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Physical Control Methods in Plant Protection

With 102 Figures and 34 Tables



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Cover photo: **Post-emergence** mechanical (between rows)
and **thermal** (on the row) weeding in a cornfield (photogr. C. Laguë).

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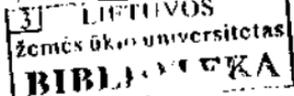
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Plant Protection and Physical Control Methods

The Need to Protect Crop Plants

Bernard PANNETON, Charles VINCENT and Francis FLEURAT-LESSARD

1 Introduction

Plants, like all living organisms, are preyed upon by various parasites of plant or animal origin, which either directly attack their tissues (fungi, insects, etc.) or compete with them for resources (air, water, nutrients in the soil, etc.). For practical as well as economic reasons, crop production has evolved toward monocultures of species grown on relatively extensive surface areas. This has simplified ecosystems, often eroding the inherent complexity of the natural environment. Since pest populations tend to expand under such circumstances, this situation has magnified the risk of serious repercussions on crop plant species (Metcalf and Luckmann 1994 ; Chap. 2).

The direct cause of the Irish potato famine in the mid-19th century was an uncontrolled infestation of potato fields by the pathogenic fungus *Phytophthora infestans* (Mont.) de Bary. Occasionally, insect damage is so severe that the harvest is completely spoiled (Matthews 1992) and competition between cultivated plants and weeds results in major yield losses ranging from 24 to 99% (Lacey 1985). On a worldwide basis, preharvest losses amount to roughly 20 to 40%, whereas post-harvest losses (stored food products) account for 10 to 20% of the total (Riba and Silvy 1989).

In view of the need to make a profit by producing high yields of quality plant products, combined with the trend toward regional specialisation in crop cultivation, crop protection is a crucial activity in agriculture and forestry. Tremendous progress has been made in crop pest management during the 20th century, thanks to scientific and technological breakthroughs, notably in chemistry (analytical and synthetic) and in biology (population dynamics, ecosystem analysis, biological control theory and practice, and biotechnology).

The rapid demographic growth which has characterised the final part of the second millennium has raised concern about potential food security problems. It has been predicted that the world population, estimated at 5.7 billion in 1995, will stabilise between 7.9 and 11.9 billion around 2050. Rapid population growth is the main factor determining world demand for food (FAO 1996) and will necessitate increasingly more effective methods of crop protection. Urbanisation and soil erosion

have exacerbated the problem by reducing the amount of arable land available for cultivation (Fig. 1). The factors governing the balance between agri-food supply and food demand are both numerous and complex. Therefore, there are many possible avenues of intervention for establishing and maintaining a balance between supply and demand. However, a consensus exists at present that *"increasing the efficiency of agricultural and food production is the key to ensuring an adequate food supply... Attainment of food security requires sustained action... Such action should be aimed at ... the development of environmentally sound new technologies"* (UN 1996).

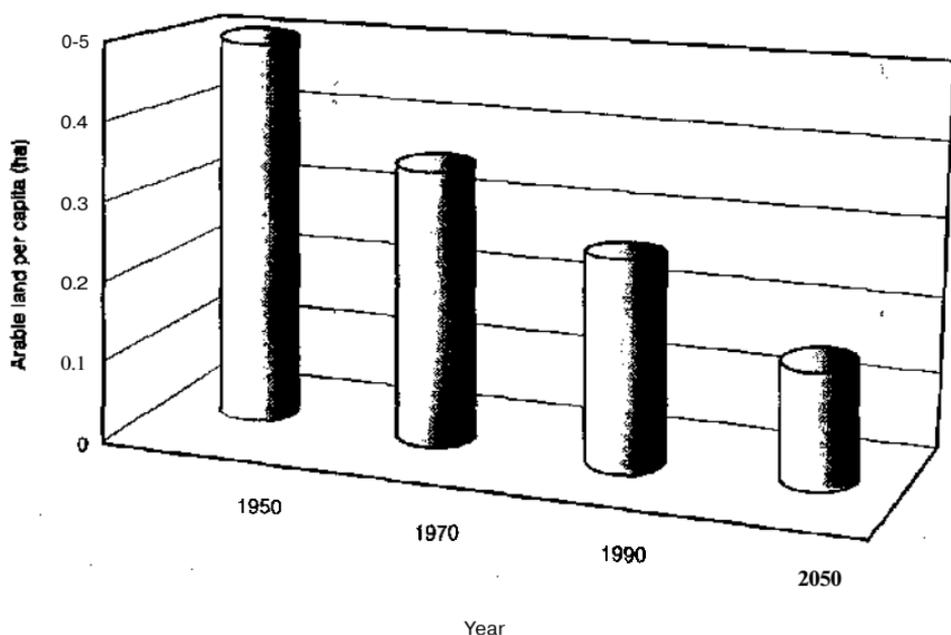


Fig. 1. Reduction in arable land per capita (After Novartis 1997).

2 Crop Protection

Crop protection can be classified according to five approaches (Fig. 2). A majority of agricultural commodities are protected using systems relying primarily on chemical control. Human factors come into play when efforts are directed at either curbing or promoting the use of chemicals. For example, owing to the stringent requirements associated with marketing standards, particularly those imposed on the cosmetic appearance of agricultural products (without considering the objective nutritional qualities of those products), producers are compelled to employ efficient control measures against harmful organisms. In the present context, this essentially means using

chemical pesticides. On the other hand, exacting, and sometimes subjective, food safety standards curb the use of chemical pesticides. In such a context, biological control and biopesticides represent tools that can facilitate the implementation of pest management programs, providing a more acceptable balance between the critical need to protect crops and the need to address ecotoxicological concerns. For the same reason, crop protection based on the application of physical control methods during production or storage is gaining in popularity. Indeed, most physical control techniques have no deleterious environmental effects and they are generally limited to the site of treatment and the period during which it is applied. Furthermore, physical control methods bring no chemical or biological substances into play and therefore do not leave undesirable residues on food commodities intended for human or animal consumption.

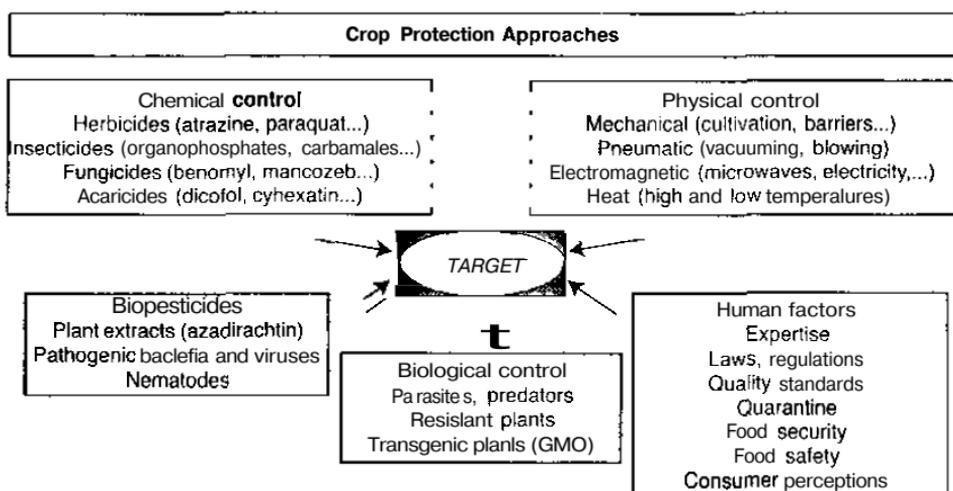


Fig. 2. Five approaches to crop protection.

3 Use of Pesticides

When synthetic pesticides first appeared on the market about 50 years ago, many people imagined that crop enemies would be completely eliminated (Metcalf 1980). That is clearly not the case. However, the increase in the quantity and quality of agricultural food products has certainly been aided by pesticide use, and usually, producers who have easy access to synthetic pesticides do not have to cope with devastating infestations (Hislop 1993).

According to Metcalf (1994), the advantages of chemical pesticides can be summed up by the following qualities: convenience, ease of use, effectiveness, flexibility and reasonable economic cost. In the case of insecticides, for example, the benefits can be summarised as follows:

1. Insecticides represent the **only effective** control measure **when pest populations** in crops approach the economic threshold. In such a case, action **must** be taken **without delay**, and the control tactic **employed must have an immediate effect** to ensure that the threshold is not exceeded.

2. Insecticides have a rapid, curative action and are **likely** to stop the dynamics of a **pest population** within a few days, even a **few hours**.

3. **Synthetic organic insecticides** belong to different categories of chemicals and feature **various modes** of action and **methods** of application; **hence**, collectively **they cover a remarkable diversity of situations** in which plants are attacked by **pest species**.

4. The **cost-benefit** ratios for insecticide treatments are generally favourable if the product involved is suited to **field crops**. Indeed, insecticides for field crops are manufactured in large **quantities** for use around the **world**, and so can be obtained at a **low cost**. Nonetheless, the costs are **rising** because of the need to continually synthesize new, **more complex chemical compounds** and to conduct **in-depth research** on their toxicology for registration purposes. **This has resulted** in an exponential increase in research and development expenses.

The **market trend** toward developing **formulations** that can be applied in liquid form has **permitted uniformity** in methods of application. Today, in **most agricultural operations**, sprayers are the **only equipment** needed for most crop protection treatments. This **standardisation** has **brought** about a reduction in machinery costs and **simplified** the task of **workers who carry out treatments**.

3.1 The Pesticide Market

In 1996, the world pesticide **market** expanded for a third year in a row. The **British Agrochemical Association (BAA)** estimated 1996 **growth** at 3.6%, which would make the **world market** for pesticides worth about FF 185 billion (US\$31.25 billion) (Anonymous 1997). According to the BAA, the breakdown of total sales in the different regions of the **world** was as follows: 30.6% in North America, 26% in Western Europe, 22.5% in East Asia and 11.9% in South America. The **growth** in pesticide use can be explained largely by the **increased acreage of crops to which large quantities of pesticides are applied**. In 1996, herbicides accounted for 48% of the **world market**, compared to 28% for insecticides and 19% for **fungicides** (Anonymous 1997). Despite the problems that have arisen in relation to pesticide use, the market has grown steadily since 1960 (Fig. 3). The market for herbicides has **grown** the most. **As we will see**, physical methods **hold considerable promise** for controlling **weeds** and **thus** for reducing pesticide use, in **furtherance** of the objectives established by many countries and agencies, such as the **European Commission**, which are seeking to decrease the **inputs** used in field crop production.

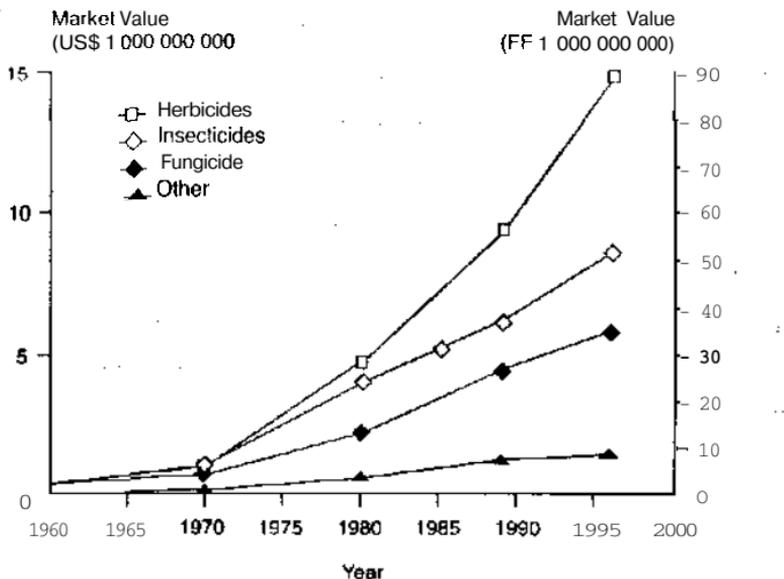


Fig. 3. Trends in the world pesticide market (Data from Matthews 1992 and Anonymous 1997).

Some factors make it more difficult to interpret the statistics on pesticide use. In the United States, for example, cropping techniques based on minimum tillage are being applied increasingly. As a rule, these methods boost herbicide requirements (Anonymous 1997). The BAA believes that pesticide sales will rise in the United States as more and more herbicide-resistant plant varieties are derived through genetic engineering. However, some genetically modified varieties may lead to a reduction in pesticide use (e.g. transgenic tomatoes that synthesise the *Bacillus thuringiensis* Berl. toxin). In the United States, the Freedom to Farm Act should boost the total acreage devoted to cereals, which could result in higher pesticide use (Anonymous 1997). In the European Economic Community (EEC), the rate of pesticide application dropped from 4.2 to 3.3 kg·ha⁻¹ between 1991 and 1995. In Sweden, critics have attributed this decline to improved application techniques and the introduction of new pesticides applied at lower doses (Anonymous-b 1997). From a quantitative standpoint, the pesticide market appears to be buoyant and this is reflected in the substantial sales volume along with recent developments like those mentioned above, which should promote further expansion of their use. However, from an operational standpoint, resistance problems and serious secondary effects, including pollution, reduced food safety and poisonings (Table 1), together with consumers' unfavourable perceptions, are constraining pesticide use.

