

Review

Integrated Management of European Cherry Fruit Fly *Rhagoletis cerasi* (L.): Situation in Switzerland and Europe

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Abstract: The European cherry fruit fly, *Rhagoletis cerasi* (L.) (Diptera: Tephritidae), is a highly destructive pest. The low tolerance for damaged fruit requires preventive insecticide treatments for a marketable crop. The phase-out of old insecticides threatens cherry production throughout the European Union (EU). Consequently, new management techniques and tools are needed. With the increasing number of dwarf tree orchards covered against rain to avoid fruit splitting, crop netting has become a viable, cost-effective method of cherry fruit fly control. Recently, a biocontrol method using the entomopathogenic fungus *Beauveria bassiana* has been developed for organic agriculture. However, for most situations, there is still a lack of efficient and environmentally sound insecticides to control this pest. This review summarizes the literature from over one hundred years of research on *R. cerasi* with focus on the biology and history of cherry fruit fly control as well as on antagonists and potential biocontrol organisms. We will present the situation of cherry fruit fly regulation in different European countries, give recommendations for cherry fruit fly control, show gaps in knowledge and identify future research opportunities.

Keywords: *Rhagoletis cerasi*; Diptera; Tephritidae; management; IPM; organic; biology; antagonists; mortality

1. Introduction

The European cherry fruit fly, *Rhagoletis cerasi* (L.) (Diptera: Tephritidae) is the most important pest of sweet cherries in Europe. Without insecticide treatment, up to 100% of fruits can be infested [1]. *R. cerasi* poses a challenge to cherry growers because the tolerance level of the market for damaged fruit is relatively low, with a maximum of 2% of infested fruits. Because fruit fly infested fruit cannot be sorted out, the whole lot is rejected if tolerance levels are exceeded. The disqualification of table cherries to distillery quality considerably reduces the market price, which causes serious financial losses. The low tolerance level is the principal reason for preventive insecticide treatments. The regulatory phase-out of “old” insecticides now threatens cherry production throughout the European Union (EU). The currently used insecticide dimethoate in particular is being challenged due to problems of ecotoxicity and residues. Yellow sticky traps are currently used as an alternative in organic cherry production. However, this strategy is labor-intensive and often does not provide sufficient control [2]. This review will explore the literature of research on *R. cerasi* conducted between 1891 and 2012. In it, we summarize the biology and history of cherry fruit fly control as well as research on antagonists and potential biocontrol organisms. Finally, we will present current practices to control cherry fruit flies in different European countries, recommend strategic practices to reduce cherry fruit fly populations, identify knowledge gaps, and suggest topics suitable for future research.

2. Taxonomy, Distribution and Host Plants of *R. cerasi*

The European cherry fruit fly (Figure 1) belongs to the family of Tephritidae, which has a worldwide distribution of about 4,000 described species in about 500 genera [3]. The genus *Rhagoletis* Loew includes about 65 known species [4]. Most species are oligophagous, attacking only a few closely related host plants. In addition to *R. cerasi*, the American cherry fruit fly species *R. cingulata*, *R. indifferens* and *R. fausta*, as well as the apple maggot *R. pomonella*, the blueberry maggot *R. mendax*, and the walnut infesting species *R. completa* and *R. suavis* are pest insects of economic importance [5]. Host plants of *R. cerasi* include various different *Prunus* sp. (Rosaceae; *P. cerasus*, *P. avium*, *P. serotina*, *P. mahaleb*) [6,7] as well as *Lonicera* sp. (Caprifoliaceae; *L. xylosteum* and *L. tatarica*) [4,8–12].

R. cerasi is distributed throughout Europe and temperate regions of Asia [4,13]. Boller *et al.* [14] assumed that there are two races, which were referred to as the northern and southern race. The southern race is found in Italy, Switzerland and Southern Germany, whereas the northern race ranges from the Atlantic Ocean to the Black Sea [4]. However, Riegler and Stauffer [15] showed that the unidirectional cytoplasmatic incompatibility is caused by maternally inherited *Wolbachia* infections. As a consequence, southern females and northern males are interfertile, but crosses between southern males and northern females are sterile [14–20].

Recently, the American cherry fruit fly species *Rhagoletis cingulata*, which is closely related to the European cherry fruit fly *R. cerasi*, was introduced to Europe [21–25]. One individual was first observed in Switzerland (canton Ticino) in the 1980s. From 1991 to 1993, there were repeated captures of American cherry fruit flies in the south of the canton Ticino [26]. Until now, no stable populations are known in Switzerland [27]. However, this may be due to insufficient monitoring intensity. A close

monitoring in the Rhine Valley (Rheinhausen, Germany) from 2002 to 2004 revealed that the American cherry fruit fly was widespread and established in many orchards [28–30]. In 2007 it was first detected in Austria [25]. The American species has a similar biology to the European species. The only differences are that the peak flight activity of the American species occurs two weeks later than the peak flight activity of *R. cerasi*, eggs are deposited in yellow fruit, and sour cherries are also heavily attacked.

Figure 1. Adult *R. cerasi*: female (**left**) and male (**right**) with its bright black thorax, yellow scutellum and characteristic wing pattern and a size of 4 mm (males) to 5 mm (females).



3. Life History *R. cerasi*

Life history characteristics of *R. cerasi*, like those of other oligophagous Tephritid species, are best suited for exploiting resources that are predictable in time and space, but are only available during a short period of the year. A close adaptation of their biology to the fruiting pattern of the host and precision in seasonal synchronization are more important than high reproductive potential and high mobility [31]. Hibernation occurs in the soil in the immediate vicinity of the hosts. Thus there is no need for dispersal flights. Adult emergence and life span are closely correlated with host plant phenology [5]. Pupal carryover for two or more winters is used for “spreading the risk” of failure of the host plants to fruit in a particular year [31,32]. There is only one generation each year and a long obligatory winter diapause [33]. Fecundity is considered to be lower than in the polyvoltine Tephritid species [5]. Relatively unspecific visual and odor stimuli are used to identify oviposition sites. Competition in the larval stages (contest type) is largely avoided by oviposition of only a single egg in each fruit and by the application of a host marking pheromone after oviposition, which ensures an adjustment of larval density to the carrying capacity of the host and maximizes dispersion over available food resources [34]. The mating system of these species is usually resource-based: The males control the oviposition substrates, and mating is often initiated by forced copulation without elaborate courtship behavior [35].

