

Pneumatical Control

Pneumatic Control of Insects in Plant Protection

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1 Operating Principle of Pneumatic Systems

The pneumatic control technique consists of using moving air to eliminate undesirable insects from crops. Pneumatic energy could be used in different modes: suction, blowing, or a combination of both. Pneumatic control systems are often referred to as vacuums. The mode used depends on the species of insect to be controlled and on the characteristics of the crops to be protected. The use of vacuums is limited to some crops and some insects. Hence, insects that easily fly as soon as they feel vibrations or when they are disturbed in their environment such as, the **Whitefly** (*Aleurodidae*), are best controlled by vacuuming. The **Colorado potato beetle** (CPB) [*Leptinotarsa decemlineata* (Say)] and insects such as the **European corn borer** (*Ostrinia nubilalis* (Hbn.)) or the **cabbage maggot** [*Delia radicum* (L.)] cannot be dislodged easily by this mode. Their behavior is completely different and requires more elaborate methods. The CPB beetle holds on to the plants firmly. Furthermore, the foliage of the host potato plants becomes denser as growth advances and the generated vacuuming force rapidly dissipates. It is therefore very difficult to suck up CPBs that are deep in the plants or those that are firmly gripped to the foliage. On the other hand, the **European corn borer** attacks corn inside the stems. In this case, it is impossible to remove this insect by a pneumatic system.

2 Background

The idea of using pneumatic systems dates back to the 1950s. The first uses to control some insect pests occurred in cotton fields of the United States (deVries 1987; Bédard 1991). However, the gradual introduction of efficient and economic chemical pesticides made this technique less attractive to growers. Currently, factors such as growing demand for food products free of pesticide residues, problems of resistance developed by some insect species to many chemicals, and risks of environmental contamination by pesticides have revived the interest in alternatives to the chemical means, and in particular, to the pneumatic control technique (Misener and Boiteau 1993a).

Box I. Aerodynamics of the Pneumatic Control

To determine the main air suction or blowing parameters allowing for a better control of insect pests, it is also important to know the drag coefficient of the insect. This non-dimensional coefficient has the advantage of allowing the force induced to the insect by an airstream of a known speed to be computed and the terminal velocity of the insect which represents the equilibrium speed between the drag force and the weight of the insect to be determined. The drag coefficient is variable according to the flow regime. It can be expressed as:

$$C_D = 2 \frac{mg}{V_t^2 \rho_a A}$$

where:

C_D - drag coefficient,

m = mass of the insect, kg,

g = gravity acceleration, $m\ s^{-2}$,

V_t - terminal velocity, $m\ s^{-1}$,

ρ_a - air density, $kg\ m^{-3}$,

A = projected surface of the insect, m^2 .

Although the shape of insects is very irregular, it is possible to estimate the drag coefficient by analogy to other objects of known shapes such as a sphere taking into account a correction factor (Misener and Boiteau 1993b). DeVries (1987) estimated that the drag coefficient of a CPB adult is about 0.35 whereas its terminal velocity is about $12.5\ m\ s^{-1}$. CPB adults reach a constant velocity after falling 10 m against 10, 9, and 8 m for the fourth, third, and second instar larvae, respectively (Misener and Boiteau 1993b). The respective terminal velocities are 9.4, 9.5, 7.3, and $5.9\ m\ s^{-1}$. This shows that larvae of the third and second instars are more susceptible to being carried by a vertical airstream (air suction case) than fourth instar larvae and adults.

At the beginning of the 1990s, at least eight companies worldwide had tried to market pneumatic systems to control insect pests (Khelifi 1996). The effectiveness of the developed machines is variable. The major drawback of these pneumatic systems is their contribution to soil compaction, destruction of beneficial insects, and mechanical damage to the crops (Moore 1990).

3 Examples of Pneumatic Systems

3.1 Beetle Eater

The Beetle Eater was designed by James Sy7.nal Sr. in the Northeast of the USA (Florence, Massachussetts) and the patent was bought by Thomas Equipment Ltd.

of New Brunswick, Canada. The approximate cost of this vacuum machine is 170 970 FF (41 700 \$Can). The system requires a 45-kW tractor. The operating speed is 8 In 9.6 km h⁻¹. Two fans (71 cm diameter) respectively generate the blowing and suction airstreams. The system has four combined blowing/suction hoods. The first fan blows air through a rectangular slot 25.4 cm long by 7.6 cm wide on each unit. The second fan vacuums the air at the summit of the units through a 30.5-cm diameter flexible plastic tube. Airflow speed in the main duct is 480 km h⁻¹. The effectiveness of this machine in controlling the CPB varies from 15 to 50% (Bédard 1991). The machine has to be modified regularly to maintain its effectiveness since it is affected by the height of the plants, the growing stage of the insects, and the roughness of the ground surface. A picture of the Beetle Eater as well as a discussion of the effects of this particular pneumatic system are presented in the chapter of Vincent and Boiteau (Chap. 19).

3.2 Bio-Collector

The Bio-Collector (Bio-land Technik, Mühlhausen, Germany) can collect CPBs over 1 ha in 1 h, at a speed of 6 km h⁻¹ with a four-row machine. Models having two, three, or four rows are available. Reynaud (1990) reported an effectiveness of 80 to almost 100% for CPB adults and of 75 to 80% for larvae. The cost of this machine is about 57 000 FF (14 000 \$Can).

