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Codling moth *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) management a potential threat to horticulture industry

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Abstract
The strategies for Codling moth (*Cydia pomonella*) control has undergone the major changes brought about by a need for more IPM- selective control tactics like, resistance development and regulatory restrictions. The pheromonal control technologies are ready to replace the organophosphates insecticides which have been the backbone of codling moth control for many years. The pheromonal control includes the use of mating disruption or attracts and kill and auto confusion, while as the other control strategies comprise of insect growth regulators and microbial agents. In contrast to synthetic chemical control, the future control programs will likely include a variety of tactics merged into a unified program to achieve population reduction and economic control without impacting biological control of other pests. Monitoring efforts of codling moth populations in commercial orchard must be intensified through mating disruption to make these programs successful and reduce the risk of unacceptable fruit damage. Considering the high annual control costs, a sterile insect release program may be economical in the long run to deal with the most important insect pests of apples and pears.

Keywords: Pest, *Cydia pomonella*, Management, Orchard, Fruit

1. Introduction
The codling moth, *Cydia pomonella* (L.), is the key pest of apple production worldwide (Reyes *et al*., 2015; McGuffin *et al*., 2014) [31, 23], and is also the most serious insect pest because the larvae feed inside the fruit, leaving an unsightly hole (Cormier *et al*., 2015) [9] that can promote internal rotting. As the growers have a low tolerance (<1%) for codling moth injury (>1 fruit/100 is usually considered unacceptable), therefore the immediate control strategies usually consist of frequent applications of broad-spectrum insecticides throughout the growing season. However, codling moth can also be managed successfully using other IPM techniques (USDA, 2015) [42]. Codling moth has developed resistance to azinphos-methyl and tebufenozide in post-diapausing larval stages, and to OP (Reyes *et al*., 2015) [31] insecticides and more recently to insect growth regulators (IGRs), has created an urgent need not only for new control tools but also for a fresh approach to codling moth management (Cormier *et al*., 2015) [9]. Neonate larvae were susceptible to all insecticides studied, but post-diapausing larvae from four populations were resistant to Chlorpyrifos. The acetylcholinesterase insensitivity mutation was not detected so far, and the sodium channel knockdown resistance mutation was present in a low frequency in one post-diapausing larval population (Reyes *et al*., 2015) [31]. Detoxifying enzymatic activity of glutathione S-transferases, esterases, and cytochrome P-450 monooxygenases in adults differed among populations, but Chlorpyrifos resistance was associated only with a decreased esterase activity as shown by a significant negative correlation between Chlorpyrifos mortality and esterase activity (Reyes *et al*., 2015) [31]. Insecticide resistance is a widespread problem for codling moth management around the world. Reductions in insecticide efficacy on codling moth have been studied in several pome fruit production areas in Europe, the Middle East, North America (Magalhaes *et al*., 2012) [22] and South America (Soleno *et al*., 2012) [39]. Those reports include resistance to substances like: neurotoxic insecticides and neonicotinoids (Knight 2010) [19] insect growth regulators (IGRs), such as diacylhydrazines and benzoylureas (Ioriatti *et al*., 2009) [14]; and granulosis virus (Kaiser *et al*., 2007) [16]. The article on codling moth and its management breadth the control approaches and technologies which are being pursued at the present time and which can form the building blocks for long-term management of this important pest of fruit trees in future. For the management of insect pest first perquisite is that biology/life history and threshold level should be well understood before any management tactics are employed.

Biology and Life history: Codling moths overwinter as mature larvae in silken cocoons spun under loose bark, in the soil, or in trash at the base of the tree. Pupation takes place in the spring at the time of first blossom and adults emerge around bloom. Adults are active at dusk and dawn and lay eggs on leaves, or occasionally on fruits. Larva begins feeding on fruit and may bore to center to feed on the flesh and seeds. As they mature, they push frass out of the entry hole. After a month the larvae leave the fruit to seek a sheltered spot on the tree to spin cocoons, in which they overwinter, and finally emerge in 2-3 weeks as a new flight of adults. Pest usually completes two generation in a year and brood often penetrates fruits but don't complete development before harvest or winter.