3.1. Aspects of *R. cerasi* Biology Relevant for Its Management

Emergence of adult flies and pre-oviposition period: Pupal development and adult emergence is influenced by soil temperature in spring [6,7,36,37], by temperature conditions during winter diapause [38–40] as well as by the host plants from which the pupae originated [41–44] and geographic provenance [45,46]. In Switzerland, Austria and Southern Germany, the first flies usually appear in the orchards between mid-May and mid-June [47]. The earliest attempts to develop a forecasting model for the eclosion time of flies were made in the 1930s [48–50]. This model was revised and improved in the 1960s [7,51] and 1970s [38,45]. Before oviposition, the adults go through a temperature-dependent maturation period of six to 13 days [7,47,52–56] during which they need to feed on carbohydrates, proteins and water in order for the gonads to mature. Nutrients are obtained from bird feces, honeydew, extrafloral nectaries, and bacterial colonies on leaf and fruit surfaces [49,57–61]. In addition to the temperature and nutritional status of the females, the maturity stage of the cherries can also affect the beginning of oviposition [53]. The life span of flies under field conditions is difficult to estimate and may range between four to seven weeks [47,49,53,59], which leads to a total flight period of seven to 11 weeks [47,48,62].

Mating: Mating (Figure 2) occurs on sunny days with temperatures above 15 °C [49,63]. Host fruit on sunny parts of the trees is used as a mating site. Mating is initiated when a female in search of an oviposition site lands on a fruit occupied by a male [63]. Thus, fly behavior plays a major role in locating mating partners: Due to their preference for host fruits in full sun, the flies aggregate in certain parts of the trees. In these circumstances, an elaborate long-range pheromone might be of minor importance [64]. Nevertheless, it was shown that the males produce a highly species-specific pheromone, which attracts females [63–68]. However, contrary to the pheromones of many Lepidoptera, this pheromone seems not to have a long-range attraction [64,66]. It was even hypothesized that the pheromone might function primarily as an aphrodisiac [5]. One to three copulations during a female's life span are considered to be necessary to maintain high egg fertility [49].

Figure 2. Mating of *R. cerasi*.



Dispersal and flight ability: With the relative stability of the system, *i.e.*, pests that overwinter beneath perennial hosts, there appears to be little impetus for adults to move long distances. Dispersal flights occur only in situations in which flies are deprived of suitable fruits for oviposition: Such as

when cherries are destroyed by frost or early harvest or when all fruits are already marked with the host-marking pheromone [69]. Driven by high oviposition pressure, the females leave their original tree [36], and the males follow a little later [49,69]. The flies move from tree to tree until they find a suitable host [55]. Maximum distances of dispersal flights are difficult to evaluate experimentally and might range between 100 and 500 m [7,55,70], in exceptional cases as far as 3 km [71]. Flight studies in the laboratory have shown that flies are capable of flying several kilometers in 24 h if no landing platforms are available [72]. However, within orchards, 95% of the flies move only to neighboring trees of later ripening varieties [7,73], and from there on to *Lonicera* sp. bushes [69].

Orientation during dispersal flights: Orientation during dispersal flight is mainly based on visual stimuli. Foliage color, tree shape and tree size play a role in eliciting the arrival of flies. *R. cerasi* is known to be highly responsive to visual stimuli [74], especially to yellow surfaces [70,75–78]. Prokopy [79] suggested that large yellow surfaces represent a super-normal foliage-type stimulus that elicits food-seeking behavior in *R. cerasi*. In addition to flat yellow surfaces, Prokopy [79] showed that *Rhagoletis* flies also react to red or dark colored spheres of approximately the same size as the host fruit [77,78]. Attraction of fruit flies to spherical objects is believed to represent a response to mating and oviposition site stimuli. However, none of these cues are host-specific. Boller [70] believes that the flies are not able to distinguish between host and non-host trees at greater distances, whereas Katsoyannos *et al.* [69] believes that females can identify trees with fruits at the right ripening stage from a certain distance. However, once the flies arrive at a host tree, they might be able to identify host-specific leaf stimuli with their tarsal contact chemoreceptors [80].

Oviposition: Oviposition occurs around noon and during the early afternoon [81] on sunny days when temperatures rise above 16 °C [44,47,49,82]. Weather conditions during the oviposition period are considered to be crucial for the regulation of population densities: The high oviposition activity during long-lasting periods of fine weather can lead to extreme outbreaks of this pest [50]. Both olfactory and visual cues are involved in the choice of suitable fruits for oviposition. However, the visual component appears to dominate. Females recognize the fruit by visual cues based on shape (spherical or hemispherical), size (2.5 to 10.3 mm diameter) and contrast-color against the background (dark shape in front of lighter background) [5,74,83,84]. Once a suitable fruit has been located, the female explores the surface structure (smoothness, softness and shape) by walking in circles on the surface and decides whether or not to oviposit [83,85]. During this exploration, the condition and the chemistry of a fruit might influence oviposition behavior. Cherries at the stage of color change from green to yellow, with a hardened cherry pit, and pulp at least 5 mm thick are preferred for oviposition [86]. The female pierces the fruit with its ovipositor and inserts a single egg just below the skin [87]. After oviposition the females deposit a water-soluble host-marking pheromone by dragging the ovipositor around the fruit surface [6,63,88]. This pheromone prevents further ovipositions into the same fruit [89–91]. Under field conditions with high infestation levels, however, multilarval infestations are frequently observed, which suggest multiple ovipositions into the same fruit [1,92,93]. Fecundity seems to depend mainly on the life span of females. Under field conditions, fecundity is thought to range from 30 eggs to as many as 200 eggs per female [7,47–49,56,82].

Egg and larval development: The white eggs have an approximate length of 0.75 mm and a diameter of 0.25 mm [49,59]. Fertility ranges between 54 and 100% [82,94]. A reduced fertility is mainly observed during prolonged periods of fine weather when copulation is reduced in favor of

oviposition or after oviposition in unripe cherries [94]. The duration of embryonic development mainly depends on temperature and ranges between two to ten days [7,49,50,58,86]. After eclosion, the larvae immediately move towards the cherry pit in order to find protection from parasitoids and predators [56]. Larval development lasts between 17 [7,50] and 30 days [58], depending on the temperature and the maturity stage of the cherries. The larvae go through three instars, reaching a final size of approximately 6 mm (Figure 3) [95]. During their development, the larvae tunnel in the fruit, macerate the tissue and ingest the broken down pulp [49,58]. Larvae develop better and faster in fruits with higher sugar content and lower acidity [94]. High populations of *R. cerasi* can be therefore observed in sweet cherry orchards, whereas sour cherries usually remain free from high infestations [96–98].

Figure 3. Infested cherries.



