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MANAGEMENT OF AGRICULTURAL INSECTS WITH PHYSICAL CONTROL METHODS*

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■ **Abstract** Ideally, integrated pest management should rely on an array of tactics. In reality, the main technologies in use are synthetic pesticides. Because of well-documented problems with reliance on synthetic pesticides, viable alternatives are sorely needed. Physical controls can be classified as passive (e.g., trenches, fences, organic mulch, particle films, inert dusts, and oils), active (e.g., mechanical, polishing, pneumatic, impact, and thermal), and miscellaneous (e.g., cold storage, heated air, flaming, hot-water immersion). Some physical methods such as oils have been used successfully for preharvest treatments for decades. Another recently developed method for preharvest situations is particle films. As we move from production to the consumer, legal constraints restrict the number of options available. Consequently, several physical control methods are used in postharvest situations. Two noteworthy examples are the entoleter, an impacting machine used to crush all insect stages in flour, and hot-water immersion of mangoes, used to kill tephritid fruit fly immatures in fruit. The future of physical control methods will be influenced by sociolegal issues and by new developments in basic and applied research.

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INTRODUCTION

There is a need to reduce the negative impacts of pest control methods on the environment. Increased concerns about the potential effects of pesticides on health, the reduction in arable land per capita (79), and the evolution of pest complexes likely to be accelerated by climate changes also contribute to change in plant protection practices. Insecticides are still widely used; however, more than 540 insect species are resistant to synthetic insecticides (71). Other drawbacks of synthetic insecticides include resurgence and outbreaks of secondary pests and harmful effects on nontarget organisms (82). This situation creates a demand for alternative control methods, including physical controls.

Metcalf et al. (72) wrote that physical controls "are in general costly in time and labor, often do not destroy the pest until much damage has been done, and rarely give adequate or commercial control." However, recent advances in physical controls and the restrictions placed on many chemical controls have resulted in a notable increase in research and application of physical controls. This review complements the work of Banks (6), Hallman & Denlinger (48), Oseto (80), and Vincent et al. (101) by offering a critical assessment of physical controls with the objective of formulating recommendations for further research and applications.

CONSIDERATIONS ON PHYSICAL CONTROL METHODS IN RELATION TO AGRICULTURAL PLANT PROTECTION

In physical control methods, the physical environment of the pest is modified in such a way that the insects no longer pose a threat to the agricultural crop. This can be achieved by generating stress levels ranging from agitation to death or by using devices such as physical barriers that protect produce or plants from infestation.

Many physical control methods target an ensemble of physiological and behavioral processes, whereas chemical methods have well-defined and limited modes of action.

In this review, physical control methods are grouped under two main classes, passive and active; a miscellaneous category groups those that do not readily fit this classification (follow the Supplemental Material link in the online version of this chapter or at http://www.annualreviews.org/). The active class is further subdivided into mechanical, thermal, and electromagnetic techniques. Passive methods do not require additional input after establishment to be effective over a given period. The efficacy of active methods depends on continued input over the period of control. The level of control achieved is related to the amount and intensity of the input.

Effective physical control methods protect plants during the entire season from emergence to postharvest. However, postharvest conditions are better suited to physical control methods because the environment is rather confined, the material is of high economic value, and the use of insecticides is frequently inappropriate or even unlawful. Physical control methods, such as cold, heat, and ionizing radiation, are used extensively as postharvest quarantine treatments where disinfestation of a given pest at a predetermined level of control must be achieved (47).

PASSIVE METHODS

Physical barriers may be defined as any living or nonliving material used to restrict movements or to delineate a space. They encompass a number of methods compatible with several other control methods (12). The economics of deploying barriers is closely related to the spatial scale. In that respect, it is easier to protect a stored product than a crop grown over large field areas. In the field, one major challenge is to deploy either degradable or nondegradable barriers that can be dismantled, and possibly reused, at low cost.

Trenches

Trenches to intercept walking insects such as the chinch bug were implemented as early as 1895 (72). Recently, several papers relevant to the Colorado potato beetle/potato system were published (12). A V-shaped trench lined with plastic retained up to 95% of Colorado potato beetles (74). The efficiency of the method depends on the density of the overwintered beetles and on the proportion of flying versus walking individuals (103) as well as on physical characteristics of the trenches. The furrow should be at least 25 cm deep with sides sloping at angles $>45^{\circ}$. Adults that fall in trenches covered with dust have little chance of escaping because they cannot walk up the dusty walls and because they rarely fly before walking up to the top of plants or structures (12). Rainfall has little effect on the efficacy of the trench to retain beetles. A machine has been designed to install the plastic trenches (74). In field conditions of New Brunswick, Canada, a reduction of 48% in immigrating (overwintered) adults was observed. For an 8-ha field, the cost is recovered if one insecticide treatment is saved. An aboveground version has comparable efficiency, can be reused up to 10 years, and is suited for small fields of high-value crops (11). The rate of adoption of this technology has steadily increased in the 1990s, but interest decreased as an effective insecticide and transgenic plants appeared on the market (12).

Fences

Fencing is particularly relevant to exclude low-flying insects (e.g., anthomyiids) from annual crops where few chemicals are available and the crop value is high (e.g., onion and cole crops) (12). Fences 1 m high exclude 80% of flying female cabbage flies, *Delia radicum*. Height of the fences is critical and is limited by cost and resistance to wind. Although cabbage maggot flies can be captured up to 180 cm above ground level, Vernon & Mackenzie (98) adopted fences 90 cm high as an optimal fencing method. Overhangs (25 cm) decreased cabbage maggot fly, *Delia radicum*, trap catches inside the fenced plots and reduced damage to the crop (14). If vegetable crops are strategically segregated by fences and properly rotated, the effectiveness of exclusion fences improves over time, partly because the fence congregates natural enemies of anthomyiid adults. One drawback of fencing is that excluded individuals that are good flyers can attack a nearby but unprotected crop. Also, individuals that overcome the barrier and are confined within the enclosed area may damage the fenced crop.

Organic Mulch

Straw mulch indirectly affects Colorado potato beetle populations and significantly reduces damage (108) by favoring several species of its egg and larval predators: *Coleomegilla maculata*, *Hippodamia convergens*, *Chrysopa carnea*, and *Perillus bioculatus* (16). Although the yield of potato fields is higher in mulched than in nonmulched plantings or when straw mulch is incorporated into an insecticide program (16), the cost of using straw mulch may be prohibitive to nonorganic growers (30). The interaction of straw mulch and *Bacillus thuringiensis* subsp. *tenebrionis* sprays is positive and gives results comparable to insecticidal treatments because the two technologies do not interfere with one another (17). Straw mulch is agronomically and environmentally sound and can be useful as part of an insecticide resistance management program.

