

BIOLOGY AND CONTROL OF THE  
CODLING MOTH IN THE PACIFIC NORTHWEST

by

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## ABSTRACT

The codling moth is a serious pest in apple growing regions of the world. It is the key pest of apples in the inland Pacific Northwest. Control programs that attempt to keep damage levels below 1% of the apple crop are required in North America. Cultural, biological and chemical approaches to control of the codling moth are reviewed and considered in relation to its biology and the requirements of commercial apple production in North America. Cultural controls that reduce codling moth habitat or physically remove the insect from the orchard are rarely used due to their high cost and moderate effectiveness. Biological control is not particularly effective in controlling the codling moth because of lack of effective predators and parasites, this in turn being related to comparative inaccessibility of the codling moth to such agents.

Sterile codling moth release programs have been effective in suppressing populations, but have been judged to be prohibitively expensive. Chemical control by organophosphates and botanical insecticides are used by conventional and organic orchardists, respectively, because of their effectiveness and acceptable cost. The organophosphates are more effective than the botanical insecticides. Monitoring and detection techniques can greatly enhance the effectiveness of control programs. Improved efficiency of control sprays can be achieved by monitoring moth activity periods with pheromone traps, and by estimating subsequent egg development time based on degree-day data. Problems still exist in codling moth control programs. Pheromone traps may give catches that are difficult to correlate with damage levels or populations. The methods for estimating development of eggs based on degree--day data are not totally

accurate. Reinfestation of orchards from outside sources or ineffective control programs occurs regularly. Areas of research which may lead to improved potential for control of codling moth in the future are considered.

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## I. INTRODUCTION

In most apple growing areas of the world, the codling moth (Cydia pomonella) (L.) is a serious pest. It is the key pest in many areas including the Pacific Northwest. A few areas of the fruit growing world do not currently have the codling moth. Japan is one of these areas and the Japanese have not imported fruit from the Pacific Northwest in an effort to keep the moth from establishing on the islands. Recently an irradiation procedure for exported apples has been developed that may open the Japanese market. This could mean a new market for North American orchardists.

The codling moth is of European origin and is now well established in all parts of North America (173). It was introduced into New England some time before 1750, when the first observation was recorded. The first Washington state observation was in 1880(162). Hosts of the codling moth include apple, pear, English walnut, quince, stone fruit, and crabapple. Wild apple trees and abandoned orchards are important sources of infestations of codling moth in commercial orchards.

The codling moth damages the apple fruit, rendering it unmarketable. The larvae burrow into the apple to feed on the seeds and core area. The larvae, when nearing maturity, burrow back out through the apple leaving holes and frass. The fruit is severely damaged and secondary rot may occur. The larvae may also damage just the surface of the apple by taking a bite and leaving a blemish called a "sting". The apple is left intact but will be downgraded because of the blemish. Damage is usually predominant in the upper third of the tree.

The apple crop losses from codling moth damage vary with region and climate. Northern continental orchard areas that are cool enough to produce only one brood a year may have as little as 10% loss of apples. In other areas, including the Inland Pacific Northwest, an unprotected orchard may suffer greater than 90% fruit damage. The coastal Pacific Northwest normally receives very little codling moth damage because of its cool climate, particularly during the evenings. The codling moth is particularly sensitive to summer evening temperatures during mating, and is inactive at temperatures below 15°C (100).

Effective control of codling moth must prevent the entry of the larva into the fruit. Once the larva enters or bites the fruit, economic damage has been done. Preventing the larva from reaching the fruit is preferable to killing the larva on the fruit, since this prevents blemishes as well as entry. Control of the moth at the time of flight and mating can reduce damage. Destruction of overwintering larvae and pupae can also be effective in preventing apple damage, but unfortunately it is difficult. Codling moth controls must also take into account multiple broods and overlapping generations. A single spray or other simple control measure is unlikely to control the codling moth adequately.

Insecticide sprays are used extensively to control the codling moth. Prior to World War II arsenical insecticides were used. These were losing their effectiveness by the 1930's (86) and DDT became the chemical of choice in the late 1940's. It was extremely effective in codling moth control programs. The grower could apply one spray and expect control for the

year, except when the spray was mistimed. Calendar instead of calyx spraying became popular, but in a warm spring year the calendar spray came too late to prevent damage (30).

The use of DDT had undesirable side effects on orchard pests. Predators and parasites of many insects were killed along with the codling moth. Mites became a major orchard problem because predatory mites were killed (25). Miticides then were needed to control the phytophagous mites. Some species of aphids increased their populations (155). Additional controls were needed for these pests. The codling moth also developed resistance to DDT within seven years of its first use (33). Other broad-spectrum chemicals can create problems in the orchard similar to those associated with the use of DDT.

After the ban of DDT in the United States in 1969, organophosphates became and are presently the most widely used insecticides for codling moth. The major problems in the use of chemicals today are accurate spray timing and complete orchard coverage.

Codling moth damage must be controlled in the orchard. Integrated orchard pest control using fewer, better timed and narrow spectrum chemicals may become an economic and environmental necessity. Alternatives to synthetic and broad spectrum chemicals are needed to allow biological control of secondary and minor pests of apples. Even partial control of overwintering larvae, moths during flight, and eggs would aid the grower in reducing the need for spraying.

The author wishes to acknowledge the review article on biology of codling moth by Putnam (173), the review article on pheromone trapping by Riedl (180), and the fine codling moth bibliography by Butt (13).

## II. BIOLOGY OF THE CODLING MOTH

### TAXONOMY

The Lepidopteran pest codling moth is currently known in North America by the scientific name Cydia pomonella (L.). Other taxonomic generic synonyms for the moth include Laspeyresia (187), Carpocapsa (186), Enarmonia, and Argyropoce (173). The specific name pomonella has one synonym which is pomonana (173). The insect is currently placed in the family Olethreutidae, but has been considered by some taxonomists (173) to be a member of the family Tortricidae.

The common name of the codling moth comes from the ancient root word "querd ling", which means hard berried, and referred to grapes (156). The word slowly evolved to mean any hard or green fruit. The earliest reference to the codling moth by its modern name was in 1747, by which time the word "codling" meant a green or unripe apple, suitable for roasting but not for eating raw (11). The moth's name thus could be defined to mean the "hard green apple" moth.

### LIFE CYCLE

#### Overwintering

Codling moths overwinter as light brown, silk-cocooned mature larvae, most of which are found on tree trunks in the first two feet above the ground

(67). The sites for cocooning are apparently picked with a preference for dark, protected areas on the trunk (118). Cocoons may also be found on tree limbs (261), in trash (20), on tree props (149), in sheds (149), in boxes (168), and on the ground (118). Overwintering cocoons on the ground, where Yothers (261) found 6% of the larvae, occur most often in dry areas such as the arid west. Gould (64) could not locate any overwintering larvae on the ground in West Virginia. Larvae in Virginia that overwintered on the ground did not survive (250).

Cocoons are waterproof and are not affected by repeated wetting and drying, but may be affected by cold temperatures. The larvae may die when chilled rapidly between the temperatures of  $-10^{\circ}\text{C}$  and  $-24^{\circ}\text{C}$  (77). The less active larvae supercool before freezing, which favors their survival (192). Newcomer (147) monitored larval survival above the snowline during the winter of 1919 and found that all larvae were killed in those areas that experienced cold of  $-32^{\circ}\text{C}$  or lower 80-90% of the larvae were killed when the temperatures were from  $-30^{\circ}\text{C}$  to  $-32^{\circ}\text{C}$ , and 70% of the larvae were killed at  $-27^{\circ}\text{C}$  to  $-30^{\circ}\text{C}$ . Snow covered larvae in the area seemed to Newcomer (147) to have had much higher survival but quantitative studies were not done. Female moths are slightly less susceptible to cold than males because of their larger size. The length of exposure is important in determining the mortality rate (77). Codling moths will often survive only one prolonged freeze (192). It should be noted that cold temperatures in the range that kills codling moth larvae also may damage fruit trees.

#### Emergence and Adults

Some time in April the cocooned larvae become brown pupae. Male pupae may

be distinguished in the cocoon by the presence of four dark bands on the tip of the wing pad, as opposed to the three dark bands found on females (161). The pupal stage lasts from four to six weeks, depending on the spring temperatures. The optimum temperature for pupation is 30°C, while the threshold for development is 11°C (61). The pupa works its way to the surface of its overwintering site when about to emerge. The adult moth often leaves part of its pupal case protruding from the tree bark after emergence (234). The first moths appear at the very end of April through May in the Pacific Northwest (131). Male moths emerge first, up to a week before the first females appear (162).

Codling moths attacking other fruits may emerge at different times. For example, a codling moth population which attacked pears in an isolated orchard emerged 3 weeks later than did the moths which attacked the closest apples (1). Pears are hard early in the season with stone cells, making entry by codling moth larvae difficult. This example was most likely a variant population, since normal populations of codling moth may spread from apples to late season pears.

The moth is variable in size and color. It is described as brown-grey (177) to grey (131), with copper colored spots or lines on the forewing. These copper spots are used as an identifying characteristic for codling moths caught in traps, but there is also a buff colored variant (99). The moth is about 6-7 mm long, with 19 mm wing span (162). The male has a dark line on the underside of the forewing, which is lacking in the female (234). The hindwings are pale and fringed (256). The moth also has the characteristic of holding its wings rooflike over its body when at rest.

Temperature has the greatest influence on the time of emergence of adult moths. The date of emergence is critical in timing control programs. This will be discussed later.

The flight and mating activities of the codling moth are also temperature dependent. The optimum temperature is between 18°C and 22°C. The critical low temperature at which moth activity stops is usually reported to be 15°C, but 13°C (5) and 12°C (186) have also been reported. The critical high temperature has been reported as 27°C (5) and 33°C (100,157). Adult codling moths become inactive but remain viable at low temperatures (239), and can survive temperatures as low as 2°C.

The time of peak activity of the first brood varies, but generally occurs from mid-May to mid-June, depending on the weather. Dense overwintering populations may cause only a light infestation if adverse spring weather prevails (65).

The moths prefer to fly at dusk. Some moths fly as early as 3 hours before sunset (5), while others fly many hours after sunset, if moonlight is present (253). The peak of activity is just after sunset. The moths prefer low light intensities (157), but they can mate in total darkness (56). A morning flight has been reported in Indiana (248) and California (5), but as far as is known to this author no tests for morning flight have been made in the Pacific Northwest.