This system was tested in Quebec in commercial and experimental plots by Dr. Raymond-Marie Duchesne, entomologist at the Ministry of Agriculture, Fisheries and Food of Quebec. It was more effective against small populations of CPBs, but success was highly variable, averaging 50% removal of all the stages. As a result, the Bio-Collector was judged not efficient for controlling the CPB in potato crops in the particular Quebec agricultural context. Some adjustments are needed to adapt this machine to potato-cropping techniques and consequently improve its overall effectiveness.

3.3 Bug-Vac

The design of the Bug-Vac by E. Show (Driscoll, Watsonville, California) dates from 1986 (Wilcox 1988). This huge vacuum was successfully tested in 1987 and its success in controlling CPB was comparable to that of chemical pesticides. The number of beneficial insects in the plots treated with pesticides was 50 to 70% lower than that in the plots controlled with the Bug-Vac. Inman (1990) indicated that this vacuum is relatively ineffective against *Lygus hesperus* at the larval stage. Pickel et al. (1995) conducted many trials with the three models of vacuums used by growers in California to control *L. hesperus* Knight in strawberry fields. These vacuums can treat one, two, or three strawberry rows. The three-row vacuum costs about 342 000 FF (83 000 \$Can.), and its control is comparable to that of chemi-

cal pesticides and higher than that obtained with the two other models. However, Pickel et al. (1995) considered that the levels of damage caused to strawberry fields are economically unacceptable despite the level of insect control that was obtained with either of the models.

3.4 Bug-Buster

The Bug-Buster was designed by Industrial Air Products Inc., Phillips, Wisconsin. It was intended for insect pests that are flying or lightly gripped to plants. Models with two, three, or four centrifugal fans are available. Each model requires a power of about 15 kW per fan. There are three possible configurations of the suction hoods, so that they can be adapted for control in strawberry, potato or lettuce crops. Three ha could be swept in 1 h by this vacuum. Many trials conducted at the University of Wisconsin (Madison) revealed that potato plant defoliation by CPB larvae could be maintained at an acceptable level with weekly treatments (Puttré 1992). Chemical and mechanical control of leafhoppers (*Cicadellidae*) in carrot and soybean crops gave comparable results.

The Bio-Vac (Premier Tech, Rivière du Loup, Quebec) and the Pash Tash (Israel) are respectively described in the chapters of Vincent and Boiteau (Chap. 19) and Weintraub and Horowitz (Chap. 21).

4 Design Criteria

The design of a pneumatic system capable of eliminating a high ($\geq 80\%$) proportion of insect pests involves analysis of the growing stage and the physical characteristics of the insect to control, as well as the growing stage, the geometry, and the resistance to airstreams of the plants to be protected.

A fundamental study of the design parameters, namely the airflow rate and speed, the shape of the control units, i.e. the hoods, and the orientation of the airstreams is thus necessary. With the exception of the study by DeVries (1987), this important aspect has often been neglected. Khelifi (1996) demonstrated the importance of these parameters in designing efficient pneumatic control systems.

5 Airstream Effects on the Plants

Plants can resist the mechanical effects of an air stream up to a threshold above which they experience considerable damages. To determine the airflow velocity threshold that can induce such damages, DeVries (1987) carried out a limited number of tests in a wind tunnel. He exposed a single 46-day-old (from planting) and 76-cm-tall potato plant (cultivar Rosa) to different airstreams for 30 s. The plant

was visually checked to assess the damage. There was little or no foliar damage up to air speeds of 12.5 m s^{-1} .

Similarly, Khelifi et al. (1995a) conducted many laboratory tests on three varieties of potato plants (Superior, Norland, and Kennebec). Three growing stages (26, 40, and 58 cm) and seven levels of airspeeds (from 12.5 to 31 m s^{-1}) were considered. Potato plants were placed inside a test bench (Khelifi et al. 1992) and then exposed to a horizontal airstream for 20 s. The degree of damage was visually evaluated. Results showed that the resistance of potato plants to airstreams is mainly related to the airspeed and the growing stage. The variety of potato plants is not important. Plants having less than 12 leaves and a mean height less than 40 cm could be exposed to air speeds as high as 27.5 m s^{-1} (at the foliage level) without incurring any visible damage.

6 Forces Required to Dislodge Insects from the Foliage

A pneumatic system to control insect pests designed without taking into account insect physical characteristics and behavior is likely to fail. Indeed, it is from such appropriate knowledge that one can consider the possibility of using a pneumatic system and define its mode of action. For example, the use of a pneumatic system to control the CPB gave results that are in general variable and sometimes contradictory. This was mainly related to the lack of information about the mobility of CPBs and their capabilities of grasping to the foliage at different levels of their growing stages. The reader willing to learn more about the forces required to dislodge the CPB can consult Vincent and Boiteau (Chap. 19).

In a similar study, DeVries (1987) indicated that CPB adults grasp more when they are at the lower surface of leaves or on their edges. The CPB uses tarsal hooks located at the end of each leg to grasp potato plants. A CPB adult can maintain its grip on the plant despite the application of forces as high as 20 times its weight. Similarly, DeVries (1987) mentioned that the CPB can resist forces of 41 mN when located on the lower surface or on the edges of the foliage as opposed to forces of 11 mN when located on the upper face of leaves.

7 Optimal Orientation of Airstreams

The optimization of the orientation of airstreams is based on insect, plant and soil factors. Knowledge of the insect behavior is used to decide whether to use a blowing or vacuuming technique and to determine the forces required to remove the insect from the foliage. The resistance of the plant to the necessary airstream should be good at the required removal force and the soil should not be easily displaced.