Mulches from Artificial Materials

Various protective materials such as paper or plastic sheets or aluminized films can be used for mulching. The primary objective of mulching is to improve productivity and reach harvest at an early date. It is usually used for high-value crops. Mulches from artificial materials can be designed for pest control. For example, plastic materials can be of such color as to modify the spectrum of incident light to alter a given insect behavior. Thrips are attracted to blue, black, and white (24), and aphids to yellow and blue (9, 24). Aluminized materials can attract some insect species while repelling others (7). The repellent properties have been related to the reflection of ultraviolet light at wavelengths <390 nm (62). In strawberry fields, reflective mulch has shown some potential by increasing productivity of the plants and by reducing damage from the tarnished plant bug, *Lygus lineolaris* (92). The use of mulches should be studied and implemented using a system approach looking not only at the impact on insect pests but also at the impact on weeds, other insects, diseases, nematodes, and yield. If one component (e.g., early harvest) provides an economic justification, then there is an opportunity for designing mulch that will have a positive impact on other segments such as insect control. Machinery to extract and roll mulch films is becoming available, and photobiodegradable materials are being developed (7).

Particle Films

Road dust drifting on crops can have a negative effect on natural enemies (29). The recent development of sprayable formulations of kaolin under the generic name "particle film technology" (43) fueled interest in this method by showing broader insecticidal activity. Several mechanisms are at play. Pear psylla, *Cacopsylla pyricola*, adults confined on a treated [hydrophobic particle film (PF)] surface become coated with tiny particles that interfere with visual cues (89). Adult behavior is disrupted to the point where they are unable to feed. Spirea aphids, *Aphis spiraecola*, lost footing and fell off the treated plant, and damage by the potato leafhopper, *Empoasca fabae*, was significantly reduced (43). Hydrophobic PF also deterred feeding and oviposition of the citrus root weevil, *Diaprepes abbreviatus* (65). Kaolin sprays reduced neonate walking speed, which reduced the rate at which neonates infested fruit, and oviposition by female codling moth, *Cydia pomonella* (96), and oblique-banded leafroller, *Choristoneura rosaceana* (58).

Hydrophobic PF have been superseded by hydrophilic PF. They have the same effects as mentioned above on pear psylla (89). One commercial formulation, Surround®, represents approximately 30% of all insecticides used in pear in the United States (G. Puterka, personal communication). In pear field trials, hydrophilic PF significantly reduced pear psylla populations and oviposition, plum curculio, *Conotrachelus nenuphar*, oviposition scars, but not codling moth damage. The treatments also increased fruit quality and yield. A potential limit of PF is the adhesion of films under heavy rain. This has been addressed by the development of new formulations, notably by using a custom spreader-sticker. Suggested negative impact of PF on natural enemies (96, 58) should be researched. Standard spraying equipment is used, and growers do not have to invest in specially dedicated machines. Owing to the wide range of insect taxa affected by PF and plant diseases (89), and to their positive effects on fruit physiology and quality (42), there should be more scientific and commercial development in PF in the near future.

Inert Dusts

There has been substantial research and development on inert dusts for two decades, resulting in the registration and commercial use of several inert dust formulations

(32, 44, 60). There are many kinds of inert dusts: lime, common salt, sand, kaolin, paddy husk ash, wood ash, clays, diatomaceous earths (ca. 90% SiO_2), synthetic and precipitated silicates (ca. 98% SiO_2), and silica aerogels (44). Because of their low mammalian toxicity, they are used to protect stored grains against a number of coleopteran pests. Diatomaceous earth is classified as a "generally recognized as safe" (GRAS) food additive by the U.S. Environmental Protection Agency (60). Inert dusts exert their effects slowly through several mechanisms that result in dehydration, notably by adsorption of cuticular lipids and, less importantly, by abrasion (29, 60). As some insects move into the grain storage area or within the stored grain, behavior also is a factor (32). There are large behavioral and physiological differences in susceptibility among species. Because of their mode of action, high relative humidity (>70%) or >14% water content in stored grain reduces their insecticidal effect. Diatomaceous earth collected from various parts of the world shows differences in diatom species, physical properties, and insecticidal efficacy (60), thus complicating the standardization of commercial formulations. Effective diatomaceous earths have >80% SiO_2, a pH <8.5, and a tapped density (a technical term refering to the specific mass for finely ground powder such as diatomaceous earth, measured from standard "tap flow" withdrawal from a bulk into 1 L vessel) of below 300 $g.L^{-1}$ (59). Problems associated with the use of diatomaceous earth in large scale operations are (*a*) machine abrasion; (*b*) a reduction in the bulk density (hectoliter mass), which is a measure of grain quality; (*c*) grain fluidity; (*d*) decrease in qualities such as color and presence of foreign material; and (*e*) health hazards (respiratory diseases) (44). Slurry formulations mitigate the latter problem for the treatment of structures (32). Korunic & Ormesher (61) demonstrated that, when exposed to diatomaceous earth for 5–7 generations, populations of *Tribolium castaneum*, *Cryptolestes ferrugineus*, and *Rhizopertha dominica* became less susceptible. More experiments should be done to make a definitive statement concerning the development of resistance by stored-product insects.

Trapping

As a management tool, perimeter trapping has been successful in intercepting flying dipterans that invade orchards from neighboring host plants [*Rhagoletis pomonella* in apple orchards (88, 15) and *Ceratitis capitata* in plum, persimmon, and pear orchards (22)]. Factors contributing to success are low infestation of pests, high density of traps, availability of an attractant, absence of nearby host plants, and trap maintenance. The use of dry, nonsticky traps (22) facilitates operations and lowers costs. It is likely that perimeter trapping will be researched and implemented in other crop and geographical situations. Mass trapping of stored-product moths has been successful with low densities of pyralid moths in storage buildings (i.e., in a tobacco warehouse infested by *Ephestia elutella*) (34, 41).

Oils

Mineral oils have been used alone or in combination with synthetic insecticides for a century to control soft-bodied arthropod pests of fruit trees. To date, no resistance has been reported. Although oils act primarily at contact sites by obstruction of the respiratory system (hypoxia), they may also act as an oviposition repellent. Several arthropod taxa are affected, e.g., mites, scale insects, mealybugs, psyllids, aphids, leafhoppers, and some lepidopteran pests such as eggs of codling moths. Because they have low residual activity, they are relatively harmless to beneficials. The most important factors explaining the pesticidal performance of oil formulations are chemical composition, paraffin (optimally of molecular weight C_{20}–C_{25}) and unsaturated compounds, and the equivalent n-paraffin carbon number (56). To minimize damage when applying oil sprays, it is recommended to avoid spraying when trees are stressed or when temperatures are too high or too low (25). Mineral oil is a reliable physical control method that is still evolving today. For example, horticultural mineral oils are optimized to have both good adjuvant and insecticidal activities and off-target spray drift management (56). Research and development of vegetable oil formulations to control arthropods are ongoing (40) and promising, particularly in organic produce markets.

Surfactants and Soaps

Surfactants may have direct or indirect effects on soft-bodied arthropods. For example, Cowles et al. (23) showed that trisiloxane, generally considered as an inert ingredient, either suffocates or disrupts important physiological processes in the two-spotted spider mite, *Tetranychus urticae*. Owing to their surfactant properties, they work as soaps, presumably allowing interaction of water with arthropod cuticles and causing drowning by permitting water to infiltrate tracheae or peritremes. They also may impair nerve cell functions (54). When assayed against citrus leafminer, *Phyllocnistis citrella*, larvae, Silwet L-77 (an organosilicone molecule) had insecticidal effects alone, and because of its surfactant effect, it might increase the insecticidal effect of *Bacillus thuringiensis* var. *kurstaki* (93). Soaps have been used to kill soft-bodied insects, and their mode of action and low residual activity resemble those of surfactants. Not all soaps have insecticidal properties and, consequently, special formulations with optimal properties should be used. Several insecticidal soaps are registered and commercially available, mainly for urban markets, as found on the World Wide Web.

