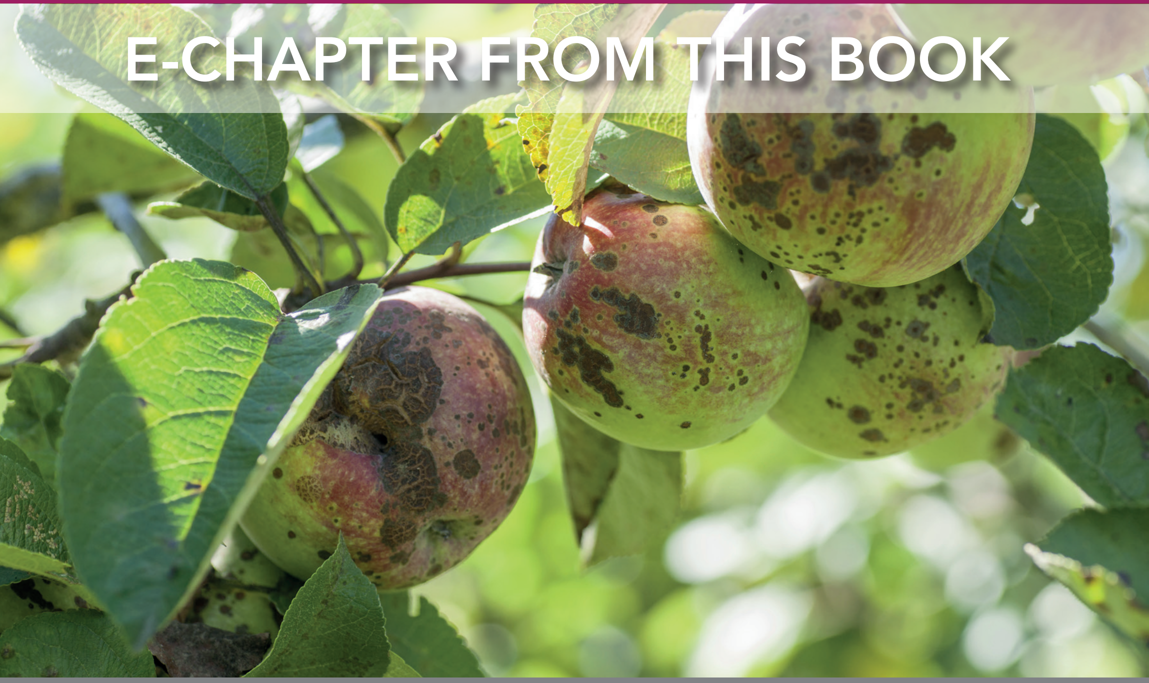
BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Integrated management of diseases and insect pests of tree fruit

Edited by Professor Xiangming Xu and Dr Michelle Fountain
NIAB EMR, UK

E-CHAPTER FROM THIS BOOK



burleigh dodds
SCIENCE PUBLISHING

Integrated management of tortricid pests of tree fruit

Alan L. Knight, USDA-ARS, USA; Gary J. R. Judd, Agriculture and Agri-food Canada, Canada; Todd Gilligan, USDA-APHIS-PPQ, USA; Eduardo Fuentes-Contreras, Universidad de Talca, Chile; and William B. Walker III, Swedish University of Agricultural Sciences, Sweden

1 Introduction

A group of relatively small moths in the family Tortricidae is commonly the most destructive insect pests of deciduous tree fruits throughout the world (van der Geest and Evenhuis 1991). Within each geographical area there is typically a defined group of tortricids. This group can include key species whose larvae feed on fruit, externally or internally, and which drives the entire seasonal pest management programme, and any number of external feeders whose larvae may cause sporadic fruit injury and require occasional management. Successful control of tortricids can have a significant impact on the global trade

http://dx.doi.org/10.19103/AS.2019.0046.19
Published by Burleigh Dodds Science Publishing Limited, 2019.

Chapter taken from: Xu, X. and Fountain, M. (ed.), *Integrated management of diseases and insect pests of tree fruit*, Burleigh Dodds Science Publishing, Cambridge, UK, 2019, (ISBN: 978 1 78676 256 6; www.bdspublishing.com)

of tree fruits and various phytosanitary regulations are in place to counter their accidental introduction into new areas.

Tactics employed to manage tortricids in tree fruits have most commonly relied on the repeated applications of insecticides from a relatively large number of mode-of-action classes. However, food safety concerns (which restrict rates, timing and maximum levels of post-harvest pesticide residues) have increasingly limited the options for insecticide use. Issues with the loss of pest susceptibility due to selection for resistance, and/or loss of product and entire insecticide class registrations due to increasing environmental and human health concerns, have been major factors in the redesigning of management programmes into the twenty-first century.

Initial attempts to find alternative methods of pest management proved problematic. Integrated pest management (IPM) and the broader concept of integrated fruit production (IFP) are paradigms pioneered in the 1970s to establish sustainable agriculture based on ecological and economic principles (Kogan 1998; Avilla and Riedl 2003). However, growers throughout the world who applied these concepts during the 1990s still experienced serious problems managing tortricids with the available arsenal of broad-spectrum insecticides and insect growth regulators (Varela et al. 1993; Sauphanor and Bouvier 1995; Pree et al. 1998; Ahmad et al. 2002). IPM programmes also failed to avoid secondary pest outbreaks from phytophagous mites, aphids, true bugs and leaf miners, further increasing the chemical inputs required to grow clean fruit (Prokopy and Croft 1994; Blommers 1994).

As a result, orchard pest management in the last decade of the twentieth century was in a serious state of flux driven by the evolution of pesticide resistance in the key tortricid pests, an unpredictable status of a suite of secondary pests, and the increasing regulatory restrictions on pest management forcing lower chemical residues, greater protection for workers and their families, and stricter containment of spray drift and surface water run-off (Beers et al. 2003; Weddle et al. 2009).

From a positive perspective these ecological and societal pressures also created new opportunities for the development of more selective pesticides that can increase the role of biological control (Jones et al. 2009a; Mills et al. 2016; Beers et al. 2016a,b), sprayer technologies (Fox et al. 2008), orchard architecture (Simon et al. 2006, 2007; Dorigoni 2016), monitoring tools and implementation of action thresholds to avoid unnecessary perturbations to the ecosystem (Knight and Light 2005a,b; Knight et al. 2014), partial replacement of pesticides with sex pheromone-based mating disruption (Miller and Gut 2015; Ioriatti and Lucchi 2016) and the rapid dissemination of expert knowledge of how to best implement IPM via sophisticated computer-aided decision frameworks (Jones et al. 2009b; Damos 2015). This chapter

Published by Burleigh Dodds Science Publishing Limited, 2019.

summarizes the recent literature associated with several applied aspects of tortricid management.

2 Tortricid systematics and general biology

The Tortricidae is a single family contained within the superfamily Tortricoidea. With approximately 11 400 described species in 1170 genera (Brown 2005; Gilligan et al. 2018) it is one of the largest families of microlepidoptera, and nearly 1000 species have achieved pest status (Zhang 1994). Tortricid adults are small moths (wingspan up to 35 mm) recognized by a combination of morphological characters, such as well-developed ocelli and chaetosema above the compound eye, an unscaled proboscis and horizontal labial palpi (Horak 1991). The structure of the flat ovipositor lobes in the female is the only character that unites the entire family (Horak and Brown 1991). Recent studies have used molecular data to reconstruct robust phylogenies for the family at the tribal level (Regier et al. 2012; Fagua et al. 2016). Tortricids are distributed worldwide, with the greatest species diversity found in the Neotropics (Regier et al. 2012). Most economically important species are found in two tribes: Grapholitini (Olethreutinae) and Archipini (Tortricinae).

Tortricid biology varies substantially. Larvae feed on foliage, in galls, bore into root stems and fruits, feed on seeds and flowers, on detritus or leaf litter, and a few species are predatory (Brown et al. 2008). Pest species can be categorized as external (most Archipini) or internal fruit feeders (most Grapholitini). External feeders construct a silken nest of rolled or folded leaves and feed on leaves, buds, flowers and sometimes directly on fruit. Economic damage is caused by their indirect feeding on fruit that causes premature fruit drop during the season or leads to secondary, post-harvest microbial infections on injured fruits. Larvae of internal feeders may feed on leaves or in stems in early instars but will eventually bore directly into fruit and feed on the seeds. Larvae of most tortricids complete four to six instar stages and overwintering can occur as an egg, larva or prepupa. Larvae are solitary feeders though more than one internal feeding larva can occur in fruits at high pest densities. Following eclosion adults are reproductively mature and sexual activity is typically limited by temperature and occurs during defined circadian periods, that is dusk through scotophase. Females lay eggs individually or as multiple egg masses and the realized fecundity can range from 50 to 800 eggs. Adults can be quite dispersive, and species can have a narrow to wide larval host range of deciduous shrubs and trees. Typically, there are a number of parasitoids attacking tortricids including tachinids and several hymenopteran families. Predation of immature stages by a suite of generalist predators present in orchards including spiders, earwigs, beetles and lacewings can be important.

Published by Burleigh Dodds Science Publishing Limited, 2019.

3 Key species, distribution and dispersal mechanisms

The importance of tortricid pests in tree fruits can be examined by considering four key species:

- codling moth (CM), *Cydia pomonella* (L.)
- oriental fruit moth (OFM), *Grapholita molesta* (Busck)
- light brown apple moth (LBAM), *Epiphyas postvittana* (Walker)
- obliquebanded leafroller (OBLR), *Choristoneura rosaceana* (Harris)

The first two species are internal fruit feeders in the tribe Grapholitini (Olethreutinae) with a worldwide distribution. OFM can also complete its development inside young shoots (Myers et al. 2006). Their management is the keystone of seasonal programmes and a driver of phytosanitary regulations and world trade of pome and stone fruits (Willett et al. 2009; Drogue and DeMaria 2012; Neven et al. 2018).

CM is apparently absent from Japan, Taiwan and Korea despite the climatic suitability of portions of the tree fruit production regions (Kumar et al. 2015). CM has been purported to be eradicated from Brazil through an organized urban host removal and pest management programme (Kovaleski and Mumford 2007). In contrast, the pest distribution of CM in China, by far the largest tree fruit producer, has increased across seven provinces (Men et al. 2013). OFM is originally from Asia (Kirk et al. 2013) but its distribution is now worldwide and in some geographical areas it has become a serious pest of pome fruits (Kovanci et al. 2004; Il'ichev et al. 2004). Geographical range expansion of OFM into new production areas such as eastern Washington State could be impacted by climate change (Neven et al. 2018).

LBAM and OBLR are in the tribe Archipini (Tortricinae) and are primarily leaf feeders with broad host ranges. LBAM originated from Australia and has been recorded from more than 500 plant species in 121 families (Brockerhoff et al. 2011). Recently, LBAM was accidentally introduced (hypothesized via importation of infested plant nursery material) into several new production areas, including California (Suckling et al. 2014). Eradication of LBAM from California with aerial applications of sex pheromone was attempted in 2007, but was terminated following public health concerns (Carey and Harder 2013). OBLR is the largest tortricid in North America and the adult dispersal into managed crops from surrounding unmanaged host plants has contributed to its importance in pome and stone fruits in both the humid eastern and arid western orchards (Chapman 1973; Evenden and Judd 1999).

Adult dispersal capacity is a variable trait with significant heritability in CM (Schumacher et al. 1997a), which can be selected under laboratory conditions and correlates with dispersal distance in the field (Keil et al. 2001a). No major differences in flight capacity between males and females were found under laboratory conditions (Schumacher et al. 1997a), but higher flight activity was found at different ages according to sex (Keil et al. 2001b). Flight activity is higher in mated than virgin females and increases during the egg-laying period; therefore, no dispersal will take place before mating and the oogenesis-flight syndrome is not present in this species (Schumacher et al. 1997b). Dispersal capacity is higher in individuals with smaller body weight associated with a significant reduction in fecundity, which suggests a trade-off between dispersal and fitness (Gu et al. 2006). Such findings indicate that CM populations are formed by a majority of sedentary individuals with low dispersal capacity and short dispersal flights, but a small proportion of dispersing individuals with smaller body sizes and lower fecundities are present and can undertake long-distance flights (Gu et al. 2006).

Spatial analyses of tortricid dispersal have mostly considered males caught in sex pheromone-baited traps (Mani and Wildbolz 1977; Sciarretta and Trematerra 2006; Basoalto et al. 2010; Margaritopoulos et al. 2012). Dispersal by females has been measured indirectly through the spread of fruit damage between generations (Knight et al. 1995), but more directly by using microsatellite markers and sibship analysis (Franck et al. 2011). The latter authors found that females mainly clustered their eggs among nearby edge trees within the same orchard (ca. 8 m away) and showed the mean dispersal distance between two oviposition sites was 30 m and the median 10 m. Geostatistical tools have been used to estimate the influence of landscape attributes on trap catch (Trematerra et al. 2004; Basoalto et al. 2010; Comas et al. 2012). A field technique which involves marking adults with low cost crude food proteins (milk, egg, wheat or soybean) and then releasing and re-capturing has been developed to study dispersal (Jones et al. 2006a,b; Basoalto et al. 2010). Overall, these studies show that CM adults can move a few 100 m between generations.

The characteristics of moth movement among host patches is important for monitoring and for optimal selection of tactics. Traps placed near orchard borders facilitate checking and are more effective indicators of pest immigration and local injury levels (Knight 2007b; Merckx et al. 2009). Dispersal from unmanaged surroundings into managed orchards is also of great relevance for insecticide resistance evolution (Fuentes-Contreras et al. 2007, 2008). Dispersal of adult CM among orchards and unmanaged hosts is affected by area and connectivity between habitat patches (Trematerra et al. 2004; Garcia-Salazar et al. 2007; Tyson et al. 2007; Ricci et al. 2009, 2011), but other factors such as patch resource quality and population density may also be relevant. For example, unmanaged host plants frequently show alternate fruit bearing, and therefore likely strongly influence seasonal dispersal patterns between habitat patches (Gu et al. 2006).