Khelifi et al. (1995b) conducted many laboratory tests to determine optimal airspeeds and adequate hood orientations for dislodging CPB adults and to verify

the **necessity** of integrating a slinking system to improve the **effectiveness** of the control system. They used airspeeds of 20.5, 24, and 27.5 m s^{-1} at the foliage level, and six configurations **beginning** with **simple horizontal** blowing to a combination of two oblique ascending air streams and air **suction** from the top. Each test was conducted over **five** CPB adults and **replicated** ten times. Potato plants (cv. Superior) were at the vegetative growing stage (mean height of 25 to 30 cm with a **dozen** leaves). The best configurations consisted of simple horizontal blowing through the plant foliage and a combination of simultaneous air suction and blowing. Airspeeds in the range of 24 to 27.5 m s^{-1} at the foliage level dislodged the maximum number of CPBs. Based on these results, a shaking system did not seem necessary.

8 Numerical **Simulation** Models

Pneumatic control of insects depends on many factors including the variability in the gripping ability of the insects at different growing stages, the geometry of the plants, and the resistance of crop foliage to airstreams according to the growing stage of the plants. Success of pneumatic control of insects appears to depend upon an appropriate design of the suction or blowing hoods. The main factors that have to be considered are the geometry or the shape of the hoods, which greatly affects the airflow pattern at the plant foliage level, the dimensions of the hoods, their position relative to the plants, and **obviously** the airflow rate that the hoods can deliver. The selection of the optimal hood geometry also depends on many factors such as the **growing** stage of the plants and the mode of action **planned**, i.e. total or partial coverage of the plants by suction, blowing, or a combination of both.

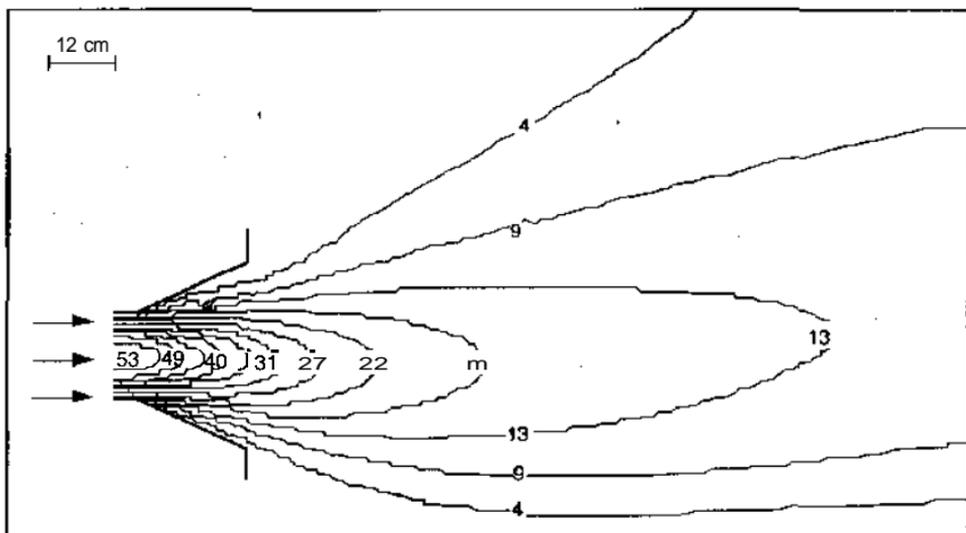


Fig. 1, Simulation for the simple air-blowing configuration (air velocities are in m s^{-1}).

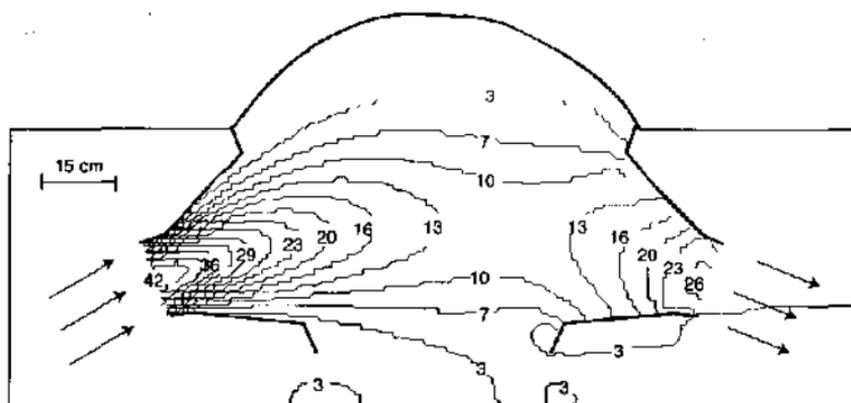


Fig. 2. Simulation for the shielded simultaneous oblique air suction and blowing configuration (air velocities are in m s^{-1}).

Because of the large number of parameters involved in the design of the hoods, the use of a numerical method of simulation, such as the finite element method (FEM), greatly facilitates the design. This has the advantage of simulating many working units and selecting the most appropriate one for pneumatic control of insect pests without extensive prototyping and testing.

Khelifi et al. (1996a) developed a finite element model to predict the airflow inside and around hoods arranged in simple geometries (air suction and blowing), and in more complicated ones (combinations of two to three hoods). This model is based on the Navier-Stokes equations and the results could be generalized to other insects. Among the eight configurations tested, two appeared promising: the simple horizontal air blowing and the shielded simultaneous oblique ascending air suction and blowing across the plant foliage (Khelifi et al. 1996b).

