CHAPTER 7

# Classical Biological Control of Codling Moth in the Western United States

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## NON-TECHNICAL SUMMARY

Codling moth (*Cydia pomonella*, Lepidoptera: Tortricidae) is a notorious global pest of pome fruit and walnuts, causing severe economic losses due to the direct damage caused by larval feeding within the flesh and core of pome fruit and the kernels of walnuts. As an invasive species, it has become a key pest for pome fruit and walnut production in almost all regions of the world, and management has generally required extensive use of insecticides to reduce damage of harvestable produce to an acceptable level. Early attempts at classical biological control led to the introduction of the egg-larval parasitoid *Ascogaster quadridentata* (Hymenoptera: Braconidae) from Europe and its establishment in the western United States in the 1920s. As this failed to provide a sufficient degree of control, a more detailed approach to the selection of candidate parasitoids for introduction from Central Asia was made in the 1990s, which led to the establishment of the gregarious cocoon parasitoid *Mastrus ridens* (Hymenoptera: Ichneumonidae). As a cocoon parasitoid, *M. ridens* exhibits several traits that may enhance the impact of parasitism on codling moth abundance. Levels of parasitism of codling moth in individual orchards during the introduction of this parasitoid to the western United States varied, but in some cases were as high as 70% in California and 52% in Washington State. The direct impact of parasitism by *M. ridens* on codling moth in pesticide-treated orchards may be limited as only very low levels of this pest can be tolerated in commercial crops. In contrast, however, such parasitism can contribute effectively to codling moth management in non-commercial habitats, such as backyard and wild trees, by greatly reducing the opportunity for mated female moths to disperse from such areas with higher density populations into commercial, pesticide-treated orchards.

## HISTORY OF INVASION AND NATURE OF PROBLEM

The codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae, **Fig. 1**), is presumed to have spread from Central Asia along with the cultivation of its host plants, particularly apple. The history of the cultivated

Mills, N. J. 2022. Classical biological control of codling moth in the Western United States, pp. 73–80. *In:* Van Driesche, R. G., R. L. Winston, T. M. Perring, and V. M. Lopez (eds.). *Contributions of Classical Biological Control to the U.S. Food Security, Forestry, and Biodiversity.* FHAAST-2019-05. USDA Forest Service, Morgantown, West Virginia, USA. https://bugwoodcloud.org/resource/files/23194.pdf

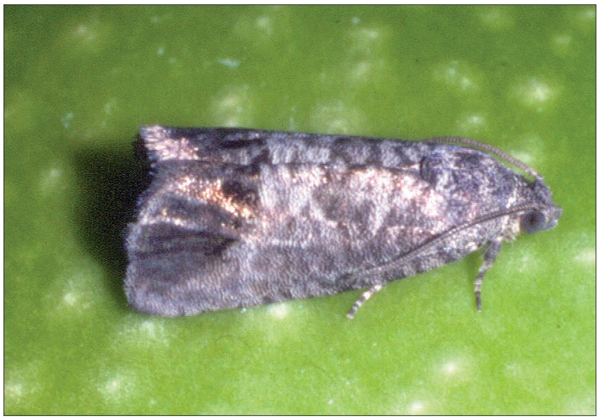

**Figure 1.** Adult female codling moth (*Cydia pomonella*) on the surface of an apple. (N. Mills, UC Berkeley)

apple is complex and began with the domestication of the wild apple (*Malus sieversii*) in the mountains of Central Asia between 4,000 and 10,000 years ago (Cornille et al., 2014). Cultivated apples subsequently travelled westward along the Silk Route to Europe and underwent extensive hybridization with Caucasian (*Malus orientalis*), Siberian (*Malus baccata*), and European (*Malus sylvestris*) crab apples. Domesticated apples, now known as *Malus domestica*, eventually arrived in North America with colonists in the 17th century. Consequently, codling moth is thought to have been present in North America since the mid-1700s and to have spread as far as California by 1872, representing a very early example of an insect invasion that was almost certainly aided by human transportation.