Sampling and thresholds: In orchards where mating disruption is not used to control codling moth, monitor adult moths with pheromone traps baited with 1mg lures set in the lower canopy at chest height level. If the pheromone trap catches exceed one to two per trap for two consecutive weeks control with the insecticide may be necessary. When mating disruption is used monitor the orchard with pheromone traps baited with 10mg lures set in the upper third of the canopy. If more than five months are captured in a trap over the first generation, check the orchard for the fruit damage or apply a conventional insecticide. If fruit damage exceeds 0.5% at the end of the 1st generation, use insecticides to provide supplemental control against the 2nd generation. If more than 2 moths are captured in a trap during the 2nd generation, a conventional insecticide may be necessary.

Codling moth attack on apple fruit

Adult of codling moth

New control tactics

Cultural control: Horticultural practices affect tree condition, orchard environment and thus influence arthropod pests and their natural enemies. The choice of rootstocks and tree training system can affect the success of codling moth in an orchard. Lack of cocooning sites on the tree can be a limiting factor. Normally codling moth larvae pupate under rough bark, in bark crevices, and in or around pruning wounds on the tree (Wearing, 1975) [43]. In plantings with smooth barked trees a larger proportion of larvae will pupate in the soil for lack of suitable pupation sites on the tree. Larval and pupal mortality is reportedly higher in the soil than on the tree. The unnecessary pruning should be avoided since it increases cocooning sites. Applying wound dressing to pruning cuts reduces wood rot and the number of cocooning sites, thus forcing larvae to pupate in the soil. Codling moth can also cocoon in the support structure, especially if wooden poles are used and the bark is not removed. Some dwarf and semi-dwarf clonal rootstocks have a tendency to develop burr knots which can also provide cocooning sites for codling moth larvae. One reason for the differences in infestation levels may be the effect of the ground cover on the microclimate in an orchard. A ground cover keeps the orchard cooler which may adversely affect codling moth and dampen population growth. More importantly, these studies suggest that a ground cover encourages biological control of codling moth and other pests by providing parasitic wasps with nectar-producing food plants and predators with habitat and alternate prey (Altieri and Schmidt, 1985) [1].

Thinning practices may help in codling moth control in two ways. Young larvae find it easier to enter where fruit contact each other. Thinning clusters of fruit down to singles will make it more difficult for young larvae to enter fruit. This will also improve spray coverage since a single fruit is easier to cover with spray. Creating an open tree through proper pruning will make it easier for spray to penetrate the canopy and thus improve coverage. This will benefit control not only of codling moth but also of other orchard pests. Summer pruning can be particularly helpful to keep the tree centre open at the time of year when codling moth sprays are applied. Codling moth can also be affected by irrigation water applied to orchards during the season.

Orchard sanitation, collection and destruction of infested fruit, elimination of cocooning sites on the tree trunk, and removal of sources of infestation near orchards were widely used control practices and were considered essential parts of an overall codling moth control strategy. Because of the effectiveness of modem insecticides, growers have seen little need in recent years to even consider these supplemental control tactics. Removal of infested fruit was widely practiced at one time. Codling moth can build up on unpicked fruit after harvest. Stripping and destroying fruit before codling moth infests it or larvae can complete development can substantially reduce the threat for next year's crop.

Chemical control

Insecticides: Azinphos-methyl (AZM) has been the most used insecticide against the Codling moth in apple orchards of United States since the late 1960s. The neurotoxic insecticides have also been the principal tools for codling moth control since the introduction of DDT, but luckily the resistance development to azinphos-methylhas not occurred suddenly as like of DDT. In field, azinphos-methyl resistance has manifested itself as a gradual decline and not as a sudden loss in control effectiveness. Growers have responded to this decline in control by reducing spray intervals and increasing application rates as, these strategies are counterproductive since they increase selection pressure and accelerate resistance development. Altacor (chlorantroniliprole) and Belt are known to control this pest efficiently at larval stage (Weinzierl, 2015) [44]. However, even in areas where resistance levels are relatively high, control with azinphos-methyl can still be achieved through more intensive use and by enhanced and efficient use of insecticides (Pszczolkowski and Brown, 2015) [29]. Selection with an insecticide often confers cross resistance to other compounds in the same chemical group or even to compounds in unrelated groups. Studies suggested that two OP compounds, Chlorpyrifos and parathion-methyl, were not affected by cross-resistance. In fact, selection with azinphos-methyl had apparently the opposite effect and has made codling moth more susceptible to these two OPs. This seems to be a rare case of negative cross-resistance. Negative cross-resistance may also have developed in other fruit-growing areas in response to selection with azinphos-methyl.