Rain can prevent flight (253), as can RH of 75% or greater (187). Wind will restrict codling moth movement because they will not fly into the wind

(157). Weather that prevents moth flight may alter the time of control spraying from that predicted by mathematical models based on temperature alone.

Codling moths are considered to be nonmigratory. For both sexes, average flight distances from release sites were reported to be 44 m (215), 61 m (205), and 152 m (253). It should be pointed out this does not account for the entire population and a 1974 study by Howell and Clift (93) indicates that 1% of the male population may travel up to 8.7 km from a release area. Females released in one codling moth-free orchard showed 90% of the damage occurred within 305 m of the release point (242). Maximum flight distances are difficult to establish. For male moths, host plants were more attractive than caged virgin female traps in open terrain (93). Apple odor increases flight activity but the moths exhibit no aerial orientation to the smell (220).

The codling moth male responds to a pheromone produced by the female. The pheromone, (E,E-8,10-dodecadien-1-ol) (128), is used in traps to detect the moth's emergence and presence. The moths are polygamous, with the average moth mating 1.5 times. Virgin female moths are 42 times more attractive to males than are those that have been mated (94). Multiple mating, however, may increase the number of infertile eggs.

The extent of multiple mating is influenced by the sex ratio. The first brood often has more females than males resulting in females mating with previously mated males. This lowers fecundity (70). There are more males in the second brood than in the first and the increased fecundity resulting



from this more balanced sex ratio, coupled with an overall moth population increase, results in an increase in larval damage to the apples (120). The proportion of females in the population decreases with increasing population density. Based on the observation that more females than males in the population correlates with lessening damage, MacLellan speculated that trapping of males might lessen orchard damage (120).

The average adult lifespan for mated moths ranges from 14 days (68, 234) to 28 days (51). The maximum lifespan for unmated moths in the laboratory is 90 days at 15.5°C, and averages 51 days at 10°C (68). The male usually dies soon after copulation (51).

#### Egg and Larval Development

Female codling moths lay from 8 to 80 (221) eggs with the average numbers laid reported as 25 (234), 45 (249), 50 (221), and 75 (51). The maximum number of eggs laid in one day is 14 (51). The female lays 90% of her eggs within the first 5 (91) to 7 (100) days after mating. The optimum temperature for oviposition is reported to be 27°C (100,157). Starved females produce as many viable eggs as do females that feed (91).

The eggs may be laid singly on leaves or on fruit, but are usually laid in groups of two or more (230). Apple odor increases oviposition; alpha farnesene is thought to be the chemical stimulant. The eggs are not laid on the source of apple odor but next to it, when the source of the apple odor is placed in a dish in the laboratory (222). Codling moths will not lay eggs on or near last year's apples (198). Geier (57) reported that 75% of 200 eggs were laid less than 6 cm from the fruit with most closer than 3

cm. Wood (249) reported more eggs laid in the upper half of the tree, whereas Parker (157) found no preference for the tops. Wind caused the eggs to be laid to leeward and the moths preferred low light intensities for egg laying (157).

The codling moth lays its eggs on a number of plant species. The commercial crops include apple, pear, English walnut and occasionally stone fruits (177). The list of ornamentals and wild hosts usually, includes quince, crab apple, wild apple and hawthorn, but there is a question as to whether or not hawthorn is actually a host. Wellhouse (232) could find no codling moth larvae on hawthorn and concluded that the lesser apple worm, Laspeyresia pranivora, which is common on hawthorn, may have been mistaken for the codling moth.

The egg of the codling moth goes through three stages of development. The freshly laid egg is a white convex disc said to resemble a drop of wax (162). The next stage is the red ring stage when the egg darkens, and the last stage, known as the black spot stage, occurs when the head capsule of the larva becomes visible (234). These stages take 6-14 days in total, depending on the temperature.

There may be a delayed development of eggs and egg hatch in adverse cold weather (65). The threshold temperature for egg development is 10°C with the maximum rate observed at 32°C (61). Temperatures above 33°C may decrease viability (68). Temperatures near the lower threshold of 10°C may result in a poor egg hatch and eggs developing only to the black spot stage (68). Rock and Shaffer (184) raised codling moths at temperatures of 16°C,

21°C, 27°C, and 32°C, and noted an increasing development rate with increasing temperature, but found the relationship was not linear. There were no differences in growth rate between the sexes (184). Cold storage at -1°C for 28 days killed 100% of the eggs, a finding relevant to storage of apples (151). Hagley (67) found that RH of 90%-95% can reduce egg hatch by 50%, but RH of 60%-75% has no effect.

The newly hatched 1st instar larva is white with a black head and 1.5 mm long. The larvae rely partially on the odor of the apple skin to guide them in their search for fruit. Apple flesh is not very attractive, but skin will attract larvae from a distance of 1.5 cm (209). However, the skin is not usually eaten since the larva just cuts through it to gain access to the flesh (191). The entrance of the burrow is closed with silk. A larva may wander as much as 3.1 m on a single tree before entering a fruit (204). Entry is often through the calyx end of the fruit (233). Scab blemishes may be entered, but there is no association between apple scab and codling moth entries (63).

The threshold temperature for larval development is 10°C, with the optimum at 30°C (61). Cutright (32) released 80 young larvae on 36 apples and found that 35 entrances took place at 30°C while at 25°C only 25 entries were found. A number of larvae die while searching for or upon entering the fruit. Rain probably has no effect on newly hatched larvae since they have been observed hatching and surviving underwater in the lab (197). Hagley (69), however, reported that late spring rainfall caused 18% mortality of 1st instar larvae beneath the epidermis of the fruit and

reduced the number of larval entries from 20 to 4 per 100 fruits. Rainfall in the late spring is uncommon in the Pacific Northwest and warm temperatures are the norm.

The codling moth larvae nearly always spend the remaining instars inside the apple, feeding on the seeds and in the core area. The rate of development of larvae may be affected by the presence of other larvae which compete for food. Larvae feeding on immature seeds develop faster than larvae eating apple flesh. An apple of 4 cm diam can support only three larvae without affecting larval growth (49). The number of larvae that can mature in an apple varies with temperature. Cutright (32) found that 29(36%) larvae matured in 20 apples at 30°C, while at 25°C only 14(17%) larvae matured per 20 apples. Larvae may also mature on buds, leaves, spurs, shoots and mummies (137).

The 5th instar larvae leave the fruit by burrowing out through their entrance hole or by cutting a new one. The full grown larvae are brown headed, pinkwhite, and 20 mm long (177). The larvae leave the apples in darkness and seek a location to cocoon (55). They prefer cocooning on the trunk and in the darkness. MacLellan (118) found that few larvae reached the tree trunk to cocoon in bright sunlight, but at night 68% found their way to the trunk from both the tree and the ground.

The fruit may or may not be attached to the tree when the larvae leave it. A high proportion of the first brood leaves the fruit before it falls whereas a low proportion of the second brood leaves the fruit before it falls (55). This can be critical to survival of the larvae. Wearing and

Skilling (223) found that larvae whose apples fell within one meter of the trunk moved to the trunk to cocoon and survived. Larvae that fell more than one meter from the trunk tended to cocoon on the ground and few survived. They found that 69% of windfall apples fell further than one meter from the trunk. Overall, less than 10% of the successful cocooning larvae come from fruit on the ground (223).

Larvae may wander before cocooning. Glen and Milson (60) followed larvae in their search for cocooning sites. They observed that 44% of the larvae wandered off the tree, and all subsequently perished. The remaining 56% cocooned on the tree. Many fell prey to birds but when protected from birds as many as 48% of the total emerged as adults. The greater the density of larvae, the greater the number of cocoons on the ground, especially in a young orchard where the bark is smooth and there are few cocooning sites on the trunk (224).

Larvae may go into diapause early in the season instead of completing development, or they may diapause as fall approaches. Temperature and day length seem to be the determining factors. A 15-hour photoperiod at 24°C causes larvae to develop normally, while a 12-hour photoperiod at 24°C causes all larvae to enter diapause (74). The majority of second brood larvae, and 10-15% of the first brood larvae may enter diapause (170). The diapausing of 1st brood larvae may make damage predictions inaccurate. Larvae may diapause for two entire winters, but Siegler (193) found he could not raise moths from two-winter larvae, and he thought it unlikely that such larvae in the field would survive. However, other researchers

have raised some moths from two-winter larvae (173). Two-winter larval populations are probably not critical to yearly control programs, but could be a problem in sterile insect release areas because the fertile two-year larvae could reinfest an area.

The characteristics of a diapausing larva include reduced: testes size, oxygen consumption, and metabolic activity. The diapause larva spins a thick-walled circular cocoon instead of the nondiapause type which has thin walls and an exit hole. A larva breaking diapause respins its cocoon within the larval cocoon and increases oxygen consumption and metabolic activity. The testes increase in size as gametogenesis and development of spermatids take place (74). Diapause can be broken by temperature changes and repeated wetting of diapaused larvae. Temperatures near 10°C seem to be most effective for breaking diapause (173).

#### Variation with Environment

The number of broods per season and the size of the total moth population varies with the climate. The Pacific Northwest usually has two broods, with a partial third brood if conditions are favorable. Favorable years are characterized by early springs, late falls, mild winters, and warm evening temperatures (227). Yearly fluctuations in moth populations are especially influenced by the May and August temperatures. Only one brood per year is characteristic in a number of apple growing areas, including Nova Scotia and the northern fringes of the apple growing belt in North America.

The distribution of damage within the tree varies with the brood. The first brood damage is mainly in the upper third of the tree, whereas the

second brood damage is lower (179). The distribution is more uniform in small or young trees.

The level of codling moth damage correlates with temperature and is influenced by rainfall. Warm dry climates have a greater codling moth problem than cool moist ones. Evening temperatures for flight are very important. Webster (228) found on the east coast of North America that codling moths are less of a problem where the mean annual temperature is below 10°C. In the arid west, rainfall becomes more important, with 25 cm per year or more correlated with reduced damage. Colorado has a very serious codling moth problem where the mean annual temperature is 11°C and the rainfall is low. Development of broods apparently accelerates with increasing temperatures and low rainfall (228). Overhead irrigation apparently does not affect moths so much as natural rainfall. Rainfall may cause decreased flight, oviposition and entry, and may aid disease spread among the codling moths.

Larval damage is related to the level of initial infestation and previous crop size. The greater the number of overwintering larvae, the greater the damage (229). A light apple crop following a heavy one will receive more damage than a heavy crop after a light one, because there are fewer moths per apple carried over from the light crop to the heavy crop (229).