Codling moth has subsequently spread to almost all parts of the globe where pome fruit and walnuts are cultivated, with the exception of South Korea and Japan. One of the more recent examples of spread has been in China, which has almost 50% of the world production of apples (Zhu et al., 2017). First recorded in China in Xinjiang Province (in the northwest) in 1953, codling moth then spread eastward to other apple-producing provinces, reaching Gansu by 1989 and Liaoning by 2009.

## WHY CONTROL THIS INVASIVE SPECIES?

As codling moth is a direct fruit-boring pest, if populations are not effectively controlled, they can build up over successive years and have severe effects on farmers' ability to harvest marketable fruit and nuts. At even relatively low levels of abundance, the extent of damage can be sufficient to cause rejection or downgrading of harvested produce, causing significant economic impact on growers. Control is not an option, but a necessity for this invasive pest. The question, however, is how best to control it over the longer-term productivity of perennial tree crops?

While control has been based on the use of insecticides, codling moth does have specialized natural enemies in its region of origin in Central Asia, and recent surveys suggested that parasitism levels there were higher than in the western United States (Unruh 1998; Lacey and Unruh, 2005; Mills, 2005). Together with an increasing demand for reduction of insecticide residues in exported fruit, these survey data refocused attention on opportunities for classical biological control of codling moth.

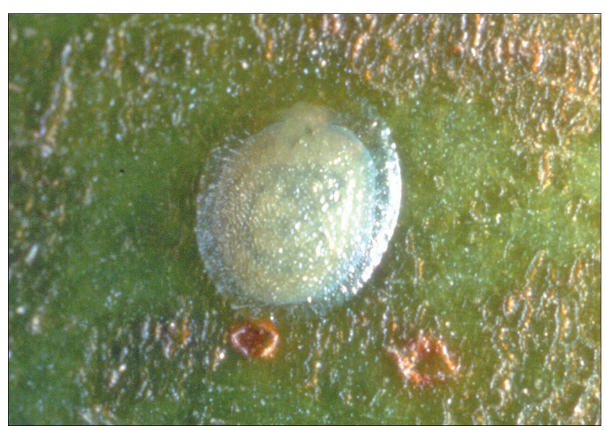

**Figure 2.** Codling moth (*Cydia pomonella*) egg on the husk of a walnut. (N. Mills, UC Berkeley)

## THE ECOLOGY OF THE PROBLEM

Codling moth is a fruit-boring pest that feeds primarily on apples, pears, and walnuts, but also occasionally on quince and stone fruit such as apricots, plums, nectarines, and peaches. It has from one to four generations a year, depending on temperature, and overwinters as mature larvae in cocoons under the bark or in debris on the ground beneath its host trees (Welter, 2009). Eggs are laid singly on fruit or leaves (**Fig. 2**), and larvae, after feeding briefly on the fruit surface, bore into the fruit and feed on the flesh and seeds (or nut kernels, **Fig. 3**). There are five larval instars, and the mature larvae exit the fruit and pupate under bark or on the ground.