Table 1: Summarized application information on chemical pesticides recommended for codling moth (*Cydia pomonella*) control during 2015.

Trade name	Target stages	Maximum number of applications	Spray intervals (days)	Pre-harvest interval (days)
Altacor (chlorantroniliprole)	larvae	3	14	14
Exirel (Cyantraniliprole)	Larvae	4	10-14	3
Assail-70WP (Acetamiprid)	Eggs, larvae	4	12	7
Calypso 480 SC (thiacloprid)	Eggs, larva	4	14-21	30
Clutch 50WDG (Clothianidin)	larvae	2	14	7
Delegate (spinetoram)	larvae	3	14	7
Entrust 80 W (Spinosad)	larvae	3	7-10	7
TwinGuard (Sulfoxaflor)	larvae	2	14	7
Confirm 240 F (tebufenozide)	Larvae	4	10-14	14
Intrepid 240 F methoxyfenozide)	Eggs, larvae	2	14-21	14
Rimon 10 EC (novaluron)	Eggs, larvae	4	10-14	14
Imidan 50 WP (phosmet)	Larvae	5	10	14
Virosoft CP4 (granulovirus)	Larvae	-	5-7	0

The research suggests that cross resistance may not involve all insecticides of similar chemistry and similar mode of action (Siegwart *et al*., 2015; Sparks and Nauen, 2014) [37], but some of the old neurotoxic insecticides may continue to be important components in future resistance management programs for codling moth. The main mechanisms of insecticide resistance in *Cydia pomonella* include metabolic resistance based on reduced or increased nonspecific esterase (EST) enzyme activity and, frequently enhance glutathione S-transferase (GST) and cytochrome P-450 monooxygenase (P450s) activities that are related to cross-resistances to insecticides (Zhang *et al*., 2015a; Yu and Powles 2015; Zhang *et al*., 2015b) [50-51].

All codling moth life stages are affected by azinphos methyl which can kill on contact and /or when ingested by the young larvae while attempting to enter fruit. The IGRs diflubenzuron and fenoxycarb control primarily the egg stage when the egg is laid on top of the residue (Bengochea *et al*., 2014) [2]. Affected eggs develop to the blackhead stage but young larvae cannot chew through the chorion. If a neonate larva successfully exits the egg, it is often too weak to enter the fruit. Topical treatment of eggs after they are laid is considerably less effective. The studies showed that diflubenzuron applied to the fruit had only weak or no larvicidal activity, however, the neonates feeding on treated fruit suffered considerable mortality (Charrnillot *et al.* 1975; Bitar 2014) [7, 3]. The tebufenozide is toxic to eggs as well as young larvae but the toxicity of tebufenozide to eggs is considerably higher when eggs are laid on top of the residue. Interestingly, the ovicidal activity of tebufenozide is higher on treated leaf surfaces than on fruit (Bengochea *et al*., 2014; Pavan *et al*., 2014; Wise *et al*., 2010) [2, 27, 46]. Similar oviposition substrate effects to eggs were also observed with other IGRs. Tebufenozide is toxic to newly hatched larvae when ingested but it has little contact activity. Neonates may ingest residue during exploratory feeding while searching for a place to enter the fruit. Codling moth larvae affected by tebufenozide first stop feeding and starve (Quarles, 2015) [30]. If they continue to live and attempt to moult to the second instar, they cannot shed the old head capsule and subsequently die.

Insect Growth Regulators (IGRs).