ACTIVE METHODS

Mechanical

CLEANING Cleaning is a common postharvest treatment. When prescribed as a quarantine treatment, it is usually followed by inspection by the importing regulatory agencies to ensure that the cleaning was successful in removing undesired pests and debris. Cleaning alone may be insufficient and often needs to be followed by another treatment.

One variation of cleaning is the soapy water and wax treatment accepted by the United States against the false spider mite, *Brevipalpus chilensis*, in Chile. It consists of immersion of cherimoyas and limes in soapy water for 20 sec, a rinse, and then immersion in a wax coating (3). The wax physically immobilizes any mites that remain after washing. This treatment shows promise against a number of small, surface-infesting pests of fruits.

PRESSURE Baling hay at a pressure of 10.3 MPa for one day killed 100% of cereal leaf beetle, *Oulema melanopus* (106). However, compression of hay must currently be accompanied by phosphine fumigation (2.12 g/m^3 for 3 days at >21°C) to be accepted by Canada. Baling hay at 7.85 MPa plus fumigation with phosphine (2.12 g/m^3 for 3 days at >21°C) for 7 days satisfies Japanese requirements of hay at risk for importation of Hessian fly, *Mayetiola destructor* (107).

POLISHING Polishing is an industrial process consisting of rubbing off the pericarp of rice grains. Polishing to a weight loss of 11% of rice grains causes 40% acute mortality in rice weevil, *Sitophilus oryzae*, eggs, followed by another 40% mortality owing to the poor suitability of polished rice grains (67). Experiments on the joint use of rice polishing and two pteromalid parasites concluded that *Lariophagus distinguendus* is less affected by polished rice than *Anisopteromalus calandrae* (68).

SOUND Sounds at frequencies <20 Hz can be defined as infrasound, and ultrasound at frequencies higher (>∼16 kHz) than human audibility (105). Sound propagating in a medium is attenuated at a rate approximately proportional to frequency. Ultrasounds propagate well under water but not in air.

All insects contain microscopic stable gas bodies that can oscillate under the influence of ultrasound. Abnormal development of *Drosophila melanogaster* resulted from these oscillations (105). Studies by Belton (8) on the use of ultrasound to protect corn from corn borers and those by Payne & Shorey (83) on the effect of ultrasound on oviposition by cabbage loopers showed promise. Ultrasonic pest control devices are available on the market; however, claims supporting ultrasonic devices in the elimination of insect pests are baseless (http://www.ent.iastate.edu/ipm/hortnews/2001/8-24-2001/ultrasonic.html).

As ultrasound transmits well through water, its use in postharvest while produce is being washed by immersion in water could be easily implemented. However, this approach was not effective in treating asparagus spears for thrips (97).

Acoustical sensors can be used to automatically monitor insect populations in stored grain. Timely insect detection and control can improve food safety and reduce the use of insecticides (52). Ultrasonic waves successfully controlled *Sitophilus granarius* adults inside a wheat grain mass (87).

STALK DESTRUCTION In central Texas, stalk shredding of cotton plants before winter results in 85%–90% larval mortality of pink bollworm, *Pectinophora gossypiella* (2). Winter burial of stalk by plowing causes 75%–80% larval mortality. Physical methods, combined with early crop production practices, allow management of the pest at acceptable population levels (2). In Nigeria, burning the stalk after harvest can destroy 100% of larvae of the sorghum stem borer, *Busseola fusca* (1). However, the practice is not implemented because the peasants use the stalk for other purposes, e.g., roofing material. Partial burning immediately after harvest to cure the stalk kills approximately 95% of larvae and would allow the use of stalk as roofing material.

PNEUMATIC Insect pests can be dislodged from plants using blown or aspirated air (57). Blowing uses energy more efficiently to dislodge insects from plants, but blown insects must be collected. Work has recently been done on *Lygus* spp. on strawberry, Colorado potato beetle (99, 63), *Liriomyza trifolii*, and *L. huidobrensis* on celery, and *Bemisia tabaci* on melons (104). Mobile insects, such as *Lygus* or *Bemisia*, are more likely to be efficiently removed than insects that cling to plants, such as Colorado potato beetle adults and larvae (73). Aspirating inlets can be located closer to plants that are flexible, resulting in a more efficient aspiration (100). Several points need to be studied if the efficiency of pneumatic technology is to be improved. Engineering should focus on aerodynamics, i.e., airflow rate and speed, design of inlets and design of control units. Work rate (ha per h) must be optimized (100). Research on insect behavior is also the key to improving efficiency. For example, both nymphs and adults of the tarnished plant bug, *Lygus lineolaris*, are present on strawberry at any time of the day and can be vacuumed at any time (90). Pneumatic control is nonspecific, and its effect on beneficials needs to be evaluated. In potato fields, it negatively affects diurnal predators belonging to the taxa Arachnida, Chrysopidae, and Coccinellidae, while having no effect on generalist-nocturnal predators (e.g., Carabidae and harvestmen) (63). No significant effect was measured for the *B. tabaci* parasites *Eretmocerus mundus* and *Encarsia lutea* (104). Shortly before the passage of a vacuum machine, 19% of pollinators flew away and, of the individuals remaining on the plants, 61% were aspirated (21). In potato fields, several passes of a vacuum machine did not spread the PSTV (potato spindle tuber viroid) and the PVX (potato mosaic virus) viruses, even if large proportions of infected plants were treated (10).

MECHANICAL IMPACT Disinfestation of wheat grain or wheat flour in mills by impacting machines (entoleter) has been routinely used for more than 50 years in the flour industry to destroy all insect stages (86).

Thermal

Temperature control is widely used in postharvest to slow down degradation of produce caused by physiological processes, pathogens, and insects. For control of insects, both high (37) and low temperatures (30a) can be effective. Temperature, rate of temperature change, and duration of exposure are contributing factors. The biological effects of temperature can be summarized on a thermobiological scale (37). In the field, thermal control is more complicated to implement because heat transfer is difficult to control and the differences in thermosensitivity between crops and pests can be subtle (64). The use of kinetic models to describe intrinsic thermal mortality is a promising approach to implement high-temperature short-time thermal treatments in a quarantine context (95).

COLD STORAGE One of the oldest and most widely used quarantine treatments is storage of fresh commodities at −0.6° to 3.3°C for 7 to 90 days, depending on the pest and temperature. It is used on a wide variety of fruits and vegetables (3). Advantages of cold treatment are its tolerance by a wide range of commodities, including many tropical fruits, and the fact that some fruits, such as apples, are stored for long periods of time at low temperatures lethal to insects to increase the marketing season. Also, unlike most other treatments, cold storage can be applied after the commodities have been packed and in slow transit such as in ships. The chief disadvantage is the length of the treatment period required.