The number of orchards in an area may also influence the level of moth damage. There are great concentrations of orchards surrounded by rangeland in the arid west (228). The rangeland or orchard environment may be

unfavorable habitats for predators and parasites of the codling moth, rendering these controls ineffective. Abundance of the moths in one orchard may also be influenced by migration from another orchard. It is interesting that Wearing (219) found migration into the orchard he was studying to be a major factor in codling moth population fluctuations in New Zealand, since they are considered a nonmigratory species.

### III. TECHNIQUES FOR DETECTION AND MONITORING OF THE CODLING MOTH

#### FIRST BROOD DETECTION

Counts of overwintering larvae may be useful for estimating the population of codling moths in an area. The critical measure is the number of cocooned larvae per tree trunk, excluding holes that may have attracted unusual concentrations of larvae (67). Twelve cocoons per six vertical feet of trunk were found to be the economic threshold in Nova Scotia (117). Cocooned larval counts are more useful as a research tool for testing the effectiveness of various control measures than for predicting first brood emergence or exact population levels of codling moths.

Knowledge of first brood emergence is crucial for timing control measures. The date of adult emergence varies with weather, especially temperature. Early attempts at predicting emergence relied on a summation of degree-days, based on temperatures above the threshold of 50°F, with spraying started when the total reached 360°F. This technique included caged moth emergence to correct the temperature data (217).



Several researchers in the 1970's constructed models to predict the development of the overwintering larvae and emergence of the first brood. The computer models BUGOFF (35) and CODLMOTH (10) use degree-days based on minimum and maximum daily temperatures to calculate the approximate date of first brood emergence, flight, and egg development. CODLMOTH is the model used in the Pacific Northwest. The calculations for CODLMOTH are read from a table that uses ranges of low temperature and daily maximum temperature to yield a degree-day figure. The degree-day value from the table is then added to the previous daily total to yield the cumulative number of degree-days for that day in the season. These cumulative degree days are used to time the four cover sprays thought necessary to control the codling moth in most of eastern Washington state.

Both the BUGOFF computer model and the CODLMOTH tables require pheromone traps to pinpoint emergence dates. The first consistent catch or large catch (3-4 in a single trap) establishes a point called the Biofix which is usually 200 degree-days into the season. The timing of spraying is directly calculated from the Biofix point, with the first spray being applied at 450 degree-days.

Problems with degree-day data stem mainly from the inability to detect microclimatic differences and the effects of adverse weather (rain, wind,) on the activity of the moth or on egg development (182). For example, the model would predict the need for spraying earlier than needed if rainy, windy conditions delay mating and oviposition. Conversely, temperatures warmer on or in plant tissue than those measured in surrounding air would

produce an opposite effect. Insects may bask in the sun to accumulate heat, and a degree-day with a hypothetical value of zero may still have had a few hours in which development took place (162).

Dr. Howell of the USDA, Yakima, Washington, has worked on a model using degree-hours instead of degree-days. A temperature integrator placed in the orchard records the hourly temperature fluctuations. Timing of sprays based on degree-hours is claimed to be more accurate than when based on degree-day information.

## TRAPS

### Bait Traps

The first types of traps used for codling moth were bait traps. These were treetop pans, buckets or cups filled with sugar solutions. A mixture of apple cider, brown sugar and yeast diluted with water was used in one trap (200). Others utilized molasses mixed with pine tar oil (109), a mixture of molasses, brown sugar and yeast diluted with water (258), and pine tar traps used next to sugar-yeast baits (216). Both sexes are attracted to baits of molasses mixed with water for feeding.

Bait traps are useful in detecting moth emergence and as a gross measure of infestation. The guidelines for using these traps call for one 6-7 inch trap in the upper third of every second tree, an attractive and refillable bait, and monitoring throughout the season (23). Catch per trap increases with the number of trees per trap, but not linearly (258). Bait traps can catch great numbers of moths in an infested orchard. One 18-acre orchard

with a single trap per tree yielded 19,000 codling moths during the season but, as in all cases with bait trapping, the level of damaged apples was extensive (in this case 70%) (73). Bait traps do not reduce damage effectively because more males are caught than females, and the females that are caught have already laid their eggs (73).

Discussion of bait trap efficiency may be dated. A recent popular magazine article recommends red, molasses filled bait traps as a codling moth damage control measure (54). This author is skeptical at best of this recommendation, however because codling moths are not attracted to red and bait traps did not reduce damage in the 1950's.

#### Light Traps

Light traps are attractive to codling moth adults during the evening flight. The preferred colors are blue (160) or ultraviolet (138). The light source is surrounded by an electric grid that kills the insects, which then drop into a collection plate placed under the trap (75). The traps should be placed in the top of the tree (257).

Light traps are also used in reducing moth populations that emerge in warehouses. Such traps employ a 75-watt bulb coupled with an electrocutor (254). A bait pan may increase their effectiveness. Light traps are most effective if other sources of light are not present.

One study showed more males than females caught in light traps (28), whereas a second showed equal sex ratios (45). Females captured by light traps were reproductively younger than those caught by bait traps (132).

If so, light traps may provide earlier notice of codling moth activity and be useful for timing spray applications.

Light traps do not control codling moth damage effectively, though they indicate moth emergence and flight dates. Damage is not controlled because some moths may fly and oviposit during the day (160) or at dawn (45) when light traps are not effective. Large areas also need many traps high in the trees which are difficult and time-consuming to service, and the results are variable even when extensive systems are used (28). The use of light or bait traps for detection of codling moths is compatible with biological controls because they do not reduce percentage parasitism (27).

An alternative to systems using many light traps is total illumination of an orchard to prevent flight. A reduction in damage from 21% to 14% was noted in one old study where the lights were left on all night (82). Given the costs involved, this approach is only of academic interest.

#### Pheromone Traps

Pheromone traps are the most recent major development in detection techniques for the codling moth. In the 1960's, several compounds from extracts of virgin codling moth females were found to induce sexual response in male moths (15, 126, 127). The pure pheromone was isolated by chromatography and characterized chemically. By the early 1970's the chemically synthesized pheromone with the common name of codlemone (E,E-8,10-dodecadien-1-ol) became commercially available (4).

The original pheromone traps used caged virgin female moths to attract males because live moths worked better than the first synthetic pheromone

preparations (15). The trap was a round gallon carton with a caged female above and stickum (tanglefoot) below to catch male moths entering the trap (97). Inexpensive caged female traps were also made from rectangular milk cartons (90). A later trap used a pan under the caged female moth to trap males (3). This trap was easier to service.

More modern traps employed codlemone on rubber bands or tubing in wing or barrel traps (18). The pure pheromone was found to be as attractive as virgin female moths both night and day (4), in addition to being cheaper and easier to use. The pheromone is currently used in a septum that releases the chemical slowly over a period of weeks. A septum load of 0.1 to 1.0 mg is optimal; both lower and higher doses are less attractive (31).

The efficiency of a trap in catching moths is influenced by many factors including the area serviced by the trap and its location, design, and maintenance. The larger the area served by one trap, the greater will be the number of moths caught by that trap (181). The location and design of the trap are important. Different types of pheromone traps catch different numbers of moths when placed next to each other but no one trap design has proven to be the best (180). Traps must be maintained or they will become too soiled to catch moths. Pheromone trap catch data can be compared only under conditions of similar trap design, placement, spacing and maintenance.

The ideal pheromone trap is inexpensive, easy to service, located low enough in the tree for quick checking, catches moths at low population densities and releases pheromones at an even rate over extended time. The

Pherocon traps made by Zoecon Co., Palo Alto, CA, are considered among the best (31). New pheromone traps are still being developed.

Dr. Howell, of the USDA, Yakima, Washington, is working on a new style of cup trap. He considers this trap less expensive and superior to the Zoecon trap for finding minor localized infestations when placed at four traps per hectare (92).

#### FRUIT DAMAGE

Counts of damaged fruit may be used to assess codling moth damage, but are usually used in conjunction with other data. Entries into fruit at midseason may point to the need for spraying even if few or no codling moths have been trapped (133). Any midseason fruit entry found by spot checking is considered justification for a control spray. Midseason counts may be a useful research tool to check control practices or seasonal phenology of the moth. Prevention of larval entries is the objective of any codling moth control program. Thus, midseason fruit damage indicates program failure.

Fruit damage at harvest is much easier to quantify than midseason spot checking. Cull fruit can be examined for stings and entrances. The amount of damaged fruit at harvest, expressed as a percentage of the total crop, is commonly used for evaluation of codling moth control programs. Fruit damage at harvest also gives a rough estimate of the overwintering population as well as an approximation of the damage potential for the next spring, but the data must be taken for several years before the predictions

of harvest damage can be used as effective indicators for the next year's problems.

#### THRESHOLDS

The threshold level for any trapping method is the point at which treatment should be implemented to yield an economic return over the cost of the control via reduction of codling moth damage to below economic damage levels. The more moths per fruit, the greater the economic damage (223). How much damage is acceptable is a function of economics, not biology. When the cost of damage is greater than the cost of the control, the economic threshold has been reached. The economic threshold will rise as the cost of treatment rises. This will become more important as spray costs increase, but it must be remembered that cover spraying affects many insects besides the codling moth.

The fixing of threshold levels based on trap catches is difficult due to different trapping variables, climate and potential for codling moth damage, but with experience useful thresholds can be established. Brood emergence and brood peaks are identifiable from trap records (180). Female moths competing with traps may influence midseason catches by giving a lower than expected catch (182). Regions with univoltine populations of codling moth tend to have higher thresholds than do those with multivoltine populations (180). Five moths per trap in England (29), and 10 moths per trap in Nova Scotia (122)(both areas having univoltine populations) are used as the weekly threshold. Weekly threshold trap catches of 2 moths per trap in multivoltine B. C. are reported (133), and 2 moths per trap in each

trap of an orchard block or 3-4 moths in a single trap are the threshold in Washington State (265).

Cumulative trap catches through the season correlate with eventual infestation levels and damage (181). In South Africa with a univoltine population, 10, 20 & 50 moths per trap per season correlate with fruit damage of 0.05%, 1.5% and 4% respectively (144). In Nova Scotia a catch of 60 moths per trap in June is considered the threshold when working with a univoltine population where 1% is tolerable (122). However, in Michigan, a multivoltine seasonal catch of 10-15 moths per trap correlates with a 1-2% infestation (180). There may be local populations of codling moths in the Pacific Northwest that are univoltine and thus the univoltine thresholds from other areas might apply.