Pupation: Around harvest [56], mature larvae bore exit holes through the fruit skin (Figure 4), usually close to the fruit stem [49,99]. Under field conditions, pupation usually occurs within three hours after entering the soil [49]. Most pupae are therefore found directly under the tree canopy, especially under the south and southeast parts of the tree, which is also where the highest fruit infestation levels are observed [100]. Pupation depth is mainly influenced by soil type and usually ranges from 2 to 5 cm [7,56,101,102]. The puparium is straw yellow in color, cylindrical, up to 4 mm long and 2 mm in diameter (Figure 5) [8,49,59].

Diapause and pupal mortality: The cherry fruit fly is a univoltine species: The pupae remain in the soil until the following spring. Overwintering pupae enter diapause and require a chilling period before development can continue. Approximately 180 days at temperatures below 5 °C are required for maximum emergence [6,7,38,43,103]. Pupal mortality during the nine to 10 months of diapause is high and is mainly attributed to unfavorable climatic conditions and predation: Usually only 5% [104] to 15% [94] of the pupae emerge in the following year. A few individuals remain in diapause for an additional year or sometimes for several years [6,36,49,50,105]. This pupal carryover is a highly adaptive trait, ensuring that the population will not perish on account of failure of host plants to fruit in some years. However, literature data on the percentage of pupae diapausing for more than one year show wide ranges: from 1 to 21% [101,106], 10% [7,49,105], 7 to 21% [36], 47% [50] and 25 to 100% [107].

A higher percentage remains in diapause for an additional year more frequently in heavy clay soils than in sandy soils [36].

Figure 4. Damaged cherries with exit holes of larvae.



Figure 5. Pupae of *R. cerasi*.



3.2. Population Dynamics and Mortality Factors

Many factors (biotic and abiotic) can influence the dynamics of cherry fruit fly populations by directly or indirectly affecting survival and development rates or female fecundity. The most important factors are climatic conditions and host availability. The mortality within one generation can reach 99.6% [94]. However, only a few quantitative studies evaluate the causes of mortality [108]. The basic demographic parameters have been determined by Boller [94]. In cherry production, harvest, and the consequent removal of larvae from the orchard, is considered to be one of the main mortality factors [94]. In addition, temperature and rain have a major impact on mortality.

Egg and larval stages are well protected inside the cherry. Mortality is generally low during the egg stage [94]. The hatching rate may be reduced when females oviposit in unripe cherries [94]. In

addition, some cherry varieties (Schattenmorelle) are known to produce a hard tissue to seclude the eggs [109].

Destruction of cherries by fungal diseases can also lead to increased egg and larval mortality. The first serious cherry fruit fly infestation was observed in Switzerland between 1930 and 1937—it started only three years after a routine treatment of shothole disease (*Stigmia carpophila*) was introduced: Regular yields also lead to improved life conditions for cherry fruit flies [110,111].

Different degrees of infestation are due to phenological differences among cherry varieties and weather conditions during oviposition: Early ripening varieties show lower infestation levels because the fruits are harvested before the first flies are ready to oviposit [47,48,58,98]. Generally, the later a cherry variety is harvested, the higher the potential infestation level [7,98]. Sunny conditions during oviposition lead to high infestation levels [50,102]. Rainy conditions during early ripening stages prevent oviposition and mating [36,49,63,102,112] and might lead to a decay of fruits causing first and second instar larvae to die [110]. However, rainy conditions during harvest, which cause the cherries to crack and the farmers to leave the trees unpicked, might increase the infestation level the following year [7]. Differences in sugar content and acidity of cherry varieties lead to differences in larval nutrition and consequently to differences in fecundity of emerging females [94]. Females from sweet cherry orchards therefore usually show a higher fecundity than females from sour cherry orchards.

The life stages most exposed to climatic conditions and natural enemies are those associated with the soil: mature larvae, pupae and emerging adults. Boller [94] compared the number of larvae dropping from the fruit with the number of pupae in the soil and noted that 35 to 63% of the larvae were not able to pupate because of predation and arid soil conditions. He also monitored the number of pupae in the soil and observed a decline in numbers of pupae during the summer (July, August, September) and during the following spring, which he attributed to predation, parasitism and disease. During emergence, flies are also exposed to different enemies: Boller [94] observed that only 7 to 50% of pupae in the soil during spring produced adult flies. A similar observation was made by Engel [101]: The average number of 147 flies per tree evaluated by treatments with a knockdown insecticide was not consistent with the average number of 9,000 pupae under each tree.

3.3. Antagonists of *R. cerasi* and Other Tephritidae

Viruses: No literature is available on the effects of viruses on *R. cerasi*. For other Tephritid flies, picornaviruses have been described in *Ceratitis capitata* [113] and in *Bactrocera tryoni* [114]. In addition, reoviruses are known for *Bactrocera oleae* [115,116] and *C. capitata* [117]. No field application strategy has yet been developed for controlling Tephritid flies with viruses.

Bacteria: Only few references are available on the use of bacteria to control Tephritid flies, and no references are available for *R. cerasi*. Different isolates of *Bacillus thuringiensis* were screened against larvae and adults of *B. oleae* [118] and *Anastrepha ludens* [119,120]. Endotoxins of different *B. thuringiensis* isolates were tested against adult *C. capitata* [121] and L₃ larvae of *Anastrepha* sp. [122]. *Bacillus pumilis* was tested against adults and larvae of *C. capitata* in laboratory experiments [123]. In field experiments with four to six applications of *B. thuringiensis* per year against the olive fruit fly *B. oleae*, fruit infestation was reduced by 60% to 80% [124].

Entomopathogenic fungi: Many studies have been conducted on the control of *C. capitata*, *Anastrepha fraterculus*, *A. ludens*, *B. oleae* and *B. tryoni* with different entomopathogenic fungi [125–139]. Yee and Lacey [140] demonstrated that adult western cherry fruit flies (*R. indifferens*) are susceptible to *Metharizium anisopliae*. Cossentine *et al.* [141] demonstrated that preimaginal *R. indifferens* are susceptible to *Beauveria bassiana*. Until recently, only little was known on fungal pathogens of *R. cerasi*. Wiesmann [49] described adult flies as being susceptible to *Empusa* sp. (Zygomycetes: Entomophthoraceae). In 2009, first evidence was provided that adult *R. cerasi* are susceptible to hyphomycetous fungi [142]. A laboratory screening of different fungus isolates showed that all tested isolates (*B. bassiana*, *M. anisopliae*, *Isaria fumosorosea*, *Isaria farinose*) caused mycosis but virulence varied considerably among the isolates. *B. bassiana* and *I. fumosorosea* caused 90%–100% mortality and had the strongest influence on fecundity. *M. anisopliae* also induced high rates of mortality, while the pathogenicity of *I. farinosa* was low. The effects on L₃ larvae were tested as well: None of the fungal isolates induced mortality in more than 25% of larvae [142]. These results led to the development of a field application strategy using foliar applications of *B. bassiana* against adult flies [106,143].