4 Insecticide programmes

Registered insecticides from 13 mode-of-action classes (Elbert et al. 2007) remain the primary approach to manage tortricids in orchards (Damos et al. 2015). Available chemistries include broad-spectrum and more selective synthetic materials, as well as microbial insecticides (Cox et al. 1995; Dhadialla et al. 1998; Thompson et al. 2000; McCann et al. 2001; Carlson et al. 2001; Charmillot et al. 2001; Lahm et al. 2005; Dripps et al. 2008; Lacey and Shapiro-Ilan 2008; Casida 2018). Sprays are primarily targeted against the neonate larvae of the internal feeders to prevent fruit injury. Unfortunately, insecticides which primarily rely on oral uptake typically have only marginal effectiveness against internal feeders, and timing is critical to contact larvae before they bore into plant tissue (Cox et al. 1995; Ballard et al. 2000a). Tortricid larvae feeding inside rolled leaves are more exposed and the spray timing is less critical (Jones et al. 2005). Some insecticide classes are also effective as ovicides (Charmillot and Pasquier 1992; Borchert et al. 2004; Gökce et al. 2009; Magalhaes and Walgenbach 2011). Activity against the adult stages can be significant though sprays are not typically timed for this life stage (Knight 2010a; Navarro-Roldán et al. 2017). Regardless, spray coverage is a key factor affecting the efficacy of insecticides and growers have adopted specialized sprayers to both minimize drift and maximize coverage (Panneton et al. 2005). Border sprays can be used to supplement programmes on uphill slopes and borders with proximity to extra-orchard populations (Trimble and Vickers 2000). The selectivity of insecticides against the natural enemies of tortricids, as well as their impact on key natural enemies of secondary pests, has allowed development of programme strategies that optimize the role of biological control during the season (Valentine et al. 1996; Beers et al. 2005; Biondi et al. 2012; Mills et al. 2016).

Insecticide-based management programmes are inherently threatened by the evolution of pest resistance (Roush and Tabashnik 1990). Levels of resistance to deltamethrin in populations of CM were found to be nearly 1000-fold in southern France (Sauphanor et al. 1997) and 10 000-fold to granulosis virus in Europe (Asser-Kaiser et al. 2007); yet, resistance levels <10-fold were associated with CM control failures in organophosphate-based pear programmes in California (Varela et al. 1993). The history of insecticide usage in tree fruits, as well as other crops, has been characterized as a 'reactive' approach to sequential failures with one class of insecticides adopted as the older class failed (Onstad 2008). Loss of pest susceptibility to sprays has tremendous practical and economic impacts which can drive major transformations in pest management, including in tree fruits (Knight and Norton 1989; Kazmierczak et al. 1993).

Baseline field surveys for resistance in tortricid populations have been conducted with several classes of insecticides across most geographical areas

Published by Burleigh Dodds Science Publishing Limited, 2019.

of these pests using a variety of bioassay approaches (Knight et al. 1994, 2001a; Sauphanor et al. 2000; Pasquier and Charmillot 2003; Knight 2010b). In some cases significant differences among bioassay methods suggested the need to standardize methodologies (Sauphanor et al. 1998a; Reyes and Sauphanor 2008; Magalhaes et al. 2012). In response, standardized surveys have been conducted across large geographical areas (Reyes et al. 2007, 2009). To date, significant resistance levels in CM have been found to all but one class of insecticides (anthranilic diamides) (detailed by Bosch et al. 2018). The susceptibility of OBLR to the newest classes of insecticides is more variable (Sial and Brunner 2010). In addition, laboratory experiments with OBLR demonstrated that resistance to chlorantraniliprole can be selected for over 12 generations, but reverted back to baseline levels after removing selection for five to six generations (Sial and Brunner 2012).

Growers have been fortunate to be able to switch to other classes of insecticides when resistance occurs, but the frequent occurrence of cross-resistance can severely limit these options (Sauphanor and Bouvier 1995; Sauphanor et al. 1998b; Dunley and Welter 2000; Smirle et al. 2002; Dunley et al. 2006; Reyes et al. 2007; Mota-Sanchez et al. 2008; Knight 2010b; Voudouris et al. 2011). Nevertheless, organized resistance management practices have been developed and implemented such that insecticides with different modes of action are rotated or limited to a single generation (Sparks and Nauen 2015). These efforts are noteworthy, but likely the further integration of management programmes with mating disruption, microbial insecticides and physical orchard manipulations will remain the most effective approach to maintain pest susceptibility to insecticides (Kienzle et al. 2003).

Numerous studies have examined the mechanisms associated with insecticide resistance in CM, including both enhanced enzymatic detoxification response (cytochrome P450 monooxygenases, glutathione transferases and esterases) (Rodriguez et al. 2011) and target site mutations (Reyes et al. 2007). A few point source mutations have also been detected including acetylcholinesterase (Cassanelli et al. 2006) and a knockdown resistance (kdr) mutation (Brun-Barale et al. 2005). Various studies have found that development of resistance has a fitness cost to adult tortricids (Carrière et al. 1994; Boivin et al. 2001, 2003, 2004; Konopka et al. 2012; Navarro-Roldán and Gemeno 2017). Changes in sex pheromone-based communication associated with insecticide resistance has also been shown (El-Sayed et al. 2001; Delisle and Vincent 2002; Trimble et al. 2004). Pear ester ((*E, Z*))-2,4-decadienoate was identified as a potent kairomone attractive to both sexes of CM and neonate larvae (Light et al. 2001; Knight and Light 2001). Sauphanor et al. (2007) suggested that adult CM's response to pear ester, in France, was greater in insecticide-resistant populations, but this was not supported in a later Spanish study (Bosch et al. 2015). A variety of sublethal effects on larvae and adults have been documented with the newer classes of insecticides which could have significant impacts on the management of tortricids (Sun and Barrett 1999; Sun et al. 2000; Borchert et al. 2004, 2005; Knight and Flexner 2007; Barrett 2008; Navarro-Roldán and Gemeno 2017). For example, levels of mating in CM field populations were found to be lower in blocks treated with the diamide, chlorantraniliprole, than in similar blocks treated with sex pheromones for mating disruption (Knight and Flexner 2007). The observed effects on calling behaviour and mating success detailed in this chapter were consistent with the primary mechanism of diamides and the depletion of intracellular calcium stores in muscle cells interfering with muscle regulation causing paralysis and ultimately death (Cordova et al. 2005).

5 Insecticide use in organic tree fruit production

The proportion of tree fruit production under certified organic regulation continues to grow around the world due to an increasing consumer demand and favourable economics (Marliac et al. 2015; Granatstein et al. 2016). This is made possible by a greater number of tools and natural products to control key tortricids. Nevertheless, tortricid management in organic orchards has a much more limited set of insecticides than is available for conventional growers (Knight 1994; Mills 2013).

Various formulations of the gram-positive bacterium *Bacillus thuringiensis* (*Bt*) (subsp. *kurstaki* and subsp. *aizawai*) contain different groups of toxic Cry proteins and are widely used against leaf rollers (Knight 1998a). Effective uptake of Bt by leaf roller larvae early in the season is strongly impacted by temperature. Sublethal exposures to Bt can shift a population's phenology and a subsequent spray's effectiveness (Knight 1997a). Sprays applied in the spring can be timed to minimize the negative effect against the various parasitoids utilizing the larval hosts (Cossentine et al. 2003). Various feeding stimulants have been used to enhance the effectiveness of Bt (Farrar and Ridgway 1995; Pszczolkowski et al. 2004). Cry proteins are also lethal when ingested by internal fruit feeders (Atanassov et al. 2002; Boncheva et al. 2006) and are used alone or in combination with CpGV in some geographical regions, that is Argentina. Resistance to Bt has been selected for in a laboratory colony of LBAM (Harris et al. 2006), but it has not been documented in field populations with any tortricid. Incorporation of Bt genes into transgenic apple has been discussed in the literature and privately demonstrated under quarantine, but has not been developed commercially (Wearing and Hokkaner 1994).

Spinosyns, neuroactive insecticides attacking nicotinic acetylcholine receptors (Biondi et al. 2012), are allowed in certified organic orchards because they are derived from fermentation of the actinomycete bacterium, *Saccharopolyspora spinosa* Mertz & Yao, and are highly effective targeting larval tortricids (Smirle et al. 2003; Arthurs et al. 2007a). However, cross-resistance to spinosad in CM (Knight 2010b) and OBLR has been noted (Ahmad et al. 2002; Smirle et al. 2003; Sial and Brunner 2010). Repeated use of this material has also been associated with outbreaks of secondary pests, such as aphids leading many organic growers to avoid its overuse (Delate et al. 2008; Biondi et al. 2012). In addition, the total seasonal use of spinosad is limited and the organic formulation has a relatively short residual effectiveness against tortricids when compared with newer formulations of this class of insecticide (Smirle et al. 2003; Depalo et al. 2016). The addition of feeding stimulants, such as monosodium glutamate or a monosodium glutamate receptor agonist can significantly improve spinosad activity against leaf-feeding tortricids; however, this approach has not been commercially developed (Pszczolkowski and Brown 2002, 2004).

Commercial formulations of the CM granulosis virus (CpGV) are widely used (estimated at 150 000 ha annually) in organic and IFP orchards (Lacey and Shapiro-Ilan 2008). Unfortunately, the effectiveness of CpGV is limited by its sensitivity to ultraviolet (280–320 nm) radiation and the need for larval ingestion (Lacey et al. 2004). Growers in Washington State can apply up to 14 applications of the virus during the season and achieve only moderately effective fruit protection within a season (Arthurs et al. 2005). The repeated use of CpGV over a number of years can be effective in reducing populations (Lacey and Shapiro-Ilan 2008).

Efforts to protect the virus from solar radiation have tried various adjuvants but improvements have been marginal (Ballard et al. 2000b; Arthurs et al. 2008). A second approach to improve the performance of CpGV has been the addition of feeding stimulants, and have included sugary baits, non-nutritive sugar substitutes, that is monosodium glutamate, and the amino acid, L-aspartate (Ballard et al. 2000a,b; Pszczolkowski and Brown 2002, 2004; Arnault et al. 2016). Results from several studies examining the potential of using pear ester in both apple and pear to enhance CpGV have been inconsistent (Arthurs et al. 2007b; Schmidt et al. 2008; Knight et al. 2015). However, field studies showed that the activity of CpGV could be enhanced by adding either the common brewer yeast *Saccharomyces cerevisiae* Meyen ex E. C. Hansen, or one of several yeasts isolated from field-collected larvae in combination with brown cane sugar (Knight and Witzgall 2013; Knight et al. 2015). Importantly, the numbers of overwintering larvae on trees was significantly reduced following a seasonal programme of CpGV plus yeasts and sugar in this latter study. Achieving reductions in fruit injury was more problematic with all adjuvants, as larvae commonly caused small 'stings' to the fruit and levels of unblemished fruit were not increased with the additives.

High levels of field resistance to CpGV have been detected in some European populations (Fritsch et al. 2005; Sauphanor et al. 2006). Unfortunately, this resistance is stable and does not confer a fitness cost (Undorf-Spahn et al. 2012). This resistance to commercial isolates of CpGV was overcome by identifying new effective virus isolates (Berling et al. 2009). CpGV isolates can also exhibit activity for OFM (Lacey et al. 2005; Zingg et al. 2012). Viruses have been isolated from other tortricids, but none have been commercialized (MacCollom and Reed 1971; Pronier et al. 2002).

Horticultural oil is widely used alone and as an adjuvant (spreader, penetrant) with various insecticide sprays targeting a range of soft-bodied arthropod pests, for example aphids, psyllids, scales and mites (Davidson et al. 1991; Hilton et al. 1992). Oil can also be effective as a topical treatment of tortricid eggs via suffocation (Riedl 1995; Fernández et al. 2005). Modern summer spray oils are highly refined with a narrow molecular weight range to minimize phytotoxic effects (Davidson et al. 1991). However, growers generally avoid their overuse and must consider the sensitivity of plant tissue based on air temperature, rate and fruit sensitivity (Willett and Westigard 1988; Hilton et al. 1992).

Various plant extracts and essential oils have been evaluated to control tortricids (Larocque et al. 1999; Landolt et al. 1999; Lowery and Smirle 2000; Machial et al. 2010; Durden et al. 2010; Pszczolkowski et al. 2011). One focus has been on the potential role of water soluble sugar metabolites on oviposition by CM (Lombarkia and Derridj 2002). Significant differences in CM oviposition across several apple cultivars was correlated with the cultivars' different sugar and sugar alcohol levels (Lombarkia and Derridj 2008). The addition of sugars with a neonicotinyl insecticide was evaluated and the observed reduction in fruit injury was associated with reduced oviposition (Arnault et al. 2016). Studies suggested that some of the activity of CpGV is due to reductions in oviposition associated with changes in leaf chemical signals (Lombarkia et al. 2013).

Pear ester sprayed on leaves or fruit causes increased larval wandering and longer arrestment times which can both extend the topical exposure of larvae to insecticides (Light and Beck 2010, 2012). Greater exposure to insecticides when combined with pear ester could allow managers to reduce rates of insecticides, boost the effectiveness of some classes of insecticides, and ameliorate the effects of poor spray coverage. Choice and no-choice bioassays demonstrated that pear ester stimulated CM oviposition (Knight and Light 2004) and increased the median distance eggs were laid from fruits which was hypothesized to contribute to the observed reduced fruit injury (Pasqualini et al. 2005a,b). A microencapsulated (MEC) formulation of pear ester (CideTrak DA-MEC, 5% A.I.) has been registered for conventional and organic production and has been carefully characterized, including capsule density, size range, emission rates and shown to have a residual attractiveness of 14 days (Light and Beck 2010). Various field trials were conducted that added pear ester to different classes of insecticides with a range of residual and oral route of exposures in both walnut, *Juglans regia* L. (Light and Knight 2011) and apple (Knight and Light 2013). In general, pear ester significantly improved the performance of synthetic insecticides with residual effectiveness and also reduced nut injury by the navel orangeworm, *Amyelois transitella* Walker, in walnut (Light and Knight 2011). Results with pear ester in both laboratory and field trials with insecticides requiring ingestion even when used with purported feeding stimulants have been more variable (Arthurs et al. 2007b; Schmidt et al. 2008; Light and Knight 2011; Knight and Witzgall 2013; Knight et al. 2015).

