an inflection point. The second is characterized by an exponential increase in current. The release of steam from the plant occurs at the inflection point (Martens and Vigoureux 1983). Near the end of the first stage, the current reaches a plateau corresponding to maximum damage and death of the plant. If the current is maintained beyond that point, excessive structural damage occurs. The plant eventually breaks, thus interrupting the current (Diprose and Benson 1984; Diprose et al. 1980).
Several factors affect the amount of energy required for electrical weed control. They include species, size, life span and age of the plant, chemical composition and root structure arrangement, and soil composition and moisture content.

Multistem species were more difficult to control effectively than weeds with a single main stalk (Rasmusson et al. 1979; Vigoureux 1981).
For a constant electrode height, tall plants will remain in contact with the electrode for *a* longer period of time than shorter plants, and the former will absorb more energy. To ensure that shorter plants are killed, sufficient energy per plant must be provided either by increasing the voltage or decreasing the electrode height. This results in an excess of energy being provided to tall plants. Thus, the average energy applied per plant will be greater than the minimum required to kill a single plant.

4 Concept of Lethal Threshold Energy

The analysis of energy requirements for weed control in row crops is based on the mean threshold energy required to kill target plants. Diprose et al. (1984, 1985) suggested that field-grown plants require two to three times more lethal energy than plants grown in greenhouses. Tests have confirmed that the energy required for a lethal effect on field plants is five (Diprose and Benson 1984) to ten (Chandler 1978) times that required for the same effect on weeds grown indoors. Under experimental conditions, the lethal threshold energy varied from 4 to 111 kJ plant^{-1} (Table 1). In contrast, the energy required for a lethal effect on field-grown weeds often exceeds the minimum thresholds (Table 2).

Table 1. Lethal energy applied (kJ plant^{-1}) under experimental greenhouse conditions. The voltage were applied until the plant severs (Diprose et al. 1978).

Species	Plant height (m)	Voltage (kV)	Contact time contact (s)	Lethal energy (kJ plant^{-1})
Beta vulgaris L.	-[a]	1.0	33.7	4
		2.5	32.2	32
		5.0	8.5	28
Chrysanthemum segetum L.	-	2.0	37.2	65
		3.0	8.5	21
		5.0	6.9	23
Sinapis arvensis L.		2.0	147.8	86
Large	1.0	3.0	52.0	111
		4.0	13.2	71
Small	0.2-0.6	2.0	16.2	6
		3.0	8.9	7
		4.0	4.8	17

[a] Information not available.

Table 2. **Lethal energy (kJ plant**$^{-1}$**) required** to kill **weeds under experimental** field conditions (Vigneault et al. 1990).

Species	Age of plant	Voltage (kV)	Electrode contact time	Lethal threshold energy (kJ plant^{-1})
Abutilon theophrasti Medik.	3 weeks	3.0	0.116	0.365
	4 weeks	4.0	0.175	1.908
Beta vulgaris L.	Bolting	4.0	21.8	104[a]
	"	5.2	11.6	137
	"	6.2	9.9	139
	"	7.2	8.1	156
	"	7.6	8.7	207
	"	8.4	4.3	104
Brassica campestis L.	Fruiting	14.4	0.41	2.13
	"	14.4	0.27	0.47
Chenopodium album L.	Fruiting	14.4	0.65	3.20
	"	12.0	0.62	2.93
	"	12.0	0.20	0.53
	"	12.0	0.23	1.81
Xanthium strumarium L.	3 weeks	1.0	0.110	0.040
	4 weeks	2.0	0.094	0.254

[a] Voltage was applied until the sugar beet severed.

A machine applying electric voltage ranging from 12.0 to 14.4 kV destroyed lamb's quarters *(Chenopodium album* L.) and birdsrape mustard *(Brassica campestris* L.) with an average of 2.12 and 1.30 kJ applied per plant respectively (Table 2). This indicates that it would take an average of 1.71 kJ plant^{-1} to kill mature weeds. These values are much lower than those previously reported by Diprose et al. (1980) for the control of bolting beets (Table 2), since the values they mentioned represented the lethal energy required to sever the plants.