Entomopathogenic nematodes: Various fruit fly species are known to be susceptible to entomopathogenic nematodes [144–150]. Yee & Lacey [151] showed good efficacy of *Steinernema* sp. against larvae of the western cherry fruit fly *R. indifferens*. Moreover, recent laboratory studies have indicated promising results of entomopathogenic nematodes to control the third instar larvae of *R. cerasi* [152]. However, results of laboratory experiments conducted in the scope of the European COST 850 project were disappointing: In a screening of 18 different nematode strains, the highest mortality rates in third instar larvae were below 30% (observed after application of *Steinernema feltiae* at a concentration of 1×10^5 infective juveniles m⁻² on soil, [153]). Field applications of *S. feltiae* and *S. carpocapse* at the rate of 2×10^6 infective juveniles m⁻² in a cherry orchard in Aesch (BL, northwestern Switzerland) in June 2003 reduced the emergence rate of adults the following year by only 33% (*S. carpocapse*) and 41% (*S. feltiae*), respectively [154]. Similar results (20% reduction of emerging adults) were obtained by Herz *et al.* [104], who conducted field experiments with *S. feltiae* to control *R. cerasi* and noted that the effect of nematodes was masked by high natural pupal mortality during the winter. Due to the limited time frame and the different spatial activity, the potential for entomopathogenic nematodes for controlling *R. cerasi* under field conditions was considered to be rather small.

Parasitoids: Most Tephritid species are attacked by a complex of native parasitoids [145,155]. For *R. cerasi*, 21 species of parasitoids (larval ectoparasitoids, larval endoparasitoids and puparium parasitoids) have been described [156]. No egg parasitoids of *R. cerasi* are mentioned in the literature. In cherry production, however, the effectiveness of larval parasitoids is greatly impaired by the short ovipositor of parasitoid females, which cannot reach *R. cerasi* larvae in large cultivated cherries. Monaco [157] observed that 10 to 30% of *R. cerasi* larvae in wild cherries (*P. mahaleb*) are parasitized by *Utetes (Opus) magnus* (Hymenoptera: Braconidae), whereas no parasitization was observed in cultivated cherries. Similar observations were made by Haisch *et al.* [95] and Hoffmeister [66], who noted that *R. cerasi* individuals from *Lonicera* sp. generally showed higher levels of parasitization than individuals from cultivated cherries: *U. magnus* [66] and *Halticoptera laevigata* (Hymenoptera: Pteromalidae) [66,158] have only been observed in individuals from *Lonicera* sp., whereas *Psytalia*

(*Opius*) *rhagleticola* [66,159] was also found in individuals from cherries—although in lower numbers. Contrary to these observations, Leski [7] showed *P. rhagleticola* to be the principal parasitoid of cherry fruit flies in Poland. However, with parasitization rates of 22 to 32%, *P. rhagleticola* could not control *R. cerasi* populations [7]. Pupal parasitization seems to be more important. *Phygadeuon wiesmanni* (Hymenoptera: Ichneumonidae) occurs throughout Central Europe [94,160–165] and has been shown to be responsible for a pupal mortality rate as high as 72% [94,101]. Under bushes of *Lonicera* sp., however, the parasitization rates of pupae were found to be higher than under cherry trees [6]. Other puparium parasitoids, such as *Phygadeuon elegans* [165], *Gelis bremeri* (Hymenoptera: Ichneumonidae) [6,7,66], *Polypeza försteri* (Hymenoptera: Diapriidae) [166], and *Spilomicrus hemipterus* (Hymenoptera: Diapriidae) [66], were observed in lower numbers. Until now, no biocontrol strategies based on parasitoids of *R. cerasi* were evaluated under field conditions.

Predators: Wiesmann [49] mentions two species of *Odontothrips* sp. (Thysanoptera: Thripidae) attacking the eggs of *R. cerasi*. However, the impact of these predators is considered to be low, as only 10% of the eggs were attacked [49] and as Boller [94] did not observe these predators in his comprehensive studies. Therefore, *R. cerasi* is most likely to be attacked by predators only during the short time span after leaving the fruit and pupation or immediately after emergence. Ants (*Myrmica laevinodis*, Hymenoptera: Formicidae), carabid beetles (*Anisodactylus binotatus*, Coleoptera: Carabidae) or staphylinid beetles (*Paedrus litoralis*, Coleoptera: Staphylinidae) are of particular importance [94,167]. Boller [94] noted that up to 80% of larvae were destroyed by predators before pupation, and that ants seemed to be the most important enemy. According to Boller [94], however, ants are not able to detect and crack the puparia in the soil. This is in contrast to Sajo [168], who observed ants attacking and destroying pupae in the soil. Schwöpe [169] noted that ants attacked and killed about 40% of the emerging flies. In addition, Boller [94] observed in his experiments that about 15% of pupae were destroyed by small, unidentified organisms, which he believed to be mites.

4. History of Cherry Fruit Fly Control

The strategies used to control *R. cerasi* reflect the history of insect control in general. Peaks of research activity for new control strategies coincide with periods of increasing cherry fruit fly populations: The cherry fruit fly usually exhibits four- to five-year periods of high population densities followed by an interval of decline to very low population levels. Boller *et al.* [170] presented the data for Switzerland from 1929 to 1969 and noted that fluctuations in population density were frequently observed throughout Central Europe at the same time. During the first recorded cherry fruit fly outbreak in the 1930s, research mainly focused on bionomics and the behavior of the pest. Initial control methods focused on destruction of infested fruit and the application of inorganic insecticides. During the second wave of high populations in the mid-forties and early fifties, new insecticides (DDT and organophosphorus compounds) were introduced. During the early sixties, the focus shifted toward the development of biotechnical (traps, synthetic host-marking pheromones, and sterile male releases) and biological control methods. Recently, the cherry production is challenged by the withdrawal of insecticides in many countries. The importance of reliable biocontrol strategies is therefore increasing.