Freezing is used for commodities that will be processed, such as fruit pulp as well as fresh fruit and vegetables directed to the consumer market. Freezing for at least one day will generally kill most insects that are not in diapause. Quick freezing at temperatures ≤ -15°C usually will kill diapausing insects.

HEATED AIR Quarantine treatments using heated air were used during the first Mediterranean fruit fly infestation in Florida in 1929. These treatments expose commodities to air at temperatures in the range of 43°–52°C from a few to many hours. The treatment can be done in one third the time if air is forced through the fruit load. The speed of treatment is dependent on temperature, size of individual commodities, density and arrangement of the load, air speed through the load, and moisture content of the air. These factors, combined with the generation of heat shock proteins modifying the susceptibility of both the insect and the living commodity to heat (46), contribute to the variability in the results of heated-air treatments in terms of efficacy and commodity quality. Preconditioning of fruits by a mild heat treatment before the pesticidal treatment reduces damage to commodities. However, that same pretreatment may also make the pest more tolerant of the pesticidal treatment (51). Heated-air treatments are generally not well tolerated by temperate fruits.

Dry air treatments at temperatures higher than those used for fresh produce (up to 100°C) are used to treat agricultural products such as meal, grain, straw, and dried plants for ornamental purposes and construction (such as pallets).

HOT-WATER IMMERSION Immersion at 43°–55°C ranging from a few minutes to a few hours is used to kill a variety of arthropods and nematodes on plant-propagative materials. Hot-water immersion is a simple, economical, and rapid treatment. It has been used to disinfest tephritid fruit flies virtually from all mangoes entering the United States since 1987 (3). Many fruits, especially temperate ones, are damaged when immersed in water hot enough to kill insects. This damage has been alleviated in some cases by gradual heating (70). As with heated-air treatments, tolerance of hot-water immersion can be increased by exposing some fruit to 25°–46°C for 0.5–72 h prior to the heat quarantine treatment (55). A variation of hot-water immersion is a hot-water drench, which is proposed to cause less damage to fruits than total immersion (13).

FLAMING When treating with a propane flamer, thermosensitivity of the target insect and the potato plant must be such as to allow the destruction or impairment of the pests without harming the crop (28). Temperature of exposure is used as an indicator of thermosensitivity, e.g., 70°C for Colorado potato beetle adults. Eggs, larvae, and adults are either injured or killed. Leaf shielding lowers egg mortality rates by 5%–20% and, for a given temperature and exposure duration, mortality is higher in spring than later when the canopy is developed. Because flaming is associated with soil compaction due to the need for repeating treatments, has no residual activity in the field, and above all, has negative environmental effects (i.e., release of combustion by-products: CO, CO_2, nitrous and sulphur oxides) that can be as important as those associated with pesticide use (64), its potential as an environmentally friendly alternative is questionable.

STEAMING In the field, the effects of steaming on insects are similar to those of flaming. Based on the fact that legs can be damaged by exposing them to temperatures from 68° to 75°C and that muscles of the legs are inactivated by dipping the insect from 0.2 to 0.4 sec in hot water (84), steam has been researched in laboratory and field conditions to impair locomotion of Colorado potato beetle adults (85). The proportion of adults impaired is positively correlated with temperature and exposure time. Because only 35% of adults are critically injured at the maximum acceptable temperature (ca. 79°C) for the potato plant (85), it is unlikely that this method could be of commercial use. Furthermore, steaming requires a large water supply that increases soil compaction, equipment, and operational costs (64).

SOLAR HEATING A solar heater made of dark cloth and translucent plastic sheeting has been tested for bruchid control in stored grains (75). The solar heater reaches temperatures >60°C. As all stages of the cowpea weevil, *Callosobruchus maculatus*, inside grains are destroyed at temperature >60°C for approximately 100 min, this method should prove useful, particularly for developing countries where the cost of energy is prohibitive. All stages of *Callosobruchus* spp. were killed when pigeonpea, *Cajanus cajan*, was solarized in polyethylene bags in India (20). Grain germination was minimally affected by solarization in the these two studies.

Electromagnetic Radiation

Electromagnetic radiation transfers energy from a source to a target without a need for an energy transfer fluid. Electromagnetic energy can be absorbed by ionizing atoms at the target site or by inducing vibration of charged particles within the matter, thus increasing temperature because of internal friction (66).

IRRADIATION Ionizing radiation provided by cobalt 60, cesium 137, or linear accelerators is an effective quarantine treatment that has a different measure of efficacy than all other treatments that have been used commercially (47). Heat produced by ionizing radiation does not contribute to insect control. To provide acute mortality of insects (the measure of efficacy of most quarantine treatments) with radiation requires higher doses than those tolerated by fresh commodities. However, radiation is effective at stopping development or providing sterility at doses tolerated by fresh commodities, and prevention of the establishment of exotic organisms does not require acute mortality. In 1995, papayas and other fruits began to be shipped from Hawaii to the mainland United States for irradiation and marketing. In August 2000, an electron beam facility built in Hawaii began treating and shipping fruits, and shipment of fruits for irradiation on the mainland ceased. In 1999, guavas irradiated against infestation by the Caribbean fruit fly began to be shipped from Florida to Texas and California; in 2000, Florida sweet potatoes irradiated against sweetpotato weevil began to be shipped to California. On limited occasions, South Africa has irradiated imported grapes and other fresh commodities that were considered a phytosanitary risk. Use of the treatment is expected to rise strongly if APHIS approves irradiation protocols for imported fruits first proposed in May 2000 (4).

RADIO FREQUENCY HEATING The radio frequency (RF) part of the electromagnetic spectrum spans roughly from 3 kHz to 300 GHz. These are nonionizing waves. RF transfers energy faster and more efficiently than heated air or water treatments. Although RF energy has been known to kill insects for more than 70 years and much research has been conducted on its effects (49, 50, 77), it has rarely been used on a commercial scale as an insect-control technique. RF heating would most likely work as a quarantine treatment against pests in dried products, such as walnuts (102), where the insect would have a much higher moisture content than its host and thus be more susceptible to RF heating, especially at lower frequencies of 10–100 MHz (78). Furthermore, dried products are more tolerant than fresh produce to the high temperature spikes that may occur with RF heating. When RF heating is studied as a quarantine treatment for pests of fresh commodities, many complicating factors affecting efficacy arise, such as moisture on the fruit surface that may conflict with microwave energy coupling, whether the insects were on the surface of the fruit or right under the surface, or minor differences in fruit size (53). Major challenges in developing effective RF quarantine treatments are providing uniform heating throughout the commodity and developing means to monitor and control end product temperature (95).

Little has been published on the effects of RF heating on insect physiology and histology. A notable exception is the finding that, after sublethal exposures, the yellow mealworm, *Tenebrio molitor*, last instar larvae and pupae produced adults at the end of their developmental cycle with malformations caused by the overheating of heat-sensitive tissues and cells (such as those forming imaginal discs) before ecdysis (39).

INFRARED HEATING Infrared radiation can disinfest grain provided that the product is exposed in a thin (ca. 2 cm) layer (19).