6 Physical crop protection

Particle films are widely used in apple production for a number of management objectives. Originally, the use of a hydrophobic kaolin formulation was developed to broadly suppress pests and diseases in tree fruits (Glenn et al. 1999). Subsequent studies showed that particle films could enhance plant growth, fruit yield and quality, in pome and stone fruits (Glenn et al. 2001; Lalancette et al. 2004). A liquid formulation was subsequently developed, and growers created specific uses for this, including early season management of pear psylla, *Cacopsylla pyricola* (Foerster), in pear orchards (Puterka et al. 2005), and mid- to late-season use in apple to reduce heat stress (Glenn et al. 2002). Studies showed that particle films could also suppress CM and OBLR populations (Unruh et al. 2000; Knight et al. 2000a; Sackett et al. 2005) and impact moth movement within and between orchards (Jones et al. 2006a,b). Unfortunately, seasonal use of kaolin films has been associated with several pest problems due to disruption of biological control of pests, such as leaf miners and phytophagous mites (Knight et al. 2000b; Sackett et al. 2007; Marko et al. 2008; Bostanian and Racette 2008).

Two additional physical methods have been considered and used on a limited basis to manage tortricids: bagging individual fruits on trees (Sharma et al. 2014; Zheng et al. 2015) and the use of overhead watering to disrupt moth flight, oviposition, and egg and larval survivorship (Knight 1998b). Bagging is obviously a highly labour-intensive method and likely has no practical use in commercial fruit production in developed countries, except very niche markets, that is special gifts in Japan. Overhead watering has been used for evaporative cooling of orchards to minimize fruit sunburn (Evans et al. 1995), and levels of fruit injury from CM could be reduced by up to 90% with daily watering. This use of water, however, had severe limitations on the availability of water to irrigate blocks concurrently, and the build-up of mineral deposits on fruits. The use of water for sunburn protection has declined as growers made greater use of netting and particle films (Gindaba and Wand 2005).

The most practical and effective physical approach to manage tortricids is likely the use of exclusion netting (Lawson et al. 1994). Originally, overhead netting of orchards provided insurance for rare hail events or was used before harvest in select orchards prone to bird predation (Whitaker and Middleton 1999). The high cost of installation compared with these risk factors limited its use. However, observations that overhead nets could also reduce fruit injury from tortricids dramatically improved the economics of installing nets (Graf et al. 1999). The occurrence of resistance to CpGV forced many growers in southern France to adopt the use of single row hail nets with side walls (Alt'carpo) to manage CM (Severac and Romet 2008). Subsequent studies have shown how netting can interfere with the sexual activity and flight of CM (Tasin et al. 2008; Sauphanor et al. 2012; Ioriatti and Tasin 2018). The occurrence of nets in eastern Washington appears to be expanding rapidly due to this effect and to protect fruits from sunburn while enhancing tree physiology (Lloyd et al. 2005; Bastias et al. 2012). Unfortunately, the use of netting may exacerbate management of other pests such as aphids (Dib et al. 2010). It is exciting to hypothesize that future tortricid management programmes could require very few chemical inputs due to the integration of netting, MD and the release of natural enemies (Chouinard et al. 2016).

The physical structure of tree canopies and entire orchards can have significant effects on the management of pests, including tortricids (Stoeckli et al. 2008; Costes et al. 2013). Canopy architecture directly impacts spray coverage and the occurrence of refugia within orchards (Xu et al. 2006; Duga et al. 2015). Tree size and canopy porosity affects the distribution of microclimates and the phenology of pests (Kührt et al. 2006). Fruit trees are complex perennial resources and canopies can be manipulated to minimize pest incidence and maximize natural enemies (Simon et al. 2006, 2007). The use of cover crops in orchards to enhance biological control of various pests has been considered (Fernández et al. 2008; Bone et al. 2009; Mullinix et al. 2010; Marko et al. 2012), including to benefit natural enemies of tortricids (Sarvary et al. 2010a,b; Mullinix et al. 2011; Song et al. 2014).

7 Biological control

The transition of tree fruit production to the use of selective insecticides has greatly increased the role of biological control to suppress tortricid populations (Beers et al. 2016a). However, the importance of biological control varies widely between the internal fruit feeders and the foliage feeders. The use of natural enemies for the key pests, CM and OFM, has not been relied on for several reasons (Mills 2005):

- the low threshold for fruit injury
- internal larval feeding which reduces the availability of susceptible life stages to parasitoids and predators

- the widespread use of pesticide sprays on tree fruits
- the paucity of hosts immediately surrounding orchards

Moderate levels of parasitism of CM occurs in unsprayed habitats from wasps that attack the egg stage, such as *Trichogramma* spp. and the egg-larval braconid, *Ascogaster quadridentata* Viereck (DeLury et al. 1999; Suckling et al. 2002). Inundative releases of *Trichogramma* spp. have had only marginal success due to the biology of the parasitoids, the quality of mass-reared insects and the significant pesticide residues in orchards (Lawson et al. 1997; McDougall and Mills 1997; Mills et al. 2000; Mills 2003; Brunner et al. 2005). One novel integrated effort demonstrated that egg parasitoid populations could be sustained after a single release in orchards via releases of sterile moths, with parasitoids developing from the sterile eggs laid in the orchard (Bloem et al. 1998). Significant classical biological control efforts importing parasitoids from Kazakhstan have been attempted and a few species have been disseminated to other fruit-producing regions (Unruh 1998; Kuhlmann and Mills 1999). The biology of the ichneumonid, *Mastrus ridibundus* (Gravenhorst), an ectoparasitoid that attacks cocooned larvae, has been intensively studied (Bezemer and Mills 2001; Hougardy et al. 2005; Devotto et al. 2010). Predation of CM eggs and diapausing larvae is likely a more important aspect of biological control (Riddick and Mills 1994; Knight et al. 1997; Monteiro et al. 2012; Boreau de Roince et al. 2012) and gut content analysis has been used to characterize the major predators, that is carabids, spiders, earwigs and harvestmen (Unruh et al. 2016).

The use of more selective insecticides has also expanded the importance of natural enemies of leaf rollers (Vakenti et al. 2001; Cossentine et al. 2004; Pluciennik and Olszak 2010; Monteiro et al. 2012). In some regions the combined activity of these guilds has likely contributed to significant declines in their pest status (Blommers 1994; Lo et al. 2018). Interestingly, parasitism of LBAM introduced into California quickly rose to levels found in Australia (Burgi and Mills 2014; Burgi et al. 2015). Predation of eggs and larvae is often important (MacLellan 1973; Miliczky and Calkins 2002). An ingenious conservation approach to establish a sustained role for biological control of leaf rollers involves the orchard planting of rose/strawberry gardens infested with the tortricid *Ancylis comptana* (Frölich), an alternate host for the eulophid parasitoid, *Colpoclypeus florus* (Walker) (Pfannenstiel et al. 2010; Unruh et al. 2012).

Parasitic nematodes have also been investigated to supplement management of tortricids (Lacey et al. 2006; Negrisoli et al. 2013). Their use requires careful handling to be effective, including selection of the best adapted nematode species for the local climate (Lacey et al. 2006). The required occurrence of suitable temperatures for nematode searching behaviours and maintenance of high humidity by wetting tree trunks are difficult factors to control during late season when larvae move into overwintering sites in the arid production areas of the world (Unruh and Lacey 2001; Lacey et al. 2006).

8 Mating disruption

Identification of tortricid sex pheromones has been a key driver in the design of effective management programmes allowing both improved decision-making for the need and timing of sprays and in direct control via disruption of mating (Witzgall et al. 2008; Ioriatti and Lucchi 2016). Grower adoption of various MD tactics, that is sprayable microencapsulated formulations, various hand-applied dispensers, and the use of aerosol emitters (Miller and Gut 2015) and has allowed significant reductions in insecticide applications (Knight 1995, 2008; Gut and Brunner 1998). Other tortricids have become more problematic following the initial adoption of MD for CM and associated reductions in broad-spectrum insecticides (Knight 1995; Walker and Welter 2001). The level of female mating under MD appears to be high for CM (Knight 2006, 2007a) and OBLR (Knight et al. 2017), and much lower with OFM (Cichon et al. 2013; Mujica et al. 2018). The effectiveness of MD may also be achieved through causing a delay in mating (Knight 1997b; Vickers 1997; Fraser and Trimble 2001; Foster and Howard 1999; Jones et al. 2008a). Sex pheromone dispensers for MD are a sizeable upfront cost for growers, but dual dispensers for CM and OFM (Stelinski et al. 2007, 2009) and CM and leaf rollers (Judd and Gardiner 2006a; Lo et al. 2013; Porcel et al. 2014) have been registered to help reduce application costs.

Pear ester has also been developed to improve mating disruption of CM (Light and Knight 2005). Studies have shown that the proportion of unmated female moths is significantly higher in blocks treated with various dispensers releasing both sex pheromone and pear ester than only sex pheromone (Knight et al. 2012a,b). The repeated applications of a microencapsulated formulation of pear ester to improve insecticidal activity (Knight and Light 2012) can also increase the level of MD in treated blocks (Knight and Light 2014).

9 Precision pest management

With the rapid development of GPS-driven applications including mapping, record keeping and variable-rate spray technology, new opportunities are available to further optimize aspects of orchard management (Sonka and Coaldrake 1997). Combined with new monitoring tools and the ability to process voluminous data remotely site-specific pest management seems plausible (Fleischer et al. 1997, 1999; Zijlstra et al. 2011). Development of more effective traps and lures including female attractants has improved correlations of moth catches with local pest levels (Knight et al. 2005, 2014; Knight and Light 2005b; Padilha et al. 2017). Standardized methodologies for trap density, placement within the orchard and proximity to MD dispensers are some of the important factors affecting the reliability of traps (Gut and Brunner 1996; Knight et al. 1999; Knight 2007b; Hsu et al. 2009). Kairomone blends including acetic acid combined with, either pear ester or nonatriene for CM (Landolt et al. 2007; Knight and Light 2012); 2-phenylethanol for OBLR and *Pandemis* spp. (Judd et al. 2017a; Knight et al. 2017); phenylacetonitrile for LBAM and eye-spotted bud moth, *Spilonota ocellana* (Denis and Schiffermüller) (El-Sayed et al. 2016; Judd et al. 2017b); and terpinyl acetate for OFM (Mujica et al. 2018) have significantly increased growers' ability to monitor moths even under MD programmes. Improved phenological monitoring, including more accurate models (Knight 2007c; Joshi et al. 2016), are more effectively timed with female moth catches (Knight and Light 2005c; Barros-Parada et al. 2015).

The ability to monitor female tortricid populations creates an opportunity to redesign orchard pest management (Light et al. 2001; Hughes et al. 2003). Precision management of CM can be defined as an approach that restricts the spatial application of sprays based on site-specific pest monitoring data (triggers), such as moth catch, that is conveniently matched to the coverage provided by spray tank capacity (Knight et al. 2009). The first step is to map the orchard and create management subunits surrounding each trap. Treatments are then applied to designated areas in response to the magnitude of moth catches and consideration of other factors, such as risk preference, pest history, status of other pests and biological control agents in the orchard, and the requirements imposed by other crop production practices. This approach has been demonstrated over several years to reduce total production costs through reduced spray applications. Additional benefits from reduced spraying may be derived from conservation of biological control agents (Knight et al. 2011). The orchard managers also appreciated the programme, because treating only portions of orchards allowed them to move labour crews around the spray teams within the same location and reduced the costs of moving labour and associated equipment to alternate orchard work locations during treatment and re-entry intervals. The result was less downtime and increased efficiencies in other production tasks. Development of smart traps, especially if multiple species can be monitored together, will likely facilitate this approach (Guarnieri et al. 2011; Kim et al. 2011).

A complicating factor in improving precision in pest management is climate change. The predicted scenario of a gradual warming trend across the major fruit production areas will impact tortricid pests by increasing their generation numbers per year and disrupting diapause induction and termination (Bale and Hayward 2010; Luedeling et al. 2011; Stoeckli et al. 2012). Phenological models are widely used with tortricid pests to target the most susceptible life stages (Knight 2007c). Development of female-based models using new bisexual attractants can reduce the error associated with predicting egg hatch (Knight and Light 2005c; Barros-Parada et al. 2015). The approach of using a 'Biofix' (first sustained male catch in sex pheromone-baited traps) to shorten the time between the start of male flight and egg hatch has been widely adopted (Riedl et al. 1976). However, the widespread use of MD and a general decline in the amplitude of moth flights has made selecting a Biofix more difficult (Jones et al. 2008b). Instead, predicting the timing of egg hatch with the accumulation of degree days from 1 January has been developed (Jones et al. 2013). Unfortunately, this method is particularly sensitive to the warming trends that are occurring. In particular, variable accumulations of degree days in the winter months can disrupt the typical spring emergence patterns of CM which could dramatically increase the error in predicting egg hatch (Neven et al. 2000). The magnitude of this error could be more severe in the warmer geographical areas supporting tree fruit, that is California in North America.

10 Area-wide IPM

Tortricid adults readily disperse among both managed agricultural habitats and a variety of surrounding unmanaged host plants (Jeanneret and Charmillot 1995; Knight 2001; Thistlewood and Judd 2003a; Ellis and Hull 2013; Ferrer et al. 2014). Urban encroachment into traditional agricultural areas affects the proximity of unmanaged hosts for tortricids impacting orchard management and production, for example homeowners want their own fruit trees but not the added labour of growing their trees to mitigate risks to commercial crops.