Table 3. Effect of tractor speed on the energy required for a lethal effect on *Chenopodium album*[a] (Vigneault et al. 1990).

Tractor speed (km h^{-1})	Voltage (kV)	Electrode contact time (s)	Lethal threshold energy (kJ plant^{-1})	Mortality (%)
2.72	14.4	0.65	3.20	100
4.12	14.4	0.49	1.16	50
6.17	14.4	0.34	0.79	28

[a] Average plant height: 85 cm.

Table 4. Effect of voltage and plant height on the energy required for a lethal effect on *Chenopodium album*[a] (Drolet and Rioux 1983).

Voltage (kV)	Average plant height (cm)	Electrode contact time (s)	Lethal threshold energy (kJ plant^{-1})	Mortality (%)
12.0	28	0.20	0.53	100
12.0	39	0.23	1.81	100
12.0	79	0.62	2.93	100
14.4	81	0.65	3.20	100

[a] Average tractor speed: 2.80 km h^{-1}.

Drolet and Rioux (1983) studied the relationship between mean lethal threshold energy, tractor speed and applied voltage. For a constant voltage, the electrode contact time and the energy applied per plant decreased as tractor Speed increased (Table 3). The percent mortality decreased in direct proportion to the energy applied per plant (Table 3). Increasing the voltage from 12 to 14.4 kV increased the energy applied per plant but had no effect on percent mortality (Table 4). Percent mortality remained unchanged even when the height difference between the plant was greater, electrode contact time was longer and greater mean energy was applied per plant (Table 4). The relationship between applied voltage and contact time is not linear (Diprose et al. 1978). Doubling the voltage decreases the required contact time by four (Diprose et al. 1980).
Where weed density is very high and the weeds occur in patches, the largest plants can shield the smaller plants from contact with the electrode (Diprose et al. 1985; Drolet and Rioux 1983; Rasmusson et al. 1979), thereby reducing the overall efficiency of the treatment. Drolet and Rioux (1983) have shown that in lamb's quarters, the first plants in a patch had higher percent mortality than the last plants (Table 5). When two passes were made in opposite directions, the total energy applied per plant was doubled, but more uniform mortality was obtained throughout the patch.

5 Comparison of Energy Requirements and Cost of Weed Control Techniques

Electricity can be used either as the primary method of weed control, or to destroy the weeds remaining after one or more conventional treatments. The density of the target weed population will vary, depending on whether the electrical treatment is applied to the initial population or to the residual population. Population densities

Table 5. Effect of the number of passes[a] on average mortality of a group of plants[b] and the lethal threshold energy applied per plant (Drolet and Rioux 1983).

Number of passes	Total number of plants treated	No. of plants/patch	Mean distance between 1st and 3rd plant	Average mortality			Average mortality/patch	Lethal threshold energy
				1st plant	2nd plant	3rd plant		
			(cm)		(%)		(%)	(kJ plant^{-1})
1	30	3	21.2	80	60	50	63.3	1.32
2[c]	33	3	14.7	64	64	64	64	2.21

[a] Electrical machine characteristics Tractor speed: 2.79 km h^{-1}, Voltage: 14.4 kV, Electrode contact time: 0.65 s.

[b] Average plant height: 82.5 cm.

[c] Each pass was made in the opposite direction.

are also affected by treatment time, soil type, field history ant! previous weed control practices. Initial weed densities of 168 plants m^{-2} in onion (*Allium cepa* L.), 569 plants m^{-2} in tobacco (*Nicotiana tabacum* L.) (Roberts 1967) and 1075 plants m^{-2} on fallow land (Drolet and Rioux 1983) have been reported prior to treatment. Residual weed densities were generally much lower, being 0.2 and 1.0 plant per linear metre of row crop (Kaufman and Schaffner 1982). Since studies of electrical control of residual plants involved different weed densities, the findings cannot be readily converted to practical advice.