Miscellaneous Treatments

FLOODING Flooding is used as a standard agronomic practice in cranberry production, and its insecticidal value against a number of insects was recognized more than 70 years ago. Two types of management are used in cranberry plantations (5). "Early water" is defined as a bed where the winter flooding, used to protect the plant from winter injury, is removed in March without further flooding. "Late water" is flooding for 30 days from mid-April to mid-May to manage cranberry fruitworm, *Acrobasis vaccinii*, southern red mite, *Oligonychus ilicis*, and early-season cutworms. Late water significantly reduced cranberry fruitworm egg populations compared to early water. One additional benefit is that late water controls cranberry fruit rot. Flooding can only be used where water is abundant and where the crop would tolerate it for a prolonged period.

OVERHEAD IRRIGATION Overhead irrigation of watercress at night reduced the number of eggs laid by the diamondback moth, *Plutella xylostella* (94). The experiments could not preclude other possible mechanisms such as interference with egg hatching, larval development, pupation, adult emergence, and mating. In apple orchards of Washington, overhead watering significantly decreased codling moth, *Cydia pomonella*, flight, oviposition, and egg and larval survival. Limitations of the methods include damage caused to fruit by poor-quality water, limited availability of water in some regions, and, depending on timing and quantities of water use, increase in apple scab, *Venturia inaequalis*.

Combination of Methods

Physical methods can be used simultaneously or in sequence, especially if there are synergistic effects. A few selected examples follow.

HEAT AND CONTROLLED ATMOSPHERES Low-oxygen and high–carbon dioxide atmospheres in airtight enclosures have a higher efficacy rate when temperature is elevated to levels that cause hyperactivity (26). The reduction of time needed for the disinfestation process is significant even for species that are concentration insensitive to carbon dioxide such as *Tribolium confusum* (18). The synergy between these two types of physical stresses has been demonstrated with other stored-product species (35, 38).

HIGH PRESSURE AND MODIFIED ATMOSPHERES Combining pressure ranging from 2 to 5 MPa in an autoclave with a carbon dioxide–enriched atmosphere allows a complete disinfestation of raw material (e.g., pet food, spices, aromatic plants) packaged in non-airtight enclosures in less than 4 h (91).

MODIFIED ATMOSPHERE AND PACKAGING Modified atmospheres with high (50%–60% v/v) carbon dioxide content or low (<1% v/v) oxygen content are effective methods when food products are stored in an airtight enclosure or in an insect-resistant packaging film (36). However, due to the difficulty of remaining airtight for days or even months to achieve complete insect kill (35), only such methods are used with high-value commodities such as dried fruits or cut flowers.

CONCLUSION

The chain of food production constitutes a continuum with increased legal restrictions as the produce reaches the consumer. The replacement of one technology by another (e.g., chemical control by physical control) can be based upon several considerations, among which economics plays a major role. In preharvest large-scale situations, commercial growers can choose from several options that have, from a technical point of view, their own relative merits (82). The implementation of physical control technologies in preharvest situations has been hampered by several factors, including cost relative to competing technologies, technical difficulties in implementing the strategy, availability of products, and dependence on chemicals (81). Some methods, such as steaming of Colorado potato beetle in the field, simply lack technical efficacy (64). Other methods, such as field vacuuming, can be improved further by fundamental engineering and entomological research (99). Other methods (e.g., trenches) are technically and environmentally acceptable but are impractical and costly relative to an efficacious chemical. Many physical methods rely on energy transfer by diffusion, convection, or radiation. In the field, this is a major obstacle because it is difficult to use the energy efficiently without excessive losses to nontarget substrates. For example, when using flaming against the Colorado potato beetle, only a minute amount of the total energy is used in killing the insect compared to what is being lost heating air, soil, and plants. Targeting is therefore a major challenge in developing physical control methods for field use. The same difficulty exists with insecticide sprays where it has been estimated that less than 0.03% of the foliar spray against aphids on field beans is effectively used for killing the pest (69).

As we move up the chain, increased legal regulations restrict the number of options. In postharvest situations, especially stored grains, the use of pesticides is highly restricted and, consequently, physical control methods are widely used in these situations (e.g., entoleters, inert dusts, modified atmospheric storage). It is noteworthy that most successes and implementation of physical control methods actually occur in postharvest situations.

In physical control methods as in any components related to integrated pest management, the tandem science and technology should work hand in hand. Basic science should not be overlooked, and several fundamental questions remain to be answered. Can insects become resistant to some physical control methods? Studies on heat shock proteins (45) suggest that their modulation could be explained by genetic factors. Likewise, it is not certain if insects can become resistant to inert dusts (61). If the control method allows the insect to adapt and reproduce, such as anthomyiid adults flying over fences (12), then genetics is at play and resistance can develop. Except for a few studies related to the effects of vacuum on insect pollinators (21) and predators (63), little is known about the effects on nontarget organisms, especially in preharvest situations. Little is known also about the effects of physical control methods on plant diseases. Physical stresses induce general mechanisms of physiological responses that, in most cases, have nonspecific targets or receptors, in contrast to the chemicals. This "global physiological response" is a complex phenomenon that has received little attention in insects and associated host plants, except for drought stress in infested plants or cold acclimation in stored-grain insects (31). Consequently, to improve the efficiency of physical control methods and to respect the integrity of host plants, these physiological mechanisms must be identified and quantified in both pest targets and host plants. Basic research on the combined or synergistic effects of two or more methods is also needed.

From a technological point of view, advances in computer technologies (e.g., expert systems) in the past decade created favorable conditions to develop applications of physical methods. For example, modeling the process of energy transfer to target insect pests and host plants may foster progress in simulating practical situations (95). Laboratory pilot experiments currently allow an accurate assessment of the efficiency-to-cost ratio for each novel technique. Thus, the potential of physical control techniques can or should be entirely reassessed in light of recent computer capabilities and high-speed-response sensor technologies.

The sociolegal context of plant protection is key to the adoption of new technologies, and it is likely to evolve in the near future. For example, countries that signed the Montreal protocol are to replace methyl bromide with alternative methods by 2005 (33), offering a good opportunity for physical control methods. The United States is expected to adopt new standards in plant protection, including irradiation of foodstuff for quarantine, and to meet the new requirements of the Food Quality and Protection Act (FQPA).

Of particular concern is the widening technological and economic gaps between developed and developing countries (27). Although agronomic and entomological problems of temperate and tropical countries differ, the adoption of standards to fulfill the demands of global markets should not be at the expense of peasant agriculture. Technical solutions to manage insects should fit the socioeconomic and ecological realities of the countries. For example, Navarro & Noyes (76) provide standardized solutions to manage insects by aeration, but they also discuss aeration methods based on geographically diverse climatic conditions. Because their success generally depends on context, many physical control methods should be as useful and desirable in developed and developing countries.