Pheromone traps may miss small infestations in portions of an orchard due to low population density. Trap catches tied to models such as CODLMOTH are more accurate than trap catch threshold alone in implementing control measures.

#### IV. APPROACHES TO CONTROL OF THE CODLING MOTH

##### CULTURAL CONTROLS

Cultural control of the codling moth has been largely ignored since the advent of effective chemical controls, but, measures such as sanitation to prevent orchard reinfestation and destruction of wild apple trees would aid all growers, conventional as well as organic. Selective thinning of



infested apples and scraping and banding tree trunks are the two main techniques that organic growers might use to lessen their codling moth population, although probably not below the 5-10% range of damage.

This section is written primarily for the organic orchardist and presents selected methods that may help him to lessen his codling moth problems. None has been subjected to modern research techniques even though they appear as recommendations in the "organic" literature (116, 185).

Cultural control of the codling moth really starts when planting the orchard. Different varieties show various susceptibilities to codling moth damage although modern varieties apparently have not been studied regarding susceptibility. King David, Winesap, and Golden Delicious are less susceptible than many other varieties (34). However, if they are next to even a moderately susceptible variety, such as Jonathan that supports a large codling moth population, they will have a greater level of infestation than if planted near other resistant varieties (261). Infestation on varieties that are susceptible will be greater on the cultivar with the larger annual crop (121) probably due to the flight increase response of moths to apple odor.

The characteristics of susceptible trees include large fruit size, strong bouquet, tender skin, sub-acid or sweet flavor, and mid-season ripening (34). The most susceptible varieties include Delicious, McIntosh, and Rome (34). Early maturing varieties such as Transparent and Duchess grown in isolation often need only one cover spray before harvest (101). Unfortunately, when these varieties are mixed with later-maturing varieties

they sustain heavy damage due to a large overwintering codling moth population from the second brood that matures on the late varieties (101). Semi-dwarf trees are easier to apply control measures to than are standard sized trees (136).

Ideally, nearby wild apple trees and abandoned orchards should be destroyed to help combat moth immigration into the commercial orchards. In preparation for a sterile insect release program near Yakima, Washington, 2400 wild trees were removed or sprayed and the population of codling moth was reduced 96% in one year in the one isolated valley before the sterile insects were released (17). Failure to remove wild trees may greatly reduce the effectiveness of any other control measures.

#### Sanitation

Selective thinning of apples infested by first brood larvae will provide some control (36), but must occur in June before the larvae leave the apples (149). Infested apples must be removed from the orchard and destroyed. Collection and destruction of fallen apples also gives some reduction in codling moth damage (85), but is less effective than thinning. Fallen apples are customarily left to rot in conventional orchards.

Codling moths cocoon in many places besides tree trunks. Orchard boxes were found in 1935 to average 14 larvae per box and one in five props also harbored a larval cocoon (150). In a 1975 study 12 moths were captured from 500 boxes (168). Steam treatment of boxes was recommended in the 1930's (37). Steam kills the larvae and sterilizes the boxes (140). Chemicals can also be used. Other control measures include shed

sanitation, trash clean-up (149) and boxes left in a warm, closed building to force moth emergence and death (168).

### Scraping and Banding

Scraping and banding may not have received the attention from growers which it merits. The technique is reasonably successful but was perfected at the same time that DDT, which was very effective, was introduced. Should insecticides become impractical in the future due to codling moth resistance or to deleterious effects, scraping and banding may become important in codling moth control. The best information on scraping and banding may be found in the 1950 USDA Circular 828 (263).

Scraping reduces cocooning sites and kills cocooned larvae. The initial scraping may kill 85% of the cocooned larvae in an orchard while subsequent yearly scraping removes 50% (263). Trees with smooth bark support fewer codling moth larval cocoons than do trees with rough bark. Scraped trees were found to have 14 cocooned larvae per tree while unscraped trees yielded 108 cocooned larvae per tree (261).

Scraping is done by drawing a dull metal blade along the bark to rub the loose bark off (187). The scraper should start high in the tree, fill cracks as they are scraped, and remove most of the rough bark that provides cocooning sites on the tree. The bark should be collected on sheets under the trees and burned (185).

Trees may be banded after scraping. Bands made of corrugated paper (cardboard) (263) are wrapped around the trunk or branches. Bands were

originally untreated but bands treated with Beta-naphtol were shown to be more effective. The powder is mixed with mineral oil or crankcase oil (190) and the bands are dipped in it before affixing them to the tree. Larvae in such bands have less than 1% emergence (47). Treated bands may be left on the tree for the season with only periodic checking, while untreated bands must be removed and destroyed every 10-14 days through the summer or the cocooned larvae will emerge if the population is multivoltine.

Many codling moths do cocoon in the bands provided. In a 1935 study, 90% of the larvae on a scraped tree spun-up in the bands (150). This was determined by comparing the number of larvae overwintering in bands to the total overwintering population on the tree. A 1944 study found that 74% of the larvae that developed over the season used bands for cocooning on scraped trees (2). The main point seems to be that diapausing larvae use the bands in greater numbers than non-diapausing larvae.

The results of scraping and banding are variable. One 1932 study showed results of only 5% wormy apples when bands were used with sprays in comparison to 15% wormy fruit when spraying was used alone (152). Another study in 1939, had 13-29% less damage when using bands plus spraying in comparison to spraying alone (259).

The major points to follow in a scraping and banding program are to scrape every year before spring emergence, to apply new bands by the first of June, and to integrate these measures with other general orchard sanitation measures (259). Whole orchards or blocks of orchards should be treated

together (261). Migration from old orchards, wild trees or alternative hosts will reduce the effectiveness of scraping, banding, and sanitation (205).

#### Other Techniques

Watering techniques should be chosen so as not to interfere with spray programs. The effect of an overhead sprinkler is to wash sprays off the tree, leaving the apples unprotected and probably increasing codling moth damage (202). Codling moths do not like rain, but nevertheless they are major pests in overhead irrigated orchards of the Pacific Northwest, because not all of an orchard is watered at any one time, and the warm evening temperatures promote moth activity. Many orchards are irrigated by rills or trickle irrigation, neither of which affects the codling moth.

Cultural control of codling moths includes such things as painting pruning cuts and filling crevices (185). These actions help to destroy larval cocooning sites. Pruning that opens the tree to sunlight also increases spray penetration (149). Cultivation under trees may kill larvae. However, none of these procedures has been tested in replicated trials.

The technique of trapping out has been tried for many years. Early attempts using light and bait traps were largely unsuccessful. Modern techniques have been tried using pheromone traps. In New York, an orchard with low codling moth population was studied with both high density (30 traps/ha) and low density (10 traps/ha) trapping schemes. There was no significant difference in the results between trap treatments. The random damage ranged from 0-5% in the various areas of the orchard but was

greatest along one border (246). The spread of codling moth migrants into the orchard from an adjacent orchard along this border was slowed by the traps. An isolated British Columbia orchard with 10 traps/ha during a three-year trial had less than 1% damage in all of the years (134). A nearby comparable orchard suffered 15% damage.

A few measures that have been tried but without success include mothballs, smudging, sulfur, tarpaper on trunks to catch larvae (136), and sticky bands of tanglefoot (263).

#### BIOLOGICAL CONTROL

Even though the codling moth is not subject to effective biological control by any agent in its region of origin in Europe (112), it does have a number of predators and parasites. Most of the parasites found in North America today were introduced along with the moth. An example is a braconid wasp, the larval parasite Ascogaster quadridentata Wesm.(7). This parasite has appeared in or been introduced into many apple growing regions but fails to provide economic control (26). Others are more generalized feeders such as the egg parasite Trichogramma minutum Riley. They are found throughout the range of the codling moth but also fail to control it.

The most important factor in the failure of biological control utilizing released parasites may be the protection afforded the larvae by the surrounding apple (26). The parasites are simply not able to attack the larvae. Ascogaster and Trichogramma overcome this by ovipositing in the egg. Parasites that attack cocooned larvae have difficulty locating them

since the larvae spinup in dark, out-of-reach places. Hyper-parasitism of codling moth parasites may also contribute to their overall ineffectiveness (26).

The predators of the codling moth are mostly native species that feed on codling moth eggs, larvae or cocoons as the opportunity presents itself. These include earwigs that feed on eggs, ants and beetles that feed on larvae and birds that feed on cocoons. Birds, primarily including the woodpeckers and tits, are the most important type of biological control agent of the codling moth, with predation rates commonly reaching 90% (20, 67, 199).

The prerequisites for a biological control program, such as parasite and predator studies, mortality factors, and quantifying crop damage have been researched (111). The problems lie in an extremely low economic threshold for the codling moth, interference by chemical spraying, and in the habitat requirements of biological control agents. Improvements in parasite and predator habitats, such as mixed stands of trees (174), weedy orchard floors (42), and wild flowers in the orchard (110) are not consistent with modern conventional orcharding. Bare ground and grass cover are not considered good habitat for parasites. Weedy covers of strawberry, buttercup, alfalfa, dandelion, violets, mustard, carrots, milkweed, sweet clover and daisy have given a 34% increase in percent parasitism over grass covered orchards (110). A weedy, unsprayed orchard may have a high percent parasitism; 71% has been reported (42). A last problem with the general principles of biological control is that a program for biological control

of codling moth may require several years for the parasites and predators to become established, and large areas need to be involved (164). This would require intense cooperation among growers and probable economic loss.

#### Egg Parasites

The most common egg parasites are Trichogramma spp. They oviposit in codling moth eggs, favoring those less than 48 hours old (39). The codling moth egg is not preferred by these parasites over other insect eggs. The parasites search randomly for eggs and may overlook the singly laid codling moth eggs in their two-day life span (39). Trichogramma spp. are usually found in orchards but, nevertheless, the percent parasitism of eggs is often low (42). Parasitism has been reported at 2.4% (119), 5-14% (8), 25% (249), 32% (208) and 56% (226). Parasitism in an unsprayed orchard was reported to be 80-84%, by late season (August) (264). This orchard also had 20% parasitism and codling moth damaged apples in June. Apple damage and percent parasitism do not correlate well. List and Davis (114) found that an orchard with 90% parasitism following mass release of the parasite also had 85% of the apples damaged.

The egg parasite Trichogramma minutum has been released in many areas in an attempt to control the codling moth. Although it does establish itself in the orchard environment, its effectiveness has been minimal (105). Part of the problem in using T. minutum is an apparent unclear understanding of accretive and inundative techniques when releasing parasites. The accretive system calls for an initial release of parasites early in the season with a natural population buildup following the host population.