4.1. Before-Insecticide Strategies—1900 to 1935

Before insecticides were available, farmers knew that an early and complete harvest was the most effective control measure for *R. cerasi* [8,53,56,58,60,171]. Early ripening varieties were recommended for reduced fly damage [53]. The recommendation of eradicating wild and secondary hosts (*Lonicera* sp.) of *R. cerasi* was controversially discussed between Thiem [9] and Wiesmann [172]. However, because the flies from *Lonicera* sp. emerge a few days later than the flies from cherries [42], and because the flies from *Lonicera* sp. show a strong preference for *Lonicera* sp. berries for oviposition [173], it is doubtful whether this recommendation was necessary or justified.

Because *R. cerasi* pupae spend more than 10 months per year in the soil [94] and because the area of pupation is strictly limited to the surface directly under the canopy of infested trees [49], the possibility of soil treatments was appealing [159]. Soil treatments were considered by different authors: Frank [174] suggested soil cultivation in order to bury the pupae more deeply, whereas Mik [8] recommended compression of the soil surface prior to adult emergence. However, according to the results of Thiem [6], a mechanical treatment of the soil surface is not sufficient. He suggested using creosote on larvae shortly before pupation and Tetrachloroethane to kill the pupae. Wiesmann [36] tested a broad range of different means, such as arsenic compounds, naphthalene, dichlorobenzene, nicotine, and kerosene, to control emerging flies or pupae in the soil. He stated that kerosene treatments completely prevented emergence, but that one out of three experimental trees died and another third were badly damaged. Most authors concluded that soil treatments are ineffective to kill the pupae [6,49,53,174,175]. When organo-chemical insecticides such as DDT became available in the 1950s [176], research on soil treatments was abandoned.

4.2. First Insecticides Lead Arsenate & DDT—1905 to 1950

The first insecticides—pyrethrum, rotenone, and lead arsenate—were focused on adult flies and were mainly applied in combination with food baits [36,54,60]. However, the efficacy of pyrethrum and rotenone was poor, and lead arsenate was not considered as an option in most European countries due to its high human toxicity [53]. First organo-chemical insecticides such as DDT became available in the 1950s [176] and led to better results in control of adult flies [169,177,178]. However, applications had to be timed exactly to the emergence of flies and repeated treatments were necessary.

4.3. Organophosphorus Insecticides—1950 to 2000

With the development and registration of quick-acting organophosphates and carbamates around 1965, a systemic control of eggs and larvae inside the fruit became possible [179,180]. The emphasis of control shifted from the adult to the egg and larval stages. The application date and therefore the flight period became less important. Applications were timed according to the degradation of the various products, as pesticide residues in the harvested crop had to be avoided [181]. Currently, Dimethoate is still in use in some European countries (Table 1), whereas Fenthion is no longer registered because of its high avian toxicity. First attempts to find alternatives to Dimethoate applications were already made in the 1960s.

4.4. Research on Population Dynamics and Biotechnical Approaches—1960 to 1990

In order to avoid toxic residues on harvested fruit, great efforts were made to find biological or biotechnical control methods. Different approaches were considered: yellow sticky traps, synthetic host-marking pheromones, and sterile insect technique [14,17,42,170].

Sticky traps were developed based on the visual preference of the flies for the color yellow [182]. Remund [75] determined that daylight fluorescent yellow-colored flat surfaces were most attractive. Prokopy [79] suggested that large yellow surfaces represented a super-normal foliage-type stimulus eliciting food-seeking behavior in *R. cerasi* and *R. pomonella*. He also hypothesized that flies reacted to yellow on the basis of true color discrimination. This hypothesis was supported by Agee *et al.* [183], who showed that adult *R. cerasi* had a major peak of electroretinographically assessed spectral sensitivity at 485 to 500 nm (yellow green region) and a secondary peak at 365 nm (ultraviolet region). Traps with a sharp increase of reflectance in the 500 to 520 nm region were found to be the most attractive for *R. cerasi* [183,184]. Based on this knowledge, a three-dimensional wing-shaped trap was developed (Rebell® amarillo) and is now used throughout Europe for monitoring, forecasting and mass trapping purposes [185]. Moreover, mass trapping of flies by Rebell® amarillo became the standard regulation method for *R. cerasi* in organic production. However, in order for mass trapping strategies to be effective, several traps per tree are needed [2]. Remund & Boller [186] suggest using one to eight Rebell® traps, depending on the size of tree, on the southeast side of the canopy. Because the traps should be hung in the upper part of the canopy, much labor is involved, thus making this strategy uneconomical for conventional cherry production (Table 2).

The use of the **host-marking pheromone** to prevent oviposition was investigated in the 1970s [88,91,187]. In field experiments using naturally derived pheromone, an efficacy of 63 to 90% was observed [187,188]. High synthesis costs, however, prevented the use of this pheromone in commercial cherry growing. In addition, efficacy was low at high infestation levels and under rainy conditions. Moreover, about 10% of the trees had to remain untreated in order to provide unmarked fruits for oviposition [89].

The **sterile insect technique** for cherry fruit fly control was developed between 1960 and 1980 [14,71,189–191]. The sterile insect technique is based on the concept that by overflooding natural populations with mass reared, sterilized insects, a high degree of sterility is induced among the eggs produced in the field [170]. Boller [71] could show that the release of sterile males in an isolated 2.5 km² area could reduce infestation below detectable levels. The major bottleneck of this technique is the artificial rearing of the fly [170,192–194]. Several points in the insect's biology complicate rearing: *R. cerasi* is univoltine, has an obligatory diapause of at least 150 days, and *R. cerasi* is monophagous with a strongly selective host choice [88]. The lack of a suitable rearing method for producing enough sterile insects for mass releases prevented this strategy from being commercially introduced.

4.5. Development of Biocontrol Strategies—1990 to 2010

Based on first promising laboratory results [152,195], **entomopathogenic nematodes** were considered to be a possible solution for the cherry fruit fly problem. However, field experiments gave disappointing results [104,154] (see Section 3.3).

The pathogenicity and virulence of different **entomopathogenic fungi** on different life stages of *R. cerasi* were also first evaluated in laboratory experiments. Adult flies were found to be the only life stage susceptible to fungus infection. *B. bassiana* ATCC 74040 showed a high virulence, the flies died during the pre-oviposition period. These results were the first evidence of the susceptibility of *R. cerasi* to infection with hyphomycetous fungi [142]. Field application strategies were therefore focused on adult flies using the fungus isolate *B. bassiana* ATCC 74040, which is formulated in the commercial product Naturalis-L (Intrachem Bio Italia). Repeated applications of Naturalis-L during the flight period of *R. cerasi* were shown to reduce the infestation level of fruits by 60%–70% [143]. The application of Naturalis-L is a suitable and economically reasonable strategy for controlling *R. cerasi* in organic agriculture (Table 2).