The airflow maintains a considerable velocity even very far from the hood outlet (Fig. 1). The flow pattern is also wide enough to cover a large section of the plant. The effectiveness of air blowing appears to be far better than that of suction because the air can penetrate more deeply into the foliage. This configuration is simple and requires less energy than the others tested. It can be efficiently used provided that an adequate catching device is used to collect the CPBs blown off the plants. The air blowing/air suction configuration includes a semicircular shield (40 cm radius) centered at the intersection point of the y and horizontal hood axes (Fig. 2). In addition, hoods are tilted upward 20° from their horizontal axis. This directs the airflow more toward the upper part of the plant where the CPB tends to feed first. The advantage of this configuration is to keep the plant near the suction hood under the effect of the blown air, thus providing high suction effectiveness. This shielded simultaneous oblique ascending air suction and blowing configuration does not require a catching system because the suction hood vacuums the insects. However, the perfect semicircular shape of the shield has to be slightly modified to keep it in contact with the airstream and consequently prevent recirculation of air.

9 Conclusion

The pneumatic control of insect pests is an interesting alternative to chemical insecticides. This technique is successfully used to control insects that easily fly as soon as they are disturbed in their environment, in particular, the whitefly (*Aleurodidae*) and the tarnished plant bug [*Lygus lineolaris* (P. de B.)]. Less success was reported for other insects like the Colorado potato beetle [*Leptinotarsa decemlineata* (Say)].

When designing a pneumatic system, it is imperative to take into account the characteristics of the plants to be protected and the behavior of the insects to be controlled at different life-growing stages. The success of the control process is mainly related to the adequate design of the hoods. The designed system has to be as light as possible to avoid any excessive compaction of the soil. Also, the pneumatic control system must cause no damage to the plants.

Numerical modeling is a powerful tool for optimizing the parameters required to design pneumatic control systems. It allows many configurations of variable degrees of complexity to be simulated without the need of costly prototyping. Thus, the numerical method not only allows the design process to be accelerated, but also the time and the cost of field testing to be greatly reduced.

However, it would be wise to recall that pneumatic control does not represent a magic and complete solution to the problems caused by insect pests. This technique cannot, alone, like some other non chemical means available on the market, efficiently control the populations of insect pests. It has to be used within an integrated pest management program.

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Current Status and Prospects for the Use of Physical Control in Crop Protection

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Often a new paradigm emerges, at least in embryo, before a crisis has developed far or been explicitly recognized. T. S. Kuhn, 1970

Physical control in crop protection goes back a very long time. At the dawn of agriculture, it is easy to imagine our distant ancestors pulling weeds from their small plots. With the rapid advances that have occurred in the physical, chemical and biological sciences since the late 19th century, agriculture has been transformed from a strictly empirical activity, largely based on tradition and aimed primarily at staying off famine, to a quantitative form of agriculture focussed on producing a certain amount of food. During this transition, which has been sustained at an increasing rate over the last 50 years, physical control methods have been set aside because of the tremendous success of chemical control. It is only natural that some people should view the use of physical control methods as a step backward to those distant ancestral practices. The many different examples in this book illustrating the effectiveness of physical control provide a clear picture of the technological changes that have occurred over the past 50 years and underscore the new opportunities that now exist for the application of physical control techniques. Thanks to various refinements and greater precision in the implementation of such methods, physical control now has all the necessary attributes to be part of integrated pest management strategies.

The different methods of physical control that can be used against crop pests have some common characteristics. One of the characteristics that differentiates physical tactics from the other control methods (Table 1) is the absence of persistence. In almost every case, the effect of a treatment is limited to the period of application. When treatment stops, the stressor disappears immediately or dissipates quickly and the only damage that subsists is that which has already been caused. By contrast, chemical and biological control agents continue to have an effect after the treatment has been applied. From the standpoint of exercising control over the treatment and its secondary effects, the absence of a residual action is an advantage. However, this characteristic can also be regarded as a drawback, since it means that the treatment has to be repeated every few days to control crop pests that emerge subsequently and are active for a few days or a few weeks. In such a case, persistent chemicals constitute a much more convenient approach for users, although they are often undesirable from an environmental standpoint.

Table I. Comparison of control methods for crop protection.

Characteristic	Method		
	Chemical	Biological	Physical
Advent	20th century	20th century	With agriculture
Registration	Required	A few cases	Never
Supporting sciences	Analytical chemistry, chemical synthesis , biology	Biology, biotechnology, ecology	Engineering (mechanical, electrical, electronic)
Scientific references	Very abundant	Abundant	Few
Residual action (residues and persistence)	Yes (variable)	Yes, if reproduction occurs	Negligible
Possibility of combining with another method	Yes (sometimes difficult with biological methods)	Yes	Yes
Active or passive method	Active	Active	Active and passive
Application to large acreage	High	Low	Low to moderate
Application to crops with a high profit margin per hectare	High	Moderate to high	Moderate to high
Safety for crop	Moderate to high (phytotoxicity)	High	High (passive) Low (active)
Labour requirements	Low	High	Medium to high
Work rate (hectares treated per hour)	High	Variable	Low (active) High (passive)
Site of action	Photosynthetic system , nervous system (few genes involved)	Systems allowing adaptation to biotic stresses	Systems allowing adaptation to abiotic stresses
Environmental or toxicological requirements, safety	High and costly	Moderate (e.g. virus)	Low (exception: electromagnetic radiation)
Geographic impact	Drift, runoff, evaporation, food chain	Colonization of non-target habitats by parasites or predators	Restricted to area treated (exception: electromagnetic radiation)
Energy requirements	High for production	Low	Low (passive) High (active)
Machinery required	Ground or aerial sprayer	Little or none	Many types of equipment, few machines are suited for more than one purpose
Current market	US\$32 billion (FF 192 billion)	About 1.5% of the chemical pesticides market	Negligible

In addition to being restricted to the time of application, the impact of a physical control method is limited spatially. Mechanical, pneumatic, electrical and thermal energies are dissipated locally over a distance of up to a few metres from the site of application. Electromagnetic radiation, which propagates over considerable distances and is subject to numerous restrictions (reserved frequency bands, maximum power, absence of interference), is an exception. Some pesticides have the unfortunate ability to disperse over considerable distances and become a non-point source of contamination, thereby presenting a level of risk that is difficult to quantify. Similarly, many biological control agents can disperse or become dispersed outside the treatment area. Although the risk of contamination is low or non-existent in this case, the dispersal itself represents a loss of efficiency and effects on the ecosystems surrounding the treated area must be taken into consideration.