Table 1. Disadvantages of pesticide use.

1	Pesticide resistance Decline in the useful life of a pesticide Increased cost of pesticides associated with managing resistance Ongoing monitoring of the level of resistance
2	Resurgence and outbreaks of secondary pests
3	Harmful effects on non-target organisms (lack of "ecological selectivity") Nāturai enemies Bees and other pollinators Wildlife
4	Hazards of pesticide residues Chronic intoxication of beneficial species Alteration in the reproductive potential of pests Alteration in the biotopes of nāturai enemies of pests Human exposure to residues Food safety problems
5	Hazards directly associated with pesticide use Occupational illnesses in workers Pesticide drift during application

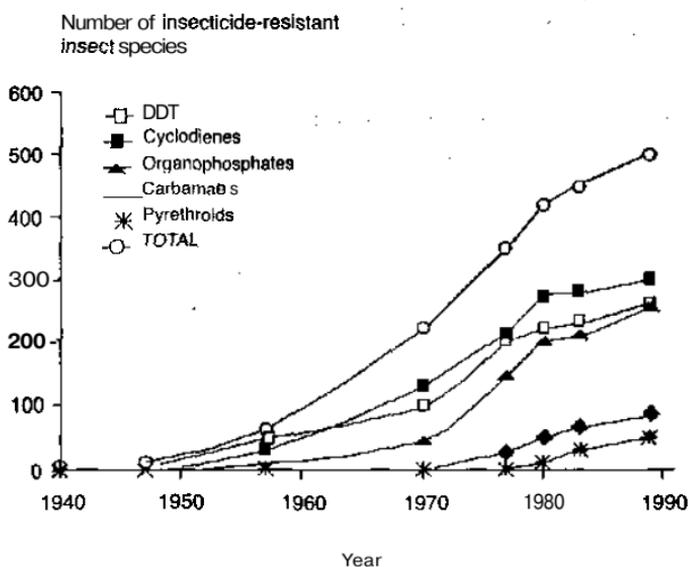


Fig. 4. Time history of the number of **insecticide-resistant** insect species in the **world** (After Metcalf and Luckmann 1994).

3.2 Resistance

Pesticide resistance involves insecticides, herbicides and fungicides (See Box 1). This phenomenon is not recent; insecticide resistance was first reported in 1914 (Metcalf and Luckmann 1994). Fungicide resistance has been of concern since modern fungicides came onto the market (Urech 1994). In the case of herbicides, a few cases of resistance had already been reported before the discovery in 1968 that *Senecio vulgaris* L. was resistant to triazines (Heap 1997).

The sharp rates of increase in the number of insect species (Fig. 4) or weed species that have become resistant to pesticides paint a telling picture. Since the 1970s, these rates have been fairly steady, despite awareness of the phenomenon of resis-

Box 1. Pesticide Resistance

It is important to distinguish between tolerance and resistance in individuals. Whereas tolerance occurs naturally, resistance is induced. Pesticide resistance results from the selection of individuals that are genetically predisposed to survive a pesticide. Cross-resistance is the phenomenon whereby a resistance mechanism for one pesticide provides resistance to a different pesticide having a different mode of action. In multiple resistance, several mechanisms simultaneously operate to produce resistance to a specific pesticide. The mechanisms involved may include:

- Behavioural resistance, which consists in avoidance of certain chemicals.
- Physiological changes, such as sequestration (accumulation of toxic substances in certain tissues), reduced cuticular permeability or accelerated excretion.
- Biochemical detoxication (called metabolic resistance), often mediated by enzymes such as esterases and mixed-function oxidases.
- Decreased sensitivity to the pesticide at the site that it normally targets (called target site resistance).

Resistance may be mono-, oligo- or polygenic. Although resistance is reversible, the rate of regression to wild levels of susceptibility depends on the mechanism involved and the degree of selection pressure. Resistance management programs are based on determining the mechanism(s) of resistance, monitoring resistance levels, implementing control methods whose mode of action differs from that of pesticides and creating refuges that will attract wild (and therefore susceptible) populations which will dilute the genome of the resistant populations.

More than 550 species of insect pests have acquired some form of resistance to chemical insecticides. Natural enemies (parasites or predators) are often more susceptible to insecticides than are insect pests, and Croft (1990) reports that only 30 species have developed resistance of some type.

tance and efforts to **implement** strategies to **check** the development of **resistant populations**. **Between** 1980 and 1990, the average rate of increase in resistance was seven insect species per year (Fig. 4) and ten weed biotypes per year (Heap 1997). Today, it is **clear** that resistance can **arise** in response to any type of **pest control** product. The occurrence of cases of cross-resistance to active ingredients that act on **different** physiological target sites, **fortunately** a rare occurrence, is **nonetheless** a factor **which aggravates** the risk of failure. **This** limits the possibilities for prolonged use of new active ingredients designed for crop protection purposes (Urech 1997). Consequently, prolonged use can no longer be envisaged outside integrated **pest management** programs designed to prevent the development of resistance. Physical control methods need to be developed and integrated to enhance **such programs**, **which** cannot at any rate be based solely on pesticide **use**.

3.3 Secondary Effects

The secondary **effects** of pesticide **use** are numerous: impacts on the **health** of humans, flora and fauna and contamination of water, soil and air. Pimentel et al. (1997a) report that, based on **official** statistics from the World Health Organization (WHO), 3 million poisonings and 220 000 deaths occur around the world annually from the **use** of pesticides. **Back** in 1969, **Simmons** (as cited in Bouguerra 1986) estimated that **there** were 150 000 poisonings and 150 fatalities annually in the United States due to insecticides. **Although** the corresponding figures are slightly lower nowadays, the most **reliable** estimates cover only **industrialized** countries. **Elsewhere** in the world, fatal accidents are probably a **more** common occurrence. In France, more than 8500 cases of **poisoning** by **pest control** products were recorded in 1991 (Harry, 1993).

Table 2. Social and environmental costs of pesticide use in the United States (Adapted from Pimentel et al. 1992).

Impact	Relative cost (%)
	(Total cost: US\$8 123 000 000 year ⁻¹) (Total cost: FF 48.7 billion)
Wild birds	25.8
Groundwater contamination	22.2
Costs associated with pesticide resistance	17.2
Crop yield losses	11.6
Public health	9.7
Decrease in natural enemies	6.4
Honeybees and effect on pollination	3.9
Government oversight (e.g. regulatory framework)	2.5
Other	<1

Economic indicators, compiled by Pimentel et al. (1992), are useful for comparing the magnitude of the different secondary effects (Table 2). Environmental costs are predominant, while costs with a direct impact on agricultural production account for 39.1% of the total (e.g. resistance, crop losses, decrease in natural enemies and pollination). The public health costs make up nearly 10% of the total.

Although economic indicators are inherently flawed (what cost can be assigned to the acute poisoning of an agricultural worker?), they make it possible to reevaluate the cost-effectiveness of employing pesticides. In the United States, \$4 billion (24 billion FF) worth of pesticides is used in producing \$16 billion (FF 96 billion) worth of agricultural products. While this outcome may appear very cost-effective, when social and environmental costs are factored into the picture, the profit margin decreases considerably (Pimentel et al. 1992).

In recent decades, the attention devoted to the secondary effects of pesticides has profoundly modified perceptions of these chemicals. Once hailed as miracle products, pesticides have come to be viewed by some people as hazards that should be banned outright or, at best, as a necessary evil. The pesticides industry has sought to modify this perception by disseminating information that puts the secondary effects into perspective. For example, it has been claimed that a glass of apple juice made from fruit treated with Alar poses a risk 58 times lower than the carcinogenic substances found in a single edible mushroom (<http://www.cropro.org/history.html>; December 1997). The industry has also responded by developing new products that meet the increasingly stringent standards designed to protect public health and the environment. These more exacting ecotoxicological criteria have driven up the development costs of new pest control products. For new chemical compounds undergoing registration, the cost of environmental impact studies tripled between 1982 and 1992 (Silvy 1992). As a result of the growing costs, few new pesticides will be registered for crops grown on relatively small surface areas because the world market is too small, nor will registration be sought where the higher profit associated with pesticide use does not offset the cost of the product concerned. For the crops involved, physical control techniques might represent a promising alternative in the near future.

3.4 Rational Pesticide Use

In all situations necessitating the use of pesticides, efforts must be made to minimize secondary effects through the wise application of chemical control, a goal which entails augmenting selectivity. In fact, lack of selectivity is the most serious drawback of broad spectrum pesticides. Selectivity can, however, be achieved in several ways (Metcalf 1994).

1. *Physiological selectivity.* Certain molecular structures augment pesticide specificity and reduce the toxicity of residues. For example, insect growth regulators, a class of natural chemicals which disrupt insect developmental patterns or cuticle synthesis, are highly effective against arthropods and non-toxic to mammals.

2. **Ecological selectivity.** Knowledge of a given pest's behaviour and dispersal and its areas of aggregation can be used to **more effectively** time applications so as to protect **beneficial** species and reduce the quantities of pesticide applied. **Localized** application of **herbicides** is based on the **same** rationale. This type of approach is viewed as highly promising, considering the possibilities offered by the global positioning system (GPS).

3. **Selectivity through improved application.** Reduced-dosage programs have been put in place over the past 10 years. This approach centres on using chemicals that degrade **quickly** (non-persistent) and applying them at the **most** appropriate time of day. Selectivity can also be achieved by adapting the formulation (**granular** applications at planting and **micro-encapsulation**) and choosing pesticides with the most appropriate **mode** of action (**systemic** or contact type). Thanks to **technological** improvements in spraying equipment (e.g. air-assistance, **specialized nozzles**, **electrostatics**), operators **now** have a range of options to choose from in carrying out various treatments.

4. **ti behavioural selectivity.** This strategy involves using traps in order to **make** applications at the most **effective** time.

4 From Pesticides to Integrated Pest Management

In **light** of the pesticide resistance developed by many plants and animals and the deleterious effects of these chemicals on the environment, **human** health and **agri-**culture, it is now widely **acknowledged** that pesticides are not a panacea for protecting plant life. Control strategies for crop pests **incorporating** a variety of complementary techniques appear to offer **much** better chances of success than does exclusive reliance on synthetic pesticides (Metcalf and Luckmann 1994). Integrated **pest** management (**IPM**) is an approach that involves selecting, integrating and applying control methods for crop pests based on predictions of the **economic**, **ecological** and **social** effects (Anonymous 1986). This integrated approach should to take into account the concerns associated **with** the **use** of toxic chemicals in the **natural** environment.

The concept of **integrated pest** management centres on the ecosystem, that is, the **relationships** between **living** organisms and their environment or **habitat**. In the beginning, **this** strategy **was** aimed at reducing pesticide applications and minimizing secondary effects. In Quebec **apple** orchards, for example, the number of insecticide applications per season **has** fallen from over six to at most three **without** increasing the average damage **level** at harvest. Subsequently, the progress achieved in harnessing **natural** enemies for **biological** control has resulted in a **shift** from simple **pest** management to integrated **pest** management. Introductions of **natural** enemies of pests, for example phytoseiid **mites** which prey on harmful spider **mites** (Tetranychidae), played a decisive role in the implementation of integrated **pest** management strategies (IPM programs). **Typhlodromous** strains that are resistant to **organophospho-**

Box 2. Integrated Management of Weeds

Integrated management programs should be developed for weed control in order to reduce chemical inputs and curb the amount of herbicide residues in soil, water and agricultural products. It is also imperative to avoid inducing resistance through the prolonged use of chemical agents. Application of the principles of sustainable agriculture in weed control has been slow because of the difficulty of making generalized predictions like those derived for insect pests primarily on the basis of climatic data. General advices cannot be produced for weed species because predicting the infestation dynamics of a given field depends above all on its past history (Debaeke 1988). In addition, the diversity of weed species is enormous and cannot be compared with the small number of truly harmful insect pests. This flora is the site of diverse crop plant-weed species interactions and interactions between different weed species, which complicate the task of setting action thresholds.

Achieving a better understanding of the biology, life cycles and dynamics of weed populations is the foundation of integrated weed management (Debaeke 1997). To implement this approach, it is necessary to provide training for IPM managers and to make decision-support tools available to decision-makers (e.g. software programs for identifying weed species) along with tools that provide information on species ecology (Marnotte 1995). Expert systems are being developed that cover all the stages involved in making treatment decisions: inventory of species, evaluation of yield loss, choice of chemical, cost of treatment (Stigliani et al. 1993). Criteria have been devised for assessing the environmental risks associated with each type of active ingredient (Gillet and Dabene 1994); these could soon be incorporated into decision-support expert systems (Debaeke 1997). The main stumbling block in terms of moving from today's chemically based weed control practices toward an integrated management approach is the difficulty of incorporating various control measures into a technically coherent program, guided by an expert system. Work is still under way to attain this goal.

rous insecticides have made it possible to use chemical and biological control together. This combination of techniques has proven successful in previously uncontrollable situations where the prevailing conditions were too unfavourable for introduced beneficial species. More recently, integrated pest management has given way to sustainable agriculture (Cross, 1997), particularly in orchards, by incorporating social aspects (e.g. consumer demands, health protection issues related to workers who apply pesticides and environmental issues) and ecotoxicological concerns, such as preventing adverse effects on pollinators. These considerations has helped to further reduce reliance on pesticides.