These arethe chemicals which interfere with insect growth and development. Fenoxycarb, an analog of the juvenile hormone (JH) in insectsexhibits potent insect juvenile hormone mimic activity and causes serious disturbances in the development, reproduction and behavior of a wide range of insects (Govind, 2014) [12]. The fanoxycarb treatment caused a significant decrease in carbohydrate and lipid concentrations in ovaries. Three other major groups of IGRs which have been used for insect and mite control on fruits trees includes: the chitin-synthesis inhibitors (CSI); juvenile hormone mimics and the ecdysone agonists (Riedl and Brunner, 1996) [32]. The chitin-synthesis inhibitors interfere with the formation of chitin, an essential component of the insect cuticle (Kelkenberg *et al*., 2014) [18]. Depending on the pest species, chitin-synthesis inhibitors have ovicidal and/or larvicidal activity, further it is necessary for maintaining the peritrophic matrix barrier in insects. The insecticidal effects of chitin synthesis inhibitor diflubenzuron are mediated by the disruption of the cuticle synthesis during the metamorphic molt rather than by interfering with larval nutrition. However, diflubenzuron clearly affects peritrophic matrix permeability. It is therefore suitable to increase the efficiency of pesticides targeting the midgut (Kelkenberg *et al*., 2014) [18]. The diflubenzuron, a successful CSI which was first field-tested in the 1970s, similarly a large number of other CSIs were developed for use against codling moth and other fruit tree pests.

In insects, the transition from juvenile to adult stages is triggered by the decline of the juvenile hormone (Mirth *et al*., 2014) [25], but the molecular mechanism underlying the dramatic morphological and physiological changes remain poorly understood. The E93 factor controls juvenile-to-adult transition in hemimetabolous and holometabolous insects, thus acting as the universal adult specifier in winged insects. Interestingly, E93 not only promotes adult metamorphosis but also represses the expression of the antimetamorphic genes *Krüppel-homolog 1* and *Broad-Complex*, ensuring the proper juvenile–adult transition. Juvenile hormone mimicscontrols insect development from the immature to adult stage by acting on the E93 factor thereby blocks and/or impairs the transition from juvenile to adult stage. The JH mimics have shown ovicidal and larvicidal activity against several groups of insects. On tree fruits, fenoxycarb is primarily used for control of lepidopterous pests (e.g., codling moth) and pear psylla. Fenoxycarb and related JH mimicpyriproxyfen and diofenolan have ovicidal activity against codling moth. The third groups of IGRs, with application for codling moth control, are the ecdysone agonists. Ecdysone controls the moulting process. Ecdysone agonists such as tebufenozide and methoxyfenozide have both ovicidal and larvicidal activity. Further, the ecdysone receptor complex binds ecdysone agonists to regulate gene transcription, development, and growth in insect pests (Wu *et al*., 2015) [47]. In contrast to the chitin-synthesis inhibitors and the juvenile hormone mimics, ecdysone agonists are primarily active against lepidopterous species. This makes them very selective to natural enemies and other beneficials insects such as bees. IGRs have not only a narrower activity spectrum than neurotoxic insecticides, but they are also more stage specific.

IGRs *vs*azinphosmethyl-resistant codling moth

The different mode of action of IGRs suggests their suitable replacements for OPs and other neurotoxic insecticides. Unfortunately, there is evidence that this may not be the case due to cross-resistance. Codling moth resistance to the IGR diflubenzuron was reported for the first time from a single orchard in southern Oregon. This was apparently a case of cross-resistance to azinphos-methyl (Moffitt *et al.,* 1988; Reyes *et al*., 2015) [31, 26]. Only a small decrease in azinphos-methyl susceptibility made diflubenzuron ineffective in the field. In addition to the evidence from southern Oregon, research on resistant codling moth strains from California suggests that selection with azinphos-methyl confers cross-resistance to chitin-synthesis inhibitors and possibly also to other IGRs (Welter *et al.,*1992) [45]. This is surprising since IGRs have very different modes of action than OP insecticides. A link between OP and chitin-synthesis inhibitor resistance has also been found in populations of tufted apple bud moth, *Platynotaidaeusalis* (Lepidoptera: Tortricidae). A pyrethroidselected resistant field strain was cross-resistant to the IGRs teflubenzuron and tebufenozide. However, there may be exceptions. The patterns of cross-resistance may vary between fruit-growing areas and perhaps even within regions. Cross-resistance studies need to be carried out to elucidate which IGRs are still effective and can be used in aresistance management program.