5.1 Experimental Method

The energy input of chemical weed control was assessed for corn (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.), crops for which herbicides are the principal method of weed suppression. Total energy requirements were calculated using herbicides at the rates recommended in Ontario (Anonymous 1996). Whereas the cost for corn was based on the use of metolachlor with atrazinc and bromoxynil, the computation for beans used metobromuron and bentazon. The calculation of total energy inputs included the energy required to manufacture the herbicides (Southwell and Rothwell 1977) and the energy required to transport and apply the product in the fields. The energy input for herbicide application was determined from data provided in ASAE standards (Anonymous 1990). The calculation method used to establish the energy input of chemical weed control was similar to that reported by Sanwald and Koch (1978).

The energy requirements of mechanical weed control were calculated for an 80-kW tractor pulling three types of cultivators. Productivity was estimated based on the data obtained in cultivation tests (Anonymous 1990).

Weed densities of 5, 30 and 200 stems m^{-2} were used to calculate the energy requirements of electrical weed control. These densities correspond to light, moderate and severe infestations of emerging weed seedlings, respectively. Assuming that an average of 1.76 kJ^{-1} plant is required, the transformer must supply 3,520 MJ ha^{-1} for an infestation density of 200 weeds m^{-2}. Total energy consumption in the form of tractor fuel will be considerably higher since substantial energy is lost due to inefficiencies of the tractor engine, drive train, generator, transformer and rolling resistance. According to Drolet and Rioux (1983), overall tractor efficiency, including the energy required to move and operate both the tractor and the machine, was 21.4%. The power available for the electrode represented 54 to 59% of the power output from the tractor power takeoff (Drolet and Rioux 1983; Kaufman and Schaffner 1980).

The Lasco electrical weed control system consists of a low voltage AC generator driven by the tractor power takeoff, a stepup transformer to modulate the voltage, an insulator-mounted electrode suspended above the crop and a rolling coulter ground contact device to complete the circuit (Fig. 3). The horizontally positioned

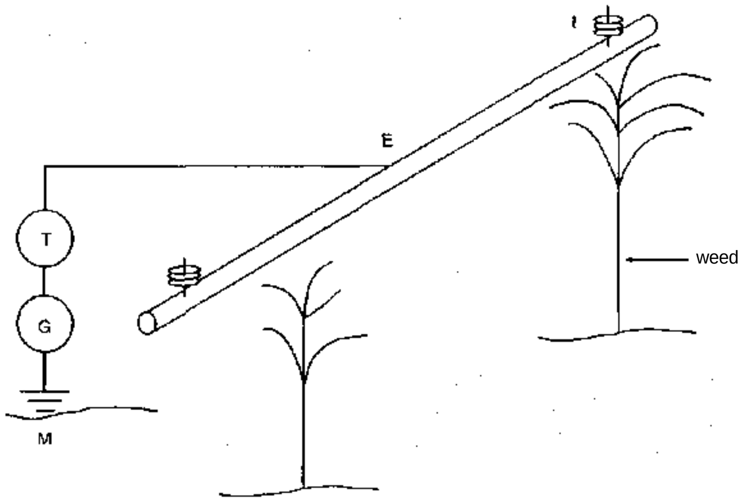

Fig. 3. Diagram of **an electrical weed** control **system. G Current generator. T** Transformer. **R** Electrode. **I Insulator. M Grounding** using a **rolling** coulter.

electrode conducts the current to the plants and is protected by a plastic shield to prevent accidental contact.

An 80-kW tractor with a 50-kW generator operating in a field with a weed density of 200 plants m^{-2} can supply an average of 1.76 kJ plant $^{-1}$ and will consume 16.5 GJ ha^{-1}. The full operating capacity of the electrical weeder is 0.047 ha h^{-1} [Eq. 9]. The actual capacity will be somewhat lower, however, because of time lost in headlands and because the generator is rarely used at full capacity.