Theoretically, integrated pest management can accommodate any type of crop protection technique (Fig. 1) based on its particular merit in a known situation. The move to integrated pest management began with classical biological control. The development of biopesticides is a distinct component of biological control. As we will show in this book, a number of physical control techniques likewise offer sufficiently attractive advantages and benefits to enrich the IPM arsenal.

4.1 Biological Control

In a sustainable agriculture context, biological control (taken in its broadest sense) provides many alternatives to the use of synthetic insecticides (Vincent and Coderre 1992; Hokkanen and Lynch 1995; Van Driesche and Bellows 1996; Jervis and Kidd 1996). Biological control is underpinned by several fundamental theories, including population dynamics theory and optimal foraging theory. In practice, the application of biological control often hinges on a multitude of actions and complex and detailed information.

Biological control gathered a great deal of enthusiasm in the early 20th century because of the success obtained with *Rodolia cardinalis* (Mulsant) in California (Caltagirone and Doutt 1989). This type of approach is attractive from a scientific standpoint and it is viewed favourably by the general public. In spite of this, biological control has generated only a few commercial successes during the 20th century because of its own limitations (Greathead 1995).

Table 3. Biological control strategies (After Cloutier and Cloutier 1992).

-
1. Use of inert biocides (biotoxins of microbial origin)
 2. Use of autonomous biocides (microbial or animal control agents)
 - A. Direct manipulation through the release of natūrai enemies into the environment
 1. Introduction of exotic control agents (classical biological control)
 2. Mass release of control agents with demonstrated efficacy
 - a) Inoculative release (preventive control)
 - b) Inundative release (curative control)
 - B. Indirect manipulation by changing the environment
 1. Protection of natūrai enemies through specific measures
 2. Provision of supplementary hosts/prey insects at a low density
 3. Provision of food resources or favourable niches (shelter)
 4. Crop rotation (weeds, nematodes, disease)
 5. Chemical stimulation of the activity of control agents
-

There are several different biological control strategies (Table 3). The first, which involves the use of inert biocides, is the biopesticide approach (next section). The second strategy consists in employing autonomous biocides, which can be released using a classical control approach (i.e. inoculative or inundative releases). Biological control can also be enhanced through environmental manipulation.

4.2 Classical Biological Control

Variability is an inherent and fundamental characteristic of biological organisms and constitutes one of the major limitations of biological control. For example, Lewis et al. (1990) have stated that the performance of parasites as biocontrol agents is often erratic. Among other things, this situation is linked to the parasites' foraging behaviour, which is a function of their genotypical and phenotypical diversity, their physiological condition and the environment in which they are living. These variables have a limiting effect in a commercial context where standardization and quality control are acquiring ever-greater importance.

The augmentation of natural enemies as part of a biological control program can lead to undesirable side effects if insects shift to a non-target species. In biological control of weeds, for example, if the biocontrol agent damages the cultivated plant species as well, the net result may be negative. A change in the hierarchy of risks is another potential consequence that must be carefully weighed. Once a crop pest has been brought under control, another species which is normally a secondary pest may benefit from the absence of competition. In such a case, this pest may cause serious damage that can no longer be ignored.

A major problem with biological control is its incompatibility with chemical control, since natural enemies of insects are often more susceptible to the pesticides applied than are the insect pests themselves (Croft 1990). Releases of natural enemies can, however, be alternated with insecticide treatments.

Biological control is not suitable in all crop protection contexts. There are many situations in which this type of approach does not work. For example, it is not effective against the tarnished plant bug, *Lygus lincolaris* P. de B., as discussed in Chapter 19 of this book. The cost-benefit ratio is the main drawback, since it is much higher for biological control than for chemical pesticide.

4.3. Biopesticides

Among the different tools of biocontrol, biopesticides (Table 4) hold a leading position because they often can be mass produced, which is a prerequisite for industrial use, and they can be applied with a conventional sprayer, which facilitates their adoption by agricultural producers. They are generally compatible with classical biological control methods (e.g. releases of predators or parasites), although they may have adverse effects on beneficial organisms (Giroux et al.

1994, Roger et al. 1995). Biopesticides may be composed primarily of bacteria, fungi, viruses, nematodes or plant extracts.

Until the early 1980s, most studies of biopesticides were based on the classical principles of pathology, as described in Tanada and Kaya (1993). The advent of molecular biology techniques gave a tremendous boost to biopesticide development. The creation of transgenic plants, for example those that may manufacture their own protective toxins from *Bt* crystal proteins, represents an important achievement. It was announced in a fall 1984 press release by the Belgian firm Plant Genetic Systems (PGS), and subsequently detailed in a scientific publication (Vaeck et al. 1986). Transgenic corn (a genetically modified organism, or GMO), in which the *CryIA(B)* gene that codes for a protoxin protein has been inserted, is now commercially available in Europe and North America (Novartis 1997).

Table 4. Examples of biopesticides developed for use in controlling pests and weeds.

Class of biopesticide	Organism
1. Entomopathogenic bacteria	<i>Bacillus thuringiensis</i> Berl.
2. Mycopesticides	<i>Metarhizium anisopliae</i> and <i>M. flavoviride</i> <i>Beauveria bassiana</i> , <i>B. brognardtii</i> , etc.
3. Entomopathogenic viruses	Baculovirus (e.g. Carpovirusine)
4. Bioherbicides	<i>Colletotrichum</i> spp. (Waage 1995).
5. Micro-organisms antagonistic to pathogens	<i>Trichoderma</i> spp.; <i>Gliocladium</i> spp. <i>Pseudomonas</i> spp.
6. Entomopathogenic nematodes	Genera <i>Steinernema</i> and <i>Heterorabditis</i>

There are several ways to enhance the efficacy of biopesticides. One method consists in finding more virulent strains of the candidate species. Alternatively, efforts can be devoted to developing formulations with extended persistence in the field or incorporating synergistic chemicals which are non-toxic at the doses applied but greatly increase the toxic effect of the biopesticide (Bernard and Philogène 1993). Finally, transgenic plants may offer continuous or modulated protection (depending on the genetic expression systems employed) against insects.

The biopesticide that has had the greatest commercial success, *Bacillus thuringiensis*, now accounts for about 1.5% of the world insecticide market (Peferoen 1991). *Bt* is not a panacea, given the small number of species against which it is effective and its lack of stability in the field. Since it has to be ingested, it is only useful once pests have begun feeding. Furthermore, the development of *Bt*-resistant populations has been observed in several insect species (Tabashnik 1994).

The scientific criteria used to determine the safety of synthetic pesticides are also applied to natural pesticides (Coats 1994) within the same regulatory framework for registration. The legislation in industrialized countries has become so constraining and restrictive that private-sector companies are now reluctant to work on registering

new synthetic pesticides. Riba and Silvy (1993) and Powell and Justum (1993) suggested that pathogen-based biopesticides should be subject to less stringent standards than synthetic insecticides in terms of the information required for registration. According to Powell and Justum (1993), the four elements governing the commercial success of a biopesticide are:

1. occupation of a commercial niche in which synthetic chemicals are ineffective or unacceptable owing to specific production principles (for example, in organic farming),
2. an environmental niche where there is protection from UV radiation, desiccation and extreme temperatures,
3. an environmental niche where the biological agent provides an advantage in terms of colonization,
4. a commercial niche where a small amount of damage can be tolerated.

Box 3. Biological Control of Fungal Diseases

Soil-dwelling bacteria of the genus *Pseudomonas* are beneficial to plant health and provide effective protection against certain root diseases (e.g. *Thielavopsis basicola* in tobacco). Genetically modified (GMO) strains of *Pseudomonas* have been introduced that have a greater root colonizing ability than antagonistic flora which have not received a boost from genetic engineering. Initial applications of this biocontrol agent to wheat roots have shown that the risk of indigenous (natūrai) flora being displaced is low (at season's end, less than 2% of roots were colonized by the genetically modified *Pseudomonas*; Weller et al 1983). However, the results may vary depending on the soil type, crop type and possibly the variety.

Biological control of leaf diseases may be feasible using natūrai antagonists of the causal pathogen, following an approach similar to that used for insect pests. The phyllosphere is composed of yeasts (mainly the genera *Sporobolomyces* and *Cryptococcus*), bacteria and a few fungal hyphae (e.g. the genus *Cladosporium*; Blackeman 1985) that are potential candidates for that purpose.

Trichoderma, a soil fungus, has proven effective in checking the development of *Botrytis cinerea* on grapes, strawberries, apples and tomatoes (Dubos 1987). *Gliocladium roseum* can also be used for preventive control of *Botrytis* in strawberry (Peng and Sutton 1991). In biological control of fungal pathogens of grapevines, fungicide use can be reduced by about 50% even though it is impossible to reduce fungicide use below five to eight applications during the vegetative phase.

Some fungi that are hyperparasites of pathogens are also the focus of intensive research activities: *Ampelomyces quisqualis*, *Tilletiopsis* spp., *Verticillium lecanii* (A. Zimmerm.) Viégas and *Stephanascus* are the most common ones. Drought-resistant mutants are also being sought to stimulate the action of these hyperparasites on pathogenic fungi.

5 Physical Control Methods in Agricultural Production

Physical control in crop protection comprises all pest management techniques whose primary mode of action excludes biological and biochemical processes. In contrast, **all** other methods of control are only effective where an interaction is **established** between the target pest (through physiology, behaviour, ecology) and the control agent. Sometimes, in physical control, the primary action has a direct impact, such as when insects are killed immediately by mechanical shocks. In other cases, the desired effect is attained through the stress responses that are induced.

The use of physical control methods needs to be incorporated into an integrated pest management strategy. Like any pest management approach, physical methods have certain strengths and weaknesses, and some of them are likely to have secondary effects on fauna and flora. In an **IPM** context, the decision to employ a physical control tactic must therefore be made on a case-by-case basis according to the same criteria as in decision making regarding the appropriateness of pesticide applications: efficacy, cost-effectiveness and undesirable effects. In addition, no physical control technique is sufficient on its own for all pest control treatments in a given crop. While the self-sufficiency of pesticide applications for crop protection systems is the primary strength of chemical control, it is probably also the Achilles' heel of the chemical approach, given the fact that chemical applications tend to accelerate the development of resistance and slow down the introduction of alternative control tactics. Integrated pest management offers the only hope of avoiding the pitfalls of relying on a single approach. Moreover, it simultaneously opens up possibilities for the commercial application of physical control methods. It is important to distinguish between the two basic types of physical control methods: active and passive methods. Active methods consist in using some form of energy to destroy, injure or induce stress in crop pests or to remove them from the environment. This type of approach has an effect at the time of application, with virtually no residual action. Passive methods, on the other hand, cause changes in the environment and have a more lasting effect. Physical methods of control can also be classified according to the mode of energy use. That is the classification which has been used in this book. Four categories have been established: mechanical control, thermal **control**, electromagnetic control and pneumatic control. It would be quite conceivable to add other categories, as appropriate, such as acoustic control and thermodynamic control.

There is no clearcut relationship between categories of physical control methods and the broad groups of crop pests: weeds, insects, mites and microscopic pathogens. Obviously, there are some natural associations, such as the use of mechanical control against weeds (tillage); however, in almost every case at least one method in the different control categories applies to a specific group of crop pests. Pneumatic control is an exception to the rule, however, because it is limited to insect control.

5.1 Physical Control of Weeds

Physical control of weeds is based on the use of several techniques. Active methods include manual weeding, hand pulling, mowing, thermal methods (electricity, microwaves, and heating or cooling) and tillage. Mulching and flooding are classified as passive techniques.

Manual weeding and hand pulling are commonly used around the world (see Chap. 13). An estimated 50 to 70% of agricultural producers use this type of weed control (Wicks et al. 1995). Pulling is generally done by hand, although various tools are available for mechanically removing weeds that are higher than the crop plants (Wicks et al. 1995).

Grazing and mowing can also be used for weed control. This approach is often applied in controlling orchard vegetation and in promoting the establishment of forage crops. Mowing allows forage species to grow taller than the weeds and become better established. In orchards and vineyards, this technique is useful for controlling weed height and minimising competition with the crop plants (Kempen and Greil 1985).

Mulches (see Chap. 15), which are frequently used to suppress weed growth, are applied before or after crop establishment. Mulches can be divided into two groups: mulches made of natural materials and synthetic mulches. These types of products prevent weed emergence by forming a physical barrier and blocking sunlight. In hot, sunny regions, plastic mulches can also be employed to destroy weeds through solarization (Braun et al. 1988; Silveira et al. 1993).

Thermal methods consist in applying high or low temperatures in order to destroy weeds. Electricity (see Chap. 12), infrared radiation, microwaves, hot water, steam and flame weeding (see Chap. 2 and 3) are all techniques that employ high temperatures to kill weeds (Ascard 1995). Flame weeding can be done in a non-selective manner throughout the field, or selectively by directing the burner at weeds while taking care not to damage crop plants.