The inundative system requires season-long mass releases of T. minutum to meet the demands of low economic threshold, and synchronization with the host life cycle (53). The inundative approach is necessary in high value crops where pest injury must be kept low.

Problems with early work in mass releasing T. minutum included late releases (July) and not enough parasites per tree. List and Davies (114) in 1932 released 10,000 of these parasites in an 8-acre orchard but released them only on the 10 innermost trees of the orchard block. Given even distribution within the orchard, the number of parasites would have been about 25 per tree. Morrill (143) reported that 1,000 parasites are needed per tree, while Dolphin et al. (39) put the figure at 10,000 per tree. The parasites, which are raised on Angoumois grain moths, were available at the per thousand price of \$0.10 in 1927 (52), the 1932 price of \$0.18 (143) and the modern price of \$0.32 (Organic Gardening, August, 1984 classified ad). They must be released every few days because the adults live only two days at 27°C (39). Feeding the adults raisins doubles the life span (114). The insects will also reproduce on infertile eggs of the codling moth, such as those laid after release of sterile males which mate with native females producing an inviable egg (145). This would mean T. minutum could be released along with sterile codling moths to help control other Tortricid and Olethreutid moths that may be secondary pests. This may be the best use of T. minutum since it is not capable of controlling the codling moth economically.

T. minutum is affected by a number of sprays. Parathion spraying reduces the population partially (123). The botanical insecticide, pyrethrum, is

as devastating as DDT (123). Elemental sulfur used as a fungicide eliminates the parasite, while summer oil spraying only partly reduced the population (123). Ryania has not been tested in regards to T. minutum (124).

The egg of the codling moth is also attacked by another parasite, Porspaltella sp., that blackens the egg as does Trichogramma (50). This insect has not been released for control measures.

#### Egg Predators

The egg of the codling moth is preyed upon by a number of species that either eat the egg or suck out its juices. The thrips, Leptothrips mali Fitch, feeds on codling moth eggs (104). In one orchard first brood predation of eggs by the thrips was 16.4% while second brood predation was 21.9% (104). L. mali populations are eliminated by parathion use, and are adversely affected by sulfur and summer oil (123). Ryania does not affect the predaceous thrips (124).

Other egg predators include a number of Heteroptera species. Glen (59) found Blepharidapterus angulatus Fall, Malacocoris chlorizens Panzer and Phytocoris tiliae Fab. members of the Miridae or Capsid bug family, sucking codling moth eggs. He also observed a few species in the family Anthocoridae, including Anthocoris memorum L., A. nemoralis Fab and Orius minutus L., and a predatory red velvet mite, Anystis sp., all sucking eggs. Between 12% and 86% of the codling moth eggs were sucked out by all seven species (59). MacLellan (119) reported another mirid, Diaphridia sp., sucking out 13% of a sampled population of codling moth eggs. The egg

predators in the Miridae are eliminated by parathion and malathion insecticides (124), but spraying with ryania (124), sulfur, summer oil, and pyrethrum have no effect (123).

Earwigs, Forficula auricularia L., are present in small numbers in orchards and are thought to account for eggs that disappear. Glen (59) found that between 3% and 29% of the eggs vanished during any one week during the summer in his orchard research. Chrysopa was also reported to be a predator of moth eggs (119), but another researcher failed in the attempt to get chrysopid larvae to feed on them (104).

#### Larval Parasites

The most intensively researched parasite of the larval stage of the codling moth is Ascogaster quadridentata Wesm. (= carpocapsae Vier.). This braconid wasp oviposits on the eggs of the codling moth and other species of Lepidoptera (7). The time required for development of the insect is 36 days (40) but the adults live only a few days (7). The percent parasitism from A. quadridentata is low, having been reported as 9% (119), 21% (225), and 31% (148). A. quadridentata is attacked by Perilampus sp., which has been reported to hyperparasitize up to

37% of Ascogaster larvae in Georgia (225).

Releases of A. quadridentata, which were reared from collections made in eastern North America, took place in the Wenatchee and Yakima Valleys in the 1920's (105) and also in British Columbia (148) in an effort to control the codling moth (7). The wasp established in these areas but did not provide economic control of the codling moth.

The failure of Ascogaster has been attributed to several factors, including the previously mentioned low economic threshold, larval inaccessibility, hyperparasitism, chemical spraying and also lack of host-parasite synchronization (112). The parasite population never catches up with the host population. Inundative releases might be done but by the time the parasite destroyed the codling moth larvae the apples would have been damaged.

Chemical spraying influences the effectiveness of Ascogaster. Sulfur has a deleterious effect, not by killing the wasp but by preventing oviposition (9). Summer oil exerts little influence on Ascogaster (123). The sprays that control the codling moth effectively may also reduce the level of this parasite. No data on modern organophosphate or botanical insecticides and their effect on Ascogaster are available.

At least five species parasitize cocooned codling moth larvae, none of which has been studied with regard to level of parasitism in the orchard. They oviposit into the spun-up cocoon, paralyzing the host and feeding on it to complete their own life cycle. Liotryphon (=Apistephialtes) caudatus Ratz. is the most extensively researched parasite of codling moth larval cocoons, likely because it is easily mated and reared (161). Oviposition must take place in the prepupal stage (146). With Cryptus sexannulatus Grav., L. caudatus has been reared and released for codling moth control in North America. Neither insect established. The numbers released may not have been sufficient, since in British Columbia only 500 C. sexannulatus were released and 4,000 L. caudatus (129). They may have been eliminated

by climatic problems or chemical spraying. Glabridorsum stokesii Cam. is a long-lived, prolific cocoon parasite from Australia (66). It was released in a codling moth control effort, but no followup report was noted. Surprisingly, the releases were in 27 locations, from New Jersey to Idaho, with only 95 female insects per site (66), hardly enough for an effective parasite population. Masdtrus carpocapsae Cush. (125) is also a parasite of codling moth larvae. M. carpocapsae oviposits only in the early summer or in the autumn, since it diapauses during the heat of the summer (115). As many as 7-10 eggs are laid per host and the larvae complete their development within the host (115).

#### Larval Predators

A number of arthropods are opportunists that prey upon codling moth larvae and larval cocoons as an incidental part of their diet. Ants, beetles and spiders may attack the larvae while they are seeking cocooning sites and may account for the low survival of larvae away from tree trunks (104). Ants, especially Formica subsericea Say, subdue the codling moth larvae and drag them back to the colony for consumption (104). This ant species may attack 30% or more of the larvae on the ground, and it is also active on the tree trunk. Other ant species may cut into spun or partially spun cocoons and consume the codling moth larvae. These species include Solenopsis molesta Say, Aphaenogaster aquia Buckley, and Tetramorium caespitum L. (13).

Many species of ground dwelling Coleoptera, mostly Carabidae, attack codling moth larvae (104). Woodside (251) found the beetle larvae of

Tenebroides corticalis (Ostaviidae) feeding on cocooned codling moth larvae on tree trunks. The percent predation is not accurately known for beetles.

A few spiders may feed on larvae, such as Ixeuticus martius which has been reported from New Zealand (224). Jaynes and Marucci (104) mention not only various spiders but also wireworms, centipedes, and predaceous mites feeding on cocoons that were spun on the ground (104).

The effectiveness of predators is a function of habitat requirements being met and the availability of alternative prey. These relationships are not well studied. Hagley and Simpson (71) tried feeding predators to enhance predation but found no effect on codling moth damage, although green fruitworm damage lessened.

A deleterious effect from orchard spraying would be expected on beetles, spiders, ants, and earwigs.

The most effective predators of cocooned codling moth larvae are birds. The major species are the tits (135, 199), the woodpeckers (199), the tree creepers, nuthatches, and chickadees (188). Woodpeckers and tits search the trunks by sight and touch for cocooned larvae which they then dig out and eat, mainly in the summer and fall. Three birds per 100 acres were found in and near orchards in a population survey done by MacLellan in Nova Scotia (117). The woodpeckers in the area studied kept the overwintering codling moth population below the economic threshold 75% of the time. The lowest reported percent predation by birds was 55% (135), while two other reports found predation as high as 95% (8, 199). All bird related codling

moth predation studies have been researched in eastern North America and Europe. No information is available from the Pacific Northwest.

Manipulation of bird numbers in an orchard is difficult, and it should be noted that the average arid western North American orchard is very poor bird habitat. Birds require nesting sites, shelter, water and sufficient food. Dead trees or nest boxes near orchards would need to be provided (256). Entries to boxes must be of the proper size to preclude harmful birds. Water might need to be provided. Beneficial tits and woodpeckers feed on insects, they do not eat apples. Therefore, an alternate food supply might be necessary. Woodpeckers are attracted by beef suet hung in an orchard (117). Bird territorial needs would have to be met, since woodpeckers live within defined acreages. Whether or not bird population enhancement, coupled with another control measure, might give economic control of the codling moth in the Pacific Northwest is unknown but unlikely.

One often overlooked group of codling moth predators is domestic animals. Hogs (218), sheep (48, 252) and poultry (212) have been presumed to aid in codling moth control. The general control action is thought to be one of sanitation of fallen apples and ground disturbance by movement but no replicated scientific studies involving these animals has ever been done. Tripp (213) observed that 100 laying hens in an 8-acre orchard, scratching the ground and eating larvae, produced an apple crop with "hardly a worm".

#### Diseases

The codling moth larva is susceptible to several bacterial diseases,

including Bacillus cereus Frankland (206) and B. thuringiensis Berliner (153). Both are consumed by the larvae while entering the apple or possibly when feeding on shoots. The bacteria then multiply slowly, killing the host larvae with toxins. B. cereus has been shown to be 70-85% effective (136). Several selected strains are more pathogenic than others (201). Unfortunately, the concentration of bacteria needed in the spray is costly and the larvae are hard to kill, since they must receive a lethal dose during entry into the apple (207). Stephens (207) tried spraying with B. cereus and reported 53% wormy apples, far above tolerable levels. Testing over more than one year may yield different results. Oatman (153) noted 90% wormy apples the first year of trials with B. thuringiensis but only 1-5% wormy apples the second year of spraying.

Beauveria bassiana Bals. has been recovered from mature larvae (104, 173). This fungus is highly pathogenic in the laboratory (104) but little work has been done on commercial dissemination. Spraying or dusting with spores gave a 3 increase in infection rate but the maximum percent of larvae killed was 36% (104). B. bassiana is most effective in cool, wet seasons, since it needs water for infection (103). The inland Pacific Northwest is not prone to cool, wet growing seasons. One other fungal parasite, Hirsutella subulata Patch, has been reported from one orchard (21).