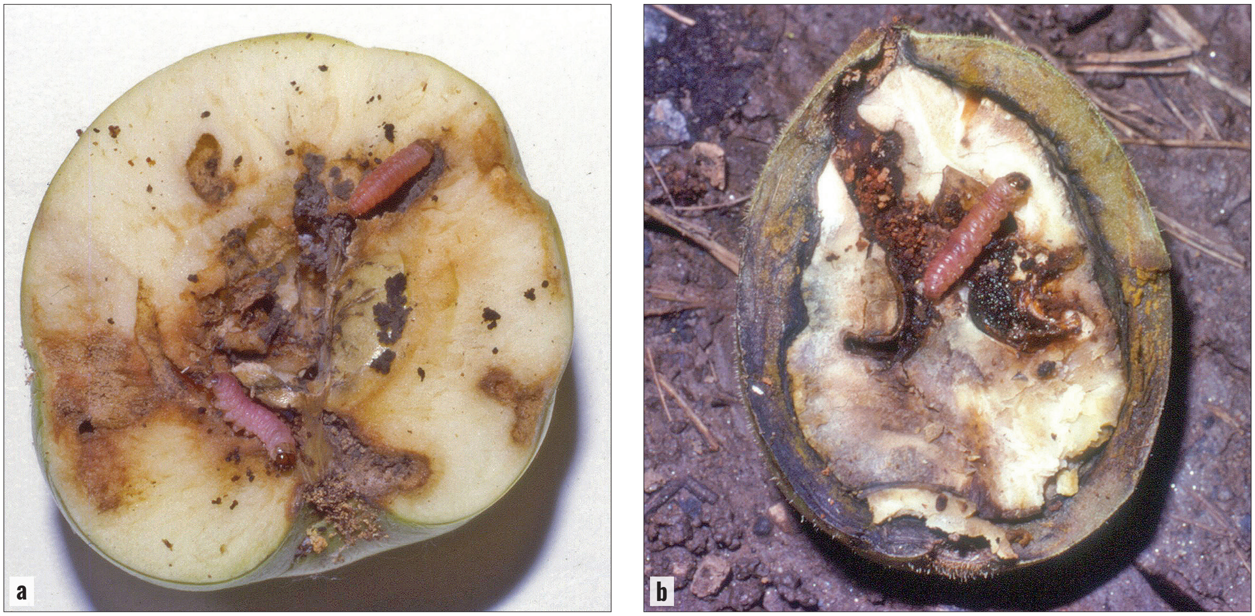


**Figure 3.** Codling moth (*Cydia pomonella*) larvae in (a) the flesh and core of an apple and (b) the kernel of a walnut. (N. Mills, UC Berkeley)

As a direct fruit pest, codling moth can cause extensive crop damage. The potential for damage increases with the number of moth generations per year (which varies by region) and is greater in apples than walnuts or pears. In regions with two or more generations per year, damage in apples can exceed 80%, whereas damage in walnuts can vary from 55 to 72% and more typically averages 42% (Barnes, 1991). By 2002, apple and walnut production in the western United States had each exceeded 80,000 ha (198,000 acres), with annual revenues of $1.15 billion and $0.3 billion, respectively. Pear production covered 28,000 ha (69,000 acres), with an annual revenue of $0.25 billion (Mills, 2005).

Management of codling moth has relied heavily on the use of insecticides, beginning with lead arsenate in the early 1900s, switching to DDT in the 1940s, organophosphates in the 1950s, carbamates and pyrethroids in the 1970s, and to newer classes of insecticides (insect growth regulators, neonicotinyls, diamides) in the 1990s (Croft and Riedl, 1991; Doerr et al., 2012). As a consequence, insecticide resistance has consistently occurred throughout the history of codling moth management, starting with resistance to lead arsenate in 1929 (Croft and Riedl, 1991). The introduction of pheromone-based mating disruption in the 1990s provided an opportunity to reduce reliance on insecticide use and at the same time to both slow the development of resistance and increase the potential for control by natural enemies (Jones et al., 2009, 2016).

In addition to conventional fruit and nut orchards, pome fruit and walnuts are often planted in residential gardens and even as roadside trees. These non-commercial settings are often unmanaged and serve as a reservoir for codling moth populations that can colonize surrounding commercial orchards. While insecticide use has been the standard approach for coddling moth control in conventional orchards, classical biological control has the advantage that it can also contribute to management of populations in organic settings and consequently can reduce the pressure from this pest on neighboring commercial, pesticide-treated orchards.