Water can be used for weed control in rice crops (*Oryza sativa* L.) and cranberry crops (*Vaccinium macrocarpon* Ait.). Total submersion of weed plants kills them through asphyxiation. This technique is very effective in limited agricultural contexts and under suitable conditions (Schlesselman et al. 1985).

Tillage is the second most widely used physical control technique for suppressing weeds. Tillage is divided into primary, secondary and tertiary methods. Whereas primary methods of tillage are designed to prepare the field for crop establishment, secondary methods prepare the seedbed. Tertiary techniques consist of hoeing and cultivation operations performed throughout the season. There are many types of cultivators, which have proven effective for weed control in the majority of crops; in some situations, they are the only tools available for this purpose or the primary alternative to herbicide use (Chap. 13 and 14).

5.2 Physical Control of Insects and Mites

Physical control methods for insect pests comprise a number of technologies, some of which are based on active methods: thermal shock (heat), electromagnetic radiation (microwaves, infrared and radio frequencies), mechanical shock and pneumatic control (blowing or vacuuming tools). In the field, physical barriers represent the only passive technique available.

Various applications that employ thermal shock for crop protection in the field have been developed and research is continuing in this regard (see Chap. 4). This type of approach is nonetheless based on the premise that the commodity or crop to be protected will be less sensitive than the target pest to an abrupt change in temperature. Research on thermal sensitivity thresholds (Chap. 2) and physiological reactions to short-duration thermal stresses is central to the development of control methods based on thermal shock.

Several avenues have been explored for applying the different forms of electromagnetic radiation as a tool for controlling insects. Non-ionizing electromagnetic radiation (see Chap. 7, 8 and 11) kills insects by raising their internal temperature. The utilization of radio, microwave and infrared frequencies is based on a principle similar to that of thermal shock methods except that, with applications involving electromagnetic radiation, the transfer of energy occurs without using a heat transfer fluid. Technologies that harness electromagnetic radiation are often too expensive for use in the field. Furthermore, existing regulations restrict the available frequency bands, either for reasons of user and environmental safety, or because certain frequency bands have been set aside for specific applications that do not tolerate interference (e.g., microwave-based landing guidance systems for aircrafts).

There is a wide variety of physical barriers used as physical control techniques (see Chap. 15 and 16). The technologies associated with physical barriers can be applied in the field or in greenhouses. Barriers used in the field can take several forms (trenches, vertical nets, etc.) and can be deployed on a range of scales to protect either a complete field, a crop row or a group of plants.

Pneumatic control consists in using an airstream to dislodge insect pests (see Chap. 18, 19, 20 and 21). Insects that are removed by vacuum are killed when they pass through the moving parts or the blower (mechanical shock). After being dislodged by a blowing device the individuals are injured and die because they are unable to climb back onto the host plant. Other machines are equipped with a device for collecting the dislodged insects, which are subsequently killed. Sound knowledge of the target insect's behaviour is necessary in order to enhance the effectiveness of this type of approach.

5.3 Physical Control of Microscopic Pathogens

There are fewer scientific studies dealing with the application of physical control in the area of plant pathology. The research described in Chapter 9 demonstrates

how a physical control approach can be used against *Botrytis* in the greenhouse. The treatment employs polyethylene films that have the ability to filter out specific parts of the solar radiation spectrum. It is therefore a passive technique based on the use of a physical barrier. Researchers have tested a microwave treatment for eradicating *Fusarium graminearum* Schw. in wheat seed (Reddy et al. 1996), and similar trials have been conducted by the same team with the aim of suppressing *Ustilagonuda* (Jens.) Rostr. on barley seeds. In potato growing, a fungicide is often used in combination with a chemical defoliant as a sanitary measure to prevent the spread of *Phytophthora infestans* (Mont.) de Bary to the next crop grown in the infected field. Thermal top killing, used instead of chemical defoliation, significantly reduces the viability of *P. infestans* present in the foliage at the time of treatment (Désilets et al. 1996).

6 Post-Harvest Physical Control

In long-term storage of non-perishable agricultural commodities (seeds and grain, dried fruits, by-products, dried and dehydrated plants, spices, herbs, coffee, cocoa, etc.), the most serious losses are due to the action of insects and mites or the spoilage by certain microorganisms (fungi). All other organisms have a negligible effect (Fig. 5). Chemical control using highly persistent insecticides is the most commonly used approach at present for preventing damage by insect pests to grain and seed. Some of the benefits of this strategy are its low cost, ease of implementation and protection that lasts for several months, until the quantity of active residues falls below the lethal threshold for the target species. However, regular use of insecticides entails serious problems such as the possibility of creating resistant strains and the risk of exceeding maximum residue limits (MRL) owing to multiple applications of insecticides by different players in the commercial grain system. This situation is problematic, because pesticide residues resulting from improperly applied procedures create a bad impression among final consumers. When residues are found, pressure is exerted by both the processing industry for which the treated grain is destined and by informed consumers to ensure that chemical treatment is restricted to situations of absolute necessity and to guarantee residue-free finished products. Strategies for using insecticides with an extended residual action (these products are authorized solely for bulk grain) involve risk assessment prior to each application and an evaluation of the results taking into account the economic cost and the potential loss of markets.

This situation has spawned many studies worldwide over the past 20 years on physical procedures for preventing infestations and protecting inventories of stored agricultural products from insect pests, and on the use of such methods in food processing plants. Physical control applications developed for post-harvest treatments have focussed on procedures for controlling physical conditions in stocks of stored grain (temperature and water content; see Chap. 5, thermal (Chap. 5 and 11) or mechanical shock (Chap. 17), the establishment of extreme conditions for insect

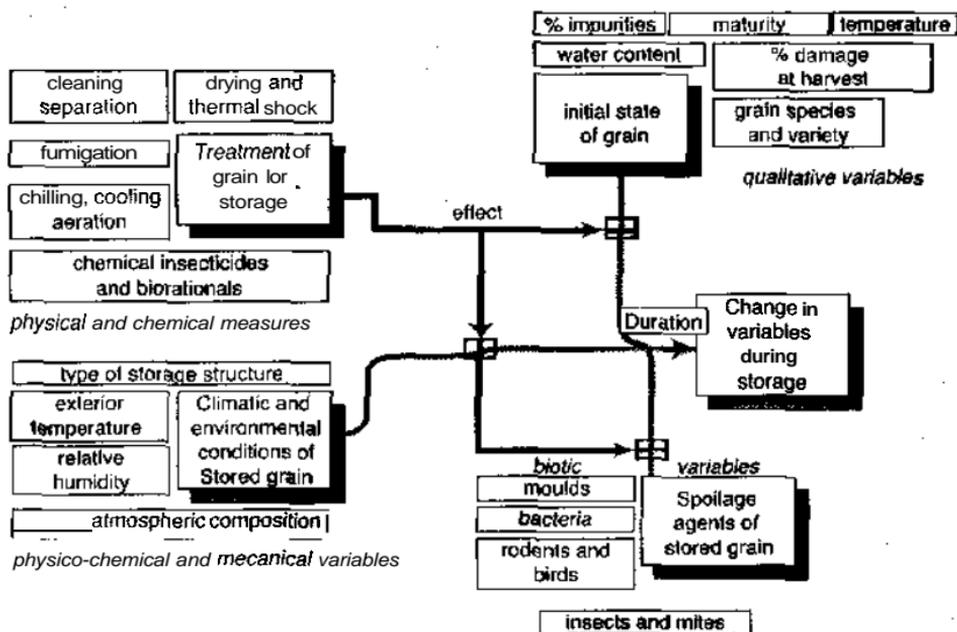


Fig. 5. Key components of the stored grain ecosystem and associated interactions, along with effects on spoilage agents and final quality (for industrial processing).

pests (anaerobiosis, pressure and modified atmospheres; Chap. 5), the use of abrasive or dehydrating minerals (Chap. 17) and the erection of physical barriers to keep insects out (Chap. 17). Post harvest control approaches are essentially based on passive methods, although thermal and mechanical shock treatments are exceptions. In post-harvest situations, most physical methods are suitable solely for prevention against pest and hence cannot be compared with classical chemical control. A thorough knowledge of integrated pest management strategies is required, since these techniques afford no protection following application, unlike persistent insecticides. Practical use of physical control necessitates multiple verifications and supporting data, particularly in relation to secondary effects on the quality of treated products (for example, the germinating power of malting barley or the baking quality of bread-making wheat). Nonetheless, the prospect of registration reviews for several insecticides (e.g. dichlorvos, methyl bromide) that are currently used in post-harvest protection of raw foodstuffs or in processing and storage facilities for intermediate or finished products has revived interest in post-harvest physical control. Furthermore, since the use of persistent contact insecticides on processed food products (e.g. wheat flour, semolina, dried fruit) is prohibited worldwide, the industry has to rely exclusively on fumigants or physical procedures to eradicate insects in such products. Fumigants are used only marginally in many developed countries like France, the United Kingdom and Canada, and their use is likely to decline further when methyl bromide production and use are pha-

scd out, sometime between 2002 and 2005. In view of this situation, physical control is the only **strategy** likely to ensure successful outcomes in the highly specific context of **pest** and **mite** suppression for **post-harvest** food stocks (Jayas et al. 1995). Physical methods hold promise as a complement to chemical pesticides, and a means of moving away from the excessive reliance on chemical control, which is being called into question increasingly and is no longer justified today. Furthermore, the most accessible physical methods for this pest management sector, such as dry heat treatments or airtight storage using inert gases, should help to diminish the secondary risk of spoilage of raw foodstuffs by storage moulds, which is something that cannot be achieved with chemical control measures.

7 Conclusion

Physical control deserves to be recognised as a well-defined area of expertise as is the case for biological control. This recognition is bound to come as the quest for alternatives to chemical pesticides intensifies. Although physical control went out of use with the advent of chemically based pest control methods in the middle of the 20th century, the limitations of pesticide use, coupled with the difficulties of implementing biological control, have created a crossroads for the renewed development of physical control.

Practical application of physical control methods requires collaboration among professionals trained in fields that are often quite distinct and separate. For example, a physicist specializing in electromagnetic energy might be expected to work with an expert in plant physiology or an entomologist. These individuals have acquired expertise in different branches of science and they use different languages and work tools. Furthermore, research activities are organized in such a way that these persons undoubtedly work in different laboratories, pursuing goals that are often incompatible. In spite of this state of affairs, most of the studies described in this book are the fruit of collaborative efforts among persons working in very different areas of research.

It is our hope that this book, the first of its kind on the use of physical control methods in crop protection, will help to raise the **status** of physical control to that of a true field of research, development and application; promote fruitful initiatives and collaborative work; and provide guidance to individuals interested in making it their field of endeavour.

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Thermal Control Methods

Thermal Control in Plant Protection

Claude LAGUË, Jacques GILL, Guy PÉLOQUIN

1 Introduction

This chapter presents the status of the use of thermal control in plant protection. After a brief presentation of the operating principles of thermal control, a review of the most important milestones in the evolution of this technology is presented. The different uses of thermal control in plant protection are presented along with the criteria that are used when evaluating the performances of the different types of equipment used. A description of the different modes and strategies of application of thermal control follows. A discussion about the environmental impacts of thermal control, as compared to those of pesticides, closes this chapter.

2 Principles of Thermal Control

2.1 Effects of Temperature on Living Organisms

For plant protection purposes, thermal control of insects is generally aimed at inducing internal injuries that will lead to death over a short period of time. Heat treatments leading to internal temperature increases of 50 to 100 °C for at least 0.1 s will result in either heat-induced rupture of the cell walls or in the coagulation of cell proteins (Pelletier et al. 1995; Morelle 1993). Similarly, reducing the temperature of these living organisms below freezing will lead to similar injuries caused by the crystallization of the cells content (Fergedal 1993) (See Box 1).

2.2 Thermal Sensitivity

The efficiency of a thermal control treatment aimed at a specific target can be evaluated using two parameters: (1) the amount of heat transferred between the ther-

Box 1. Heat and Temperature in Thermal Control

Thermal control in plant protection relies on heat transfer between two bodies (the thermal control apparatus and the agricultural pest to be controlled) that have different temperatures. Temperature is an indicator of the quantity of thermal energy contained within a physical body. One will refer to heat treatments when the temperature of the thermal control apparatus is greater than that of the pest to be controlled and to cold treatments in the opposite situation. In the first case, the purpose of thermal treatments is to increase the thermal energy of the pests while cold treatments are intended at reducing their thermal energy. In both cases, the heat transferred between the thermal treatment apparatus and the pest is equal to the quantity of energy effectively exchanged during the heat transfer process.

mal control equipment and the targeted organisms and (2) the duration of exposure of the targeted organism to the thermal control treatment. For a given equipment, the heat transferred is proportional to the combustion rate of the fuel used (for heat treatments) or to the refrigerating power of the cooling apparatus (for cold treatments). The exposure time depends on the field travel speed or on the operating time of the apparatus if it is stationary (e.g. during crop storage). The increase or decrease in temperature of the targeted organisms is a result of both parameters. The exposure temperature can be used as an indicator of the thermal sensitivity of different living organisms (Laguë et al. 1997).