The modes of action of physical control techniques differ markedly from those of chemical or biological control methods. Pesticides (chemical pesticides and biopesticides) function by inducing biochemical reactions, while biological control methods other than the use of biopesticides are based on alterations in the biotic environment of the target pest. If this environmental manipulation short-circuits the target organism's mechanisms of adaptation to biotic stresses, the control tactic will be successful. Physical control affects the mechanisms of adaptation to abiotic stresses. The various modes of action offered by the broad array of physical control measures allow diversification and open up promising opportunities for managing pesticide resistance in noxious organisms.

Abiotic stresses are non-specific. Plants, animals, microorganisms, in short all organisms living in a homogeneous climatic zone, are exposed to the same abiotic stresses, both qualitatively and quantitatively. This probably explains the lack of selectivity exhibited by many methods of physical control. Two different plants that thrive in the same environment have to adjust to the same changes in abiotic conditions. Weeds and cultivated plants therefore have comparable capacities for adaptation. Therefore, devising selective treatments is a problem. On the one hand, we need to gain greater insight into mechanisms of adaptation to abiotic stresses in order to identify avenues for improving treatment selectivity; but we also need to work on enhancing the selectivity of physical control methods by developing more sophisticated machines equipped with appropriate sensors and controls to ensure that the treatment suppresses the target pest without harming the crop. Both of these aspects are illustrated with the example of flame weeding in corn (Chap. 3). With the flame weeding approach, the phenological stage of the crop offering the greatest resistance to thermal stress provides selectivity, and proper positioning of the burners in relation to the crop plants enhances this selectivity.

Only a few passive physical techniques are available for crop protection (see Chap. 9, 15 and 16). All of the chemical and biological measures are active techniques. Passive methods should be employed whenever possible, because they extend treatment over a lengthy period. For example, mulching done to keep weeds in check is effective as long as the mulch is kept in place.

Most physical methods of **control** can be used in a crop protection program incorporating both chemical and biological **controls**. A potential problem occurs when physical barriers are still in place during chemical or biological treatments. Chemical and biological methods are sometimes incompatible, particularly in production systems eschewing chemical pesticides. In the latter case, **only** biological and physical methods can be applied. Although not economically significant at present, organic crops represent a growing market segment. This is a niche that will definitely provide leverage for the development of physical control measures.

The regulatory framework for physical control differs markedly from that for agrochemical products. First, many physical techniques are subject to rules concerning their use (i.e. the registration process), which are designed to protect users and the general public. Sometimes, such as with the use of propane gas, specialized training is required. The use of electromagnetic radiation is constrained by telecommunications regulations, some of which stem from international agreements. In the case of microwave energy, for instance, only a handful of frequencies have been set aside for industrial, scientific and medical applications (see Chap. 11, Table 2). With regard to the regulatory framework for physical control technologies, it is completely defined a priori. In short, the equipment employed must meet the applicable standards (mostly related to user safety). With chemically or biologically based methods, the difficulty of anticipating secondary effects precludes the establishment of comprehensive specifications which would be known a priori. This explains the need for increasingly costly test protocols designed to evaluate pesticide safety from the standpoint of human health as well as ecotoxicology.

A number of factors tend to complicate the implementation of physical control methods, and physical tactics cannot be readily compared with crop protection systems based solely on the use of an agricultural sprayer to apply pesticides in liquid form. For agricultural operations, this system entails low variable costs and fixed costs. In contrast, the equipment used for physical control is often very specific: cultivators for weeds, vacuuming device for Colorado potato beetles, and so on. Very few physical control tools offer the operational versatility that would allow them to perform several types of crop protection operations. Integration efforts, such as those described in this book, in which researchers have sought to design burners for use in **controlling** Colorado potato beetles, killing weeds, performing top-killing and dealing with mildew (Chaps. 2,3 and 4), are needed to enable physical control tools to penetrate the crop protection market.

Compared with traditional chemical control, present methods of physical control are more labour intensive and have a lower operational yield (hectares treated per hour). That is one of the main reason why physical control techniques have had very little success in penetrating the field crop market. Given these circumstances, crops with a high profit margin per hectare represent an obvious market for physical control methods. This is **all** the more true when one considers that crop protection treatments often account for a large percentage of the inputs in that market segment. From the viewpoint of implementation, physical methods compare favour-

rably with biological methods (other than biopesticides), which often entail labour-intensive field observations and are difficult to apply in a field crop setting.