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LITERATURE CITED

1. Adesiyun AA, Ajayi O. 1980. Control of the sorghum stem borer, *Busseola fusca*, by partial burning of the stalks. *Trop. Pest. Manage.* 26:113–17
2. Adkisson PL, Wilkes LH, Cochran BJ. 1960. Stalk shredding and plowing as methods for controlling the pink bollworm, *Pectinophora gossypiella*. *J. Econ. Entomol.* 53:436–39
3. APHIS. 1998. *Treatment Manual*. Frederick, MD: USDA
4. APHIS. 2000. Irradiation phytosanitary treatment of imported fruits and vegetables. *Fed. Regist.* 65:34113–25
5. Averill AL, Sylvia MM, Kusek CS, DeMoranville CJ. 1997. Flooding in cranberry to minimize insecticide and fungicide inputs. *Am. J. Altern. Agric.* 12:50–54
6. Banks HJ. 1976. Physical control of insects-recent developments. *J. Aust. Entomol. Soc.* 15:89–100
7. Bégin S, Dubé SL, Calandriello J. 2001. Mulching and plasticulture. See Ref. 101, pp. 215–23
8. Belton P. 1962. A field test on the use of sound to repel the European corn borer. *Entomol. Exp. Appl.* 5:281–88
9. Black LL. 1980. "Aluminium" mulch: less virus disease, higher vegetable yields. *LA Agric.* 23:16–18
10. Boiteau G, Misener GC, Singh RP, Bernard G. 1992. Evaluation of a vacuum collector for insect pest control in potato. *Am. Potato J.* 69:157–66
11. Boiteau G, Osborn WPL. 1999. Comparison of plastic-lined trenches and extruded plastic traps for controlling *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae). *Can. Entomol.* 131:567–72
12. Boiteau G, Vernon RS. 2001. Physical barriers for the control of insect pests. See Ref. 101, pp. 224–47
13. Bollen AF, De la Rue BT. 1999. Hydrodynamic heat transfer—a technique for disinfestation. *Postharvest Biol. Technol.* 17:133–41
14. Bomford MK, Vernon RS, Päts P. 2000. Importance of overhangs on the efficacy of exclusion fences for managing cabbage flies (Diptera: Anthomyiidae). *Environ. Entomol.* 29:795–99
15. Bostanian NJ, Vincent C, Chouinard G, Racette G. 1999. Managing apple maggot, *Rhagoletis pomonella* (Diptera: Tephritidae), by perimeter trapping. *Phytoprotection* 80:21–33
16. Brust GE. 1994. Natural enemies in strawmulch reduce Colorado potato beetle populations and damage in potato. *Biol. Control* 4:163–69
17. Brust GE. 1996. Interaction of mulch and *Bacillus thuringiensis* subsp. *tenebrionis* on Colorado potato beetle (Coleoptera: Chrysomelidae) populations and damage in potato. *J. Econ. Entomol.* 89:467–74
18. Buscarlet LA. 1993. Study on the influence of temperature on the mortality of *Tribolium confusum* J. exposed to carbon dioxide or nitrogen. *Z. Naturforsch.* 48c: 590–94
19. Busnel RG. 1953. Application du chauffage par infra-rouge à la destruction des parasites dans divers produits agricoles.

C. R. 3th Int. Congr. Electrotherm. 427(4): 907–12

20. Chauhan YS, Ghaffar MA. 2002. Solar heating of seeds—a low cost method to control bruchid (*Callosobruchus* spp.) attack during storage of pigeonpea. *J. Stored Prod. Res.* 38:87–91
21. Chiasson H, Vincent C, de Oliveira D. 1997. Effect of an insect vacuum device on strawberry pollinators. *Acta. Hortic.* 437:373–77
22. Cohen H, Yuval B. 2000. Perimeter trapping strategy to reduce Mediterranean fruit fly (Diptera: Tephritidae) damage on different host species in Israel. *J. Econ. Entomol.* 93:721–25
23. Cowles RS, Cowles EA, McDermott AM, Ramoutar D. 2000. "Inert" formulation ingredients with activity: toxicity of trisiloxane surfactant solutions to twospotted spider mites (Acari: Tetranychidae). *J. Econ. Entomol.* 93:180–88
24. Csizinsky AA, Schuster DJ, Kring JB. 1990. Effect of mulch color on tomato yields and on insect vectors. *Hortscience* 25:1131
25. Davidson NA, Dibble JE, Flint ML, Marer PJ, Guye A. 1991. Managing insects and mites with spray oils. *IPM Educ. Publ., Univ. Calif. Public* 3347
26. Denlinger DL, Yocum GD. 1998. Physiology of heat sensitivity. See Ref. 48, pp. 7–53
27. Donahaye EJ. 2000. Current status of nonresidual control methods against stored product pests. *Crop. Prot.* 19:571–76
28. Duchesne RM, Laguë C, Khelifi M, Gill J. 2001. Thermal control of the Colorado potato beetle. See Ref. 101, pp. 61–73
29. Ebeling W. 1971. Sorptive dusts for pest control. *Annu. Rev. Entomol.* 16:123–58
30. Ferro D. 1996. Mechanical and physical control of the Colorado potato beetle and aphids. In *Lutte aux Insectes Nuisibles de la Pomme de Terre*, ed. RM Duchesne, G Boiteau, pp. 53–67. Québec, Can.: Agric. Agri-Food Can. 204 pp.

30a. Fields PG. 2001. Control of insects in post-harvest: low temperature. See Ref. 101, pp. 95–107

31. Fields PG, Fleurat-Lessard F, Lavenseau L, Febvay G, Peypelut L, et al. 1998. The effect of cold acclimation and deacclimation on cold tolerance, trehalose and free amino acid levels in *Sitophilus granarius* and *Cryptolestes ferrugineus* (Coleoptera). *J. Insect Physiol.* 44:955–65
32. Fields PG, Korunic Z, Fleurat-Lessard F. 2001. Control of insects in post-harvest: inert dusts and mechanical means. See Ref. 101. pp. 248–57
33. Fields PG, White NDG. 2002. Alternatives to methyl bromide treatments for stored-product and quarantine insects. *Annu. Rev. Entomol.* 47:331–59
34. Fleurat-Lessard F. 1986. Utilisation d'un attractif de synthèse pour la surveillance et le piègeage des pyrales *Phycitinae* dans les locaux de stockage et de conditionnement de denrées alimentaires végétales. *Agronomie* 6:567–73
35. Fleurat-Lessard F. 1990. Effect of modified atmospheres on insect and mites infesting stored products. In *Food Preservation by Modified Atmospheres*, ed. M Calderon, R Barkai-Golan, pp. 21–38. Boca Raton, FL: CRC
36. Fleurat-Lessard F. 1990. Résistance des emballages de denrées alimentaires aux perforations par des insectes nuisibles. 1. Méthodes d'étude et protocoles expérimentaux. *Sci. Aliment.* 10:5–16
37. Fleurat-Lessard F, Le Torc'h JM. 2001. Control of insects in post-harvest: high temperature and inert atmospheres. See Ref. 101, pp. 74–94
38. Fleurat-Lessard F, Le Torc'h JM, Marchegay G. 1998. Effect of temperature on insecticidal efficiency of hypercarbic atmospheres against three insect species of packaged foodstuffs. In *Proc. 7th Int. Working Conf. Stored Prod. Prot., Beijing*, ed. Z Jin, Q Liang, Y Liang, X Tan, L Guan, 1:676–84. Chengdu, PR. China: Sichuan Publ. Sci. Tech.