In addition to the biocontrol strategies, research on **baits** for possible attract-and-kill-strategies have recently been conducted. Although some of the food baits tested in combination with yellow sticky traps were able to double the number of captured flies [106], none of the baits tested showed economic potential as an effective attract-and-kill system or for mass trapping in commercial production (Table 2). The spinosad GF-120 fruit fly bait (Dow AgroSciences) was tested in several experiments against *R. cerasi* [196]. However, results under humid climate conditions in Switzerland were disappointing. Until now, this strategy is not available for the farmers.

5. Currently Used Strategies to Control *R. cerasi*

Until recently, one application of **Dimethoate** was the standard for controlling *R. cerasi* in Swiss sweet cherry production, because it is by far the most cost-efficient method (Table 2). Since 2011, however, this product is no longer registered for use in fruit production in Switzerland because of problems of ecotoxicity and residues on harvested cherries. Two applications of **Acetamiprid** are currently recommended for cherry fruit fly control in Switzerland. The situation in many other European countries is comparable. However, implementation and transition periods differ between the countries. Mainly neonicotinoids and pyrethroids are currently used to control *R. cerasi* (Table 1).

The application of **Naturalis-L** (entomopathogenic fungi *B. bassiana*) is considerably more expensive than the application of Dimethoate or Acetamiprid (Table 2). However, the higher prices obtained for organically grown cherries might justify the higher input for pest control [106]. For good efficacy, four treatments of 0.25% Naturalis-L (5×10^4 CFU mL⁻¹) with 1,000 L water per hectare should be applied at seven to ten day intervals. The first application should be made five to ten days after the beginning of the flight period. The time period between the last application and harvest should not exceed seven days. Other phytosanitary measures (early and complete harvest; removal of infested cherries) can further enhance the efficacy of Naturalis-L treatments. Because the use of fungicides can interfere with entomopathogenic fungi, close attention has to be paid to the whole pest management program. In Swiss organic cherry production, only sulfur and neem oil are likely to be applied during the critical period. Fortunately, both pesticides were found to be compatible with entomopathogenic fungi [197–199]. However, many of the synthetic fungicides used in integrated pest management strategies were found to be highly toxic to *B. bassiana* [200,201]. Among 36 fungicides tested, only three were compatible with *B. bassiana*, whereas insecticides were less toxic: 24 out of 54 tested insecticides interfered with fungus development [199]. In some cases, differences were found among

products containing the same active ingredient (Dimethoate) in different formulations. Thus, the integration of mycoinsecticides for cherry fruit fly control in an organic plant protection system seems possible; including mycoinsecticides into integrated pest management programs might, however, be challenging.

With the increasing number of dwarf tree orchards shielded from rain to prevent the large sized cherry varieties (>24 mm fruit diameter) from splitting, **crop netting** has become a possible method of cherry fruit fly control [202]. Experiments using netting to cover the trees were conducted at the Palatinate Agricultural Service Centre (DLR Rheinpfalz, Germany [203]), at the Bavarian State Research Centre for Agriculture (LfL Bayern, Germany [204]) and at the Research Institute of Organic Agriculture (FiBL, Switzerland, Häseli, personal communication). Available data show that crop netting is a viable, cost-efficient strategy (Table 2) for protecting cherries from infestation. The “Rantai K” net-type with a mesh size of 1.3 mm was used in all experiments. Netting should be installed before the beginning of the flight period and the netting should remain in place until the latest ripening cherry varieties are harvested.

Covering the soil under the tree canopy with netting to prevent the hatching flies from reaching the fruit is another efficient management strategy. The netting can reduce fruit infestation by 91% [73]. Because the flies can survive for a long time under the netting, it is advisable to bury the edges of the netting completely. This, however, leads to high labor costs (Table 2). Moreover, expensive, fine-mesh netting (0.8 mm mesh width) is considered to be necessary, because young flies after emergence can easily get through nets with mesh widths of 1.3 mm. Nevertheless, this method could be an option for controlling *R. cerasi* in extensively managed standard tree orchards.

Mass trapping by yellow sticky traps is considered to be too expensive for commercial production of cherries (Table 2). Nevertheless, mass trapping may still be the only option for controlling *R. cerasi* in home gardens, in which the application of insecticides is often impossible due to the lack of proper application equipment. Due to the lack of registered alternatives, yellow sticky traps are still widely used in organic cherry production throughout Europe (Table 1).

Table 1. Situation of cherry fruit fly control in different European countries in 2011.

Country harvested area [205]	Management in conventional production	Management in organic production	Reference (personal communication)
Turkey [35,800 ha]	Cypermethrin Delthamethrin Malathion Methomyl Thiacloprid	Azadirachtin Mass trapping with yellow sticky traps	T. Koclu & (Bornova Plant Protection Research Institute) S. Tezcan (Ege University, Bornova)
Italy [28,900 ha]	Dimethoate Etofenprox Fosmet Thiamethoxam	<i>Beauveria bassiana</i> Crop netting Pyrethrum Spinosad	F. Molinari (Università Cattolica del Sacro Cuore, Piacenza) A. Grassi (Istituto Agrario di San Michele all’Adige)

Table 1. Cont.

Country harvested area [205]	Management in conventional production	Management in organic production	Reference (personal communication)
Spain [24,671 ha]	Lambda-cyhalothrin (bait sprays)	<i>Beauveria bassiana</i> Yellow sticky traps	E. Viñuela (Universidad Politécnica de Madrid)
Bulgaria [11,800 ha]	Alpha-cypermethrin Bifenthrin Cypermethrin Deltamethrin Gamma-cyhalothrin Lambda-cyhalothrin Zeta-cypermethrin	Yellow sticky traps	H. Kutinkova (Fruit Growing Institute, Plovdiv)
France [10,752 ha]	Acetamiprid Dimethoate Deltamethrine	Yellow sticky traps	S. Simon (INRA-URI Gotheron)
Greece [10,000 ha]	Cypermethrin, Deltamethrin, Dimethoate, Thiamethoxam	<i>Beauveria bassiana</i>	B.I. Katsoyannos (University of Thessaloniki)
Poland [9,903 ha]	Acetamiprid Pyrethroids Thiacloprid	Yellow sticky traps Soil covering	D. Gajek (Agro Research Consulting, Łowicz)
Portugal [6,255 ha]	Deltamethrin Dimethoate	Azadirachtin Yellow sticky traps	R. Rodrigues (Escola Superior Agrária de Ponte de Lima—Instituto Politécnico de Viana do Castelo)
Germany [5,449 ha]	No registered insecticide	Use of side effects of pyrethrum applications against aphids (Crop netting)	H. Vogt (JKI Dossenheim)
Croatia [3,100 ha]	Dimethoate	Yellow sticky traps	B. Baric (Faculty of Agriculture, Zagreb)
Austria [2,400 ha]	Acetamiprid	Use of side effects of pyrethrum applications against aphids	C. Lethmayer (AGES Wien)
Hungaria [1,795 ha]	Acetamiprid Cypermethrin Dimethoate Lambda-cyhalothrin Thiacloprid Thiamethoxam	Yellow sticky traps	B. Péntes (Corvinus University, Budapest)
Albania [1,500 ha]	Dimethoate	No key pest: no organic strategy	E. Isufi (Institute for organic Agriculture, Durrës)

Table 1. Cont.