Given that many tortricids are mobile as both juveniles and adults, and both managed and unmanaged hosts occur within any given production region, the design of effective orchard management programmes should consider pest population dynamics across large areas, including neighbouring orchards and alternate hosts. Implementation of the first area-wide management programme for CM in the western United States (CAMP) demonstrated that increased sampling and monitoring efforts greatly diminished the use of insecticides (Calkins and Faust 2003). The programme in Washington State was very successful in terms of pest management, but more importantly, it served as a vehicle to quickly disseminate new knowledge to the grower community and extension agents, particularly as it related to MD (Knight 2008). The key lesson learned from the CAMP programme was that pest management requires attention, experience and skill to be effective (Knight 1999). Several operational and organizational factors contributed to the success of the CAMP programme. First, effective and selective tactics for both the key and secondary pests backed by technical support were available. Second, the project was well-funded, coordinated and directly involved growers, researchers, industry leaders and government administrators. However, the single key factor affecting the success of each area-wide programme was the creation of an organizational structure that allowed neighbouring growers to come together to eliminate 'problem orchards or blocks' through cooperation, peer pressure and education (Knight 2008).

Sterile insect technology (SIT), MD and host-plant removal have all been used in area-wide programmes in different pome fruit producing areas with varying levels of success. The programme established along the United States–Canada border in 1995 combined the use of sterile moths and MD (Calkins et al. 2000). A similar programme to CAMP was conducted across both apple and peach growing regions in eastern USA by implementing MD for CM, OFM and OBLR (Agnello et al. 2009; McGhee et al. 2011). The area-wide management of CM and OBLR in Washington State used MD for both pest species supplemented by targeted use of selective insecticides including microbials (Knight et al. 2001b). Development of a landscape-scale programme for OFM in Australia required coordination between pome and stone fruit growers (Il'ichev et al. 2002). The effort to eradicate LBAM from California used aerial applications of pheromones (Brockerhoff et al. 2012) and the area-wide eradication programme for CM in Brazil involved removal of host plants across a large urban region outside of agricultural lands (Kovaleski and Mumford 2007).

The longest-running, most successful area-wide effort to control CM in North America, and arguably the world, is the Okanagan-Kootenay Sterile Insect Release Program, OKSIR (Dyck et al. 1993). This socially and environmentally responsible initiative serves as a unique example of the power of community-based IPM that has clearly enabled the largest organic tree fruit industry in Canada. The programme began in 1992 as an effort to eradicate CM from 8500 ha of pome fruit and surrounding urban properties in the Okanagan, Kootenay and Similkameen valleys located in the southern interior of British Columbia (Dyck et al. 1993). Eradication of CM promised producers and local homeowners the opportunity to grow pome fruits without the use of insecticides during the fruit development period. Elimination of OPs was the key environmental target of this programme, which, ironically, was eventually achieved in totality in 2012 through legislative powers, not pest management. The lofty goal of eradication was abandoned in 1998, but the SIT effort continues as part of a more sustainable programme supplemented by targeted use of MD and selective insecticides (Thistlewood and Judd 2003b; Judd and Gardiner 2005). The programme currently services ca. 3550 ha of apples and pears, and reports that throughout the past decade at least 90% of the orchards it services have suffered less than 0.2% CM fruit damage at harvest (www.oksir.org).

Several aspects of the Canadian SIT programme are significant to its success. Firstly, special legislative powers were granted by senior government to local municipal governments to allow the taxation of all homeowners and pome fruit growers residing within the designated service area. This taxation provides an annual operating budget (Dyck and Gardiner 1992) that now exceeds $3 million CAD annually (www.oksir.org). Programme implementation also needed senior levels of government to provide the capital funding ($7.7 million CDN in 1992) to build a large CM rearing facility, and another $1 million CDN in 1994 to pay growers to apply insecticides to reduce CM populations. Often overlooked is the fact that during the first 10 years of the programme nearly 80% of the existing apple orchards were replanted into high-density dwarfing systems under a government-assisted industry-wide replant programme. Removal of old, derelict orchards, often harbouring CM populations, and with higher overwintering survivorship than new orchards, helped to reduce existing wild populations. Urban property owners were encouraged to remove unmanaged pome trees often enticed by free tree- and fruit-replacement programmes.

Weaknesses of this ongoing SIT programme include continuing concern about the fitness of the sterilized moths to compete with wild moths under field conditions (Judd and Gardiner 2006b; Judd et al. 2011). Currently moths are sterilized with ionizing gamma radiation from a Cobalt^{60} source (Bloem and Bloem 2000) but advances in alternative sterilization methods using safer, and less debilitating X-ray methods (Mastrangelo et al. 2010; Yamada et al. 2014) may improve moth quality. Poor performance of sterile CM, especially in cool springs (Judd et al. 2004), is also related to the mass-rearing system and cold storage before release (Judd et al. 2006a,b, 2011). Studies on thermal acclimation of CM offer hope that use of appropriate thermal pre-treatments may improve field performance of sterile CM under adverse thermal conditions (Chidawanyika and Terblanche 2011).

Currently the OKSIR programme mostly releases a uniform predetermined number of moths (2000 mixed-sex moths per ha) once each week to each orchard across an established grid using ground-based delivery from all-terrain vehicles over a 4-month period (May–August), regardless of local pest pressure (Bloem and Bloem 2000). The programme is unable to adjust moth production quickly in the event of an early spring or during peaks of moth flight as needed. The programme is unable to target problem sites that emerge during the season with additional releases of moths due to the lack of adequate resources to assess its effectiveness. Moth monitoring efforts are carried out weekly and automated trapping systems (Kim et al. 2011) that could provide daily information are not yet able to distinguish wild and sterile moths. This means the programme often reacts to information about inadequate or even excessive sterile to wild ratios long after the problem has occurred. Targeted moth releases based on daily trapping would be advantageous because moths could be shunted from where they are not needed to where they are. The potential for fast targeted release might be easier if human drivers with fixed daily schedules could be taken out of the equation. The potential for using drone technology to deliver moths in this way is being investigated by a number of research groups most notably in New Zealand (Horner at al. 2016). Researchers are partnering with commercial drone companies like M3 Consulting Group (www.m3cg.us) that are looking to expand the range of services they can provide to the agricultural industry.

One of the challenges frequently faced by new SIT initiatives is the capital cost of building an insect rearing facility (Addison 2005; Botto and Glaz 2010; Blomefield et al. 2011; Horner et al. 2016). Researchers in South Africa (Blomefield et al. 2011) and New Zealand (Horner at al. 2016) have overcome this capital investment challenge by importing sterile Canadian moths for local release. Sales of OKSIR moths into southern hemisphere countries, especially during the Canadian winter, may provide additional funding which could be used to refine or subsidize the Canadian programme. If moths from the Canadian programme can be produced, shipped and released into other production regions for costs that are competitive with local methods of CM pest control, then SIT can potentially become another useful management tactic that could be integrated into existing programmes needing help, such as organic production (Judd and Gardiner 2005).

11 Post-harvest management

The need to manage tortricids continues after harvest to avoid international trade disruptions (Vail et al. 1993). Irradiation and heating fruit has been investigated as a substitute to methyl bromide treatments (Follett and Snook 2012; Wang et al. 2006). A systems approach has been conceptualized that includes both within-season and post-harvest practices to minimize the probability (probit 9 efficacy = 99.9968329% mortality) of the introduction of quarantine tortricid pests (Follett and Neven 2006). Effective culling of fruits on packing lines is influenced by both fruit characteristics, that is colour, size of insect injury, the co-occurrence of other visual defects and operational factors, such as the numbers of fruits sorted per worker-second (Knight and Moffitt 1991). Progress in developing automated defect inspection processes based on machine vision and learning is progressing rapidly (Sofu et al. 2016; Gupta et al. 2018) and the possibility of detecting internal pests in apples in packinghouses has been explored but does not seem practical due to the handling times required (Li et al. 2018).

Wooden bins used to harvest fruit are placed in orchards at variable times before harvest and can become infested with CM larvae that build cocoons in the bins (Higbee et al. 2001). Stacking of bins during the off-season changes the temperatures that larvae are exposed to in different areas of the stack and interferes with moth emergence times during the season. This is problematic for timing effective sprays and also causes unexpected hot spots to be created in orchards near bin stacks. Sharing bins among infested and uninfested orchards contributes to the regional spread of CM. Bin sterilization with acetic acid to eliminate insects and disease pathogens has been investigated (Randall et al. 2011); some packinghouses have developed routine bin sterilization programmes using hot water emersion (Hansen et al. 2006). The concept of disinfesting wooden bins through treatment with nematodes has also been studied (Lacey and Chauvin 1999) and the transition to picking fruit into plastic instead of wooden bins may reduce the incidence of overwintering larvae (Waelti 1992).

12 Molecular tools

Advances in molecular biology, genetics and genomics research have provided various tools and technologies that have and will likely contribute more towards the management of tortricids. Several molecular genetic tools have been developed that facilitate identification of these internal feeding fruit pests relevant to quarantine, importation and management situations. DNA barcoding via polymerase chain reaction (PCR), quantitative real-time PCR (qRT-PCR) and PCR restriction fragment length polymorphism (PCR-RFLP) amplification of mitochondrial cytochrome oxidase I (mCOI) have been utilized for this purpose (Barcenas et al. 2009; Chen and Dorn 2009; Kwon et al. 2018). qRT-PCR assay of ribosomal RNA has also been used for diagnostic identification of LBAM in North America (Barr et al. 2011). Simple sequence repeat microsatellites are rapidly evolving genetic loci that are selectively neutral and vary in number of repeated units. These features make microsatellites very useful for studying population genetics and gene flow (Franck et al. 2005, 2011; Fuentes-Contreras et al. 2008; Chen and Dorn 2010; Kirk et al. 2013). A better understanding of the population structures of tortricid pests at the genetic level informs IPM through identification of source populations for invasive species, identification of host races and characterization of dispersal rates and migratory patterns (reviewed in Chen and Dorn 2010; Kirk et al. 2013). Next-generation sequencing methods may also be used for characterization of genetic structure of populations and study of gene flow within and across populations. Genotyping-by-sequencing combines high-throughput sequencing of biological samples with broad-scale single nucleotide polymorphism analysis. With this methodology it has recently been shown for OFM moth in Brazil that geographic distance is the primary factor that affects genetic structure and gene flow (Silva-Brandao et al. 2015). Insecticide resistance mechanisms in European populations of CM have been characterized at the genetic level with individual genes identified that correlate with resistance (Reyes et al. 2007). Genetic studies of the genes and

Published by Burleigh Dodds Science Publishing Limited, 2019.

genotypes that mediate resistance facilitate assessments of the prevalence of resistance within populations (Franck et al. 2007; Franck and Timm 2010).

Genetic engineering of apple trees has proven to enhance apple varieties with various traits including food quality (Murata et al. 2001), fire blight (Norelli et al. 2003) and resistance to pest insects (Markwick et al. 2003; Maheswaran et al. 2007). Genetically modified non-browning apples have recently been approved for market in the United States (Waltz 2015). Transgenic cv. Royal Gala apples that express biotin-binding proteins avidin and streptavidin in shoot foliage displayed increased resistance to LBAM damage; larvae feeding on transgenic plants displayed increased mortality and decreased fitness compared to those feeding on controls (Markwick et al. 2003). LBAM fitness parameters were also impacted in larvae feeding on Royal Gala leaves in which a *Nicotiana alata,* Link & Otto, proteinase inhibitor was transgenically expressed (Maheswaran et al. 2007).

CRISPR/CAS9 technology has recently revolutionized biological research by providing methodologies for efficient, site-specific genome editing (Jinek et al. 2012). To date, utility of this technology has been applied to several plant species (Xu 2013). Given that creating transgenic apple is well established, and CRISPR/CAS9 utilizes similar entry point methods, CRISPR/CAS9 editing of the apple genome is anticipated. This has implications for pest control vis-à-vis generation of edited cultivars that display greater resistance to pests. This may be carried out through the introduction of foreign genes (transgenesis) or knockout of native genes, the latter of which may be beneficial in avoiding regulatory hurdles that come with the introduction of foreign genetic materials. Moreover, CRISPR/CAS9 has been demonstrated, proof of principle, for CM (Garczynski et al. 2017). Development of this technology in CM, and its application in other tortricid pest species may enhance multiple fronts of pest control. Utilization of molecular genetic resources to improve the effectiveness and efficiency of SIT/IS with CM has been proposed (Vreysen et al. 2007). Specifically, CRISPR-mediated transgenic introduction of dominant conditional lethal mutations that specifically target females would facilitate production of genetic sexing strains, which has been proven to dramatically improve the efficiency and economics of SIT with the medfly, *Ceratitis capitata* (Wiedemann). Additionally, utilization of repressible dominant lethal genes that are present in males, but active only in females, would circumvent the need for sterilizing radiation, which can reduce fitness of released insects (Alphey and Bonsall 2018; Thomas et al. 2000). Recent biotechnology efforts have been aimed at bioengineering transgenic plants or fungi that produce insect pheromones. Transgenic *Nicotiana benthamiana* Domin engineered to produce the pheromones of two small ermine moths were shown to be effective in trapping male moths of the respective species (Ding et al. 2014) and reconstitution of moth pheromone biosynthetic pathways in yeast demonstrate an additional means of pheromone production (Ding et al. 2016; Hagstrom et al. 2013). Application of these technological systems to the production of tortricid moth pheromones may directly contribute to IPM of target species by providing alternative, efficient and cost-effective pheromone production and delivery systems. A final point with respect to basic research: *in situ* genetic manipulation of key tortricid pest species has the potential to add to our basic understanding of the biology and ecology of these organisms.

13 Future trends and conclusion

Tortricids utilizing tree fruits are lovely little moths (an entomological researcher's perspective) with a worldwide importance as a serious threat to the production and shipping of valuable, pristine commodities. These are exciting times in the realm of tortricid management in tree fruits. The tools and knowledge of how to manage tortricids is available to all growers, and the development and marketing of new more valuable cultivars has provided the funds for many growers to implement effective management programmes. Overall, it seems that the future heralds a reduced pest status for tortricids within orchards. Instead, growers will have to continually refocus on effectively managing the introduction of other pests, and be forced to rebalance their IFP programmes in order to maintain low pesticide residues and the important ecological services provided from biological control. Perhaps this is too optimistic and too ethnocentric, ignoring the dogma that 'Nature always finds a way!' We will see, and growers can always worry and remain on guard each growing season armed with an arsenal of tactics for these seemingly gentle moths dispersing into their orchards to wreak havoc!