Botanicals and other natural products

Today botanical insecticides such as Ryania, are only used to a very limited extent for codling moth control, primarily by organic apple and pear growers. However, one botanical which may have some promise for codling moth control is azadirachtin. It was recently registered in the United States for use on stone and pome fruits used up to harvest time. Azadirachtin is a natural constituent of neem oil which is extracted from seeds of the neem tree. It acts as an antagonist to the moulting hormone ecdysone and disrupts the moulting process in insects. Affected insects cease to feed and their development is disrupted. Azadirachtin can also deter egg-laying in adult insects. Topical applications of abamectinat 100 ppm were toxic to codling moth eggs. Spinosad (mixture of spinosyn A and D) is produced by another soil organism, *Saccharopolysporaspinosa*, and has activity against several important orchard pestsincluding codling moth. However, both products will assist in codling moth control when applied after bloom against other orchard pests.

Horticultural spray oils (HMOs)

Interest in the use of oil sprays during the foliar season to assist with control of codling moth and other orchard pests has increased during recent years. Pheromone traps can be used to accurately time the first spray (Pscheidt *et al*., 2015) [28]. Use of oil sprays after bloom has been limited because of concern about phytotoxicity to foliage and fruit. However, modem spray oils are safer and have a lower risk of phytotoxicity. Perhaps the most notable benefit of oil is as a resistance management tool due to its different mode of action. Oil kills insects by suffocation. This mode of action makes it less likely for resistance to develop. Its effect against codling moth is primarily ovicidal when applied topically to eggs (Riedl *et al.,* 1995) [33]. There is some residual toxicity to eggs at higher concentrations, but no direct toxicity to adults and neonate larvae. Female moths lay fewer eggs on plant surfaces treated with oil at concentrations above 1% (Riedl *et al.,* 1995) [33]. The toxicity of oil to codling moth eggs also depends on the surface on which they are laid and on the environmental conditions. Oil is more toxic to eggs on the fruit but less to eggs on upper and lower surfaces of fruit spur leaves. Most eggs are laid on leaves close to fruit (Blomefield *et al.,* 1997) [4]. Low humidity increases the susceptibility of eggs to oil, especially of eggs on leaves. This suggests that oil might be a more effective ovicidal for codling moth control in arid climates than in areas with high humidity during the summer. Oil sprays alone are probably not sufficient to achieve economic seasonal control of codling moth. The added benefit of foliar oil sprays is their suppressive effect on other pests including spider mites, scale insects, and pear psylla. A major concern with oil use after bloom remains the potential for phytotoxicity to fruit and foliage as well as long-term effects on the tree. Unless it can be demonstrated that oil can be used safely during the foliar period, fruit growers will be reluctant to include foliar oil sprays in seasonal codling moth control programs.

Microbial insecticides

Entomopathogens could be of considerable benefit if used as part of a comprehensive codling management strategy (Dreves *et al*., 2015) [10]. Their selectivity and unique modes of action make them useful components of a resistance management program which could be used in rotation with other controls. The *Cydia pomonella* granulosis virus (CPGV) has the best prospect for being used commercially and it is registered now in several countries for codling moth control. This virus was first recovered from a codling moth strain collected in Mexico; which has become the original source for CpGV formulations available worldwide for codling moth control.

Drawbacks of CPGV

Virus particles are susceptible to rapid degradation from UV radiation. Therefore, UV screens have to be added to virus formulations to increase their stability in the environment and extend their residual activity. In areas with high incident UV, CpGV applications have not been very effective against

codling moth due to rapid breakdown and lack of persistence of the residue. The neonate larva ingests virus particles that replicate in the stomach lining. Larvae continue to feed for several days before the virus kills them. Insecticide resistance apparently does not confer cross-resistanceto CpGV as reported in southern France where a codling moth population resistant to deltamethrin but still susceptible to CpGV. *Bacillus thuringiensis* (BT) produces endotoxins which arelarvicidal to lepidopterous larvae including codling moth.
Another insect pathogen, which may have some use for codling moth control, is *Beauveria bassiana.* Further, an entomopathogenic nematode, *Neoplectana carpocapsae* was isolated from overwintering codling moth larvae and when applied to trunk, up to 95% mortality reported during the winter but only 32%mortality summer conditions. In a study of several entomopathogenic nematodes, Lacey and Unruh (2005) found *Steinernema* (previously *Neoplectana) carpocapsae* (Weiser) to have good potential for control of diapausing codling moth larvae under a variety of environmental conditions.