In the post-harvest sector, some staple products of the processing industries are protected from pests either through the use of persistent insecticides (which leave residues that remain active for several weeks or even months), or fumigant insecticides, such as methyl bromide. There is a definitive trend at present to decreasing pesticide residues at all stages in post-harvest processing of agricultural products, particularly in cereals which are a staple food for all of humanity. Furthermore, methyl bromide, which for a long time has played an effective and leading role as a pest control tool in food processing plants and in the eradication of quarantine pests, was recently identified as an ozone-depleting substance. As a result, all industrialized countries are currently phasing out most uses of methyl bromide and this substance is to be banned completely by the year 2005. This situation has prompted a quest for new alternatives to the use of chemical control. Some advanced physical control technologies have gained renewed popularity as efforts get under way to implement integrated pest management in the post-harvest sector. Mechanical barriers to keep pests out, combined with physical suppression techniques, are the cornerstone of the systemic approach adopted by the most dynamic countries with a view to replacing methyl bromide (e.g. the Food Safety Enhancement Program (FSEP) of the Canadian Food Inspection Agency). In parallel, the program to reduce pesticide residues also draws to a great extent on physical procedures for suppressing post-harvest pests (thermal treatment using microwaves or radio-frequencies, inert atmospheres, etc.). Over the past 5 years, intensive research has been devoted to elucidating the physiology of the physical stress induced in insects found in food products with a low moisture content. These studies, which are aimed at devising practical solutions, have enriched the otherwise scarce scientific literature on this topic.

The size of the corpus of scientific and technical literature in any field provides an indication of the amount of research that has been done. In the area of chemical control, tens of thousands of scientific and technical articles (more than 50 000) have been written over the past 50 years or so. There are many specialized journals that disseminate the results of research on pesticides (e.g. *Pesticide Science*, *Weed Science*, *Journal of Toxicology and Environmental Health*, *Pesticide Biochemistry and Physiology*), and there are many books on the subject (e.g. Coats 1982; Hayes and Laws 1991; Tomlin 1994; Ware 1994). Chemical control is therefore a mature area of research combining the expertise of chemists and biologists.

In the field of biological control, several thousand articles have been published over the past 50 years. Specialized journals exist in this field as well, such as *Biological Control*, *Biocontrol Science and Technology*. There are quite a few books on biological control, such as the ones by Debach (1974), van den Bosch (1982), Vincent and Coderre (1992), Hokkanen and Lynch (1995), Van Driesche and Bellows (1995) and others. As well, specialized monographs have been published by New (1991), Godfray (1994) and Jervis and Kidd (1996). On the whole, biological control is viewed favourably by the general public. This field draws on

the expertise developed in many **branches** of science: biology, **population** dynamics, animal behaviour, ecology, physiology and so on.

Physical control should be an integral part of integrated pest management (Chap. 1, Fig. 1). In the classic textbooks on integrated pest management (Riba and **Silvy** 1989; Metcalf and **Luckmann** 1994), physical control is barely mentioned from either a theoretical or practical standpoint. A book by the US **National** Academy of Sciences (1969) on integrated pest management contains only one chapter on physical control. There are approximately **4000** scientific and technical articles on the use of physical control for crop protection, but no books currently exist on this topic. Obviously, physical control has not benefited from the same research and development efforts as chemical and biological control. This approach did not emerge as a true alternative to conventional pesticide use until the early 1990s, when it began to be studied using means equivalent to those in biological control: models were built to identify the impacts of physical stresses on insect pests and weeds and to **link** them to physiological mechanisms in an effort to **understand** the lethal process from a mechanistic modelling viewpoint. Physical control involves a variety of scientific and technical challenges, and many teams of researchers have been set up in an effort to solve them. As pressure for sustainable agriculture increases, new research groups will form and new companies will be created with the goal of marketing the resulting technologies. Since physical control offers promising **opportunities** for cutting down on the use of synthetic pesticides, the development of new physical techniques can go a long way toward achieving the pesticide reduction **objectives** that have been set by many countries and organizations. In this context, stakeholder agencies should actively support the development and implementation of physical control methods within integrated pest management programs for crop protection. In the current context of protection of crops and post-harvest food products, the contribution of physical control to integrated protection is considered insufficient. However, we hope to have shown that some highly effective methods are **current**ly available and that they are compatible with **IPM** programs. Furthermore, in certain specific situations, the physical control measures can be the primary component of such a strategy. It should be kept in mind that intensive cropping systems are bound to lessen in **extent** gradually, given the need to adapt to price reduction policies, consumer demands in relation to food safety and security and the **decli**ning number of new pesticide registrations in many crops. Research associated with the expansion of physical control applications and with process engineering will help to bring about this evolution, which now seems inevitable.

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Glossary

Acclimation (cold): In a living organism, result of a **physiological** adaptation in response to changes in surrounding temperature. During a cold acclimation phase, insects synthesise and accumulate various compounds known as cryoprotectants, in their tissues. Inside the insect body, the primary role of these sugars and polyols is to lower the temperature where ice crystals start to form spontaneously.

Adventive (adj.): Refers to plants growing on cultivated land which were not intentionally established through seeding or **planting**. (syn. weeds).

Apterous (adj.): Wingless.

Biopesticide: Pesticide whose active ingredient is composed of, or extracted from or derived from a living organism. For example, the most widely sold bioinsecticide in the world, *Bacillus thuringiensis* var. *kurstaki*, is a mixture of bacteria, protein crystals and cellular debris. This mixture results from an industrial fermentation process.

Climacteric: The climacteric stage is an important stage in the ripening process of several fruits. It is characterised by a sudden and significant increase in the respiration rate at the onset of **ripening**.

Cold stupor: Cessation of motor activity and slowing of **vital** functions in an animal caused by exposure to cold temperatures. **Stored-grain** insects, for example, stop moving when the temperature is about 4 °C or lower, but they can survive for several weeks or even months at temperatures around this threshold.

Commensal (adj.): Denotes a species living in a beneficial association with another species, which is not harmed by the relationship.