The lessons learned from the success of area-wide management will continue to shine attention on the value of substituting out prophylactic sprays with increased knowledge about the pest status of tortricids. The most effective programmes will be where unmanaged hosts are not located near orchards, where all growers use high-level management programmes, where monitoring and thresholds are used to minimize the use of disruptive tactics and to maximize their effectiveness. Protection of orchards with netting will likely increase. It is uncertain if new classes of insecticides will be developed so custodianship of the active materials will continue to be critical through their judicious use. Targeting localized problem areas with mass trapping, releases of sterile moths, and removal and replanting of orchards will become more important.

14 Where to look for further information

The first place to look when researching information on tortricids is the amazing book edited by Geest and Evenhuis. A second source would be to scan the *Annual Review of Entomology* for reviews of tortricid biology and management. Also, the key journals listed in the literature review are likely to continue to be the most important sources of new information on tortricids. Several IOBC working groups in Europe, including the 'Integrated protection of fruit crops', and 'Pheromones and other semio-chemicals in integrated production' hold meetings every few years and consistently bring together the experts in various management fields related to tortricids. In addition, the annual meetings of the Entomological Society of America and the Orchard Pest Management Disease Conference held in the second week of January in Portland, Oregon, are always extremely educating and excellent opportunities to hear the latest scientific developments related to tortricids and other insect groups impacting tree fruit.

15 References

Addison, M. F. (2005), Suppression of codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae) populations in South African apple and pear orchards using sterile insect release, *in* Theron, K. I. (Ed.), *Proceedings of the Ninth International Pear Symposium*, Stellenbosch, South Africa, 1–6 February 2004, International Society for Horticultural Science, Lueven, Belgium.

Agnello, A. M., Atanassov, A., Bergh, J. C., Biddinger, D. J., Gut, L. J., et al. (2009), Reduced-risk pest management programs for eastern U.S. apple and peach orchards: A 4-year project, *Am. Entomol*. 55(3), 184–97.

Ahmad, M., Hollingworth, R. M. and Wise, J. C. (2002), Broad-spectrum insecticide resistance in obliquebanded leafroller *Choristoneura rosaceana* (Lepidoptera: Tortricidae) from Michigan, *Pest Manag. Sci*. 58, 834–8.

Alphey, N. and Bonsall, M. B. (2018), Genetics-based methods for agricultural insect pest management, *Agric. For. Entomol*. 20, 131–40.

Arnault, I., Lombarkia, N., Joy-Ondet, S., Romet, L., Brahim, I., et al. (2016), Foliar application of microdoses of sucrose to reduce codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae) damage to apple trees, *Pest Manag. Sci*. 72, 1901–9.

Arthurs, S. P., Lacey, L. A. and Fritts, R. (2005), Optimizing use of codling moth granulovirus: Effects of application rate and spraying frequency on control of codling moth larvae in Pacific Northwest apple orchards, *J. Econ. Entomol*. 98(5), 1459–68.

Arthurs, S. P., Lacey, L. A. and Miliczky, E. R. (2007a), Evaluation of the codling moth granulovirus and spinosad for codling moth control and impact on non-target species in pear orchards, *Biolog. Control* 41, 99–109.

Arthurs, S. P., Hilton, R., Knight, A. L. and Lacey, L. A. (2007b), Evaluation of the pear ester kairomone as a formulation additive for the granulosis virus of codling moth (Lepidoptera: Tortricidae) in pome fruit, *J. Econ. Entomol.* 100(3), 702–9.

Arthurs, S. P., Lacey, L. A. and Behle, R. W. (2008), Evaluation of lignins and particle films as solar protectants for the granulovirus of the codling moth, *Cydia pomonella*, *Biocontrol Sci. Technol*. 18(8), 829–39.

Asser-Kaiser, S., Fritsch, E., Undorf-Spahn, K., Kienzle, J., Eberle, K. E., et al. (2007), Rapid emergence of baculovirus resistance in codling moth due to dominant, sex-linked inheritance, *Science* 317(5846), 1916–18.

Atanassov, A., Shearer, P. W., Hamilton, G. and Polk, D. (2002), Development and implementation of a reduced risk peach arthropod management program in New Jersey, *J. Econ. Entomol*. 95(4), 803–12.

Avilla, J. and Riedl, H. (2003), Integrated fruit production for apples – principles and guidelines, *in* Ferree, D. C. and Warrington, I. J. (Eds), *Apples: Botany, Production and Uses*, CABI Publishing, Wallingford, UK, pp. 539–49.

Bale, J. S. and Hayward, A. L. (2010), Insect overwintering in a changing climate, *J. Exp. Biol*. 213, 980–94.

Ballard, J., Ellis, D. J. and Payne, C. C. (2000a), Uptake of granulovirus from the surface of apples and leaves by first instar larvae of the codling moth *Cydia pomonella* L. (Lepidoptera: Olethreutidae), *Biocontrol Sci. Technol*. 10, 617–25.

Ballard, J., Ellis, D. J. and Payne, C. C. (2000b), The role of formulation additives in increasing the potency of *Cydia pomonella* granulovirus for codling moth larvae, in laboratory and field experiments, *Biocontrol Sci. Technol*. 10, 627–40.

Barcenas, N. M., Unruh, T. R. and Neven, L. G. (2009), DNA diagnostics to identify internal feeders (Lepidoptera: Tortricidae) of pome fruits of quarantine importance, *J. Econ. Entomol*. 98(2), 299–306.

Barr, N. B., Ledezma, L. A., Farris, R. E., Epstein, M. E. and Gilligan, T. M. (2011), A multiplex real-time polymerase chain reaction assay to diagnose *Epiphyas postvittana* (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 104(5), 1706–19.

Barrett, B. A. (2008), Assessment of methoxyfenozide exposure on the sexual attractiveness and responsiveness of adult codling moth, *Cydia pomonella* L., in small orchard blocks, *Pest Manag. Sci*. 64, 916–22.

Barros-Parada, W., Knight, A. L. and Fuentes-Contreras, E. (2015), Modeling codling moth (Lepidoptera: Tortricidae) phenology and predicting egg hatch in apple orchards of the Maule region, Chile, *Chilean J. Agric. Res.* 75(1), 57–62.

Basoalto, E., Miranda, M., Knight, A. L. and Fuentes-Contreras, E. (2010), Landscape analysis of adult codling moth (Lepidoptera: Tortricidae) distribution and dispersal within typical agroecosystems dominated by apple production in central Chile, *Environ. Entomol*. 39, 1399–408.

Bastias, R. M., Manfrini, L. and Grappadelli, L. C. (2012), Exploring the potential use of photo-selective nets for fruit growth regulation in apple, *Chilean J. Agric. Res*. 72(2), 224–31.

Beers, E. H., Suckling, D. M., Prokopy, R. J. and Avilla, J. (2003), Ecology and management of apple arthropod pests, *in* Ferree, D. C. and Warrington, I. J. (Eds), *Apples: Botany, Production and Uses*, CABI Publishing, Wallingford, UK, pp. 489–519.

Beers, E. H., Brunner, J. F., Dunley, J. E., Doerr, M. and Granger, K. (2005), Role of neonicotinyl insecticides in Washington apple integrated pest management. Part II. Nontarget effects on integrated mite control, http://www.insectscience.org/ (accessed 16 May 2005).

Beers, E. H., Horton, D. R. and Miliczky, E. (2016a), Pesticides used against *Cydia pomonella* disrupt biological control of secondary pests of apple, *Biol. Control* 102, 35–43.

Beers, E. H., Mills, N. J., Shearer, P. W., Horton, D. R., Milickzy, E. R., et al. (2016b), Nontarget effects of orchard practices on natural enemies: Lessons from the field and laboratory, *Biol. Control* 102, 44–52.

Berling, M., Blachere-Lopez, C., Soubabere, O., Lery, X., Bonhomme, A., et al. (2009), *Cydia pomonella granulovirus* genotypes overcome virus resistance in the codling moth and improve virus efficiency by selection against resistant hosts, *Appl. Environ. Microbiol*. 75(4), 925–30.

Bezemer, T. M. and Mills, N. J. (2001), Host density responses of *Mastrus ridibundus*, a parasitoid of the codling moth, *Cydia pomonella*, *Biol. Control* 22, 169–75.

Biondi, A., Mommaerts, V., Smagghe, G., Vinuela, E., Zappala, L., et al. (2012), The non-target impact of spinosyns on beneficial arthropods, *Pest Manag. Sci*. 68, 1523–36.

Bloem, K. A. and Bloem, S. (2000), SIT for codling moth eradication in British Columbia, Canada, *in* Tan, K.-H. (Ed.), *Area-Wide Control of Fruit Flies and Other Insect Pests. Joint Proceedings of the International Conference on Area-wide Control of Insect Pests, and the Fifth International Symposium on Fruit Flies of Economic Importance*, May–June 1998, Penerbit Universiti Sains Malaysia, Pulau Penang, pp. 207–14.

Bloem, S., Bloem, K. A. and Knight, A. L. (1998), Oviposition by sterile codling moths, *Cydia pomonella* (Lepidoptera: Tortricidae) and control of wild populations with combined releases of sterile moths and egg parasitoids, *J. Entomol. Soc. Brit. Columbia* 95, 99–109.

Blomefield, T., Carpenter, J. E. and Vreysen, M. J. B. (2011), Quality of mass-reared codling moth (Lepidoptera: Tortricidae) after long distance transportation: 1. Logistics of shipping procedures and quality parameters as measured in the laboratory, *J. Econ. Entomol.* 104, 814–22.

Blommers, L. H. M. (1994), Integrated pest-management in European apple orchards, *Annu. Rev. Entomol*. 39, 213–41.

Boivin, T., d'Hières, C. C., Bouvier, J. C., Beslay, D. and Sauphanor, B. (2001), Pleiotropy of insecticide resistance in the codling moth, *Cydia pomonella*, *Entomol. Exp. Appl*. 99, 381–6.

Boivin, T., Bouvier, J. C., Chadoeuf, J., Beslay, D. and Sauphanor, B. (2003), Constraints on adaptive mutations in the codling moth *Cydia pomonella* (L.): Measuring fitness trade-offs and natural selection, *Heredity* 90, 107–13.

Boivin, T., Bouvier, J. C., Beslay, D. and Sauphanor, B. (2004), Variability in diapause propensity within populations of a temperate insect species: Interactions between insecticide resistance genes and photoperiodism, *Biol. J. Linnean Soc*. 83, 341–51.

Boncheva, R., Dukiandjiev, S., Minkov, I., de Maagd, R. A. and Naimov, S. (2006), Activity of *Bacillus thuringiensis* gamma-endotoxins against codling moth (*Cydia pomonella* L.) larvae, *J. Invert. Path*. 92, 96–9.

Bone, N. J., Thomson, L. J., Ridland, P. M., Cole, P. and Hoffman, A. A. (2009), Cover crops in Victorian apple orchards: Effects on production, natural enemies and pests across a season, *Crop Prot*. 28, 675–83.

Borchert, D. M., Walgenbach, J. F., Kennedy, G. G. and Long, J. W. (2004), Toxicity and residual activity of methoxyfenozide and tebufenozide to codling moth (Lepidoptera: Tortricidae) and oriental fruit moth (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 97(4), 1342–52.

Borchert, D. M., Walgenbach, J. F. and Kennedy, G. G. (2005), Assessment of sublethal effects of methoxyfenozide on oriental fruit moth (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 98(3), 765–71.

Boreau de Roince, C., Lavigne, C., Ricard, J.-M., Franck, P., Bouvier, J.-C., et al. (2012), Predation by generalist predators on the codling moth versus a closely-related emerging pest the oriental fruit moth: A molecular analysis, *Agric. Forest Entomol*. 14, 260–9.

Bosch, D., Rodriguez, M. A. and Avilla, J. (2015), Captures of MFO-resistant *Cydia pomonella* adults as affected by lure, crop management system and flight, *Bull. Entomol. Res*. 106(1), 54–62.

Bosch, D., Rodriguez, M. A., Depalo, L. and Avilla, J. (2018), Determination of the baseline susceptibility of European populations of *Cydia pomonella* (Lepidoptera: Tortricidae) to chlorantraniliprole and the role of Cytochrome P450 monooxygenases, *J. Econ. Entomol*. 111(2), 844–52.

Bostanian, N. J. and Racette, G. (2008), Particle films for managing arthropod pests of apple, *J. Econ. Entomol*. 101(1), 145–50.

Botto, E. and Glaz, P. (2010), Potential for controlling codling moth *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) in Argentina using the sterile insect technique and egg parasitoids, *J. Appl. Entomol*. 134, 251–60.

Brockerhoff, E. G., Suckling, D. M., Ecroyd, C. E., Wagstaff, S. J., Raabe, M. C., et al. (2011), Worldwide host plants of the highly polyphagous, invasive *Epiphyas postvittana* (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 104 (5), 1514–24.

Brockerhoff, E. G., Suckling, D. M., Kimberly, M., Richardson, B., Coker, G., et al. (2012), Aerial application of pheromones for mating disruption of an invasive moth as a potential eradication tool, *PLoS ONE* 7(8), 1–8.

Brown, J. W. (2005), *World Catalogue of Insects, Volume 5: Tortricidae (Lepidoptera)*, Apollo Books, Stenstrup, Denmark, 741pp.

Brown, J. W., Robinson, G. and Powell, J. A. (2008), *Food plant database of the leafrollers of the world (Lepidoptera: Tortricidae) (Version 1.0.0)*, available at: http://www.tortricidae.com/foodplants.asp (accessed 13 April 2018).

Brun-Barale, A., Bouvier, J.-C., Pauron, D., Bergé, J. B. and Sauphanor, B. (2005), Involvement of a sodium channel mutation in pyrethroid resistance in *Cydia pomonella* L, and development of a diagnostic test, *Pest Manag. Sci*. 61(6), 549–54.