Biological Control

Only natural enemies are not able to keep codling moth populations below economic levels (UC IPM, 2015) [41]. In orchards were mating disruptants are used, augmentative release of the tiny naturally occurring parasitic wasp *Trichogramma platneri*, which attacks the codling moth eggs, can be helpful to the eggs laid by mated female moths immigrating into the area from surrounding areas. All principal natural enemies of codling moth are hymenopterous parasitoids which attack eggs, larvae, or pupae. Various arthropod predators, primarily mirids, feed on eggs as well as neonates before they enter fruit. However, codling moth has not been a very successful target for biological control approaches because of its low economic threshold. Nevertheless, several laboratories around the world are actively engaged in biological control studies of this pest. However, natural enemies can be an important mortality factor for codling moth populations which reside on wild and unmanaged host trees outside orchards. The most common natural enemy of codling moth is the egg parasitoid *Trichogramma luteum* (Hymenoptera: Trichogrammatidae) and the parasitization levelwere as high as 86% have been observed in orchards. Recent research in California has shown that a substantial reduction in codling moth damage can be achieved with releases of large numbers of *Trichogramma platneri* Nagarkatti (Hymenoptera: Trichogrammatidae) egg parasitoids (Mills, 1995) [24]. However, parasitoid releases have a natural fit with other selective control tactics such as IGRs, granulosis virus, mating disruption, and sterile insect release programs.

Pheromonal Control. The codling moth sex pheromone was initially identified as a twelve chain alcohol, (E, E-8, 10-dodecadien-1-ol), also called codlemone (Roelofs *et al.,* 1972) [35]. An additional minor component identified includesdodecanol and tetradecanol. The sex pheromones has widespread application for monitoring (Weinzierl, 2015) [44] in various trapping devices and for control with mating disruption or 'attract& kill'. Mating disruption, also referred to as the male confusion method, aims to stop reproduction by preventing male moths from locating females. This is achieved by permeating the atmosphere in an orchard with sex pheromone, which is slowly released from many point sources. It has been suggested that following the many ' false trails ' created by the artificial pheromone sources in an orchard or the competition between pheromone sources and wild female moths might decrease the probability of mating. Further, the male moths might become habituated in the presence of large amounts of pheromone in the atmosphere, which inhibits their responsiveness to wild females. However, mate finding is not totally disrupted in pheromone-treated orchards and a surprisingly high proportion of moths still mate. Mating disruption requires that the pheromone is present throughout an orchard at an adequate concentration. However, it has not been resolved whether the pheromone must be distributed evenly throughout an area or whether the pheromone must be present in pulses or filaments to achieve the desired effect. The design objective for pheromone dispenser systems is to release pheromone slowly and at a more or less constant rate over the season. The release of the pheromone occurs through the wall of the dispenser. The rate of release can be controlled by the type of plastic used and by the wall thickness of the dispenser. Constant release is difficult to achieve since the amount of pheromone released with passive dispenser systems depends primarily on temperature. Dispensers release less pheromone in cool weather and more in hot weather.
If codling moth infested trees are close by or are immediately adjacent to orchards under mating disruption, insecticide treatments along the borders will be helpful to prevent codling moth damage in those areas.
The measures are as:

1. Double the dispenser density along the borders;
2. Apply a full insecticide program to borders (20 to 30 m wide)
3. Apply dispensers to the first 20 to 30 m of adjacent insecticide-treated blocks. Especially the uphill borders are thought to be more vulnerable to attack. The same is true for windy sites due to the lower pheromone concentrations along the upwind border of an orchard.

A major limitation to the acceptance of mating disruption for codling moth control has been its cost compared with standard insecticide programs. This is especially true for those areas where codling moth pressure is light due to fewer generations and/or lower susceptibility of the host and where insecticides are still working well due to lack of resistance.