Cooling front: During grain cooling through ventilation, there is a sharp boundary between the chilled grain and the unchilled portion of the grain **bulk**. The term "cooling front" aptly illustrates the progression in space of the **cooling** operation of the grain. As the cooling front moves, all the grain behind the cooling front has been chilled. **Silothermometry** is used to track the position of the cooling front in the bin during **chilling operation**. (syn. **cold transition zone**).

Degree-day accumulation: It is often useful to be able to predict periods of insect emergence and activity. Since the development of these poikilothermic organisms is a function of temperature and occurs within a specific range of temperatures (between a lower temperature limit and an upper limit), their development can be modelled. For example, in temperate zones, entomologists use simple physiological models based on the use of a reference temperature below which no development can occur. Degree-days are computed by integrating over time, the difference between suitable mean temperatures (typically daily means) and the reference temperature. For instance, if an insect begins developing at a base temperature of 5 °C and mean temperatures of 3, 10, 16, 22 and 18 °C have been recorded, the temperature differences of 0, 5, 11, 17 and 13 °C add up to 46 degree-days for this time period. The degree-days are correlated to the physiological development of insect species. Degree-days are also used to model plant growth by selecting appropriate reference temperatures.

Dielectric material: Perfect dielectric materials do not conduct electricity but respond to electromagnetic fields by storing energy within their internal structure. In alternating fields, the internal structure of a dielectric is continuously changing at the same frequency as the electromagnetic signal. During this process, internal friction or losses occur and heat is generated. The amount of heat generated is a function of the properties of the dielectric and of the frequency of the electromagnetic field. The dielectric properties of a material are the permittivity (measure of the material's capacity to polarise in an electrical field) and the dielectric loss factor (determines the material's rate of heating in an electrical field). (See Chap. 7).

Dislodging: Action of taking an insect off a plant. Once insects have been dislodged using a pneumatic control system, the air stream must direct them to a collecting device before they fall to the ground.

Drag coefficient: Dimensionless parameter. It is the ratio of the drag force exerted on a body in relative motion with respect to a surrounding fluid, to the inertia of the body. With the exception of very small spherical bodies, the drag coefficient is calculated using fairly complex empirical equations.

Entoleter: Apparatus designed to mechanically injure insects by impact. It is named after the Trade Mark given by the company that manufactures the machine. See "impact disinfestor" in this glossary.

Epidemiology: Epidemiology in plants (as in human and veterinary medicine) is the study of disease outbreaks and the factors that affect their onset and progression. A detailed understanding of the mechanisms underlying the development and spread of plant diseases is essential for developing more effective and more environmentally friendly control methods.

Flame weeding: Physical control method where weeds are exposed to high temperatures either through direct contact with heated gases or through thermal radiative transfer. The thermal shock induced causes the expansion and bursting of cells

along with the coagulation of proteins. Direct combustion of plant material is not involved.

Fluidized bed: Bed of small particles which results when a fluid, usually a gas, flows upward at a velocity high enough to buoy and suspend granules or heavy particles. Substances that are **fluidized** in this manner can be transported over considerable distances (pneumatic transport) or undergo thermal transfer or rapid treatment in a fixed bed (e.g., puffing of cereals or seed treatment).

HACCP process: Quality control concept that originated in the United States (HACCP stands for **Hazard Analysis and Critical Control Point**). In the agri-food sector, the purpose of a HACCP system is to ensure consistent standards of safety and quality in manufactured products. A holistic and rational approach is employed which focuses on identifying the risks of poor quality products, evaluating them and establishing preventive measures for managing those risks, which may be **microbiological**, physical or chemical in nature.

Heat stupor: Physiological state of an insect exposed to a temperature higher than the heat stupor point, which generally ranges from 42 to 48 °C depending on the species. This is the temperature at which the insect's motor activity completely stops.

Hypercarbia: Atmosphere whose composition has been modified through the addition of carbon dioxide.

Ice-nucleating bacteria: Found widely in nature, these bacteria promote the crystallisation in organisms with a high moisture content by raising the temperature corresponding to the supercooling point (see Chapter 6) by a few degrees. They are responsible for triggering freezing in plants and are used primarily in the manufacture of artificial snow. The most commonly employed species is *Pseudomonas syringae*. Once ice-nucleating bacteria have been ingested and end up in the gut of an insect, they cause a significant reduction in tolerance to freezing.

Impact disinfector: Machine that uses centrifugal force to hurl flour or wheat against plates that revolve on a central shaft at high speed and against the metal housing of the machine. The impact of the infested grain or flour hitting the revolving plates is sufficient to kill all insect life in the product.

Magnetron: Electronic device using a resonant cavity to generate electromagnetic signals in the microwave range.

Modified atmosphere: Storage atmosphere whose composition differs from that of normal air owing to the removal or addition of gases (nitrogen, oxygen, carbon dioxide or argon), either in pure form or as a mixture.

Mulching: Operation where foreign material (e.g. plastic film) is **laid** on the ground around the stems of cultivated plants.

Mycochrome: In a fungus, photoreceptor excited at specific wavelengths of light in the 300–500 nm range. **Excited** mycochromes can either induce or inhibit sporulation.

Normalised airflow rate (grain aeration): Volume of air introduced at atmospheric pressure per unit time per unit volume of the grain mass. Typical units are $\text{m}^3/\text{h}/\text{m}^3$. In grain cooling, it is estimated that about 10 nights of ventilation at a rate of $7 \text{ m}^3/\text{h}/\text{m}^3$ are required to bring the temperature in near equilibrium with ventilating air temperature. This translates to using 1000 m^3 of air for cooling 1 m^3 of grain (Lasseran 1994 - see Chap. 6)

Persistence: Property of a crop protection agent to remain intact or active. Quantitatively, it is measured as the duration of the persistence. Persistence of chemical pesticides varies from a few hours to several days following application. In biological control, persistence refers to the length of time control agents (parasites or predators) will survive following an inundative release. In physical control, the persistence of a treatment is often nil. Persistence is a function of the chemical or organism used and of the environmental parameters (e.g. degradation by ultraviolet radiation, heat, rain).