Brunner, J. F., Dunley, J. E. and Doerr, M. (2005), Effect of pesticides on *Colpoclypeus florus* (Hymenoptera: Eulophidae) and *Trichogramma platneri* (Hymenoptera: Trichogrammatidae), parasitoids of leafrollers in Washington, *J. Econ. Entomol*. 94, 1075–84.

Burgi, L. P. and Mills, N. J. (2014), Lack of enemy release for an invasive leafroller in California: Temporal patterns and influence of host plant origin, *Biol. Invasions* 16, 1021–34.

Burgi, L. P., Roltsch, W. J. and Mills, N. J. (2015), Allee effects and population regulation: A test for biotic resistance against an invasive leafroller by resident parasitoids, *Popul. Ecol*. 57, 215–25.

Calkins, C. O. and Faust, R. J. (2003), Overview of areawide programs and the program for suppression of codling moth in the western USA directed by the United States Department of Agriculture – Agricultural Research Service, *Pest Manag. Sci*. 59, 601–4.

Calkins, C. O., Knight, A. L., Richardson, G. and Bloem, K. A. (2000), Area-wide suppression of codling moth. Area-wide control of fruit flies and other insect pests, *Joint Proceedings of the International Conference on Area-wide Control of Insect Pests*, 28 May – 2 June 1998 and the Fifth International Symposium on Fruit Flies of Economic Importance, Penang, Malaysia, 1–5 June 1998.

Carey, J. R. and Harder, D. (2013), Clear, present, significant, & imminent danger: Questions for the California light brown apple moth (*Epiphyas postvittana*) technical working group, *Am. Entomol*. 59(4), 240–7.

Carlson, G. R., Dhadialla, T. S., Hunter, R., Jansson, R. K., Jany, C. S., et al. (2001), The chemical and biological properties of methoxyfenozide a new insecticidal ecdysteroid agonist, *Pest Manag. Sci*. 57, 115–19.

Carrière, Y., Deland, J. P., Roff, D. A. and Vincent, C. (1994), Life-history costs associated with the evolution of insecticide resistance, *Proc. R Soc. Lond. B Biol. Sci*. 258, 35–40.

Casida, J. E. (2018), Neonicotinoids and other insect nicotinic receptor competitive modulators: Progress and prospects, *Annu. Rev. Entomol*. 63, 125–44.

Cassanelli, S., Reyes, M., Rault, M., Manicardi, G. C. and Sauphanor, B. (2006), Acetylcholinesterase mutation in an insecticide-resistant population of the codling moth *Cydia pomonella* (L.), *Insect Biochem. Mol. Biol*. 36(8), 642–53.

Chapman, P. J. (1973), Bionomics of the apple-feeding Tortricidae, *Annu. Rev. Entomol*. 18, 73–96.

Charmillot, P. J. and Pasquier, D. (1992), Modification de la fertilite du carpocapse *Cydia pomonella* a la suite du contact des adultes avec un régulateur ou un inhibiteur de croissance d'insectes, *Entomol. Exp. Appl*. 63, 87–93.

Charmillot, P. J., Gourmelon, A. L. and Pasquier, D. (2001), Ovicidal and larvicidal effectiveness of several insect growth inhibitors and régulators on the codling moth *Cydia pomonella* L. (Lep., Tortricidae), *J. Appl. Ent*. 125, 147–53.

Chen, M. H. and Dorn, S. (2009), Reliable and efficient discrimination of four internal fruit-feeding *Cydia* and *Grapholita* species (Lepidoptera: Tortricidae) by polymerase chain reaction-restriction fragment length polymorphism, *J. Econ. Entomol*. 102(6), 2209–16.

Chen, M. H. and Dorn, S. (2010), Microsatellites reveal genetic differentiation among populations in an insect species with high genetic variability in dispersal, the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), *Bull. Entomol. Res*. 100, 75–85.

Chidawanyika, F. and Terblanche, J. S. (2011), Costs and benefits of thermal acclimation for codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae): Implications for pest control and the sterile insect release programme, *Evol. Appl*. 4, 534–44.

Chouinard, G., Firle J. A. and Cormier, D. (2016), Going beyond sprays and killing agents: Exclusion, sterilization and disruption for insect pest control in pome and stone fruit orchards, *Sci. Hortic*. 208, 13–27.

Cichon, L., Fuentes-Contreras, E., Garrido, S., Lago, J., Barros-Parada, W., et al. (2013), Monitoring oriental fruit moth (Lepidoptera: Tortricidae) with sticky traps baited with terpinyl acetate and sex pheromone, *J. Appl. Entomol*. 137, 275–81.

Comas, C., Avilla, J., Sarasúa, M. J., Albajes, R. and Ribes-Dasi, M. (2012), Lack of anisotropic effects in the spatial distribution of *Cydia pomonella* pheromone trap catches in Catalonia, NE Spain, *Crop Prot*. 34, 88–95.

Cordova, D., Benner, E. A., Sacher M. D., Rauh, J. J., Sopa, J. S., et al. (2005), Anthranilic diamides: A new class of insecticides with a novel mode of action, ryanodine receptor activation, *Pest. Biochem. Physiol*. 84, 196–214.

Cossentine, J., Jensen, L. B. and Deglow, E. K. (2003), Strategy for orchard use of *Bacillus thuringiensis* while minimizing impact on *Choristoneura rosaceana* parasitoids, *Entomol. Exp. Appl.* 109(3), 205–10.

Cossentine, J., Jensen, L., Dedglow, E., Bennett, A., Goulet, H., et al. (2004), The parasitoid complex affecting *Choristoneura rosaceana* and *Pandemis limitata* in organically managed apple orchards, *Biocontrol* 49, 359–72.

Costes, E., Lauri, P. E. and Andrieu, B. (2013), Plant architecture, its diversity and manipulation in agronomic conditions, in relation with pest and pathogen attacks, *Eur. J. Plant Pathol*. 135, 455–70.

Cox, D. L., Knight, A. L., Biddinger, D. J., Lasota, J. A., Pikounis, B., et al. (1995), Toxicity and field efficacy of avermectins against codling moth (Lepidoptera: Tortricidae) on apples, *J. Econ. Entomol*. 88(3), 708–15.

Damos, P. (2015), Modular structure of web- based decision support systems for integrated pest management: A review, *Agron. Sustain. Dev*. 35, 1347–72.

Damos, P., Escudero-Colomar, L. A. and Ioratti, C. (2015), Integrated fruit production and pest management in Europe: The apple case study and how far we are from the original concept? *Insects* 6, 626–57.

Davidson, N. A., Dibble, J. E., Flint, M. L., Marer, P. J. and Guye, A. (1991), Managing insects and mites with spray oils, *IPM Edu. Pub. Statewide Integr. Pest Manag. Project University California* pub. 3347.

Delisle, J. and Vincent, C. (2002), Modified pheromone communication associated with insecticidal resistance in the obliquebanded leafroller, *Choristoneura rosaceana* (Lepidoptera: Tortricidae), *Chemoecol*. 12, 47–51.

Delate, K., McKern, A., Turnbull, R., Walker, J., Volz, R., et al. (2008), Organic apple production in two humid regions: Comparing progress in pest management strategies in Iowa and New Zealand, *HortSci*. 43(1), 12–20.

DeLury, N. C., Gries, R., Gries, G., Judd, G. J. R. and Khaskin, G. (1999), Moth scale-derived kairomones used by egg-larval parasitoid *Ascogaster quadridentate* to locate eggs of its host, *Cydia pomonella, J. Chem. Ecol*. 25, 2419–30.

Depalo, L., Masettia, A., Avilla, J., Bosch, D. and Pasqualini, E. (2016), Toxicity and residual activity of spinetoram to neonate larvae of *Grapholita molesta* (Busck) and *Cydia pomonella* (L.) (Lepidoptera: Tortricidae): Semi-field and laboratory trials, *Crop Prot*. 89, 32–7.

Devotto, L., del Valle, C., Ceballos, R. and Gerding, M. (2010), Biology of *Mastrus ridibundus* (Gravenhorst), a potential biological control agent for area-wide management of *Cydia pomonella* (Linneaus) (Lepidoptera: Tortricidae), *J. Appl. Entomol*. 134, 243–50.

Dhadialla, T. S., Carlson, G. R. and Le, D. P. (1998), New insecticides with ecdysteroidal and juvenile hormone activity, *Annu. Rev. Entomol*. 43, 545–69.

Dib, H., Sauphanor, B. and Capowiez, Y. (2010), Effect of codling moth exclusion nets on the rosy apple aphid, *Dysaphis plantaginea*, and its control by natural enemies, *Crop Prot*. 29, 1502–13.

Ding, B. J., Hofvander, P., Wang, H. L., Durrett, T. P., Stymne, S. and Lofstedt, C. (2014), A plant factory for moth pheromone production, *Nat. Commun.* 5, 3353.

Ding, B. J., Lager, I., Bansal, S., Durrett, T. P., Stymne, S. and Lofstedt, C. (2016), The yeast ATF1 acetyltransferase efficiently acetylates insect pheromone alcohols: Implications for the biological production of moth pheromones, *Lipids* 51(4), 469–75.

Dorigoni, A. (2016), Innovative fruit tree architecture as a nexus to improve sustainability in orchards, *Acta Hortic*. 1137, 1–10.

Dripps, J., Olson, B., Sparks, T. and Crouse, G. (2008), Spinetoram: How artificial intelligence combined natural fermentation with synthetic chemistry to produce a new spinosyn insecticide, *Plant Health Prog*. doi:10.1094/PHP-2008-0822-01-PS.

Drogue, S. and DeMaria, F. (2012), Pesticide residues and trade, the apple of discord? *Food Policy* 37, 641–9.

Duga, A. T., Ruysen, K., Dekeyser, D., Nuyttens, D. Bylemans, D., et al. (2015), Spray deposition profiles in pome fruit trees: Effects of sprayer design, training system and tree canopy characteristics, *Crop Prot*. 67, 200–13.

Dunley, J. E. and Welter, S. C. (2000), Correlated insecticide cross-resistance in azinphos-methyl resistant codling moth (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 93, 955–62.

Dunley, J. E., Brunner, J. F., Doerr, M. D. and Beers, E. H. (2006), Resistance and cross resistance in populations of the leafrollers, *Choristoneura rosaceana* and *Pandemis pyrusana*, in Washington apples, *J. Insect Sci.* 6, 14. Available online: insectscience.org/6.14

Durden, K., Sellars, S., Cowell, B. Brown, J. J. and Pszczolkowski, M. A. (2010), *Artemisia annua* extracts, artemisinin and 1,8-cineole prevent fruit infestation by major cosmopolitan pest of apples, *Pharma. Biol*. 49, 563–8. doi:10.3109/13880209.2010.528433.

Dyck, V. A. and Gardiner, G. T. (1992), Sterile-insect release program to control the codling moth *Cydia pomonella* (L.) (Lepidoptera: Olethreutidae) in British Columbia, Canada, *Acta Phytopath. Entomol. Hung.* 27(1–4), 219–22.

Dyck, V. A., Graham, S. H. and Bloem, K. A. (1993), Implementation of the sterile insect release programme to eradicate the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Olethreutidae), in British Columbia, Canada, *in Proceedings of the FAO/IAEA International Symposium on Management of Insect Pests: Nuclear and Related Molecular and Genetic Techniques*, 19–23 October 1992, Vienna, IAEA-SM-327/29, International Atomic Energy Agency, Vienna, Austria, pp. 285–97.

Elbert, A., Nauen, R. and McCaffery, A. (2007), IRAC, insecticide resistance and mode of action classification of insecticides, *in* Kramer, W. and Schirmer U. (Eds), *Modern Crop Protection Compounds*, Wiley, New York, NY, 600pp.

Ellis, N. H. and Hull, L. A. (2013), Factors influencing adult male *Grapholita molesta* dispersal in commercial *Malus* and *Prunus* host crops, *Entomol. Exp. Appl*. 146, 232–41.

El-Sayed, A. M., Fraser, H. M. and Trimble, R. M. (2001), Modification of the sex-pheromone communication system associated with organophosphorus-insecticide resistance in the obliquebanded leafroller (Lepidoptera: Tortricidae), *Can. Entomol*., 133, 867–81.

El-Sayed, A. M., Knight, A. L., Byers, J. A., Judd, G. J. R. and Suckling, D. M. (2016), Caterpillar-induced plant volatiles attract conspecific adults in nature, *Sci. Rep.* 6, 37555. doi:10.1038/srep37555.

Evans, R. G., Kroeger, M. W. and Mahan, M. O. (1995), Evaporative cooling of apples by overtree sprinkling, *Appl. Eng. Agric*. 11(1), 93–9.

Evenden, M. L. and Judd, G. J. R. (1999), Adult eclosion, flight and oviposition of *Choristoneura rosaceana* (Lepidoptera: Tortricidae), in British Columbia apple orchards, *J. Entomol. Soc. Brit. Columbia* 96, 77–88.

Fagua, G., Condamine, F. L., Horak, M., Zwick, A. and Sperling, F. A. H. (2016), Diversification shifts in leafroller moths linked to continental colonization and the rise of angiosperms, *Cladistics* 33, 449–66.

Farrar, R. R. and Ridgway, R. L. (1995), Enhancement of activity of *Bacillus thuringiensis* Berliner against four lepidopterous pests by nutrient-based phagostimulants, *J. Entomol. Sci*. 30(1), 29–42.

Fernández, D. E., Beers, E. H., Brunner, J. F, Doerr, M. D. and Dunley, J. E. (2005), Effects of seasonal mineral oil applications on the pest and natural enemy complexes of apple, *J. Econ. Entomol*. 98, 1630–40.

Fernández, D. E., Cichon, L. I., Sánchez, E. E., Garrido, S. A. and Gittins, C. (2008), Effect of different cover crops on the presence of arthropods in an organic apple (*Malus domestica* Borkh.) orchard, *J. Sustain. Agric*. 32(2), 197–211.