Different species of weeds, insects or crops respond differently to a given thermal treatment due to physiological differences (Ellwanger et al. 1973a,b). Morelle (1993) reported that broadleaf weed species are more sensitive to thermal treatments than grasses and that perennial weeds are the most resistant. The thermal sensitivity of most living organisms varies according to their stage of growth (Leroux et al. 1995; Ascard 1994). Since young weed plants are generally more heat-sensitive, this can translate into substantial energy savings when thermal weeding is done early in the season.

An appropriate knowledge of the thermal sensitivity thresholds is thus a prerequisite to the development of efficient thermal control systems for plant protection (Leroux et al. 1995). For some applications, only the thermal sensitivity of pest organisms (e.g. pre-planting or pre-emergence thermal weeding) or of the crops (e.g. thermal top killing of mature potato plants, thermal renovation of lowbush blueberry plants) need to be determined. For selective applications (e.g. post-emergence thermal weeding, thermal control of pest insects present on the crop), the crops must tolerate the temperatures required for control of the pests. Many selective applications of thermal control have been successfully implemented: control of alfalfa weevil (Blickenstaff et al. 1967); post-emergence thermal weeding in corn (Lien et al. 1967), potato (Hansen et al. 1968) and in some horticultural crops (Chappell 1968). An appropriate knowledge of the thermal sensitivity

thresholds of the crops and of the pest **organisms** is required for development of an optima) thermal control strategy (Leroux et al. 1995). When these thermal sensitivity thresholds are very close, it may be necessary to refine the heat transfer between the thermal control equipment and the target or to **physically** protect the crops from the heat (Parish 1995).

3 Background

Thermal control in crop protection was introduced almost a century ago (Edward 1964). This author reports that many patent **applications** were filed from 1900 to 1940 for thermal weeding equipment and systems for thermal control of pest insects. Large scale use of thermal control was initiated in 1940 in US cotton production (Kepner et al. 1978). It was also at that time that liquified petroleum gases, mainly propane and butane, started to replace the kerosene and oils that were then used as fuels for the thermal control systems (Edward 1964).

Significant research on **practical** applications of thermal control in plant protection was conducted between 1940 and the mid-1960s, mainly in the USA. Thermal weeding was investigated for peanuts (Parks 1964), cotton (Matthews and Tupper 1964; Parks 1964), beans (Parks 1964), alfalfa (Thompson et al. 1967), corn (Albrecht et al. 1963; Parks 1964; Reese et al. 1964), sorghum (Reese et al. 1964), and soybeans crops (Matthews and White 1967; Parks 1964). Parks (1964), Chappell (1968) and Hansen et al. (1968) reported that thermal weeding of vegetable crops such as lettuce, broccoli, cauliflower, onions and potatoes was also studied. Work was also done for some small fruit production, mainly blueberry, strawberry and grapes (Hansen and Gleason 1965), and in **ornamental** horticulture (Wolfe and Horton 1958). Thermal weeding of irrigation and drainage ditches has also been considered (Lowry 1965). Thermal defoliation of cotton plants prior to harvest, either by direct exposure of the plants to the flames (Batchelder et al. 1973; Kent and Porterfield 1967) or by **infrared** radiation (Reifschneider and Nunn 1965), pre-harvest field drying of sorghum (Parks 1964; Reese et al. 1965), and thermal control of pest insects in alfalfa fields (Harris et al. 1970; Thompson et al. 1967) are among the other applications investigated during that period.

At the same time, many efforts were devoted at evaluating and optimizing the design parameters of thermal control equipment. Research concentrated on the general design of thermal weeders (Batchelder et al. 1970), the study of heat **distribution** in the vicinity of different types of burners (Harris et al. 1969; Page et al. 1973), the economic evaluation of thermal weeding (Parks 1964), and the use of liquid or gaseous shields to concentrate the action of the burners and to protect the crops from the heat (Kepner et al. 1978). Parks (1964) estimated that there were 15 000 thermal control units in use for different row crops in the USA alone in 1964.

The introduction of efficient and economical pesticides started in the 1950s and has been directly linked to the loss of interest for thermal control (Daar 1987; Kepner

et al. 1978). These authors reported that only a limited number of cotton growers in the southwestern part of the USA were still relying on thermal weeders to control herbicide-resistant weeds. Lambert (1990) also reported that thermal renovation of lowbush blueberry plants has continued to a certain extent until now.

4 Modes of Intervention in Thermal Control

Three different techniques may be used to expose pests to high temperatures: direct exposure to flames, use of infrared radiation or steam projection. For cold temperature control, powerful refrigerating systems are needed. The remainder of this chapter deals only with the use of high temperatures.

4.1 Direct Exposure to Flames

The equipment used for directly exposing pests to flames are similar to agricultural sprayers. They incorporate a pressurized liquid fuel reservoir, a network of pipes and hoses that carries the fuel to the burners, pressure regulators and flow controllers, and a number of individual burners where the chemical energy of the fuel is converted into heat (Kepner et al. 1978). The pests to be controlled are directly exposed to the flames generated by these burners.

Two types of burners may be used: liquid burners that incorporate their own fuel atomiser and vapor burners requiring an external atomiser located upstream from the burners. Well-designed burners generate thin flames of constant cross-section having a relatively uniform temperature profile. This allows for constant and uniform temperature rises corresponding to the thermal sensitivity of the organisms to be controlled.

Different types of thermal weeders may be used, depending on the characteristics of the crops and weeds to be treated. For field crops or row crops that are more resistant to heat than the weeds, it is possible to use thermal weeders that generate a uniform temperature rise at the soil level across the whole width of the implement. For more sensitive row crops, in-row thermal weeding can be achieved by orienting the flames of the burners toward the base of the rows, thus reducing the exposure of the crop canopy to heat. Precise guidance systems are often required to maintain proper alignment of the implement relative to the crop rows during field operation (Kepner et al. 1978). Ascard (1992) and Parsish (1989a) reported that in-depth evaluations of different types of thermal weeders were conducted in Europe.

4.2 Exposure to Infrared Radiation

In this technique, the burner flames are directed toward a metallic or ceramic surface that reflects infrared radiation toward the organisms to be controlled (Parish

1989b). This prevents direct exposure of the crops to the flames. For maximum efficiency, the generated infrared radiation must be concentrated within a narrow spectral band corresponding to maximal absorption by the pest insects or weeds targeted by the treatments. According to Parish (1989b) and Lewandowski (Chap. 7), infrared radiation in the 1.44 - 1.93- μm band is very efficient against organisms with a high body water content since it corresponds to infrared absorption band of water. However, the heating rate is not high and a rather long period of exposure is needed to control the pests. This limits the possible operating speed of such equipment in the field, which, in turn, limits the interest for this technique.

4.3 Use of Steam

Thermal control equipments using steam as the heat transfer medium have also been developed by the Aquaheat corporation of Minneapolis, Minnesota. These machines use burners that evaporate water in order to generate steam that is then projected towards the pests to be controlled. These machines are mainly used for weeding applications. In addition to fuel, they also require a large water supply, which increases their complexity and operating costs.

Kepner et al. (1978) reported that the fuel consumption of most burners used in the 1960's ranged from 7.5 to 15 $\text{l}\cdot\text{h}^{-1}$ of liquid propane, either for burners used on flaming implements or on those used on infrared machines.

5 Performance of the Field Equipment

The various field equipment used in thermal control must be designed and evaluated using three main criteria: (1) ability to transfer heat uniformly and in a controlled manner to the targets, (2) energy requirements, and (3) emission of pollutants.

5.1 Heat Transfer

The ability of thermal control equipments to maximize the transfer of heat toward the targeted pests while minimizing the negative impacts of the heat treatments on the crops is their first performance criterion. Data relative to the temperature profile within the flames generated by different burners used on flammers allow for the evaluation of the uniformity of heat distribution, the geometry of the flames and the maximal temperatures of exposure in relation to the operating fuel pressure (Laguë et al. 1997). Such data can be used to identify the most appropriate type of burner and the proper burner arrangement on the machine for either localized or full coverage treatments. The determination of the thermal sensitivity thresholds of the different living organisms of interest (crops, weeds, insects) requires data on the temperature of expo-

sure recorded during field or laboratory experiments. For example, full coverage thermal weeding requires data on the temperature of exposure of both weed and crop plants recorded at the soil level. For post-emergence treatments, it is also required to record the temperatures at which the different parts of the plants are exposed. It is thus important to determine the temperature rises at the different locations corresponding to the targeted organisms as a function of the operating parameters of the thermal control equipment (type, location and orientation of the burners; operating speed of the implement; fuel pressure). This allows for the optimization of the design of the equipments. For each type of equipment, charts that relate the temperature rises at the target level to the operating parameters of the machine can be developed to assist the operators in the proper adjustment of their equipment (Laguë et al. 1997).

5.2 Energy Use

The operating costs of most thermal control equipments depend largely on their fuel consumption. Fuel consumption varies with the type of burner used and their operating pressure. Laguë et al. (1997) have demonstrated that fuel consumption is directly proportional to pressure according to:

$$Q = ap, \quad (1)$$

where Q : unit fuel consumption of one burner (kg h^{-1})
 p : operating pressure of the burner (kPa)
 a : constant ($\text{kg h}^{-1} \text{kPa}^{-1}$),

The unit fuel requirements for a given thermal control treatment can then be easily determined:

$$q = 10 \frac{Q}{ve} = 10 \frac{ap}{ve}, \quad (2)$$

where q : unit fuel requirements of the thermal control treatment (kg ha^{-1})
 v : field operating speed of the machine (kmh^{-1})
 e : spacing between the burners (m)
 10 : conversion factor.

For banded thermal control treatments, the spacing between the burners, e , is obtained by dividing the row spacing by the number of burners used on each row. Laguë et al. (1997) have determined that the value of the constant a , found in eq. (1) and (2), ranges from 0.019 to 0.025 for three different types of open-flame burners.

5.3 Emission of Pollutants

Propane, which is currently the fuel used by most thermal control equipments, is generally considered to be a clean fuel since its complete combustion generates

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5.3 Emission of Pollutants

Propane, which is currently the fuel used by most thermal control equipments, is generally considered to be a clean fuel since its complete combustion generates

carbon dioxide and water vapour. Under field conditions, propane combustion is often incomplete, resulting in the emission of significant amounts of carbon monoxide, sulphur dioxide, and nitrous oxides, especially if the supply of oxygen to the burners is insufficient. It is thus important to identify the optimal operating zones for each type of burner in order to limit the emission of these pollutants.

6 Application Modes and Strategies

Among the different uses of thermal control in plant protection, one may include; integrated weeding (mechanical cultivation between the rows and thermal weeding on the rows) for row crops, as performed on corn in post-emergence (Fig. 1); thermal control of Colorado potato beetle early after emergence of the potato plants (Fig. 2); thermal top killing of mature potato plants that may also have a favourable impact on mildew (Fig.3), and thermal renovation of lowbush blueberry plantations (Fig. 4). In most cases, timeliness of the thermal treatments is critical to maximise their efficiency against the pests to control while minimizing their negative impacts on the crops to be protected.

7 Environmental Impacts

Since thermal control in agriculture represents an alternative to chemical pesticides, it is important that the global environmental impacts of this technology be

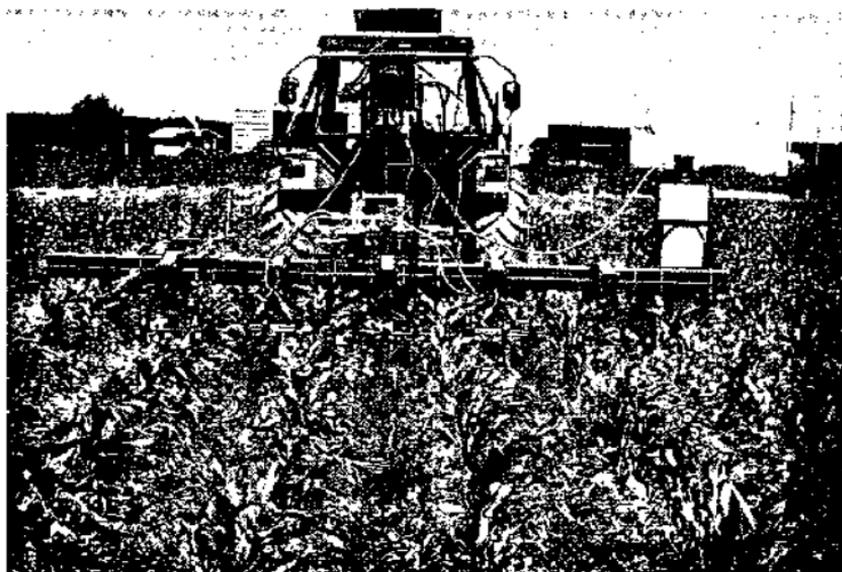


Fig. 1. Integrated mechanical and thermal weeding in row crops.