## PROJECT HISTORY THROUGH AGENT ESTABLISHMENT

Most early studies of parasitoid complexes of codling moth were conducted in Europe (Rosenberg, 1934; Lloyd, 1960). Several unsuccessful attempts to introduce parasitoids from Europe to North America were made in 1904–1905, 1921, and 1935–1936 (Clausen, 1978). From these attempts, one species, the specialized solitary egg-larval parasitoid *Ascogaster quadridentata* (**Fig. 4**), was established in Washington State in the 1920s and has since become widely distributed (Johansen, 1957). Despite being widespread, however, levels of parasitism are typically <5%, and this species has contributed little to the suppression of codling moth populations in the United States (Mills, 2005).

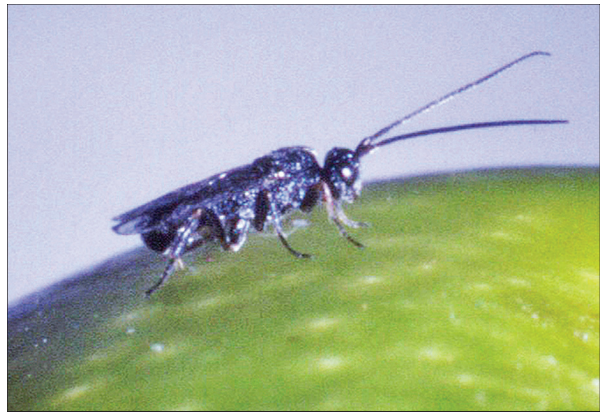

**Figure 4.** The established European egg-larval parasitoid *Ascogaster quadridentata* on the surface of an apple. (N. Mills, UC Berkeley)

**Figure 5.** The released solitary cocoon parasitoid *Liotryphon caudatus* on the bark of a walnut tree. (N. Mills, UC Berkeley)

Among the species that failed to establish in the western United States during this early phase of parasitoid importations from Europe was *Liotryphon caudatus* (= *Calliephialtes messor*) (Hymenoptera: Ichneumonidae), a solitary cocoon parasitoid (**Fig. 5**). Its successful establishment in New Zealand (Cole and Walker, 2011), however, prompted further collections from the Black Sea (Unruh, 1998) and Europe (N. Mills, pers. obs.) from 1990 to 1994. The collections in Europe were concentrated in Austria and Switzerland, where a lesser-known solitary larval parasitoid—*Microdus rufipes* (= *Bassus rufipes*) (Hymenoptera: Braconidae)—had also been documented. These collections provided evidence that *M. rufipes* was present at low abundance in the Rhone Valley region of southern Switzerland, but that the related species *Microdus conspicuus* (Hymenoptera: Braconidae) was present in eastern Austria. In addition, these collections provided a colony of *L. caudatus*, which was reared on codling moth cocoons at the University of California, Berkeley. A total of 46,000 individuals of this parasitoid were released in apple, pear, and walnut orchards in both coastal and inland regions of California from 1991 to 1997. Additional releases of 6,500 individuals were made at various locations in Washington State (Unruh, 1998; Lacey and Unruh, 2005). Although successful parasitism of codling moth cocoons was evident at some release sites during the year of parasitoid release, there was no evidence of establishment at any of the field sites in subsequent years.

Also, during the 1990s, renewed interest in biological control of codling moth was stimulated by studies of its natural enemies and their significance in Kazakhstan (Makarov, 1982; Zlatanova and Tarabaev, 1985). These studies found that not only were levels of parasitism higher in the foothills of the Tien Shan mountains in southern Kazakhstan, but that the dominant parasitoid species were different from those that had previously been found in Europe. This prompted additional surveys for parasitism of codling moth in the regions around Almaty, Kazakhstan from 1993 to 1998 and the Ili Valley, in the Xinjiang province of China, in 1993 and again from 1999 to 2002 (Unruh, 1998; Mills, 2005). These surveys confirmed that the dominant parasitoid species were the gregarious cocoon parasitoid *Mastrus ridens* (**Fig. 6**), initially misidentified as *M. ridibundus*, and *Microdus rufipes* (**Fig. 7**), which had also been found at low abundance in Switzerland. Other parasitoids recovered from these surveys included *A. quadridentata* and *L. caudatus*, the larval endoparasitoid *Pristomerus vulnerator* (Hymenoptera: Ichneumonidae), the two pupal parasitoids *Apechthis* sp. and *Dibrachys* sp., and some unidentified hyperparasitoids. It was also notable that *A. quadridentata*, though present in Kazakhstan, was not found in northwestern China.