5.2 **Comparison of Three Weed Control Methods**

There are some advantages to using electricity to control escaped weeds in a conventional weed control program. For weed densities of five plants m^{-2}, chemical and electrical weed control call for approximately the same amount of energy (Table 6). The mechanical method requires much less energy, since cultivators offer little resistance and are lighter to pull. Cultivation breaks the surface crust, generally operates at the surface and does not alter soil structure. Although mechanical cultivation does not adversely affect soil conditions, it can cause physical damage to crops and reduce crop productivity slightly. The use of electricity does not disturb the soil surface and therefore does not promote erosion or soil moisture loss. There is no danger of physical damage to crops, which is an important advantage for fruit and vegetable crops near harvest time. Chemical weed control, may entail a risk of chemical residues being left on the crops.

However, electricity is not suitable as the primary method of weed control at densities of 200 stems m^{-2} and over. Under such conditions, electrical weed control

Tnble 6. Comparison of total energy input for electrical, mechanical and chemical weed control techniques.

Weed control technique	Weed density (no m^{-2})	No. of passes	Application time	Formulation[a]	Rate[b] (kg ha^{-1})	Average total energy input (MJ ha^{-1})
Electrical	5	1	POE[c]	-[d]	-	418
	30	1	POE	-	-	2460
	200	1	POE	-	-	16500
Mechanical						
Corn						
Rigid tine harrow	-	2	PRE,POE	-	-	44
Danish S-tine cultivator	-	1	POE	-	-	34
Bean						
Rotary hoe	-	3	PRE,POE	-	-	23
Danish S-tine cultivator	-	1	POE	-	-	34
Chemical						
Corn	-	1	PRE	EC+SU	1.9-2.6+1.0-1.5	615
		1	POE	EC	0.3	45
Bean	-	!	PRE	SU	1.0-1.7	203
	-	1	POE	SN	0.8-1.1	144

[a] EC = emulsifiable concentrate; SU = suspension; SN = solution.

[b] Rates recommended in Ontario, active ingredient basis.

[c] POE = postemergence; PRE = pre emergence.

[d] Not available.

requires approximately 20 times more energy and takes 50 times longer than chemical methods (Vigneault et al. 1990). Even at a low weed density of 15 plants m^{-2}, the electrical method requires approximately twice as much energy and takes five times longer than the chemical method. Furthermore, the electrical method, like its mechanical counterpart, requires several passes to obtain an acceptable level of weed control, compared to only one treatment for chemical weed control.

6. Conclusion

If electrical weed control is to be cost-competitive with conventional methods, several improvements need to be considered (Vigneault et al. 1990). An improved electrode design having at least two diagonally opposite contact points would increase the efficiency of current flow between the electrode and the plant by up to 13% (Martens and Vigoureux 1983). The efficiency of the transfer of available energy from the tractor to the electrode could also be improved. Tractor speed could be increased to meet the requirements of an electrical machine with a better hourly operating capacity. The effect of the electric current frequency used for plants at different stages of growth should be analysed to determine which frequency is the quickest and most energy efficient (Martens and Vigoureux 1983). To avoid wasting energy, a monitoring system could be devised to identify the point at which current flow should he stopped-essentially the lethal energy threshold–because sufficient damage has already been done (Diprose et al. 1980). Further research is needed in order to quantify the resistance of different species in terms of their phenological stage and the mean lethal energy to be applied (LD_{50}), as well as to identify associated factors.

The electrical method is slower, less efficient and requires more energy to destroy small weed seedlings than conventional control techniques. It may, nevertheless, be justified for weed suppression in crops of high commercial value, such as herbs. This method is also cost-effective in fields where the area to be treated is small, in locations where persistent herbicides are not acceptable, and in regions where there is a risk of erosion or where a soil management program is in effect. In addition, electricity can be used to destroy weeds in certain situations associated with crop rotation, such as sunflowers (*Helianthus annuus* L.) growing in soybean fields (*Glycine max L.* Merr), and weed beet or bolting beet in sugar beet crops. The electrical method will not damage the crop plants given the substantial height difference; hence it represents an efficient approach in such contexts.

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