Country harvested area [205]	Management in conventional production	Management in organic production	Reference (personal communication)
Belgium [1,224 ha]	Acetamiprid Thiacloprid	Nothing	T. Beliën (PCfruit Belgium)
Switzerland [454 ha]	Acetamiprid Thiacloprid Thiamethoxam Crop netting	<i>Beauveria bassiana</i> Crop netting Yellow sticky traps	H. Höhn (agroscope ACW Wädenswil)
UK [447 ha]	<i>R. cerasi</i> does not occur in the British Isles		J. Cross (East Malling Research)
Sweden [160 ha]	No insecticide registered		B. Rämmert (Swedish University of Agricultural Sciences, Uppsala)
Slovenia [92 ha]	Acetamiprid Fosmet	<i>Beauveria bassiana</i> Protein baits	Špela Modic, (Agricultural Institute of Slovenia, Ljubljana)

Table 2. Costs per hectare of different cherry fruit fly control methods.

	Intensively managed dwarf-tree orchard	Standard trees in semi-intensive systems	Extensively managed standard trees
Trees per ha Tree size	800 trees per ha height of first branches: 0.5 m, tree height: 3.5 m, canopy diameter: 3 to 4 m (7 to 12 m ²)	200 to 500 trees per ha (350 trees per ha) height of first branches: 1.2 m, tree height: 5 to 6 m, canopy diameter: 5 to 7 m (20 to 40 m ²)	50 to 80 trees per ha (65 trees per ha) height of first branches: 1.8 m, tree height: 8 to 10 m, canopy diameter: 11 to 13 m (100 to 130 m ²)
Dimethoate treatment ¹	400 L ha ⁻¹ with 0.8 L Perfekthion®, one application: materials: 24.20 € + machines: 50.50 € + labour: 13.42 € = 88.12 €	400 L ha ⁻¹ with 0.8 L Perfekthion®, one application: materials: 24.20 € + machines: 50.50 € + labour: 13.42 € = 88.12 €	400 L ha ⁻¹ with 0.8 L Perfekthion®, one application: materials: 24.20 € + machines: 50.50 € + labour: 13.42 € = 88.12 €
Acetamiprid treatment ²	400 L ha ⁻¹ with 0.32 L kg Gazelle SG, two applications: materials: 184.80 € + machines: 101.00 € + labour: 26.84 € = 312.64 €	400 L ha ⁻¹ with 0.32 L kg Gazelle SG, two applications: materials: 184.80 € + machines: 101.00 € + labour: 26.84 € = 312.64 €	400 L ha ⁻¹ with 0.32 L kg Gazelle SG, two applications: materials: 184.80 € + machines: 101.00 € + labour: 26.84 € = 312.64 €
Mass trapping with yellow sticky traps ³	One Rebell® trap per tree: materials: 1,812.5 € + labour: 134.19 € = 1,946.69 €	Five Rebell® traps per tree: materials: 3,964.84 € + labour: 1,761.21 € = 5,726.05 €	12 Rebell® traps per tree: materials: 1,767.19 € + labour: 785.00 € = 2,552.18 €
Mass trapping with baited yellow sticky traps ⁴	0.5 Rebell® traps per tree with 0.5 TMA-cards: materials: 2,156.25 € + labour: 89.64 € = 2,245.89 €	Three Rebell® traps per tree with three TMA-cards: materials: 5,660.17 € + labour: 1,115.90 € = 6,776.06 €	Seven Rebell® traps per tree with seven TMA-cards: materials: 2,452.73 € + labour: 483.56 € = 2936.29 €
Soil covering with netting ⁵	materials: 930.75 € + labour: 1,610.25 € = 2,541.00 €	materials: 930.75 € + labour: 1,610.25 € = 2,541.00 €	materials: 930.75 € + labour: 1610.25 € = 2541.00 €

Table 2. Cont.

	Intensively managed dwarf-tree orchard	Standard trees in semi-intensive systems	Extensively managed standard trees
Application of Naturalis-L ⁶	800 L ha ⁻¹ with 2 L Naturalis-L, four applications: materials: 515.00 € + machines: 202.00 € + labour: 53.68 € = 770.68 €	1,000 L ha ⁻¹ with 2.5 L Naturalis-L, four applications: materials 643.75 € + machines: 202.00 € + labour: 53.68 € = 899.43 €	Not possible because of insufficient coverage in the upper parts of the canopy
Crop netting ⁷	materials: 242.37 € + labour: 268.38 € = 510.75 €	Not possible	Not possible

Explanatory notes: Standard costs were calculated according to Arbokost [206], a business management simulation program based on data evaluated in Switzerland. This program is provided by the Federal Research Station agroscope ACW Wädenswil and uses the following values: labor costs 13.42 € per hour; machine costs for pesticide application: 50.50 € per ha and application; time for installation and removal of crop netting 20 hours per ha. For investments: discount rate: 3.5%, amendment factor for discounting 0.6; Costs were calculated using Swiss prices for products. Currency was converted assuming an exchange rate of 1 € = 1.60 CHF.