The microsporidium, Nosema carpocapsae Paillot, may cause infestation ranging from 1% to 89% of the population (196). The mortality from infestation ranges from 51% to 58%, with the larvae being killed by secondary agents such as bacteria, chemicals, and fungi.



Nematodes of the species Neoplectana carpocapsae Weiser (106), DD136 (43), kill by bacterial release inside the codling moth larvae. The bacteria penetrate and kill the larva and the nematodes eat the cadaver and leave, taking sufficient bacteria to infect the next larva (43). The nematode is propagated on wax moth larvae to produce an insecticide with 5-year shelf life (44). A 60% kill has been reported by spraying trunks (43). This nematode may interfere with other parasites of the codling moth because the nematode may enter parasitized cocoons and kill the codling moth larvae, rendering them unavailable to the parasite (106). Only 34% Ichneumonid-and Braconid-parasitized host larvae produced adult parasites after exposure to the nematode (106). This may not be important since the nematode is more effective than parasites in controlling the codling moth.

The codling moth granulosis virus (CMGV) of the bergoldiavirus group (210) is at least moderately successful in controlling the codling moth. It affects the tracheal matrix, the fat bodies, and hypodermis of the larvae (211). CMGV can be stored at -75°C for 1 year (189) and has a low persistence from year to year, spreading after initial dissemination by spraying.

The virus gave 85% entry damage control when sprayed 2-3 times per generation (102). Unfortunately, the number of stung fruits increased. Another study found that a few larvae died before entry, the majority died after feeding on the epidermis and a few died after deep entry (46). This study also showed 45-50% of the apples were stung. A 1984 article (35) showed only 2% of the crop lost in 1983 compared to 60% lost in 1981, after

spraying 15 times in 1982 and 9 times in 1983 with SAN 406 (a CMGV preparation). The spraying was timed by traps and temperature determinations to correspond with the time period of egg hatch through larval entry.

The virus control may equal the potential of chemical spraying controls, if the initial infestation is low (4-6% damage) (96). Future problems remain in commercial availability of the preparation due to patent issues, problems in raising codling moth larvae since the virus must be cultured on live larvae and the minor importance of markets for CMGV. Current attempts at improvement of CMGV include timing, orchard life span, and increasing virulence.

#### Sterile Insect Technique

Moths must be raised in great numbers for sterile insect release programs. In the laboratory they are raised in trays on an artificial diet of wheat germ and casein (89). Hathaway et al. (81) found that the females oviposit on wax paper and six eggs are needed to produce one adult moth. In early attempts at raising codling moths the larvae were fed on apple peelings and unripe apples, but the artificial diet is much cheaper and produces insects that show no differences in oviposition, egg hatch and longevity from native insects (80). Larvae are raised in British Columbia on sawdust for bulk in the larval diet.

The first attempts to sterilize codling moths used heat as the sterilizing agent. It was found that sufficient heat to induce sterility also caused high mortality (167). Tepa was then sprayed on moths to sterilize them

(79). Tapa was abandoned when radiation became the sterilizing technique of choice.

The sterilizing level of gamma radiation on the pupae ranges from 25 (243), to 30 (235), and up to 40 (170) krad. The irradiation causes 98% sterility in the male (170), lessens mating activity (244), reduces the number of spermophores (98), and lessens male response to pheromone traps (240). Males are especially unresponsive to pheromone traps when released with females. Laboratory-raised males show fewer of these side effects than do irradiated native insects. A native female does not become unattractive to other males after mating with an irradiated male like she would in a normal mating (98) although there is no difference in oviposition behavior (238).

Females are also treated with radiation, although lower dosages are needed to induce sterility (26), with few eggs being produced after treatment. The longevity of females is increased after treatment. The advantage in raising, treating, and releasing male and female moths together is that there is reduced labor required (because no sexing is needed), reduced stress with less handling, and no need for additional female treatment (241). The incubation period of eggs is increased by irradiation (88).

Mortality of the egg from an irradiated parent usually occurs in the red ring or black spot stage. In one experiment 50% of the red ring stage and 78% of the black spot stage died (235). Approximately 2% viable eggs will result from irradiated males mating with native females (78). Fortunately, few of the eggs that hatch will produce healthy adults. White (236) followed irradiated male and normal female F1 eggs through their

development and found that 4% hatched but only .09% produced a healthy adult, compared to 21% healthy adults for a normal mating. No viable eggs were produced from native male x irradiated female crosses (78).

Releases of sterile codling moths have been made in Washington and British Columbia. Monitoring programs with pheromone traps are used to measure the ratio of sterile-to-native moths, this being practical if the sterile moths are marked (169). In the early attempts, males alone were released and the workers achieved sterile-to-native moth ratios of 1.8:1 (241), 8:1 (170), and less than 20:1 (243) instead of the desired 40:1 ratio (16). Later programs released both sterilized male and female moths (243), which gave more desirable ratios and more effective control than releasing one sex.

Damage by codling moths was reported at orchard borders in early release trials (241) and population suppression was at 89% instead of the theoretically possible 99% when the release ratio approached 20:1 (243). At even higher ratios of sterile-to-native moths 1% damage was reported, and the number of moths used to establish these ratios was excessive for economic reasons (171).

The problems in low sterile-to-native population ratios pointed to a need to reduce the native population before a sterile insect release would be successful. Accordingly, native populations were reduced 93% in one isolated valley near Yakima by destruction of abandoned trees and orchards in combination with better spray control programs in the commercial orchards (237). Wild trees were found to serve as a reservoir of codling moths even though they were seven miles from the sterile insect release

orchard (12). The commercial orchard spraying was sufficient to suppress the population below .5% damage levels (169).

With sanitation and control measures implemented before the sterile insect release, the later programs were able to achieve ratios as high as 45 sterile insects to one native insect (172), and a 99.7% reduction in codling moth population in a 102 ha area in 2 years.

Sterile insects must be released for at least three consecutive years for an effective eradication program (169). Localized reinfestations may occur near boxes or prop poles (16). Five hundred imported apple boxes were found to be the source of 12 wild moths caught in one sterile insect release orchard (168). These are enough to start an infestation.

The sterile insect release programs in both Washington and British Columbia were biological successes. The requirements of a general sterility program such as complete suppression of native population, high sterility coupled with good insect viability, and successful mass rearing were met (108). Release ratios were monitored with pheromone traps to allow adjustments in the release rates. Released insects mixed well with the small local populations resulting in low damage (14). The programs reduced the cost of orcharding in terms of spraying that the individual orchard needed (169), and did not harm beneficials. The latter effect reduced problems caused by other insects and mites (14).

Unfortunately, the sterile insect release programs were judged economic failures. The costs for releasing insects for the three-year trial were at

least double the cost of chemical control. The Canadian program ended with an estimated cost of \$225/ha compared to \$95/ha for chemical control. The costs of such a program in the future could be economic if chemical spray costs increase sufficiently, or if the cost of the sterile insect release programs can be lessened by improving the larval diet, mechanization, improved disease control on reared larvae, and a massive treatment area to lessen reinfestation problems (169), or if it can be demonstrated that the costs can be spread over a number of years.

#### Mating Confusion

Pheromones may be used to disrupt mating in insects. Fibers containing the synthetic pheromone, Codlemone, are scattered in the orchard to prevent the male moths from locating females. In one study 15g/ha of Codlemone was used to obtain greater than 85% control of codling moth damage (22). The cost of this treatment was comparable to chemical insecticide sprays, but the resulting damage levels were above economic thresholds.

Some possible controls in the future to avoid chemical pesticides are growth regulators and repellents (255). The repellency of the botanical, pyrethrum, was used in one 1944 experiment to induce larvae to spin-up in bands treated with beta naphthol (262). The pyrethrum, with oil and blood, was sprayed on the tree, leaving the trunk bands unsprayed. No repellent has been tested sufficiently to control the codling moth.

This author was told by Dr. Jay Brunner in Wenatchee about work at the Wenatchee research station on the chitinase inhibitory growth regulator, dimilin. The chemical is used on eggs, preventing hatch by causing

improper chitin formation. This compound is being developed by chemical companies as an alternative to pesticides and may be registered next year.

## CHEMICAL CONTROL

### Synthetic Insecticides

Parathion was the first organophosphate insecticide used in orchards (41). Parathion is both extremely toxic to mammals and phytotoxic, and for these reasons less dangerous organophosphates are used to control codling moths today.

The currently recommended organophosphates for commercial orchards are Guthion (azinphosmethyl), Imidan (phosmel), and Zolone (phosalone) (265). Any of the three will suppress codling moth damage below 1%, if the applications are timely; usually four per season are required. Current application rates, recommendations, and restrictions should always be followed and can be found in the Extension Spray Guides for any given area (265). There is no codling moth population known to be resistant to Imidan or Guthion, but Zolone is reported to be no longer effective in some areas of the Pacific Northwest. This apparent resistance has not been substantiated in the scientific sense.

Guthion is the most hazardous of the three registered commercial organophosphates. It has a toxicity of 13 mg/kg acute oral LD<sub>50</sub> and can be absorbed through the skin. This compares with an acute oral LD<sub>50</sub> of 120 mg/kg for Zolone and 300 mg/kg for Imidan. Both Imidan and Zolone are less hazardous than Guthion, but Zolone has a longer minimum time to harvest (14

days) than Imidan or Guthion (7 days). Guthion(\$9-18/A) is less expensive than Imidan(\$15-21/A) or Zolone(\$20/A) on a unit area basis.

Guthion is formulated as a 50% WP and is recommended for codling moth control at rates of 1 1/2 to 3 pounds a.i. per acre (1.67-3.33 kg/ha) or 1/4-1/2 lbs per 100 gallons of water ( 0.11-0.23 kg/378 l). Guthion can be phytotoxic to ornamentals such as linden and hawthorn (165). It is incompatible with heavy metal compounds and other sprays containing sulfur and calcium. At the recommended rates it may be damaging to predatory mites and is toxic to bees. The 1984 cost is \$6/lb.

Imidan is also formulated as a 50% WP and is recommended at 4 1/2-6 lbs a. i. per acre (5.0-6.67 kg/ha) or 3/4 -1 lb per 100 gallons of water (0.34-0.45 kg/378 l). Imidan is hazardous to bees. The 1984 cost is \$3.51/lb.