Attract & kill' technique

It is another use of the sex pheromone for control of codling moth, which is being developed under the trade name Sirene CM® by Novartis (Switzerland).Sex pheromone is incorporated in a sticky substance, which also contains insecticide. Pyrethroid insecticides are presently used as killing agents, permethrin or cypermethrin in Sirene CM® and cyfluthrin in the Bayer product. Small droplets of the mixture measuring from 50to 100 microliters are placed with a special applicator on the bark to avoid contamination of the fruit. The application is made in the upper canopy where male activity is highest. Male moths are attracted to the pheromone in each droplet and die after coming in contact with the insecticide. Depending on temperature, droplets release pheromone and attract males over a 40to 50day period. 'Attract & kill' has some of the same drawbacks as mating disruption since it will not protect an orchard from immigrating female moths. Therefore, isolation from outside sources of infestation is important. In areas where codling moth has developed resistance to pyrethroids, other non-cross resistant insecticides would have to be used in these' attract &

kill' formulations as killing agents. Possibly, the use ofsterilants instead of a knockdown insecticide could enhance the effectiveness of this control method since matings between sterilized males and fertile females would lead to non-viable eggs.' Attract & kill' is seen as a potential control method in orchards with small trees in combination with mating disruption at reduced dispenser rates.

Mass trapping

Achieving population control by removing large numbers of pest insects with various trapping devices is an old concept. Removing codling moth larvae with trap bands wrapped around part of the lower tree trunk was at one time a widely used control practice before insecticides became available. Trap bands, together with removal of infested fruit during the season, clean picking at harvest, and destruction of cocooning sites, provided ameasure of control, although not sufficient according to today's standards.

Sterile insect release (SIR)

The success of releasing sterile insects to control the screwworm fly, *Cochliomyiahominivorax* (Coquerel), in the southern United States led to similar programs for codling moth. Preliminary experiments in small areas in British Columbia and Washington demonstrated the technical feasibility of this method for codling moth control (Butt, 1968; Smith, 2015) [5, 38]. Hofmeyr *et al* (2015) [13] studied the radiation biology and F1 sterility of False Codling Moth *Thaumatotibialeucotreta* (phase 1), field cage experiments (phase 2) and a pilot project over 35 ha of *T. leucotreta*-susceptible citrus (phase 3). Favourable results in these studies led to the design and construction of *T. leucotreta*-specific rearing equipment and the building of a massrearing facility capable of producing up to 21 million insects per week (phase 4). Commercial sterile insect releases over 1500 ha of citrus orchards in the Citrusdal region commenced in 2007–08. This area was expanded to 3000 ha in 2008–09 and 4000 hectares in 2009–10 (phase 5). Over the three years the status of *T. leucotreta* as a pest threat was systematically reduced in the sterile insect release area compared to the non-release area. Feral male populations were reduced 3-, 8- and 10-fold, pre-harvest crop losses decreased by 50 %, 80%and 93 %, and post-harvest export fruit rejections in the SIT area dropped 13 %, 25 % and 38 %, respectively, compared to the non-SIT area.

Post-harvest control

A combination of low pressure (LP) and low temperature (LT) serve as a phyto sanitary disinfestation treatment for fresh fruit after harvest (Jiao *et al*., 2013). The 5th instar larvae were the most tolerant life stage for codling moth under LPLT treatment, however the insect mortality increased with increasing LPLT treatment time to >98% after 12 days of exposure to 10◦C temperature and 1.33 kPa pressure. Mature larvae exiting from harvested fruit often pupate in bins which are stored in large stacks at packing or processing facilities or occasionally even in orchards. Moths emerging in the spring from those bins pose a threat to the new crop. The advantages of plastic bins are that they are easier to sanitize, provide less cocooning sites for codling moth larvae than wooden bins, and reduce storage decay problems. Codling moth poses a quarantine problem in fruit destined for export to certain countries where codling moth is not present. Diapausing codling moth larvae can survive standard cold and controlled atmosphere storage conditions for 133 days or possibly longer. Other life stages do not survive storage conditions for very long. Presently, fumigation with methyl bromide is the only certified treatment method for post-harvest codling moth control. Research has focused on the last instar diapausing larvae, since this stage is more difficult to control and is more likely present in harvested fruit than other codling moth stages. Short-term heat treatments have shown promise for post-harvest control of codling moth. As codling moth develops insecticide resistance in different deciduous fruit-growing areas around the world, 'resistant' moths may become a quarantine issue when shipping fruit from an area with resistance to areas where codling moth is still susceptible.