39. Fleurat-Lessard F, Lesbats M, Lavenseau L, Cangardel H, Moreau R, et al. 1979. Biological effects of microwaves on two insects *Tenebrio molitor* L. (Col.: Tenebrionidae) and *Pieris brassicae* L. (Lep.: Pieridae). *Ann. Zool. Ecol. Anim.* 11:457–78
40. Gauvrit C, Cabanne F. 2002. Huiles végétales et monoterpènes en formulations phytosanitaires. In *Biopesticides d'Origine Végétale*, ed. C Regnault-Roger, BJR Philogène, C Vincent, pp. 285–300. Paris: Lavoisier Tech. Doc. 338 pp.
41. Genève R, Delon R, Fleurat-Lessard F, Hicaubé D, Le Torc'h JM. 1991. Intérêt des pièges à phéromones pour la surveillance des populations d' *Ephestia elutella* dans les entrepôts de tabac d'importation. In *Proc. 5th Int. Working Conf. Stored Prod. Prot.*, ed. F Fleurat-Lessard, P Ducom, 2:1331–40. Bordeaux, France: INRA
42. Glenn DM, Puterka GJ, Drake S, Unruh TR, Knight AL, et al. 2001. Particle film application influences apple leaf physiology, fruit yield and fruit quality. *J. Am. Soc. Hortic. Sci.* 126:175–81
43. Glenn DM, Puterka GM, VanderZwet T, Byers RE, Feldhake C. 1999. Hydrophobic particle films: a new paradigm for suppression of arthropod pests and plant diseases. *J. Econ. Entomol.* 92:759–71
44. Golob P. 1997. Current and future perspective for inert dusts for control of stored product insects. *J. Stored Prod. Res.* 33:69–79
45. Goto SG, Kimura MT. 1998. Heat- and cold-shock responses and temperature adaptations in subtropical and temperate species of *Drosophila*. *J. Insect Physiol.* 44:1233–39
46. Hallman GJ. 2000. Factors affecting quarantine heat treatment efficacy. *Postharvest Biol. Technol.* 21:95–101
47. Hallman GJ. 2001. Irradiation as a quarantine treatment. In *Food Irradiation: Principles and Applications*, ed. R Molins, pp. 113–30. New York: Wiley
48. Hallman GJ, Denlinger DL, eds. 1998. *Temperature Sensitivity in Insects and Application in Integrated Pest Management.* Boulder, CO: Westview. 320 pp.
49. Hallman GJ, Sharp JL. 1994. Radio frequency heat treatments. In *Quarantine Treatments of Pests of Food Plants*, ed. JL Sharp, GJ Hallman, pp. 165–70. Boulder, CO: Westview
50. Halverson SL, Burkholder WE, Bigelow TS, Plarre R, Booske JH, et al. 1997. Recent advances in the control of insects in stored products with microwaves. ASAE No. 976098. 16 pp.
51. Hara AH, Hata TY, Hu BKS, Tsang MMC. 1997. Hot-air induced thermotolerance of red ginger flowers and mealybugs to postharvest hot-water immersion. *Postharvest Biol. Technol.* 12:101–8
52. Hickling R, Wei W, Hagstrum DW. 1998. *Studies of sound transmission in various types of stored grain for acoustic detection of insects.* http://www.nal.usda.gov/ttic/tektran/data/000006/76/0000067610.html
53. Ikediala JN, Tang J, Neven LG, Drake SR. 1999. Quarantine treatment of cherries using 915 MHz microwaves: temperature mapping, codling moth mortality and fruit quality. *Postharvest Biol. Technol.* 16:127–37
54. Imai T, Tsuchiya S, Morita K, Fujimori T. 1994. Surface tension-dependant surfactant toxicity on the green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera). *Appl. Entomol. Zool.* 29:389–93
55. Jacobi KK, MacRae EA, Hetherington SE. 2001. Loss of heat tolerance in 'Kensington' mango fruit following heat treatment. *Postharvest Biol. Technol.* 21:321–30
56. Jacques DF, Kuhlmann B. 2002. Exxon Esso experience with horticultural mineral oils. In *Spray Oils Beyond 2000*, ed. GAC Beattie, DM Watson, ML Steven, DJ Rae, RN Spooner-Hart, pp. 39–51. Hawkesbury, Aust.: Univ. West. Syd.
57. Khelifi M, Laguë C, Lacasse B. 2001.

Pneumatic control of insects in plant protection. See Ref. 101, pp. 261–69

58. Knight AL, Unruh TH, Christianson BA, Puterka GJ, Glenn DM. 2000. Effects of a kaolin-based particle film on obliquebanded leafroller (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 93:744–49
59. Korunic Z. 1997. Rapid assessment of the insecticidal value of diatomaceous earths without conducting bioassays. *J. Stored Prod. Res.* 33:219–29
60. Korunic Z. 1998. Diatomaceous earths, a group of natural insecticides. *J. Stored Prod. Res.* 34:87–97
61. Korunic Z, Ormesher P. 1998. Evaluation of a standardised testing of diatomaceous earth. In *Proc. 7th Int. Working Conf. Stored Prod. Prot., Beijing,* ed. Z Jin, Q Liang, Y Liang, X Tan, D Guan, pp. 738–44. Chengdu, PR China: Sichuan Publ. Sci. Technol.
62. Kring JB, Schuster DJ. 1992. Management of insects on pepper and tomato with UV-reflective mulches. *Fla. Entomol.* 75:119–29
63. Lacasse B, Laguë C, Roy PM, Khelifi M, Bourassa S, et al. 2001. Pneumatic control of Colorado potato beetle. See Ref. 101, pp. 282–93
64. Lague C, Gill J, Péloquin G. 2001. Thermal control in plant protection. See Ref. 101, pp. 35–46
65. Lapointe SL. 2000. Particle film deters oviposition by *Diaprepes abbreviatus* (Coleoptera: Curculionidae). *J. Econ. Entomol.* 93:1459–63
66. Lewandowski J. 2001. Electromagnetic radiation for plant protection. See Ref. 101, pp. 111–24
67. Lucas E, Riudavets J. 2000. Lethal and sublethal effects of rice polishing process on *Sitophilus oryzae* (Coleoptera: Curculionidae). *J. Econ. Entomol.* 93:1837–41
68. Lucas E, Riudavets J. 2002. Biological and mechanical control of *Sitophilus oryzae* (Coleoptera: Curculionidae) in rice. *J. Stored Prod. Res.* 38:293–304
69. Matthews GA, ed. 1992. *Pesticide Application Methods*. New York: Longman Sci. Tech.
70. McGuire RG. 1991. Market quality of grapefruit after heat quarantine treatments. *Hortscience* 26:1393–95
71. Metcalf RL. 1994. Insecticides in pest management. See Ref. 72a, pp. 245–314
72. Metcalf CL, Flint WP, Metcalf RL. 1962. *Destructive and Useful Insects, Their Habits and Control.* New York: McGraw Hill. 1087 pp. 4th ed.

72a. Metcalf RL, Luckmann WH, eds. 1994. *Introduction to Insect Pest Management.* New York: Wiley. 650 pp. 3rd ed.