Zolone is formulated as a 25% WP and applied at rates of 6 lbs a. i./acre (6.67 kg/ha) or 1 lb per 100 gallons of water (0.45 kg/378 l). In addition to controlling codling moths, Zolone is also active against spider mites but is not harmful to predatory mites (130). Zolone is not hazardous to bees if applied in the evening or early morning and not during high temperatures. The 1983 cost was \$3.30/lb.

The currently approved synthetic insecticides for home orchard use are also organophosphates. Diazinon or malathion mixed with methoxychlor (a chlorinated hydrocarbon) are recommended as a calyx spray (176). This author could not find the spray rates or cost of using malathion-



methoxychlor in Washington even though it is registered for codling moth control.

Diazinon is formulated as a 50% WP and is recommended at 6 lbs a.i. per acre (6.67 kg/ha). The acute oral LD50 for diazinon is 150 mg/kg and it is hazardous to bees. Diazinon and malathion may russet some apple varieties. The 1984 cost of diazinon is \$4.50/lb. Recommended time of spraying is 10 days after full petal fall, with repetition in 7-10 days. Application of at least four diazinon sprays is recommended (176).

Synthetic pyrethroids have been tested for controlling codling moth. Several types are effective when used at two-week intervals (107). Unfortunately, they also kill predatory mites, and damaging mite populations increase after their use (95). For this reason pyrethroids are not recommended.

Another target of codling moth control is larvae in stored apples and apple boxes. Methyl bromide fumigation was tried but abandoned because the fruit was damaged by its use and a few larvae survived (141). Irradiation of apples is currently being used to assure codling moth-free fruit for overseas shipments. Apple boxes may be dipped or sprayed with disinfectant. Modern treatments have not been tested for dipping apple boxes.

#### "Organic" Insecticides

The "organic" insecticides are defined by Oregon State Law Ad 995 as naturally occurring compounds derived from plant materials, oils and inert

dusts. Powdered mixtures of naturally such material such as sulfur can be used as "organic" fungicides in that state. Washington and British Columbia have not enacted "organic" farming legislation to this author's knowledge.

A review of the "organic" insecticides will hopefully give the organic grower some basis on which to judge botanical insecticides. Most of the botanical insecticides were no longer researched after synthetic chemicals came into common use. Ryania is the exception. Only ryania and nicotine are truly effective. Ryania is by far the best choice for the organic grower.

The plant species Ryania speciosa Vahl. yields the compound commonly known as ryania, which has the active ingredient ryanodine (159). Ryanodine is stable, has low mammalian toxicity and causes flaccid paralysis of insect muscle tissue. The stem wood of R. speciosa is powdered and mixed with water at a rate of 6 lbs per 100 gallons to make an insecticide spray (72). Ryania is formulated as a 50% WP and is used in Washington currently at 8 lbs of formulation per acre ( 8.89 kg/ha). It is very effective in controlling codling moth larvae but it does not act on eggs or moths. In New Zealand, 74% of the first instar larvae were killed when an orchard was sprayed with ryania (249). Most beneficials are spared in ryania applications (72).

Ryania is especially effective in low codling moth population areas, and where the population is univoltine. Only two or three applications are needed per season in Nova Scotia, but in British Columbia at least four

applications are needed (159). Many more may be needed if the codling moth population is high (12-15 were used in one Washington orchard when 30% damage was reported.) Research in British Columbia has shown problems with apple rust mites and small apples after applications (142). Codling moth damage levels with ryania applications can be as low as 1% or up to 4% (84). This should be adequate for an organic grower. An increase in stings and shallow entries was noted with ryania spraying in comparison with other insecticides (73). It is apparently slower acting than some contact poisons. Ryania may be expensive and difficult to obtain. Currently the only known U.S. supplier is Progressive Agrisystems in Pennsylvania. It was not available for use in previous years but the 1984 cost is \$3.65/lb.

Since ryania does not disrupt predatory mite populations (note effect on apple rust mite), the greater damage caused by the codling moth with ryania treatment may be offset by reduced costs of spraying for secondary pests. Conversely, a poor crop due to reduced apple size or rust mite population increase may preclude ryania use in some areas. Ryania is registered in the United States for use on apples.

The other effective botanical spray is nicotine, which is derived from tobacco. The liquid is usually diluted with oil and water. The compound has high mammalian toxicity, with an acute oral LD50 of 50 mg/kg (165), and may reduce fruit size. It is formulated as nicotine sulfate for general insecticide spraying. Nicotine is more expensive than synthetic insecticides. It will kill eggs that are ready to hatch, larvae and even

up to 73% of the adult moths (87), but it will not kill freshly laid eggs. It is not in current use in the Pacific Northwest, probably due to its extreme toxicity at the time of application.

Rotenone, from derris root, was found in a 1934 report to be ineffective in controlling the codling moth (231). A later (1942) study perhaps using an improved formulation of the compound reported 95% control with the powdered root, but this is less control than the same author found with nicotine (76). Too few modern studies have been done on the use of rotenone for codling moth control to identify accurately whether or not it is a useful tool.

Pyrethrum, derived from certain chrysanthemum flowers, was tested for control of codling moth in the 1930's and 1940's (260). It reportedly controls all stages of the codling moth. Moths and larvae are affected by pyrethrum sprays in 3-4 minutes, with a reported 96% kill of those knocked down (62). The spray should be applied in the early morning so the moths will not leave the area when the sprayer (duster) passes by. Moths have been observed leaving the area in response to the noise and disturbance of the machinery. Pyrethrum degrades in a matter of days and must be applied often. Pyrethrum affects beneficial insects adversely. Today, the use of pyrethrum is not recommended because of its cost, its effects on beneficial insects (especially predatory mites), and its rapid degradation.

Another botanical, ricinine from the castor bean, Ricinus communis L., has been shown to be toxic to the codling moth in a laboratory study (195). This compound is not so toxic to mammals as is its sister compound ricin,

and is not registered for use. One other botanical, neriifolin, derived from yellow oleanader, Thevatia thevetioides, was reported to give 100% mortality as a contact poison at 50 mg/ml, and at lower doses to retard codling moth growth and reduce oviposition and egg hatch of the codling moth (175). The mammalian toxicity was not discussed and this compound has not been commercially used or approved.

Mineral and fish oils were reported in the 1920's to have some ovicidal properties. Many eggs developed to the black spot stage and then did not hatch (113). These oils were mixed with other chemicals or used alone (201). Problems with the use of oils for control of codling moth include the long egg laying activity of the moths, determining the peak egg laying period and weather (24). The susceptibility of the eggs to oil varies with the age of the egg, the length of the incubation, and the concentration of the oil.

The ovicidal value of mineral oil increases with increasing viscosity but there may be a reduction in fruit size with a highly viscous oil (203). A mineral oil of 50-55 seconds Saybolt with a high unsulfonatable residue is preferred and has an ovicidal value of 92% or better (230). Mineral oil can be phytotoxic at high concentrations and may react with other insecticides when used in summer spraying (265). For these reasons it is not recommended in the current spray guide (265).

Linseed oil can be used in place of mineral oil (113). Raw linseed oil is better than boiled linseed oil. Fish oil from herring and dogfish is a slow-drying oil and can replace mineral oil, alone or in combination with other insecticides (231). Fish oil has been used in organic orchards.

Road dust can adversely affect codling moths but in the orchard may be more of a hindrance than a help. It may coat leaves so that insecticide sprays do not adhere well and this will leave the apple crop unprotected. More damage was observed along dirt roads in orchards than where it was not dusty (19).

Sprays mixed with sugar may lessen larval damage by attracting the larvae to insecticides for increased consumption. An increase in clean fruit of 5-10% was noted in one study with brown sugar at 4 lbs per 100 gallons of water mixed with a pre-organophosphate insecticide (247). Brown sugar and water is most effective when used as an attractant for mixing with insecticides to increase larval feeding on apple skin, rather than the larva just cutting through and discarding the skin piece (191). Green apple peel concentrate may also increase consumption of insecticide (194). Sugar or apple peel concentrate are not needed with organophosphate insecticides, but may be useful for use with botanicals, CMGV and Bt. One commercial feeding stimulant, Gustol, is available.

Botanical insecticides will probably not be of value to conventional growers except in integrated control programs or if the codling moth develops resistance to organophosphate insecticides.

## V. CURRENT STATUS OF CONTROL

### Conventional Orchards

A conventional orchard could be defined as one that produces fruit to meet current commercial standards of size, color, freedom from pest damage and

other blemishes, at a profit. The use of synthetic pesticides and fertilizers is usually necessary in a conventional orchard.

Conventional orchardists in eastern and central Washington use organophosphate insecticides as the main control for codling moth. Codling moth sprays are applied with air blast sprayers, and four to five sprays are applied in a typical season. A codling moth spray currently costs \$25-30 per acre, including the cost of labor and equipment.

Pheromone traps to detect adult moths and indicate the need for sprays are occasionally used in Washington orchards. The Washington Extension Service Spray Guide (265) recommends that Zoecon traps be placed every 500 feet (152 m), three rows into the orchard along borders, with additional traps scattered in the orchard interior near suspected hot spots. A small orchard of 5 acres (2.03 ha) should thus have 5 traps, one on each border and one in the interior. Traps are checked weekly or more frequently. Some chemical companies in Washington provide a trap placement and monitoring service. Company fieldmen notify growers when trap catches indicate the need for a spray application. Some growers place and monitor traps themselves. The Extension Service has in the past maintained traps and alerted growers when emergence has taken place.

Trap catch thresholds vary with the area. The Extension Service (265) recommends that 3-4 moths/trap/week in any one trap is the economic threshold if no sprays have been applied for the previous two weeks or more. The threshold is 2 moths/trap/week if all traps are catching moths. In the Okanagan Valley of British Columbia the threshold is 2

moths/trap/week in two consecutive weeks (133). Exact thresholds in an area can be modified based on past experience, neighbors' control practices, existence of known "hot spots" (e.g. piles of prop poles, boxes, warehouses etc.) and local weather conditions.

The CODLMOTH computer program or other degree-day data can be used in conjunction with trap catches to improve the accuracy of pheromone traps as predictors for spray application. Such weather data are available from the local newspaper, or growers may purchase and install weather monitoring equipment.

Quality checks are run by the various warehouses at harvest. Levels of codling moth damage are brought to the attention of growers, fieldmen or consultants, and this information may be used to make modifications in the following year's codling moth control program.

Most conventional orchardists make no effort to hand-thin or to dispose of dropped apples entered by codling moths. A few growers may disinfect or sterilize poles and boxes; most do not. In general, practices other than chemical spraying are almost non-existent in conventional orchards.