Ferrer, A., Mazzi, D. and Dorn, S. (2014), Stay cool, travel far: Cold-acclimated oriental fruit moth females have enhanced flight performance but lay fewer eggs, *Entomol. Exp. Appl*. 151, 11–18.

Fleischer, S. J., Weisz, R., Smilowitz, Z. and Midgarden, D. (1997), Spatial variation in insect populations and site-specific integrated pest management, *Site-Spefic. Manag. Agric. Syst*., pp. 101–30.

Fleischer, S. J., Blom, P. E. and Weisz, R. (1999), Sampling in Precision IPM: When the object is a map, *PhytoPath*. 89(11), 1112–18.

Follett, P. A. and Neven, L. G. (2006), Current trends in quarantine entomology, *Annu. Rev. Entomol*. 51, 359–85.

Follett, P. A. and Snook, K. (2012), Irradiation for quarantine control of the invasive light brown apple moth (Lepidoptera: Tortricidae) and a generic dose for tortricid eggs and larvae, *J. Econ. Entomol*. 105(6), 1971–8.

Foster, S. P. and Howard, A. J. (1999), The effects of mating, age at mating, and plant stimuli, on the lifetime fecundity and fertility of the generalist herbivore *Epiphyas postvittana, Entomol. Exp. Appl*. 91, 287–95.

Fox, R. D., Derksen, R. C., Zhu, H., Brazee, R. D. and Svensson, S. A. (2008), A history of air-blast sprayer development and future prospects, *Trans. ASABE* 51(2), 405–10.

Franck, P. and Timm, A. E. (2010), Population genetic structure of *Cydia pomonella*: A review and case study comparing spatiotemporal variation, *J. Appl. Entomol*. 134, 191–200.

Franck, P., Guerin, F., Loiseau, A. and Sauphanor, B. (2005), Isolation and characterization of microsatellite loci in the codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae), *Mol. Ecol*. 5(1), 99–102.

Franck, P., Reyes, M., Olivares, J. and Sauphanor, B. (2007), Genetic architecture in codling moth populations: Comparison between microsatellite and insecticide resistance markers, *Mol. Ecol*. 16, 3554–64.

Franck, P., Ricci, B., Klein, E. K., Olivares, J., Simon, S., et al. (2011), Genetic inferences about the population dynamics of codling moth females at a local scale, *Genetica* 139, 949–60.

Fraser, H. W. and Trimble, R. M. (2001), Effect of delayed mating on reproductive biology of the oriental fruit moth (Lepidoptera: Tortricidae), *Can. Entomol*. 133(2), 219–27.

Fritsch, E., Undorf-Spahn, K., Kienzle, J., Zebitz, C. P. W. and Huber, J. (2005), Apfelwicklel Granulovirus: Erste Hinweise auf Unterschiede in der Empfindlichkeit lokaler Apfelwickler-Populationen, *Nach. Deut. Pflanzen*. 57, 29–34.

Fuentes-Contreras, E., Reyes, M., Barros, W. and Sauphanor, B. (2007), Evaluation of azinphos-methyl resistance and activity of detoxifying enzymes in codling moth (Lepidoptera: Tortricidae) from central Chile, *J. Econ. Entomol*. 100, 551–6.

Fuentes-Contreras, E., Espinoza, J. L., Lavandero, B. and Ramirez, C. C. (2008), Population genetic structure of codling moth (Lepidoptera: Tortricidae) from apple orchards in central Chile, *J. Econ. Entomol*. 101, 190–8.

Published by Burleigh Dodds Science Publishing Limited, 2019.

Garcia-Salazar, C., Gut, L. J. and Whalon, M. E. (2007), Hedgerow barriers and other reduced-risk controls for managing oriental fruit moth, *Grapholitha molesta* (Busck) (Lepidoptera: Tortricidae) in apples, *Renew. Agric. Food Syst.* 22, 181–8.

Garczynski, S. F., Martin, J. A., Griset, M., Willett, L. S., Cooper, W. R., et al. (2017), CRISPR/Cas9 editing of the codling moth (Lepidoptera: Tortricidae) *CpomOR1* gene affects egg production and viability, *J. Econ. Entomol*. 110(4), 1847–55.

Gilligan, T. M., Baixeras, J. and Brown, J. W. (2018), *T@RTS: Online World Catalogue of the Tortricidae (Ver. 4.0)*, available at: http://www.tortricid.net/catalogue.asp (accessed 28 December 2018).

Gindaba, J. and Wand, J. E. (2005), Comparative effects of evaporative cooling, kaolin particle film, and shade net on sunburn and fruit quality in apples, *HortSci*. 40(3), 592–6.

Glenn, D. M., Puterka, G. J., Vanderzwet, T., Byers, R. E. and Feldhake, C. (1999), Hydrophobic particle films: A new paradigm for suppression of arthropod pests and plant diseases, *J. Econ. Entomol*. 92(4), 759–71.

Glenn, D. M., Puterka, G. J., Drake, S. R., Unruh, T. R. and Knight, A. L. (2001), Particle film application influences apple leaf physiology, fruit yield, and fruit quality, *J. Am. Soc. Hortic. Sci*. 126(2), 175–81.

Glenn, D. M., Prado, E., Erez, A., McFerson, J. and Puterka, G. J. (2002), A reflective, processed-kaolin particle film affects fruit temperature, radiation reflection, and solar injury in apple, *J. Am. Soc. Hortic. Sci*. 127(2), 188–93.

Gökce, A., Kim, S. S.-H., Wise, J. C. and Whalon, M. E. (2009), Reduced egg viability in codling moth *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) following adult exposure to novaluron, *Pest Manag. Sci*. 65, 283–7.

Graf, B., Hopli, H., Rauscher, S. and Hohn, H. (1999), Hail nets influence the migratory behavior of codling moth and leaf roller, *Obst- und Weinbau* 135, 289–92.

Granatstein, D. Kirby, E., Ostenson, H. and Willer, H. (2016), Global situation for organic tree fruits, *Sci. Hortic.* 208, 3–12.

Gu, H. N., Hughes, J. and Dorn, S. (2006), Trade-off between mobility and fitness in *Cydia pomonella* L. (Lepidoptera: Tortricidae), *Ecol. Entomol*. 31, 68–74.

Guarnieri, A., Maini, S. Molaro, G. and Rondelli, V. (2011), Automatic trap for moth detection in integrated pest management, *Bull Insect*. 64(2), 247–51.

Gupta, O., Das, A. J., Hellerstein, J. and Raskar, R. (2018), Machine learning approaches for large scale classification of produce, *Sci. Rep.* 8, 5226. doi: 10.1038/s41598-018-23394-3.

Gut, L. J. and Brunner, J. F. (1996), Implementing codling moth mating disruption in Washington pome fruit orchards, Washington State Tree Fruit Research Extension Center Bulletin 1, 12pp.

Gut, L. J. and Brunner, J. F. (1998), Pheromone-based management of the codling moth (Lepidoptera: Tortricidae) in Washington apple orchards, *J. Agric. Entomol*. 15, 387–405.

Hagstrom, A., Wang, H. L., Lienard, M. A., Lassance, J. M., Johansson, T. and Lofstedt, C. (2013), A moth pheromone brewery: Production of (Z)-11-hexadecenol by heterologous co-expression of two biosynthetic genes from a noctuid moth in a yeast cell factory, *Microb. Cell Fact.* 12, 125.

Hansen, J. D., Heidt, M. L. and Anderson, P. A. (2006), Bin sterilization to prevent reintroduction of codling moth, *J. Agric. Urban Entomol*. 23(1), 17–26.

Harris, M. O., Markwick, N. and Sandanayake, M. (2006), Is resistance to *Bacillus thuringiensis* endotoxin Cry1Ac associated with a change in the behavior of light brown apple moth larvae (Lepidoptera: Tortricidae)? *J. Econ. Entomol*. 99(2), 508–18.

Higbee, B. S., Calkins, C. O. and Temple, C. A. (2001), Overwintering of codling moth (Lepidoptera: Tortricidae) larvae in apple harvest bins and subsequent moth emergence, *J. Econ. Entomol*. 94, 1511–17.

Hilton, R. J., Riedl, H. and Westigard, P. H. (1992), Phytotoxicity response of pear to applications of abamectin-oil combinations, *HortSci.* 27 (12), 1280–2.

Horak, M. (1991), Morphology, *in* van der Geest, L. P. S. and Evenhuis, H. H. (Eds), *Tortricid Pests: Their Biology, Natural Enemies and Control*, Elsevier, Amsterdam, The Netherlands, pp. 1–22.

Horak, M. and Brown, R. L. (1991), Taxonomy and phylogeny, *in* van der Geest, L. P. S. and Evenhuis, H. H. (Eds), *Tortricid Pests: Their Biology, Natural Enemies and Control*, Elsevier, Amsterdam, The Netherlands, pp. 23–50.

Horner, R. M., Walker, J. T. S., Rogers, D. J., Lo, P. L. and Suckling, D. M. (2016), Use of the sterile insect technique in New Zealand: Benefits and constraints, *N. Z. Plant Prot*. 69, 296–304.

Hougardy, E., Bezemer, T. M. and Mills, N. J. (2005), Influence of host deprivation and egg expenditure on the reproduction capacity of *Mastrus ridibundus*, an introduced parasitoid for the biological control of codling moth in California, *Biol. Control* 33, 96–106.

Hsu, C. L., Agnello, A. M., and Reissig, W. H (2009), Edge effects in the directionally biased distribution of *Choristoneura rosaceana* (Lepidoptera: Tortricidae) in apple orchards, *Environ. Entomol*. 38, 433–41.

Hughes, W. O., Gailey, D. and Knapp, J. J. (2003), Host location by adult and larval codling moth and the potential for its disruption by the application of kariomones, *Entomol. Exp. Appl*. 106, 147–53.

Il'ichev, A. L., Gut, L. J., Williams, M. S. and Jerie, P. H. (2002), Area-wide approach for improved control of oriental fruit moth *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) by mating disruption, *Gen. Appl. Ent*. 31, 1–16.

Il'ichev, A. L., Williams, D. G. and Milner, A. D. (2004), Mating disruption barriers in pome fruit for improved control of oriental fruit moth *Grapholita molesta* Busck (Lepidoptera: Tortricidae) in stone fruit under mating disruption, *J. Appl. Entomol*. 128(2), 126–32.

Ioriatti, C. and Lucchi, A. (2016), Semiochemical strategies for tortricid moth control in apple orchards and vineyards in Italy, *J. Chem. Ecol*. 42(7), 571–83.

Ioriatti, C. and Tasin, M. (2018), Hail nets enhance disruption of sexual communication by synthetic pheromone in codling moth, *Entomol. Gen.* 37(1), 7–18.

Jeanneret, P. and Charmillot, P. J. (1995), Movements of tortricid moths (Lep., Tortricidae) between apple orchards and adjacent ecosystems, *Agric. Ecosyst. Environ.* 55, 37–49.

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A. and Charpentier, E. (2012), A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity, *Science* 337(6096), 816–21.

Jones, V. P., Eastburn, C. C., Wilburn, T. D. and Brunner J. F. (2005), Instar-specific phenology of *Pandemis pyrusana* and *Choristoneura rosaceana* (Lepidoptera: Tortricidae) in Washington apple orchards, *J. Econ. Entomol*. 98(3), 875–83.

Jones, V. P., Hagler, J. R., Brunner, J. F., Baker, C. C. and Wilburn, T. D. (2006a), An inexpensive immunomarking technique for studying movement patterns of naturally occurring insect populations, *Environ. Entomol*. 35, 827–36.

Jones, V. P., Wilburn, T. D. and Baker, C. C. (2006b), Movement of codling moth between abandoned and commercial orchards, *Proc. Wash. State Hortic. Soc*. 100, 180–4.

Jones, V. P., Wiman, N. G. and Brunner, J. F. (2008a), Comparison of delayed female mating on reproductive biology of codling moth and obliquebanded leafroller, *Environ. Entomol.* 37(3), 679–85.

Jones, V. P., Doerr, M. and Brunner, J. F. (2008b), Is biofix necessary for predicting codling moth (Lepidoptera: Tortricidae) emergence in Washington state apple orchards? *J. Econ. Entomol*. 101(5), 1651–7.

Jones, V. P., Unruh, T. R., Horton, D. R., Mills, N. J., Brunner, J. F., et al. (2009a), Tree fruit IPM programs in the western United States: The challenge of enhancing biological control through intensive management, *Pest Manag. Sci*. 65, 1305–10.

Jones, V. P., Brunner, J. F., Grove, Petit, B., Tangren, G. V. and Jones, W. E. (2009b), A web-based decision support system to enhance IPM programs in Washington tree fruit, *Pest Manag. Sci*. 66, 587–95.

Jones, V. P., Hilton, R., Brunner, J. F., Bentley, W. J., Alston, D. G., et al. (2013), Predicting the emergence of the codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae), on a degree-day scale in North America, *Pest Manag. Sci*. doi:10.1002/ps.3519.

Joshi, N. K., Rajotte, E. G., Naithani, K. J., Krawczyk, G. and Hull, L. A. (2016), Population dynamics and flight phenology model of codling moth differ between commercial and abandoned apple orchard ecosystems, *Front. Physiol*. 7, 408, 1–13.

Judd, G. J. R. and Gardiner, M. G. T. (2005), Towards eradication of codling moth in British Columbia by complimentary actions of mating disruption, tree banding and sterile insect technique: Five-year study in organic orchards, *Crop Prot*. 24, 718–33.

Judd, G. J. R. and Gardiner, M. G. T. (2006a), Simultaneous disruption of pheromone communication and mating in *Cydia pomonella*, *Choristoneura rosaceana*, and *Pandemis limitata* (Lepidoptera: Tortricidae) using Isomate-CM/LR in apple orchards, *J. Entomol. Soc. Brit. Columbia* 101, 3–13.

Judd, G. J. R. and Gardiner, M. G. T. (2006b), Temperature, irradiation and delivery as factors affecting spring time flight activity and recapture of mass reared male codling moths released by the Okanagan-Kootenay sterile insect programme, *J. Entomol. Soc. Brit. Columbia* 103, 19–32.