Current strategies for management of codling moth

The conventional insecticides remain the backbone of codling moth control programs in most of the fruit-growing areas around the world. In most fruit-growing areas, the OP azinphos-methyl is still the insecticide of choice for codling moth control. Use of other OPs is low compared with azinphosmethyl. One notable exception is northern Italy, where fruit growers have turned to fenitrothionand quinalphos after codling moth developed resistance to the chitin-synthesis inhibitor diflubenzuron. In California, a substantial number of growers rely now on encapsulated parathion-methyl to control codling moth in areas where control has become difficult with azinphos-methyl due to resistance development. This approach is also being tried, but to a lesser extent, in Australia, Washington, and southern Oregon. Worldwide, phosmet use is low for codling moth control compared with azinphos-methyldue to new and more restrictive re-entry regulations.

Carbaryl use for codling moth control is very limited. Only in Argentinathe carbaryl were used on about 15% of the tree fruit acreage for codling moth control in addition to azinphos-methyl. Pyrethroid insecticides are being used in some of the warmer fruit-growing areas where codling moth has multiple generations. In Rio Negro, about 37% of total tree fruit acreage are currently treated with seasonal programs consisting ofpyrethroid and azinphos-methyl sprays. In South Africa, programs of pyrethroids and azinphos-methyl are applied to 8% of the tree fruit area. In the western United States, pyrethroid insecticides were never recommended for codling moth control because of spider mite problems associated with foliar treatments. IGRs have replaced OP insecticides for codling moth control in many of the fruit-growing areas in central Europe. Control programs with IGRs have been successful primarily in those fruit-growing areas where codling moth has only one to two generations. Diflubenzuron and other chitin-synthesis inhibitors are the most widely used IGRs in Switzerland followed by fenoxycarband tebufenozide. In The Netherlands, the IGR most widely applied for codling moth control is diflubenzuron. In region of northern Italy, most of the apple-growing area was treated at one time with diflubenzuron or related chitin-synthesis inhibitors for codling moth control. Surprisingly, mating disruption is not yet registered in France where insecticide resistance has become a major problem. The majority of growers in Washington used mating disruption at a reduced dispenser rate and combined it with insecticide applications. In southern Oregon, a program consisting of mating disruption plus three oil sprays for control of first generation codling moth eggs has been used successfully on pears.

Summery and conclusion

In most other arid deciduous fruit growing areas around the world, codling moth is the key pest of pome fruits whose control dominates the control practices for the whole pest complex. For the last fifty years the principal control strategy for codling moth has consisted of a single tactic: intensive use of broad-spectrum insecticides. Since the early apple and pear growers have relied primarily on OP insecticides, such as azinphos-methyl, for codling moth control. The fact that azinphosmethyl has remained effective for so long, makes codling moth unique among agricultural pests. Periods of effective control are followed by resistance episodes. Control is then re-established with the introduction of a new insecticide. The hope that IGRs could be suitable replacements may not come to pass since cross-resistance seems to compromise their potential usefulness for codling moth control. Avoiding resistance development is a goal not unique to codling moth but to pest management in general. To avoid resistance problems in the future, codling moth control will have to rely not on a single tactic alone but on a comprehensive strategy, which combines several different approaches. Alternation of control tactics with different modes of action must be a built-in feature of any long-term codling moth management strategy.

In future, *Cydia pomonella* management will require more intensive and more sophisticated monitoring procedures than are used today in most fruit-growing areas. Sprays were generally applied preventatively with little regard to population levels. The need for more and better information about the status of codling moth in orchards increased as the effectiveness of traditional controls began to wane due to resistance development. The new controls which are beginning to replace broad-spectrum insecticides are more specific in their activity and require more precise timing to be effective (e.g., IGRs). Also, they are more 'risky' than the old broad-spectrum insecticides and they do not provide the insurance of zero damage. Therefore, monitoring activities must be intensified to reduce the risk of unacceptable fruit damage as much as possible.

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