**Figure 6.** The established gregarious cocoon parasitoid *Mastrus ridens*, standing over a codling moth cocoon. (N. Mills, UC Berkeley)

To maximize the potential for successful suppression of codling moth populations in the western United States, efforts were made to predict the potential impact of candidate parasitoids before their introduction to the region and to select the most promising species from Kazakhstan. Stage structured matrix models were constructed to describe the demography of codling moth populations and to identify the life cycle stages that are most vulnerable to additional mortality from introduced parasitoids (Mills, 2005). Using this approach, 2$^{nd}$-instar larvae and the cocoon stage were identified as the two points in the life cycle in which parasitism would have the greatest potential to suppress codling moth populations.

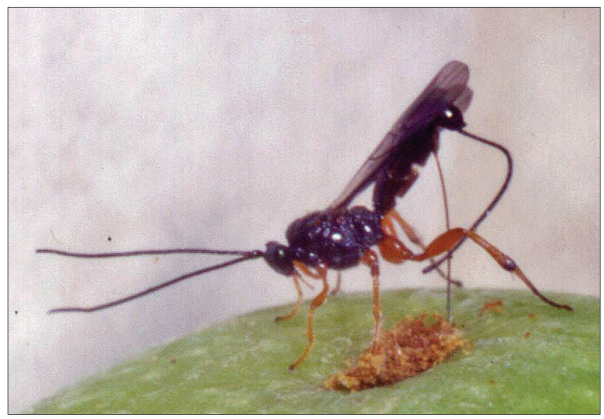

**Figure 7.** The released larval parasitoid *Microdus rufipes* probing into a codling moth larval entrance hole in an apple. (N. Mills, UC Berkeley)

Of the two dominant parasitoids in Kazakhstan, *M. rufipes* attacks early-instar larvae and *M. ridens* attacks the cocoon stage. Consequently, colonies of these two species were established on codling moth in quarantine at the University of California, Berkeley. A total of 317,000 individuals of *M. ridens* and 196 individuals of *M. rufipes* were subsequently released in California from 1995 to 2000. The low numbers of *M. rufipes* released resulted from difficulty in rearing this species. Additional releases of 7,600 individuals of *M. ridens* were also made in 1996–97 in central Washington State (Unruh, 1998; Lacey and Unruh, 2005). There were no recoveries of *M. rufipes* from release sites, but *M. ridens* became established with levels of parasitism in some cases reaching 70% in California (Mills, 2005) and 52% in Washington State (Unruh, 1998; Lacey and Unruh, 2005).

## HOW WELL DID IT WORK?

Since the initial establishment of *M. ridens* was determined, no follow-up studies have taken place to evaluate the impact of the parasitoid in the western United States. As has often been the case for classical biological control programs, funding support is available during the foreign exploration and introduction phases of a program, but often runs out before adequate evaluations can be made of the success and economic benefits of the program. Nonetheless, anecdotal observations made at the time of the parasitoid releases clearly indicated that local populations of codling moth in non-sprayed orchards were reduced substantially the year following release of *M. ridens*. The establishment of *M. ridens* in the western United States prompted interest from other countries, and this species has been successfully established in Argentina (Tortosa et al., 2014), Chile (Devotto et al., 2009), and New Zealand (Charles et al., 2019). It has also been introduced into Australia (Williams, 2018) and France (Borowiec et al., 2020). In addition, through simulation modeling, Wearing and Charles (2022) found that parasitism by *M. ridens* should be sufficient to suppress codling moth populations on non-sprayed, non-commercial trees in New Zealand, which would contribute to a reduction in adult moths colonizing neighboring commercial orchards.