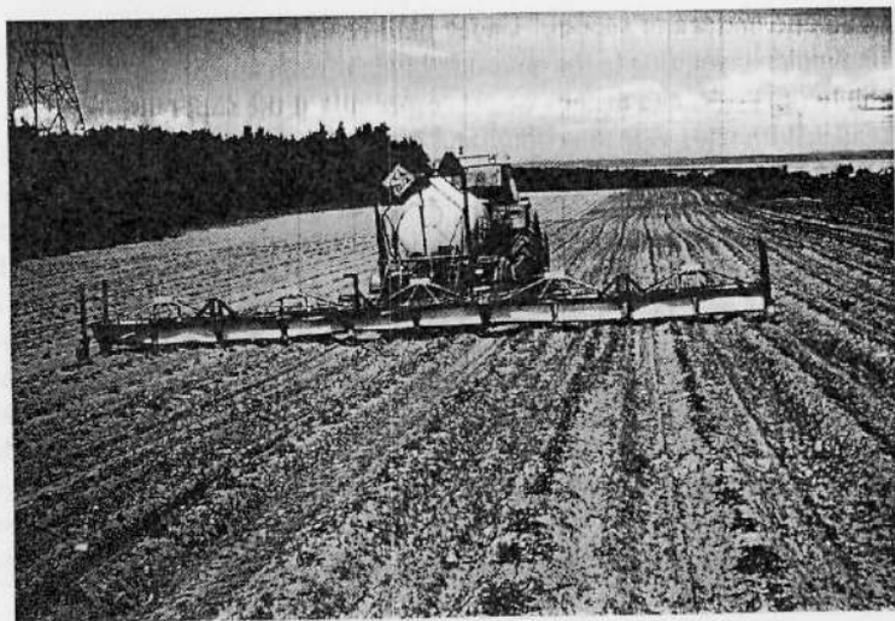


Fig. 2. Thermal control of Colorado potato beetle on young potato plants.

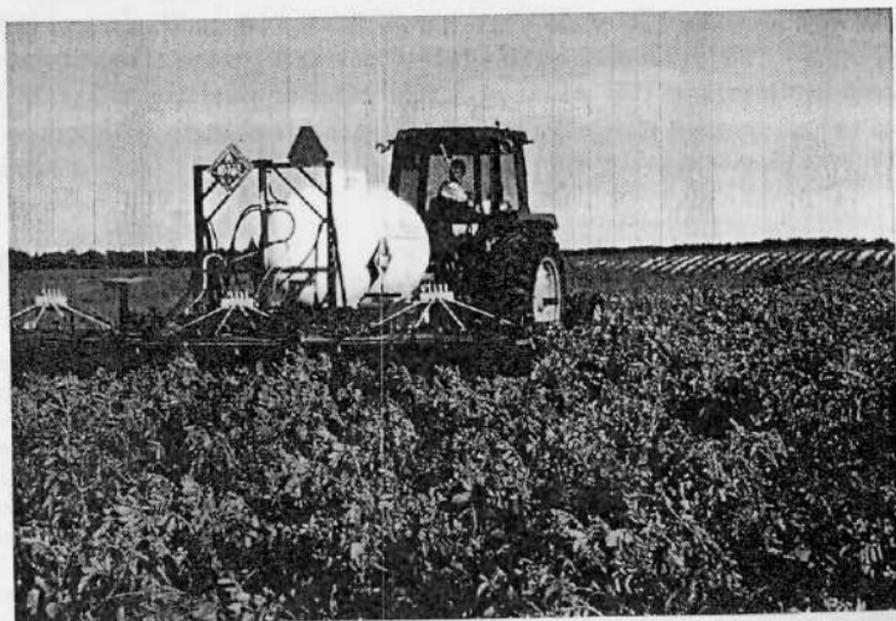


Fig. 3. Thermal top killing of mature potato plants.



Fig. 4. Thermal renovation of lowbush blueberry plants.

lower than that of the chemicals. The evaluation of the environmental impacts of thermal control has been the object of research, especially in Canada and in Switzerland. A multidisciplinary research team from Université Laval has conducted an extensive comparative study of the respective impacts of thermal control and of chemical control of pests in agriculture on soil, water, air and energy resources. This study has dealt with many different applications of thermal control: thermal weeding, potato top killing, thermal control of pest insects.

The main potential impacts of thermal control on the soil are: (1) soil compaction resulting from increased traffic of tractors and field implements in thermal control as compared to chemical control and, (2) the momentary increase in surface temperature of the soil during the treatments. It has however been demonstrated that traffic-induced soil compaction caused by the thermal treatments was not important and that it was limited to the surface layer of the soil. The soil temperature is only increased for a very short time and over a depth of only a few millimeters.

Thermal control has more negative impacts on the air than does chemical control. These impacts are directly related to the combustion by-products (CO , CO_2 , nitrous and sulphur oxides) that are important atmospheric pollutants directly related, in many cases, to the global warming of the Earth's atmosphere. These impacts are deemed more important than those associated with the use of pesticides (volatilization, drift of the sprayed products).

As opposed to most chemical pesticides, thermal control has no negative impacts on surface or underground water. On the other hand, the energy balance of most applications of thermal control in agriculture is negative when compared to that of pesticides, since thermal control requires large quantities of non-renewable fossil fuels.

This study showed that even though thermal control presents environmental benefits in terms of impacts on soil and water, it shows a negative balance for air and energy. The environmental benefits of thermal control are thus mitigated.

Jolliet (1994) conducted a similar study for the specific case of potato plant top killing. He determined the impacts on soil, air and water of five different top killing techniques: use of chemical defoliant, mechanical, thermal, mechanical-chemical, and mechanical-thermal. His conclusions were that mechanical top-killing presented the least negative environmental impacts while chemical top-killing had the most. Top-killing techniques making use of heat presented intermediate environmental impacts between these two extremes.

One may thus conclude that thermal control may, in some cases, provide environmental benefits compared to the use of chemical pesticides. These benefits will vary depending upon the type of application, the performances of the equipments used to apply the thermal treatments, the timeliness of these treatments and also the toxicity of the pesticides that can be substituted by the thermal treatments.

8 Conclusion

Recent R&D work on thermal control in plant protection have contributed to a much better understanding of this technology. Work targeted at the determination of the thermosensitivity levels of crops, weeds and pest insects coupled to determination of the operating characteristics of thermal control equipments have yielded much needed data for optimizing the different applications of thermal control in agriculture. As a result, many applications of thermal control can now be considered. In order for this technology to become more attractive to the end user, it is now necessary to better and more thoroughly integrate the agronomical, economical, environmental and technical aspects of thermal control in plant protection.

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Flame Weeding in Corn

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1 Introduction

Grain and silage corn (*Zea mays* L.) are grown in several countries throughout the world. Herbicides are currently the main method of weed control used worldwide. In Quebec, for example, one out of every three agricultural pesticides sold is a herbicide used for corn (Leroux et al. 1990). However, the intensive use of herbicides in corn results in serious environmental problems. According to several studies, herbicides used in corn have made their way into streams, rivers and drinking water in a number of countries (Ayotte and Larue 1990; Giroux and Morin 1992; Economic Commission for Europe 1993). Furthermore, owing to the appearance of a growing number of weed biotypes resistant to traditional chemical herbicides, farmers have been forced to resort to new, more expensive treatments. The increase in consumer demand for food free of chemical residues, and the desire of agricultural organizations to promote sustainable agriculture highlight the need to develop alternatives to chemical weed control. Thus, we propose the use of thermal weed control (or flame weeding) alone or in combination with traditional mechanical methods (rotary hoe, sweep cultivator).

Flame weeding was very popular in the first part of the century, until 1940. The first known prototype flamer, used for sugar cane (*Saccharum officinarum*) dates back to 1852 in the United States (Vester 1986). The use of flame weeding ceased in the late 1960s with the advent of cheap and effective selective chemical herbicides. The renewed interest in flame weeding has encouraged us to work on improving this method through research in the laboratory and in the field.

2 Principles of Flame Weeding

Theoretically, thermal weed control is a method that can comprise various forms of electromagnetic radiations such as microwaves, thermal radiations, laser beams and gamma radiations to kill weeds (see Chap. 7). Often, this radiative transfer is enhanced by heat transfer by conduction when hot gases come into contact with

plant tissues. In practice, however, only thermal radiation from flame, steam, hot air or infrared sources and heat transfer by conduction are of interest.

Open flame weeding kills weeds by heating plant tissues rather than burning them. Temperatures must be at least 95-100 °C and should be applied for at least 0.1 s (Vester 1986; Parish 1989). The resulting thermal shock destroys the above-ground parts of weeds. A study on the effects of ultra-high temperatures on corn by Ellwanger et al. (1973) showed alterations to cellular membranes leading to dehydration. Dehydration results from the expansion of the cell contents (made up of 95% water) and subsequent bursting of the cell membranes, and from the coagulation of proteins at temperatures of 50-70 °C (Morez 1985). Both effects damage plant cells to the point that normal growth is impossible. Hot, dry weather accelerates this phenomenon, which takes a few hours (Vester 1986). The resulting increase in evapotranspiration causes plant desiccation in 2 or 3 days.

3 Laboratory Studies

Thermal weed control is not a selective method. Therefore the tolerance of weeds to heat must be balanced against that of corn. Two experiments were set up. The first aimed at determining the minimum temperature required to kill weeds and the second at identifying the maximum temperature supported by corn without negative effects on yield.

3.1 Burner Configuration

Two round burners were used in the lab experiments. They were placed 8 cm above the ground surface, 20 cm apart, shifted 18 cm one from the other along the rows and tilted 30° relative to the vertical (Fig. 1). These values were dictated by the configuration of the cultivator used in the field (Fig. 2). The configuration is important since it defines the extent of temperature rise (Parish 1989; Ascard 1995).

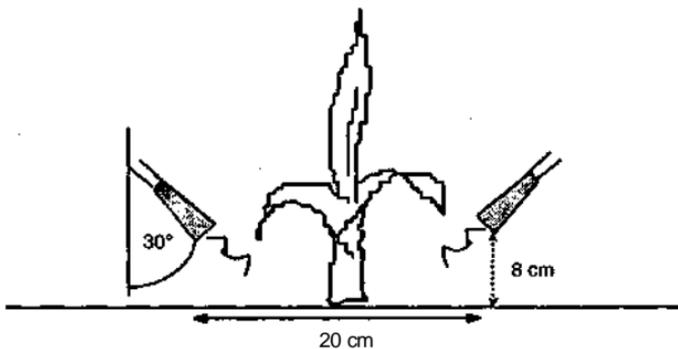
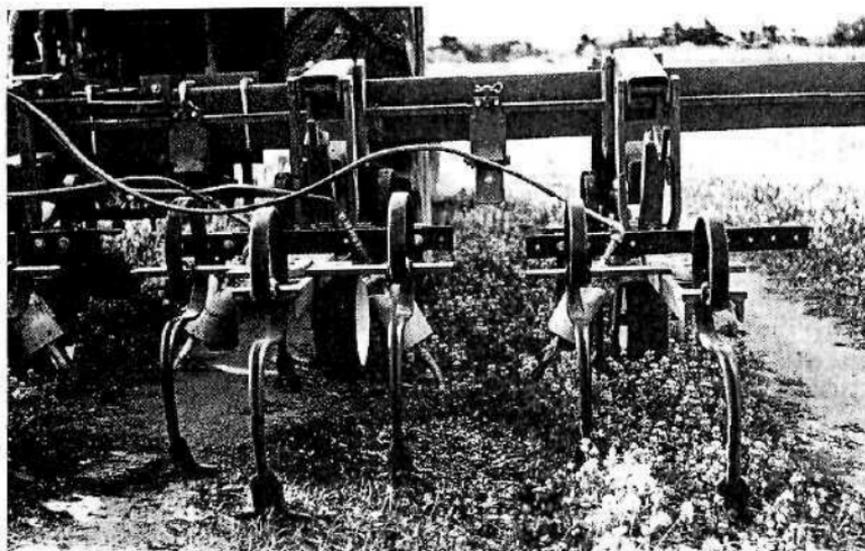


Fig. 1. Placement of burners in relation to soil and corn plants.



Fin. 2. Rear view of flame cultivator used in tests.

Since, in this case, the type of cultivator used limited the burner angle, height and spacing, the temperature rise was determined solely by the gas operating pressure in the burners and the exposure time (i.e. the travel speed of the burners in relation to the plants).

3.2 Effects of Flaming on Corn

A corn hybrid (Pioneer 3979) was sown in metal flats (30 cm wide x 75 cm long x 20 cm tall), six plants to a row. Four growth stages were studied: (1) coleoptile stage; (2) 5-8 cm tall or 2-3-leaf stage; (3) 20-25 cm tall or 4-5-leaf stage; and (4) 45-50 cm tall or 6-7-leaf stage. The corn plants were exposed to ten temperatures between 110 and 390 °C; produced by combining various travel speeds and gas operating pressures (Gill et al. 1995). The temperature probe was located 20-30 cm from the soil surface (Laguë et al. 1997).