Photomorphogenesis: Development of plant structures under the influence of light.

Photonic flux: Represents the number of photons reaching a plant per unit area and per unit time.

Photoreversion: Process whereby an active phytochrome is converted to inactive phytochrome following exposure to far-red light.

Photoselectivity: Process whereby plastic mulches absorb, reflect or transmit different wavelengths depending on the colour, content and type of material used.

Phytochrome: Light sensitive pigment in plants. Some respond specifically to the photoperiod that control morphogenesis in plants.

Pneumatic conveyor: Equipment for conveying bulk material using a high airflow rate in pipes. Industrial machines for unloading ships proceed by suction. Models designed for farm use have conveying rates ranging from 4 to $7 \text{ t}\cdot\text{h}^{-1}$, whereas the models designed for unloading ships operate at a rate of 10 to $60 \text{ t}\cdot\text{h}^{-1}$. When a pneumatic conveyor is used to empty a grain storage bin, mortality among stored-grain insects ranges from 50 to 100%.

Primary versus secondary pest: On a given crop, several insect species are present, some of which cause more damage than others. If left untreated, primary pests will cause serious damage to plants year after year. By contrast, secondary pests cause negligible damage.

Retention force: Force exerted by an insect grabbing on a surface. This force is used to counteract the effect of gravity and of other forces such as the inertia force induced when leaves rustle under the action of wind. In pneumatic control methods, suction and drag forces resulting from the airflow must overcome the retention force.

Ruderal (adj.): Relates to plants that grow in modified but uncultivated habitats (e.g., along highways and roads, on roofs, abandoned sites).

Sessile (adj.): Refers to any directly attached object that has no stem or pedicle. Some insects are sessile throughout all or part of their life cycle, and generally remain attached to a structural part of a plant. In many scale insects, for example, the immature forms and females are sessile (immobile), whereas the males are mobile.

Sheeting: Semi-forcing technique in which a semi-permeable plastic sheeting is **laid** flat over cultivated plants.

Solarization: Method involving the use of transparent plastic covers **laid** flat on the soil for several weeks prior to cultivation. Heat builds up under the covers, increasing the soil temperature to a level that eliminates most crop pests, **including** weed seeds and pathogenic **microflora**.

Specific air flow (aeration of grain): The volume of air moved through one m^3 of grain per hour during aeration of grain. Approximately $7 \text{ m}^3 \cdot \text{h}^{-1}$ of ambient air per m^3 of grain is needed to cool grain to the ambient air temperature over about 10 nights of aeration (or about $1,000 \text{ m}^3$ of air to cool one m^3 of grain, Lasseran 1994).

Stale seedbed: This technique **involves** tilling the soil as for seedbed preparation, and then **allowing** weed seeds to germinate. Once the weed seedlings have emerged, the soil is tilled again to prepare the seedbed or another stale seedbed, thereby destroying any weeds that have germinated. For the technique to be successful, the time **period** between **tillage** operations must promote **maximum** seedling. Delayed seeding minimises competition with the crop plants that become **established** and reduces the need for weed control during the season.

Stupor (cold stupor or heat stupor): cessation of motor activity associated with temperatures at both ends of the **thermobiological** scale. Among stored-grain insects, cold stupor occurs below $4 \text{ }^\circ\text{C}$ and heat stupor at temperature higher than $45 \text{ }^\circ\text{C}$. Insects die after a few minutes' exposure at $45 \text{ }^\circ\text{C}$, but at $4 \text{ }^\circ\text{C}$ they can survive for a few days to a few months.

Thanatosis: Behavioural strategy whereby an insect falls from a plant and feigns death. This may enable the insect to avoid predator attack or escape from some perceived danger.

Waveguide: Just as an electrical wire conducts **electricity** from one point to another, a waveguide is used to direct electromagnetic waves to a specific location. A waveguide serves as a connection between the electromagnetic wave source and the point being served. The characteristics of waveguides (shape, size and material) depend on the frequency of the electromagnetic waves to be **conducted**. They are generally cylindrical or rectangular in cross-section and made of materials that permit reflection without excessive loss of electromagnetic energy. The size of the

waveguide is **directly** related to the length of the electromagnetic waves. For example, visible light is channeled through optic fibres with a very **small** diameter (a few dozen microns), whereas microwaves require metallic guides **ranging** up to a few dozen centimetres in diameter. Losses through absorption or **reflection** limit the connection distance (hundreds of kilometres for optic fibres and a few metres for microwave guides). The power required to transmit electromagnetic radiation is also a factor limiting the size of waveguides.

Viral disease: disease caused by a virus.

Virulence or aggressiveness of a pathogen: The virulence of a particular pathogen strain denotes its ability to cause disease in a given plant variety or cultivar. A given strain may be virulent for some cultivars and non-virulent (unable to cause disease) in other cultivars of the same cultivated plant species. A distinction is generally made between the terms "**virulence**" and "aggressiveness." Aggressiveness refers to the difference in severity of symptoms that a virulent strain induces in a host plant. Whereas an isolate is either virulent or non-virulent for a given cultivar (qualitative assessment), a virulent isolate may be more or **less** aggressive (quantitative).