73. Misener GC, Boiteau G. 1993. Holding capacity of the Colorado potato beetle to potato leaves and plastic surfaces. *Can. Agric. Eng.* 35:27–31
74. Misener GC, Boiteau G, McMillan LP. 1993. A plastic-lining trenching device for the control of Colorado potato beetle: beetle excluder. *Am. Potato J.* 70:903–8
75. Murdock LL, Shade RE. 1991. Eradication of cowpea weevil (Coleoptera: Bruchidae) in cowpeas by solar heating. *Am. Entomol.* 37:228–31
76. Navarro S, Noyes RT, eds. 2000. *The Mechanics and Physics of Modern Grain Aeration Management*. Boca Raton, FL: CRC. 672 pp.
77. Nelson SO. 1995. *Assessment of RF and microwave electric energy for stored-grain insect control.* Presented at ASAE Annu. Int. Meet. Paper No. 956527. 16 pp.
78. Nelson SO, Bartley PG Jr, Lawrence KC. 1998. RF and microwave dielectric properties of stored-grain insects and their implications for potential insect control. *Trans. ASAE* 41:685–92
79. Novartis 1997. *Le Livre vert du Maïs Cb*. St-Sauveur, France: Novartis Seeds. 109 pp.
80. Oseto CY. 2000. Physical control of insects. In *Insect Pest Management, Techniques for Environmental Protection*, ed.

JE Rechcigl, NA Rechcigl, pp. 25–100. Boca Raton, FL: Lewis. 392 pp.

81. Panneton B, Vincent C, Fleurat-Lessard F. 2001. Current status and prospects for the use of physical control in crop protection. See Ref. 101, pp. 303–9
82. Panneton B, Vincent C, Fleurat-Lessard F. 2001. Plant protection and physical control methods: the need to protect crop plants. See Ref. 101, pp. 9–32
83. Payne TL, Shorey HH. 1968. Pulsed ultrasonic sound for control of oviposition by cabbage looper moths. *J. Econ. Entomol.* 61:3–7
84. Pelletier Y, McLeod CD, Bernard G. 1995. Description of sublethal injuries caused to the Colorado potato beetle by propane flamer treatment. *J. Econ. Entomol.* 88:1203–5
85. Pelletier Y, Misener GC, McMillan LP. 1998. Steam as an alternative control method for the management of Colorado potato beetles. *Can. Agric. Eng.* 40:17–21
86. Plarre R, Reichmuth C. 2000. Impact. In *Alternatives to Pesticides in Stored-Product IPM*, ed. BH Subramanyam, DW Hagstrum, pp. 401–17. Boston: Kluwer
87. Pradzynska A. 1982. The suitability of ultrasound for controlling stored pest. *Prace-Naukowe Inst. Roslin.* 24:77–90
88. Prokopy RJ, Croft BA. 1994. Apple insect pest management. See Ref. 72a, pp. 543–85
89. Puterka GJ, Glenn DM, Sekutowski DG, Unruh TR, Jones SK. 2000. Progress toward liquid formulations of particle films for insect and disease control in pear. *Environ. Entomol.* 29:329–39
90. Rancourt B, Vincent C, de Oliveira D. 2000. Circadian activity of *Lygus lineolaris* (Hemiptera: Miridae) and effectiveness of sampling procedures in strawberry fields. *J. Econ. Entomol.* 93:1160–66
91. Reichmuth C, Wohlgemuth R. 1994. Carbon dioxide under high pressure of 15 bar and 20 bar to control the eggs of the Indian meal moth *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) as the most tolerant stage at 25°C. In *Stored Product Protection*, ed. E Highley, J Wright, HJ Banks, BR Champ, 1:163–72. Wallingford, UK: CABI
92. Rhainds M, Kovach J, Dosa EL, English-Loeb G. 2001. Impact of reflective mulch on yield of strawberry plants and incidence of damage by tarnished plant bug (Heteroptera: Miridae). *J. Econ. Entomol.* 94:1477–84
93. Shapiro JP, Schroeder WJ, Stansly PA. 1998. Bioassay and efficacy of *Bacillus thuringiensis* and organosilicone surfactant against the citrus leafminer (Lepidoptera: Phyllocnistidae). *Fla. Entomol.* 81:201–10
94. Tabashnik BE, Mau RFL. 1986. Suppression of diamondback moth (Lepidoptera: Plutellidae) oviposition by overhead irrigation. *J. Econ. Entomol.* 79:189–91
95. Tang J, Ikediala JN, Wang S, Hansen JD, Cavalieri RP. 2000. High-temperature-short-time thermal quarantine methods. *Postharvest Biol. Technol.* 21:129–45
96. Unruh TR, Knight AL, Upton J, Glenn DM, Puterka GJ. 2000. Particle films for suppression of the codling moth (Lepidoptera: Tortiricidae) in apple and pear orchards. *J. Econ. Entomol.* 93:737–43
97. van Epenhuijsen CW, Koolaard JP, Potter JF. 1997. Energy, ultrasound and chemical treatments for the disinfestation of fresh asparagus spears. *Proc. 50th N. Z. Plant Prot. Conf.* 50:436–31
98. Vernon RS, Mackenzie JR. 1998. The effects of exclusion fences on the colonization of rutabagas by cabbage flies (Diptera: Anthomyiidae). *Can. Entomol.* 130:153–62
99. Vincent C, Boiteau G. 2001. Pneumatic control of agricultural pests. See Ref. 101, pp. 270–81
100. Vincent C, Chagnon R. 2000. Vacuuming tarnished plant bug on strawberry: a bench study of operational parameters versus insect behavior. *Entomol. Exp. Appl.* 96: 347–54
101. Vincent C, Panneton B, Fleurat-Lessard

F, eds. 2001. *Physical Control in Plant Protection.* Berlin/Paris: Springer/INRA. 329 pp.

102. Wang S, Ikediala JN, Tang J, Hansen JD, Mitcham E, et al. 2001. Radio frequency treatments to control codling moth in in-shell walnuts. *Postharvest Biol. Technol.* 22:29–38
103. Weber DC, Ferro DN, Buonaccorsi J, Hazzard RV. 1994. Disrupting spring colonization of Colorado potato beetle to nonrotated potato fields. *Entomol. Exp. Appl.* 73:39–50
104. Weintraub PG, Horowitz AR. 2001. Vacuuming insect pests: the Israeli experience. See Ref. 101, pp. 294–302
105. WHO 1982. *Ultrasound, Environmental Health Criteria 22*. Geneva: WHO. 199 pp.
106. Yokoyama VY, Miller GT. 2002. Bale compression and hydrogen phosphide fumigation to control cereal leaf beetle (Coleoptera: Chrysomelidae) in exported rye straw. *J. Econ. Entomol.* 95:513–19
107. Yokoyama VY, Miller GT, Hartsell PL, Eli T. 1999. On-site confirmatory test, film wrapped bales, and shipping conditions of a multiple quarantine treatment to control hessian fly (Diptera: Cecidomyiidae) in compressed hay. *J. Econ. Entomol.* 92:1206–11
108. Zehnder GW, Hough-Goldstein J. 1990. Colorado potato beetle (Coleoptera: Chrysomelidae) population development and effects on yield of potatoes with and without straw mulch. *J. Econ. Entomol.* 83:1982–87

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