In general, temperature rises resulted in decreased dry biomass 2 weeks after treatment, regardless of the growth stage at time of treatment (Fig. 3). However, corn growth was least affected when treatment was at the coleoptile stage, with a decrease in growth of 50% at 390 °C, compared to an average decrease of 80% at later growth stages. The 20-25-cm stage (which corresponds to the 4-5-leaf stage of corn) was the most sensitive: above 160 °C, dry biomass was reduced by at least 50% (data not shown). For the two other stages (5-8 and 45-50 cm), the threshold was around 175 °C. Below this temperature, there was little damage to corn, while above this temperature, leaf necrosis and reduced growth were observed. These results, similar to those reported at the California Weed Conference (1985) and by Daar (1987), indicate that corn is very sensitive to heat between the coleoptile

(2 cm) and 6-leaf (50 cm) stages. Heat tolerance is greatest at the 0–2-cm stage, when the apical meristem is protected. However, when the first leaves emerge, exposure to flaming may damage the plant. At the 6–7-leaf stage (50 cm), the foliage is tall enough for the flame to be directed at the base of the stem, which spares the foliage from the effects of heat (California Weed Conference 1985).

3.3 Effects of Flaming on Weeds

The experiment was carried out on four weed species common in Quebec cornfields: redroot pigweed (*Amaranthus retroflexus* L.), wild mustard [*Sinapis arvensis* L.], lamb's-quarters (*Chenopodium album* L.) and green foxtail [*Setaria viridis* (L.) Beauv.]. These weeds were treated at three different growth stages (0–2 leaves, 4–6 leaves and 8 or more leaves) at temperatures between 110 and 390 °C. At the 0–2-leaf stage, all four weed species were destroyed by temperatures at or above 110 °C (Fig. 3). At the 4–6-leaf stage, however, temperatures of at least 175 °C were required to reduce biomass by 80%. Lastly, at the 8-or more leaf stage, weeds were very difficult to control and the level of control was below 85% even at temperatures of 350 °C (data not shown). Similar studies done in Sweden by Rahkonen and Vanhala (1993) and Ascard (1995) produced the same results.

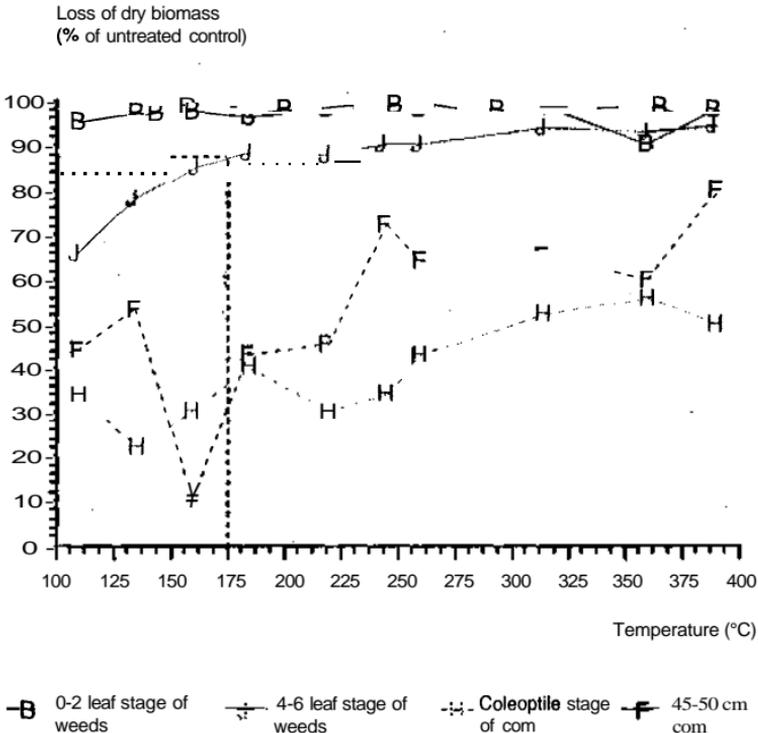


Fig. 3. Mean effect of temperature on dry biomass of weeds treated at the 0–2-leaf and 4–6-leaf stages, compared to that of corn at the coleoptile and 45–50-cm stages.

4 Field Methodology

The laboratory studies allowed us to propose the following hypotheses to be tested in the field:

- The best treatment time for corn is the coleoptile stage. The 6-leaf stage (45-50 cm) is also fairly tolerant to flaming since the foliage is not exposed to the flames to any great degree.
- Young weed seedlings (at the 0-2-leaf stage) are very sensitive to heat and even the lowest temperatures will kill weeds at a rate of over 90%.
- In older weeds, the temperatures required to obtain an 85% decrease in growth (the minimum level of effectiveness required to register a herbicide) also cause a significant decrease in growth of corn (over 200 °C for the 4-6-leaf stage and over 350 °C for the 8 leaf or more stage).

Flame weeding is therefore only feasible for controlling weeds no later than the 4-leaf stage. As the work of Geier (cited by Daar 1987) suggests, treatment must be done as early as possible, when the corn is most resistant to flaming and weeds are the most sensitive. This limits competition from weeds during the most critical period, from the 2-4-leaf stage to the 6-10-leaf stage, when corn is very sensitive to competition. Flaming can be used again once the corn has reached the 45-50-cm stage, as long as the weeds are still at a point where they can be controlled by flaming. To achieve this, weed growth has to be checked at the beginning of the season, to keep them at the 4-leaf stage when the corn is at the 6-7-leaf stage (45-50 cm).

The laboratory work showed that flame weeding can be used without risk for corn at the pre-emergence/early post-emergence stage or at the late post-emergence stage. However, the effectiveness of the treatment must be verified under field conditions, particularly regarding the maximum number of passes with the flame weeder corn plants can tolerate. Lastly, it is also essential to study the effects of flaming on corn yield and to compare the effectiveness of flame cultivation with that of mechanical or chemical treatments.

Our method of non-chemical weed control requires two separate treatments: one at the pre-emergence/early post-emergence stage and a later one when the corn is at the 6-7-leaf stage (45-50 cm). The purpose of the first treatment is to delay the establishment of weeds to ensure they are still amenable to treatment when the corn has reached the point (6-7-leaf stage or 45-50 cm) where it can tolerate flaming. The pre-emergence treatment can be mechanical or thermal. At the post-emergence stage, flame weeding is the only non-chemical method that can be used to remove weeds from the row; however, at this point, flame weeding can be combined with mechanical cultivation in the inter-row area.

4.1 Tools Used

4.1.1 Mechanical Cultivation

A John Deere rotary hoe with flex-discs was chosen (see Chap. 14) for the broadcast cultivation of corn at the pre-emergence/early post-emergence stage (Fig. 4). This machinery is used when the corn is no older than the 3-leaf stage, at a speed of at least 15 kmh^{-1} . It is most effective when weeds seedlings are sprouted but not yet emerged.

4.1.2 Flame Cultivation

Flat vapour burners were used for broadcast treatments. The burners were mounted and equally spaced on a tool bar, producing a uniform temperature rise along a 5-m-wide swath. This provides complete broadcast weed control without mechanical cultivation.

The flame cultivator used consisted of two burners per row mounted on a Kongskilde cultivator (adapted by Bervac, Thetford Mines, Quebec). Five goose-foot sweeps provided inter-row cultivation (Fig. 2). Round vapour burners (Flame Engineering Inc., LaCrosse, Kansas, USA) were used in the same configuration as the laboratory model. Gas was supplied from four 45.7 kg propane tanks mounted in front of the tractor. The cultivator was also equipped with an automatic guidance system manufactured by Sukup Manufacturing Company (Sheffield, Iowa, USA). This system uses two crop-sensing wands (free-floating metal rods) to align

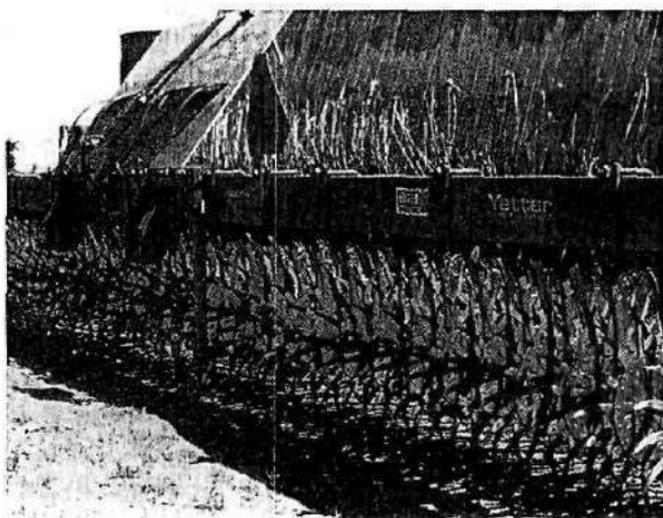


Fig. 4. Front view of rotary hoe.

the sweeps and burners with the crop rows. The rods determine the position of the corn row and control a hydraulic cylinder that directs the moves of the cultivator laterally.

4.2 Effectiveness of Pre-Emergence Weeding

We compared three methods of **pre-emergence** weeding with an unweeded control plot. They were: (1) standard herbicide treatment; (2) two passes with a rotary hoe (pre-emergence and early post-emergence of corn) and, (3) a broadcast thermal treatment (Table 1). The non-chemical treatments, which have no residual effects, were supplemented by a post-emergence treatment. The results will be discussed in the next section.

The three pre-emergence treatments all reduced weed density, with similar results in reducing the density of dicot weeds (Fig. 5). However, the broadcast thermal treatment left a greater number of annual grasses, probably because of the timing of the treatment, which was done early in the season when few grasses were present. Since thermal treatment only affects the above-ground portions of weeds, those there are not yet emerged at time of flaming remain protected. At this stage, none of the pre-emergence treatments was found to cause damage to the corn (data not shown).

Table 1. Treatments used in the field.

Treatment	Timing
1 Control (weeds left untreated)	
2 Broadcast herbicide (standard treatment) Metolachlor (2 kg-1 ha) + Atrazine (1.125 kg-1 ha)	PRE
3 Rotary hoe ^a + flame cultivation ^b	PRE + coleoptile POST (corn: 45 cm)
4 Broadcast flame weeding ^c + flame cultivation ^b	PRE POST (corn: 45 cm)

PRE: pre-emergence; POST: post-emergence.

^a Rotary hoe at 15 kmh⁻¹.

^b Flame cultivation: two round burners at 175 °C, 6kmh⁻¹, gas operating pressure: 367 kPa. The burners are used in the corn row and the treatment is supplemented by sweep cultivation in the inter-row area.

^c Broadcast flame weeding: flat burners at 175 °C, 6 kmh⁻¹, gas operating pressure: 367 kPa.

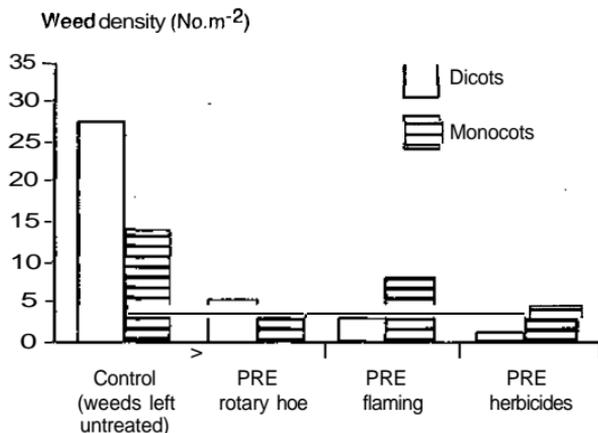


Fig. 5. Effect of pre-emergence weed control treatments on density of dicot and monocot (grasses) weeds, measured 21 days after corn emergence.

Although pre-emergence flaming does not control late-germinating grasses, it does have a significant advantage over cultivation since it can be used when the soil is wet. The rotary hoe is much less effective in wet soil because the exposed roots of the uprooted plants do not dry out. Another advantage of flame weeding is that, unlike tillage (which stirs up the soil, exposing weed seeds to the light), it does not stimulate the germination of weed seeds. Since the seeds of many weed species are photosensitive (they need a brief exposure to light to initiate germination), the rotary hoe may trigger the germination of an entire new cohort of weeds. However, the rotary hoe does have some advantages over thermal weed control since it can be operated at a faster speed (15–20 kmh⁻¹ compared to 6 kmh⁻¹): the slow speed of the flamer can be a real handicap in spring, a very busy time of year, particularly if the window of opportunity for treatment is very small.

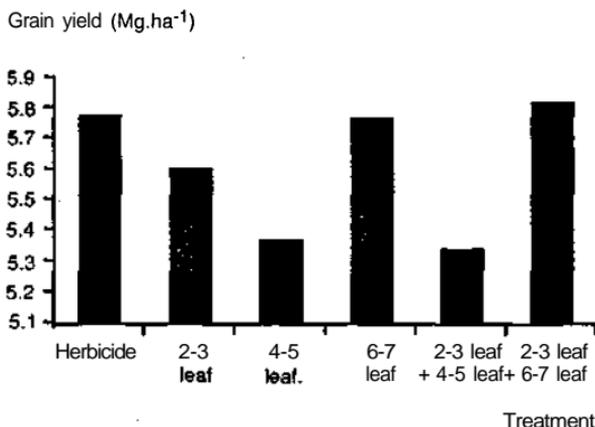


Fig. 6. Effect of various post-emergence flame weeding treatments on corn grain yields (T ha⁻¹) (at 15% moisture content).