1. Perfekthion® (Dimethoate): 30.25 € per L (Leu Gyax AG, Switzerland), 0.8 L ha⁻¹, one application. One hour per application per hectare for machine and labor costs.
2. Gazelle SG (Acetamiprid): 288.75 € per kg (Stähler Suisse SA), 0.32 kg ha⁻¹, two applications. One hour per application per hectare for machine and labor costs.
3. Rebell® amarillo: 2.27 € per trap (Andermatt Biocontrol AG, Switzerland). Labor input for installation and removal: 45 s per trap (dwarf trees), 4.5 min per trap (in standard tree orchards; estimation made by cherry growers). The traps can be cleaned and re-used: labor input 1 h for 10 traps, material input 9.00 € per 10 traps: 22.42 € per 10 traps = 2.24 € per trap (more or less the same price as new traps).
4. TMA-card: 3.13 € per card (Andermatt Biocontrol AG, Switzerland). Additional time needed to attach the bait to the trap: 15 s per trap.
5. Biocontrol Net 0.8: 0.85 € m⁻² (Andermatt Biocontrol AG, Switzerland). Because it is not necessary to cover the whole surface, the area covered per ha is reduced to 0.75 ha. Costs for net: 6,375 €; Costs per year (8 years): 930.75 €. Labor input: 120 h (estimated from time needed to set up my experiments).
6. Naturalis-L: 64.38 € per liter (Andermatt Biocontrol AG, Switzerland), 2–2.5 L ha⁻¹, four applications. One hour per application per hectare for machine and labor costs.
7. Rantai K: 0.77 € m⁻² (Hortima AG, Switzerland). Costs for net: 1,291.50 €. Costs per year (6 years): 242.37 €. Assuming that a plastic cover to shelter the fruits against rain is already installed: time for installation and removal of netting: 20 h. Size of net and time needed was calculated according to Balmer [203] and Balmer (personal communication).

6. Recommendations for Cherry Fruit Fly Control

Well-managed orchards are a prerequisite for the effective control of *R. cerasi*:

- Trees should be regularly pruned and tree height should be limited to 10 m to allow good coverage of spray applications and to facilitate an early and complete harvest of fruit.
- For new plantings of extensively managed standard trees, varieties suitable for mechanical harvest should be chosen to enable a quick harvest. Harvesting the cherries early and completely reduces the population level of *R. cerasi* by removing the larvae from the orchards before pupation.
- Infested fruits should not be dropped on the ground.
- If possible, early ripening cherry varieties should be chosen, because they mature before the majority of the flies are ready to oviposit.

- It is recommended not to cut the grass under the tree canopies until shortly before harvest. With a higher plant cover, the soil temperatures remain low, which can delay fly emergence for about ten days [207].

Knowledge of first fly appearance is important for a proper timing of control measures. Beginning of the flight period can be determined using forecasting models based on soil temperature measured at a depth of 5 cm. Emergence starts at 430 degree days above the temperature threshold of 5 °C [51,208]. Recently, a forecasting model for *R. cerasi* was included into a database [52] for online presentation and decision support [52]. In addition, depots of pupae in the soil can be used for precise monitoring of emergence [209]. Flight period and flight activity of *R. cerasi* can also be monitored using yellow sticky traps (Rebell® amarillo). In mid-May prior to fly emergence, one or two traps per cherry variety should be placed on the southeast side of the tree canopy in full sun and should be examined twice a week. As long as fly captures remain below a threshold of 0.25 flies per trap in late ripening varieties with an average yield or below one fly per trap in earlier ripening varieties with an outstanding yield, insecticide treatments can be omitted [186]. However, traps are not good indicators of the real infestation level [210]. Depending on yield, weather conditions and trap position, the economic threshold ranges between two and ten flies per trap. Treatment decisions should therefore be based on the expected yield and the infestation level in the previous year. The infestation level can be estimated using the salt solution test [211]: 100 randomly picked cherries of each cherry variety are crushed until the pits are separated from the pulp. A saturated salt solution (350 g salt per liter water) is added. Floating larvae can be counted after 10 min.

Based on economic considerations, the following strategies for cherry fruit fly control are recommended.

- If still registered, one application of Dimethoate at the stage of color change (green to yellow) of cherries is by far the most cost-efficient method.
- Alternatively, Neonicotinoid- or Pyrethroid-products provide a good efficacy with reasonable costs.
- Crop netting with fine-mesh insect net (1.3 mm) to avoid immigration of flies into the orchard provides efficient control in intensively managed dwarf tree orchards covered by plastic or hail net.
- In organic cherry production in orchards without plastic cover or hail net, foliar applications of Naturalis-L (*B. bassiana*) are most suitable.
- The use of yellow sticky traps is very expensive and only reasonable if no other control method is available.

Without the use of systemic insecticides, *R. cerasi* management is still difficult and expensive in extensively managed standard trees. Most of these trees are used to produce cherries for the distillery industry and are not suited to mechanical harvest. Therefore, fruit are usually harvested late, which allows the larvae to pupate in the soil leading to high infestation pressure in the following year. In addition, the grass under the trees is often used for hay or green fodder production. Netting to cover the soil is not always practicable. Mass trapping with traps and baits is expensive, and there are considerable side effects on non-target insects. In addition, cherry growers usually use too few traps

per tree, resulting in poor efficacy. Further research is needed to find a strategy for controlling *R. cerasi* in extensively managed standard trees.

7. Gaps in Knowledge and Future Research Opportunities

Although during the last 70 years many research projects focused on the development of new regulation strategies for *R. cerasi*, there are still some gaps in knowledge. The following approaches might lead to future regulation methods for *R. cerasi*:

Mass rearing and release of *Phygadeuon wiesmanni* (Hymenoptera: Ichneumonidae): This pupal parasitoid has been shown to be responsible for a pupal mortality rate as high as 72% under natural conditions [94,101]. A mass rearing and release of this parasitoid might lead to an effective control of *R. cerasi*. Until now only little effort was made towards this strategy.

Use of the sexual pheromone: It was shown that the males produce a highly species-specific pheromone, which attracts females [63–68]. Until now this pheromone has not been fully identified. Future work on this topic might lead to more effective traps or confusion technique for *R. cerasi*.

***Wolbachia*-induced cytoplasmatic incompatibility:** Infestations by different strains of the endosymbiotic bacterium *Wolbachia* lead to a unidirectional cytoplasmatic incompatibility in *R. cerasi* [14,15,19,212,213]. Because *Wolbachia* infestations can profoundly alter host reproduction, research on this topic might lead to new biocontrol approaches of *R. cerasi*.

Repellents or mechanical barriers to prevent oviposition: Oviposition behavior of cherry fruit flies is influenced by host fruit characteristics, such as texture [88], surface structure [83], and chemosensory stimuli [88,173,214]. Altering the surface chemistry of cherry fruits might therefore prevent oviposition. Until now only little research has been done on the reaction of *R. cerasi* to non-host volatiles [214,215]. In addition, physical properties of the fruit surface could be altered: It was shown that oil treatments prevent oviposition of *R. cerasi*, because the flies were not able to penetrate the slippery, oily skin with the ovipositor [106]. Residues on harvested fruit were a drawback with oil applications. However, mechanical barriers seem promising.

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