The potential impact of *M. ridens* on codling moth populations is enhanced by the fact that (1) it attacks the most vulnerable stage in the life cycle of its host (Mills, 2005), (2) it exploits the larval-aggregation pheromone of codling moth to locate cocooned hosts (Jumean et al., 2005), which may account for its ability to show a positive response to patches of higher cocoon density (Bezemer and Mills, 2001), and (3) it has a numerical advantage over its host due to a shorter generation time and gregarious development (Bezemer and Mills, 2003). A shorter generation time than its host is of particular importance; in California, this trait allows *M. ridens* to complete two generations on overwintering cocooned larvae in the fall with adults emerging early enough in spring to start a third generation before the cocooned larvae of codling moth pupate. Similarly, the completion of two generations on overwintering cocoons, one in the fall and a second in the spring, has been observed in New Zealand (Charles et al., 2019).

## BENEFITS OF BIOLOGICAL CONTROL OF CODLING MOTH

As a direct pest with larvae that bore into harvestable fruit and nuts, the codling moth is a difficult target for effective classical biological control in pesticide-treated orchards in the western United States. Damage thresholds for fruit and nut production tend to be lower than can be consistently achieved by parasitism from introduced parasitoids, and the widespread use of insecticides in conventional orchards is not conducive to parasitoid persistence in such environments. Consequently, the greatest benefits of biological control to the management of codling moth should occur at a broader landscape or regional scale through a reduction in its abundance in non-managed environments such as abandoned orchards and roadside or backyard trees. Unmanaged trees support much higher levels of codling moth abundance than those in commercial orchards and are a constant source of dispersing mated female moths that pose a significant threat to commercial orchards, particularly those using pheromone-based mating disruption to reduce reliance on insecticides (Wearing, 1979). The simulation model of Wearing and Charles (2022) confirms that in commercial orchards *M. ridens* would only contribute minimally to codling moth control, but that observed levels of parasitism would be sufficient to reduce mean adult population abundance by 74% in habitats where trees are not treated with pesticides.

The benefits of effective biological control of codling moth also extend to other potential insect pests in commercial fruit and nut orchards, as reduced insecticide usage leads to increased activity of the natural enemies of secondary pests that include leafrollers, leafhoppers, sap-sucking insects, and spider mites. Such benefits have been particularly notable in New Zealand where there has been a 90% reduction in the intensity of insecticide use in apple orchards and, consequently, a significant increase in export revenue (Walker et al., 2017).

## REMAINING WORK

In the absence of a post-release monitoring phase in the classical biological control program for codling moth in the western United States, there remains an ongoing need to verify both the longer-term establishment and the spread of *M. ridens* throughout the western region. As it is unlikely to be sufficiently abundant in commercial orchards, monitoring surveys of trees in unmanaged environments to assess presence and levels of parasitism would be particularly informative. In addition, given that California implemented a system for reporting applications of all pesticides in 1990 (Wilhoit, 2018), it may also be possible to document the extent to which biological control and other IPM practices, such as pheromone-based mating disruption, have contributed to a reduction in pesticide use in pome fruit and walnut orchards in this state.

## ACKNOWLEDGMENTS

Thanks to the Walnut Marketing and Pear Research Advisory Boards of California, and to the National Research Initiative of the USDA-CSREES for providing funding support for this project. I would also like to acknowledge the valuable contributions of Tom Unruh of the USDA-ARS lab in Wapato, Washington and Andre Slivkin of Kazakhstan for facilitating the parasitoid surveys and collections in central Asia.

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