4.3 Effectiveness of Post-Emergence Weeding

The performance of corn subjected to post-emergence thermal treatments, in both the absence and presence of competition from weeds was also monitored. Post-emergence flame weeding was done once, twice or three times at the following growth stages of the corn: 2–3-leaf stage (5–8 cm), 4–5-leaf stage (20–25 cm) and 6–7-leaf stage (45–50 cm). The burners were calibrated to generate a temperature rise of 175 °C.

As in the laboratory, corn treated at the 2–3-leaf stage (5–8 cm) and 4–5-leaf stage (20–25 cm) was sensitive to heat. However, despite significant foliage damage, kernel yields were reduced only in corn treated at the 4–5-leaf stage (20–25 cm), indicating that any slowdown in growth caused by flaming at the 2–3-leaf stage (5–8 cm) was made up for during the rest of the growing season. The 6–7-leaf stage (45–50 cm) of corn was more heat-resistant. With two post-emergence treatments, yield was most affected when the treatments were done at the 2–3-leaf and 4–5-leaf stages (5–8 and 20–25 cm) consecutively. When the two treatments were at the 2–3-leaf stage (5–8 cm) and the 6–7-leaf stage (45–50 cm), yields were not reduced (Fig. 6).

Although a single early post-emergence treatment (2–3-leaf stage or 5–8 cm) effectively controlled weeds, it did not cover the entire critical period for corn and yields suffered as a result. A single pass at the intermediate stage of 4–5 leaves

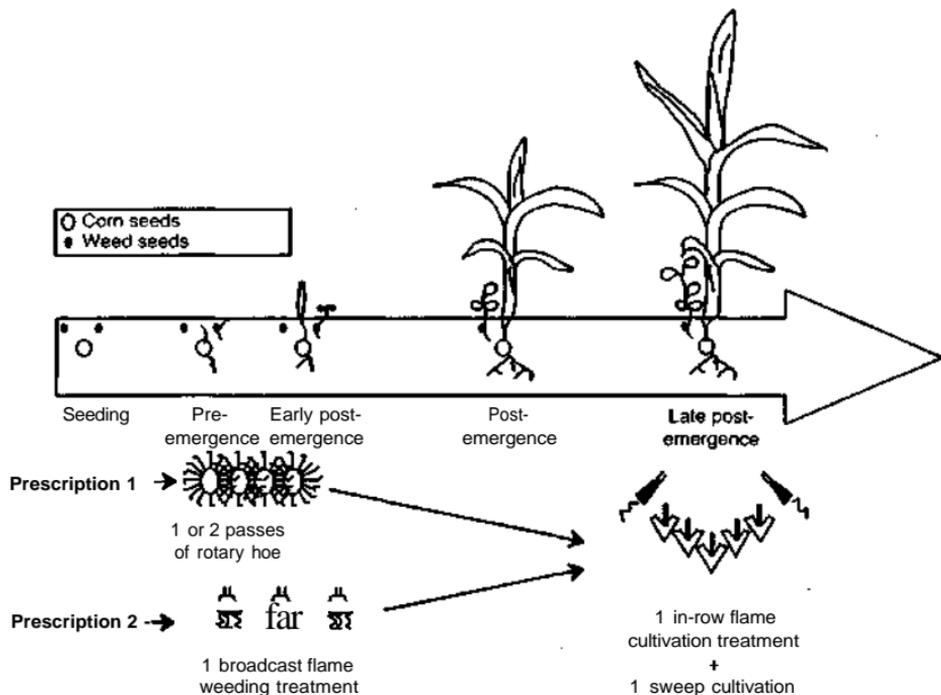


Fig. 7. Illustration of prescriptions for non-chemical weed control in corn.

(20-25 cm) controlled weeds effectively but is not advisable since corn is very sensitive at this stage. At the later stage of 6-7 leaves (45-50 cm), the weeds are too well established to be controlled effectively. The use of two passes, one at an early stage and the other at a late stage, is very effective and does not have a negative effect on yield. There is no advantage to using three flaming treatments. In presence of high weed populations, farmers forced to carry out flaming at the intermediate stage will suffer yield losses.

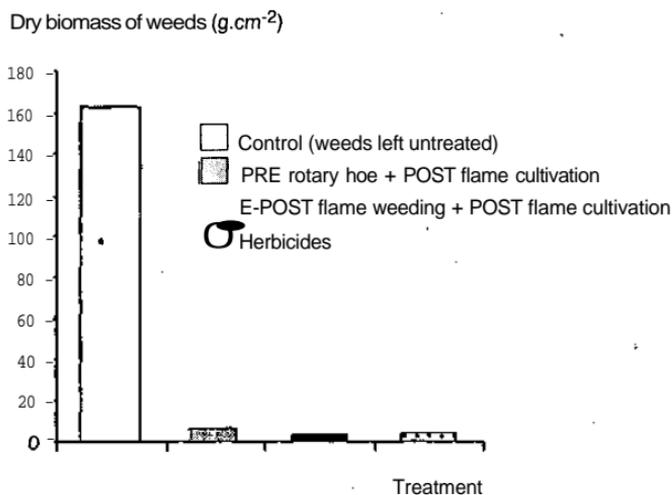


Fig. 8. Effect of prescriptions on dry weed biomass, measured 63 days after com emergence (see Table 1 for description of treatments).

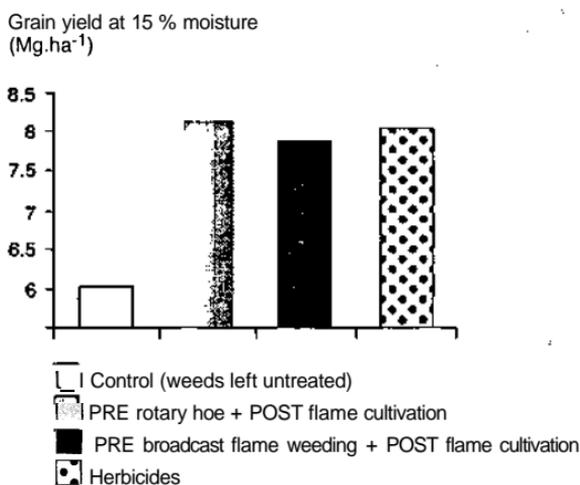


Fig. 9. Effect of weed control prescriptions on corn grain yield at 15% moisture content (see Table 1 for description of treatments).

4.4 Weeding Prescriptions

Based on these results, the best combinations of cultivation and flaming for effective weed control in corn can be determined. Weed control must be begun early in the season, either with a single pass (pre-emergence) or double pass (pre-emergence and early post-emergence) of the rotary hoe (prescription 1), or by broadcast flame weeding at the early post-emergence stage (prescription 2) (Fig. 7). At this time, the main weed cohort for the season is either in the process of germinating or has already emerged. Weather conditions will affect the choice of device used. However, if the soil is dry, the rotary hoe provides excellent results and can be operated at faster speeds than the flame weeder. If the soil is very wet or weeds have already emerged, flame weeding yields better results. These early treatments create a growth differential between the corn and weeds by destroying the first weed cohort. This approach allows the crop to reach the 6–7-leaf stage (40–50 cm) without being subjected to much competition. At this stage, weeds are at the four-leaf stage, at most, and are still susceptible to high temperatures. The corn can tolerate these temperatures, thus allowing selective flaming on the row.

Figure 7 shows the performance of both prescriptions compared to that of pre-emergence herbicides and a control group. Figure 8 shows weed biomass in plots 63 days after the emergence of corn. The treatments all resulted in a reduction of over 85% of weed biomass with respect to the control plot. There is no difference between the two prescriptions, which are also similar to the herbicide treatment. The non-chemical prescriptions resulted in identical yields to those obtained with chemical herbicides, an average of 8 Mg.ha⁻¹ (Fig. 9).

5 Economic Analysis

The figures in this study are based on those provided by the Comité de références économiques en agriculture du Québec (Quebec Committee of Economic Authorities in Agriculture). These costs include expenses for the tractor and depreciation, but not labour.

In the case of flame weeding treatments, the costs associated with the burner apparatus and gas consumption are included in the costs of using the machinery and tractor. Purchase costs, depreciation and the operating cost of the rig for broadcast flame weeding are not available since this machinery is not yet available commercially. It has been assumed that the cost is close to that of a post-emergence cultivator, 20.40 \$CAN ha⁻¹ (85 FF ha⁻¹). Similarly, the cost of the burner apparatus (burners, piping and propane bottles) mounted on the cultivator for post-emergence flame weeding in the row is difficult to evaluate and cannot be factored in at the present time. We can estimate, however, the costs of propane consumption for both pre-emergence and post-emergence treatments at 14.30 \$CAN ha⁻¹ (60 FF ha⁻¹) (Table 2). It should be noted that flame weeding treatments would probably be

contracted out on a lump-sum basis since the use of propane gas requires special training, which could add significantly to the cost.

The cost of the proposed non-chemical treatments can be broken down as follows. For prescription 1, two passes of the rotary hoe (15.60 \$CAN ha⁻¹ or 65 FF ha⁻¹), one pass of the cultivator (20.40 \$CAN ha⁻¹ or 85 FF ha⁻¹) and propane (14.30 \$CAN ha⁻¹ or 60 FF ha⁻¹), for a total of 50.30 \$CAN ha⁻¹ or 210 FF ha⁻¹, to which must be added the cost of the contract work. Prescription 2, with two flame weeding treatments, costs 69.40 \$CAN ha⁻¹ (290 FF ha⁻¹) for operating costs and propane (Table 2). The costs of the burner apparatus and contract work must be added (Table 2).

Herbicides cost 60.40 \$CAN ha⁻¹ (253 FF ha⁻¹) and spraying 22.40 \$CAN ha⁻¹ (94 FF ha⁻¹) for a single broadcast treatment, with a total cost of 82.80 \$CAN ha⁻¹ (347 FF ha⁻¹).

Table 2. Equipment and operating costs of proposed weed control prescriptions.

Treatment 1 pass covers 6 rows	Operating costs		Cost of prescriptions (FFha ⁻¹)		
	FF ha ⁻¹	\$CAN ha ⁻¹	Prescription 1	Prescription 2	Herbicide
	Prescription		1	2	
Equipment					
- Rotary hoe	32.50	7.80	32.50 x 2		
- Broadcast flame weeding	85	20.40		85	
- Cultivator	85	20.40	85	85	
- Burner apparatus	Not available		NA	NA	
- Sprayer	94	22.40			94
Products					
- Herbicides	253	60.40			253
- Propane	60	14.30	60	60 x 2	
		Total	210	290	347

6 Conclusion

The use of thermal weed control in corn is quite feasible. The difference in heat tolerance between weeds and corn, based on phenology (the stage of growth at which each is treated), is the basis for treatment selectivity. In corn, the apical meristem is located below the soil surface between the coleoptile stage and the 2–3-leaf stage, allowing the plants to resist temperatures of 175 °C. At these temperatures, weeds, in their 0–2-leaf stage, are destroyed, with over 90% efficacy. Later in the season, at the 6–7-leaf stage (45–50 cm high), corn is again tolerant to

high temperatures. At this later stage, flaming can be successful in fields where early treatments have delayed weed growth such that weeds have not grown past their 4-leaf stage before this later treatment.

A broadcast treatment is therefore required in the pre-emergence or early post-emergence stage to slow the growth of weeds, with a rotary hoe or flame weeder. One of the advantages of flame weeding is that it can be done on wet soil. After emergence, a combination of mechanical cultivation between the rows and flame weeding in the row can be done at the 6-7-leaf stage of the corn (45-50 cm). Treatments at the 4-5-leaf stage should be avoided, because corn is very sensitive to heat at this stage. Both prescriptions result in weed control and crop yields comparable to pre-emergence treatment with herbicides. Our results confirm those already obtained by Liljedahl et al. (1964), Reece et al. (1964, 1966), Lalor and Buchele (1966, 1970), Parish (1989) and Balsari et al. (1991).

To maintain the medium-term effectiveness of the proposed prescriptions, they should be integrated with a crop rotation system to prevent massive weed infestations. Physical weed control methods have no residual activity. Although they limit competition between corn and weeds during the critical period of corn is susceptibility further on, nothing can stop weeds from getting established, growing and setting seeds. Thus, the weed seedbank may still increase. This is why these techniques must be combined with cultural methods that ensure crop competitiveness. Another important point is that non-chemical treatments require more time than do herbicides. The window of application is narrow, necessitating increased monitoring of fields. In addition, two or three passes are required, which is more work than a single pre-emergence application of a residual herbicide.

The greatest advantage of the methods proposed here is that they provide an alternative to herbicides and are relatively non-polluting (see Chap. 2). Although the advantages are presently difficult to quantify in terms of low-input farming and minimising input, they probably far outweigh the additional costs of the burner apparatus. Lastly, the appearance of biotypes resistant to thermal treatments is unlikely (which is not the case with herbicides), although it must be recognized that flame weeding may promote the growth of annual grasses in fields.

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