#### Organic Orchards

An organic orchard produces fruit for a clientele that will pay a premium for the guarantee that synthetic agrichemicals have not been used in its production. A higher level of pest damage is acceptable to these consumers. Two organic orchardists, Paul Lanphere (Wenatchee) and Ron Engeland (Okanogan), were visited to obtain information on their codling moth control programs.



As with conventional orchardists, both of these growers relied heavily on spraying. Ryania was applied at 7-10 day intervals or more frequently if rain occurred. On average, at least six applications were made in these orchards, which typically encounter two broods per season (12 were used when the previous yearly infestation had reached 30%). Pheromone traps and degree-day data were utilized to assist in the timing of spray applications.

The cost of a ryania application is \$40/acre, compared with a cost of \$25-\$30/acre for an organophosphate spray. The level of control achieved with ryania is lower than that achieved with organophosphates. Less than 5% damage was reported where codling moth populations were previously suppressed by spraying with organophosphates. By contrast, damage of 30% was reported for an adjacent orchard that had not been sprayed with organophosphates for six years.

In contrast to conventional orchardists, the organic orchardists visited by this author make use of cultural practices for control of codling moths. Cultivation is used by Engeland to destroy larvae cocooned on the ground. Apples are hand-thinned in June by both orchardists and the apples with first brood larval entry holes are picked and destroyed. Cardboard boxes are used to pack apples out of the field so lessening reinfestation by larval cocoons spun up in bins. The organic orchardists with whom this author spoke do not utilize banding and scraping for control of codling moth.

#### Integrated Control

Integrated control is the coordination of various strategies that takes

into account the overall biology of the pest complex and the ecosystem to achieve a satisfactory level of control with minimal adverse side effects. What is 'satisfactory' is somewhat artificial and is a function of economics and biology. Integrated control has been needed as an answer to increases in secondary pest populations (214).

Integrated control may, in one sense, be understood as the use of various strategies focussed on one pest. The codling moth has not been controlled by integrated programs primarily aimed at it. The insect has no manipulable and effective biological control agent, and it has an extremely low economic threshold. A combination of cultural, biological and chemical controls is hardly ever used by conventional orchardists on the codling moth. But the organic orchardist is attempting to use this strategy.

Integrated control of other pests, when the codling moth is present, must be related to its role as the key pest. It is the pest that must be controlled, but the critical task is to control it without creating secondary pest problems. Phytophagous mites are a secondary pest well suited to integrated control because predatory mites, if not disturbed, will maintain the phytophagous mites below economic damage levels (183). Selective pesticides can be used to avoid killing the predators.

Most of the chemicals in use today are selective. The "mild" organophosphates, such as Zolone and Imidan, kill codling moths much more effectively than they kill mites. Guthion, applied at low rates, is not particularly damaging to mite predators but mite populations may increase when it is used at more than 1 1/2 lbs per acre (265). There is a fine

line between too low a rate and one that is effective in codling moth control. Guthion applied at low rates in an integrated program may allow a resurgence of codling moth populations (265). This may be detected by the presence of moths in pheromone traps. Ryania does not affect most mite populations.

Most writers agree that the most successful integrated orchard control program was conducted in Nova Scotia. The codling moth is univoltine there and needs a maximum of two sprays a year to control the first and only brood. The use of ryania as the selective insecticide in that program allowed other insect problems to be alleviated by biological controls or by minimal insecticide spraying, with either botanicals or synthetics. The orchards were sprayed with fungicides as well (116). It must be noted that the codling moth damage in Nova Scotia is minimal even without spraying. When the codling moth populations rebounded from the lowest levels, when DDT had been used, the damage levels still remained below 5% (158).

Areas, like the Pacific Northwest, that have multiple broods also have great damage potential. In a two-brood area in New York, after discontinuing spraying, the codling moth population grew in two years to cause damage approaching 100% (58). In British Columbia, one untreated orchard showed greater than 85% damage annually (139). The more generations of the moth, and the longer the flight period during the season the more difficult is an integrated orchard control program.

Some programs in multiple brood areas have met with success. In Massachusetts, an integrated orchard used 63% of the insecticide of a

conventional orchard and sustained only 60% of the damage suffered by the conventional orchard (166). Optimal spray timing by sampling trees, fruit, and traps was thought to have produced the best result.

An integrated control program should yield a monetary saving (6). The Massachusetts program yielded savings of \$278/ha (166). Orchard trials in Yakima that eliminated the need for a cover spray saved the cost of that cover spray, less the cost of monitoring.

The most important point in a Pacific Northwest codling moth integrated control program is timing. Pheromone traps pinpointing emergence and degree-day models such as CODLMOTH must be used to time spraying accurately (265). This should result in the application of less insecticide that can affect beneficial insects. Calendar spraying is wasteful of insecticides and money.

## VI. SUMMARY and CONCLUSION

The codling moth is the most serious pest problem for Inland Pacific Northwest apple growers. The climate of the arid west is favorable to the moth and two or more broods per year are common. The codling moth population can climb rapidly from the first to second brood. The orchards in growing districts are clustered together, making infestations easily transferable from one orchard to another.

Conventional growers expect 95-98% clean fruit from their control programs (154). The public expects unblemished apples. There have been attempts and various schemes to eradicate the codling moth since 1919 in Washington

State. British Columbia, through a system of sanitation and quarantine, was codling moth free before the 1920's (36). If the cost of a sterile insect release program could be lowered, the codling moth might again be eliminated or at least suppressed throughout the Pacific Northwest.

The codling moth is not subject to effective biological control in the area. A lack of effective biological control agents, coupled with low tolerance levels for damage, tend to preclude biological control. Cultural control of the codling moth is labor intensive and may not be economically feasible as long as the codling moth population level can be suppressed with spraying. For example, a spraying program to control the codling moth (4 sprays per season) costs about \$100/acre while a scraping and banding program which should be comparable in cost to hand thinning would cost \$200/acre (83). Compared to ryania spraying (10 sprays per season) at a cost of \$400/acre, scraping and banding might be considered by the organic grower.

Spraying with organophosphates or ryania are the only truly effective and practical controls in present use. The effectiveness of chemical sprays can be greatly enhanced when integrated with information from pheromone traps and weather monitoring data.

One major advance to codling moth control programs in the last fifteen years has been the development of pheromone traps. The traps are effective in detecting the emergence and presence of the moth even at low population levels. New developments in trap-to-damage correlations may in the future increase the accuracy of population estimates.

## Recommendations

The conventional orchard grower could best improve his control program by making effective integrated use of pheromone traps and degree-day models to time spray applications. It is senseless to spray if the codling moth is not present in the orchard. Spraying may be too early or too late for proper control if it is not timed to the moth's development.

Conventional growers may also be advised to implement some of the simpler cultural control measures into their orchard management program to prevent yearly reinfestations of their orchards. Cleaning and sterilizing bins and prop poles would cut down on the development of "hot spots" of codling moth emergence from these items. Bins could be warmed in an enclosed area after cold storage to allow for moth emergence and destruction. This would prevent the between-brood emergence that sometimes occurs and skews trap catch data, and so necessitates an extra cover spray.

The organic grower is faced with extra difficulties in controlling the codling moth. The best advice may be to isolate the orchard (116) and plant different varieties such as very early or late apples that show resistance to the codling moth, but this is often not a practical option. Marketing is the major consideration in determining what variety to plant.

Multiple-species orchard planting should also help to alleviate codling moth problems. Where an isolated, cooler-than-normal microclimate with no neighboring orchards can be exploited, the organic grower has the possibility of achieving acceptable control with a combination of practical cultural methods and ryania sprays. Organic growers should place and

monitor pheromone traps to detect moth emergence and presence. Ryania sprays can be timed using trap data and degree-day models of codling moth development.

Every organic orchardist, in an ideal situation or not, must make use of several cultural controls, such as sanitation of pruning wounds; cleaning boxes, bins, and prop poles; thinning and disposing of first brood-damaged apples so that the larvae cannot emerge and cocoon. All these are essential to prevent explosive codling moth population increases. Scraping and banding should be added to the organic orchard management scheme to depress the first brood population levels if labor and economics permit it.

The organic orchardist might also utilize biological control and add to the suppression of codling moth populations by encouraging the presence of woodpeckers in the orchard. Habitat enhancement by placing nesting boxes, suet, and water in the orchard may be rewarded with increased bird predation of cocooned larvae. Forest or scrub might be left near the orchard to provide alternative habitat for birds, but wild apple trees and other codling moth hosts should be cut down.

#### Future Research

The basic biology of the codling moth needs further study, particularly in relation to the moth's habits in the arid west. Diapause and flight habits in the environment of this region need more study, according to Dr. Brunner of Wenatchee. The percent of diapausing first brood larvae, or what causes early diapause, except that it is weather related is not known for this area. Such information could be used in the CODLMOTH type models to help

predict what percentage of the first brood will emerge as second brood adults. Knowing the exact environmental requirements for flight would help to predict when migration may be a factor in control programs.

Contrary to published reports from the literature that male moths emerge up to a week before females (162), females and males may emerge at the same time in the Pacific Northwest. Dr. Howell suspects this is so and could alter the timing of sprays based on trap catches. Female moths may also be more mature than males at emergence, which means that sterilized males released at first emergence would have a better chance of mating with the mature native females than would the immature native males.

The temperatures required for multiple mating are also relatively unknown. There is more multiple mating in the second brood than in the first, probably due to longer evenings and warmer temperatures. The percent of multiple mating can influence the progeny, especially under a sterile insect release program. This basic biological research would allow fine tuning of sterile insect release programs and codling moth development models.

Orchard "hot spots" and the conditions that create them need elucidation. Some orchards have recurring codling moth infestations despite heavy spraying. Canopy density or spraying practices (calibration, ground speed) may be responsible for this phenomenon.

Future research will also be done on trap design and damage correlations, and insecticides. Models should be of increased accuracy in the future.



The granulosis virus and dimilin may turn out to be the insecticides of the future.

Some old ideas may prove useful in the future. Pheromones might be used to attract male moths to a sterilizing agent (14). There would be no spray residues or damage to beneficial insects and no costs associated with rearing moths for release. Codling moths resistant to a specific pesticide might be sterilized and loaded with the chemical to kill others in the orchard on mating contact (245). Further work on attractants mixed with insecticides might lead to better future control (178). Whatever the method, the best times to kill the codling moth are in the adult or in the egg stages, before the possibility of apple damage by the larva.

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