Judd, G. J. R., Knight, A. L. and El-Sayed, A. M. (2017a), Trapping *Pandemis limitata* (Lepidoptera: Tortricidae) moths with mixtures of acetic acid, caterpillar-induced apple-leaf volatiles, and sex pheromone, *Can. Entomol*. 149, 813–22.

Judd, G. J. R., Knight, A. L. and El-Sayed, A. M. (2017b), Development of kairomone-based lures and traps targeting *Spilonota ocellana* (Lepidoptera: Tortricidae) in apple orchards treated with sex pheromones, *Can. Entomol.* 149, 662–76.

Judd, G. J. R., Gardiner, M. G. T. and Thistlewood, H. M. A. (2004), Seasonal variation in recapture of mass-reared sterile codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae): Implications for control by sterile insect technique in British Columbia, *J. Entomol. Soc. Brit. Columbia* 101, 29–43.

Judd, G. J. R., Thistlewood, H. M. A., Gardiner, M. G. T. and Lannard, B. L. (2006a), Is lack of mating competitiveness in spring linked to mating asynchrony between wild and mass-reared male codling moth from an operational sterile insect programme? *Entomol. Exp. Appl*. 120, 113–24.

Judd, G. J. R., Cockburn, S., Eby, C., Gardiner, M. G. T. and Wood, S. (2006b), Diapause improves spring-time mating competitiveness of male codling moth mass-reared for a sterile insect programme, *Entomol. Exp. Appl*. 120, 161–6.

Judd, G. J. R., Arthur, S., Deglow, K. and Gardiner, M. G. T. (2011), Operational mark-release-recapture field tests comparing competitiveness of wild and differentially mass-reared codling moths from the Okanagan-Kootenay sterile insect program, *Can. Entomol*. 143, 300–16.

Kazmierczak, R. F., Norton, G. W., Knight, A. L., Rajotte, E. G. and Hull, L. A. (1993), Economic effects of resistance and withdrawal of organophosphate pesticides on an apple production system, *J. Econ. Entomol*. 86(3), 684–96.

Keil, S., Gu, H. N. and Dorn, S. (2001a), Response of *Cydia pomonella* to selection on mobility: Laboratory evaluation and field verification, *Ecol. Entomol*. 26, 495–501.

Keil, S., Gu, H. N. and Dorn, S. (2001b), Diel patterns of locomotor activity in *Cydia pomonella*: Age and sex related differences and effects of insect hormone mimics, *Physiol. Entomol*. 26, 306–14.

Kienzle, J., Schultz, C., Zebitz, C. P. W. and Huber, J. (2003), Codling moth granulovirus as a tool for resistance management and area-wide population control, *IOBC/WPRS Bull*. 26(11),69–74.

Kim, Y., Yung, S., Kim, Y. and Lee, Y. (2011), Real-time monitoring of oriental fruit moth, *Grapholita molesta* populations using a remote sensing pheromone trap in apple orchards, *J. Asia Pac. Entomol*. 14, 259–62

Kirk, H., Dorn, S. and Mazzi, D. (2013), Worldwide population genetic structure of the oriental fruit moth (*Grapholita molesta)*, a globally invasive pest, *BMC Ecol.* 13, 12.

Knight, A. L. (1994), Insect pest and natural enemy populations in paired organic and conventional apple orchards in the Yakima Valley, Washington, *J. Entomol. Soc. Brit. Columbia* 91, 27–36.

Knight, A. L. (1995), The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington, *J. Entomol. Soc. Brit. Columbia* 92, 29–38.

Knight, A. L. (1997a), Optimizing the use of Bts for leafroller control, *Good Fruit Grower* 48, 47–9. 1997.

Knight, A. L. (1997b), Delay of mating of codling moth in pheromone-treated orchards, *IOBC/WPRS Bull.* 20, 203–6.

Knight, A. L. (1998a), Activity of Cry1 endotoxin of *Bacillus thuringiensis* for four tree fruit leafroller pest species (Lepidoptera: Tortricidae), *J. Agric. Entomol*. 15(20), 93–103.

Knight, A. L. (1998b), Management of codling moth (Lepidoptera: Tortricidae) in apple with overhead watering, *J. Econ. Entomol*. 91(1), 209–16.

Knight, A. L. (1999), Spatial versus sociological-based pest management: Biological and economic constraints, *Proc. Wash. Hortic. Assoc*. 95, 167–8.

Knight, A. L. (2001), Monitoring the seasonal population density of *Pandemis pyrusana* (Lepidoptera: Tortricidae) within a diverse fruit crop production area in the Yakima Valley, WA, *J. Entomol. Soc. Brit. Columbia* 217–25.

Knight, A. L. (2006), Assessing the mating status of female codling moth (Lepidoptera: Tortricidae) in orchards treated with sex pheromone using traps baited with ethyl (*E, Z*)-2,4-decadienoate, *Environ. Entomol*. 35(4), 894–900.

Knight, A. L. (2007a), Multiple mating of male and female codling moth (Lepidoptera, Tortricidae) in apple orchards treated with sex pheromone, *Environ. Entomol*. 36, 157–64.

Published by Burleigh Dodds Science Publishing Limited, 2019.

Knight, A. L. (2007b), Influence of within-orchard trap placement on catch of codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards, *Environ. Entomol*. 36(2), 425–32.

Knight, A. L. (2007c), Adjusting the phenology model of codling moth (Lepidoptera: Tortricidae) in Washington State apple orchards, *Environ. Entomol*. 36(6), 1485–93.

Knight, A. L. (2008), Areawide pest management, theory and implementation, *in* Koul, O., Cuperus, G. W. and Elliot, N. (Eds), *Codling Moth Areawide Integrated Pest Management*, CAB International, Wallingford, UK, pp. 159–90.

Knight, A. L. (2010a), Targeting *Cydia pomonella* (l.) (Lepidoptera: Tortricidae) adults with low-volume applications of insecticides alone and in combination with sex pheromone, *Pest Manage. Sci*. 66, 709–17.

Knight, A. L. (2010b), Cross-resistance between azinphos-methyl and acetamiprid in populations of codling moth, *Cydia pomonella* (L.) (Lepidoptera; Tortricidae), from Washington State, *Pest Manag. Sci*. 66 (8), 865–74.

Knight, A. L. and Flexner, L. (2007), Disruption of mating in codling moth (Lepidoptera: Tortricidae) by chlorantranilipole, an anthranilic diamide insecticide, *Pest Manag. Sci*. 63, 180–9.

Knight, A. L. and Light, D. M. (2001), Attractants from Bartlett pear for codling moth, *Cydia pomonella* (L.) larvae, *Naturwissenschaften* 88(8), 339–42.

Knight, A. L. and Light, D. M. (2004), Use of ethyl (*E,Z*)-2,4-decadienoate in codling moth management, stimulation of oviposition, *J. Entomol. Soc. British Columbia* 101, 53–60.

Knight, A. L. and Light, D. M. (2005a), Dose-response of codling moth (Lepidoptera: Tortricidae) to ethyl (*E,Z*)-2,4-Decadienoate in apple orchards treated with sex pheromone dispensers, *Environ. Entomol*. 34(3), 604–9.

Knight, A. L. and Light, D. M. (2005b), Developing action thresholds for codling moth (Lepidoptera: Tortricidae) with pear ester- and codlemone-baited traps in apple orchards treated with sex pheromone mating disruption, *Can. Entomol*. 137, 739–47.

Knight, A. L. and Light, D. M. (2005c), Timing of egg hatch by early-season codling moth (Lepidoptera: Tortricidae) predicted by moth catch in pear ester- and codlemone-baited traps, *Can. Entomol*. 137, 728–38.

Knight, A. L. and Light, D. M. (2012), Monitoring codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards with (*E*)-4,8-dimethyl-1,3,7-nonatriene or pear ester in combination with codlemone and acetic acid, *Environ. Entomol*. 41, 407–14.

Knight, A. L. and Light, D. M. (2013), Adding microencapsulated pear ester to insecticides for control of *Cydia pomonella* (Lepidoptera, Tortricidae) in apple, *Pest Manag. Sci*. 69, 66–74.

Knight, A. L. and Light, D. M. (2014), Combined approaches using sex pheromone and pear ester for behavioural disruption of codling moth (Lepidoptera: Tortricidae), *J. Appl. Entomol*. 138, 96–108.

Knight, A. L. and Moffitt, H. R. (1991), Evaluation of packinghouse removal of codling moth-injured apples, *Tree Fruit Postharvest J*. 2(1), 14–15.

Knight, A. L. and Norton, G. W. (1989), Economics of agricultural pesticide resistance in arthropods, *Annu. Rev. Entomol*. 34, 293–313.

Knight, A. L. and Witzgall, P. (2013), Combining mutualistic yeast and pathogenic virus – a novel method for codling moth control, *J. Chem. Ecol*. 39, 1019–26.

Knight, A. L., Brunner, J. F. and Alston, D. (1994), Survey of azinphosmethyl resistance in codling moth (Lepidoptera: Tortricidae) in Washington and Utah, *J. Econ. Entomol*. 87(2), 285–92.

Knight, A. L., Howell, J. F., McDonough and Weiss, M. (1995), Mating disruption of codling moth (Lepidoptera: Tortricidae) with polyethylene tube dispensers: Determining emission rates and the distribution of fruit injuries, *J. Agric. Entomol*. 12(2), 85–100.

Knight, A. L., Turner, J. E. and Brachula, B. (1997), Predation on eggs of codling moth (Lepidoptera: Tortricidae) in mating disrupted and conventional orchards in Washington, *J. Entomol. Soc. Brit. Columbia* 94, 67–74.

Knight, A. L., Croft, B. A. and Bloem, K. A. (1999), Effect of mating disruption dispenser placement on trap performance for monitoring codling moth (Lepidoptera: Tortricidae), *J. Entomol. Brit. Columbia* 96, 95–102.

Knight, A. L., Unruh, T. R., Christianson, B. A., Puterka, G. J. and Glenn, D. M. (2000a), Effects of a kaolin-based particle film on obliquebanded leafroller (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 93(3), 744–9.

Knight, A. L., Unruh, T. R., Christianson, B. A., Puterka, G. J. and Glenn, D. M. (2000b), Impacts of seasonal kaolin particle films on apple pest management, *Can. Entomol*. 133, 413–28.

Knight, A. L., Dunley, J. E. and Jansson, R. K. (2001a), Baseline monitoring of codling moth (Lepidoptera: Tortricidae) larval response to benzoylhydrazine insecticides, *J. Econ. Entomol*. 94(1), 264–70.

Knight, A. L., Christianson, B., Cockfield, S. and Dunley, J. (2001b), Areawide management of codling moth and leafrollers, *Good Fruit Grower* 52, 31–3.

Knight, A. L., Hilton, R. and Light, D. M. (2005), Monitoring codling moth (Lepidoptera: Tortricidae) in apple with blends of ethyl (*E,Z*)-2,4-Decadienoate and codlemone, *Environ. Entomol*. 34(3), 598–603.

Knight, A., Hawkins, L.; McNamara, K. and Hilton, R. (2009), Monitoring, managing codling moth clearly and precisely, *Good Fruit Grower* 60(4), 26–7.

Knight, A., Hawkins, L., McNamara, K., Borman, M. and Hilton, R. (2011), Managing codling moth clearly and precisely with semiochemicals, *IOBC/WPRS Bull*. 54, 415–18.

Knight, A. L., Stelinski, L. L., Hebert, V., Gut, L. Light, D., et al. (2012a), Evaluation of novel semiochemical dispensers simultaneously releasing pear ester and sex pheromone for mating disruption of codling moth (Lepidoptera: Tortricidae), *J. Appl. Entomol*. 136, 79–86.

Knight, A., Light, D. and Chebny, V. (2012b), Evaluating dispensers loaded with codlemone and pearester for disruption of codling moth (Lepidoptera: Tortricidae), *Environ. Entomol*. 41, 399–406.

Knight, A. L., Hilton, R. Basoalto, E. and Stelinski, L. L. (2014), Use of acetic acid to enhance bisexual monitoring of tortricid pests with kairomone lures in pome fruits, *Environ. Entomol*. 43 (6), 1628–40.

Knight, A. L., Basoalto, E. and Witzgall, P. (2015), Improving the performance of the granulosis virus of codling moth (Lepidoptera, Tortricidae) by adding the yeast *Saccharomyces cerevisiae* with sugar, *Environ. Entomol*. 44, 252–9.

Knight, A. L., El-Sayed, A. M., Judd, G. J. R. and Basoalto, E. (2017), Development of 2-phenylethanol plus acetic acid lures to monitor obliquebanded leafroller (Lepidoptera: Tortricidae) under mating disruption, *J. Appl. Entomol*. 141, 729–39.

Kogan, M. (1998), Integrated pest management: historical perspectives and contemporary developments, *Annu. Rev. Entomol.* 43, 243–70.

Konopka, J. K., Scott, I. M. and McNeil, J. N. (2012), Costs of insecticide resistance in *Cydia pomonella* (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 105 (3), 872–7.

Kovaleski, A. and Mumford, J. (2007), Pulling out the evil by the root: The codling moth *Cydia pomonella* eradication programme in Brazil, *in* Vreysen, M. J. B., Robinson, A. S. and Hendrichs, J. (Eds), *Area-wide Control of Insect Pests, From Research to Field Implementation*, Springer, Dordrecht, pp. 581–90.

Kovanci, O. B., Walgenbach, J. F. and Kennedy, G. G. (2004), Evaluation of extended-season mating disruption of the oriental fruit moth *Grapholita molesta* (Busck) (Lepidopeta: Tortricidae) in apples, *J. Appl. Entomol*. 128(9), 664–9.

Kuhlmann, U. and Mills, N. J. (1999), Exploring the diversity of central Asia to assess specialized parasitoids for biological control of apple pests in Europe and North America, *IOBC/WPRS Bull*. 22, 1–6.

Kührt, U., Samietz, J. and Dorn, S. (2006), Effect of plant architecture and hail nets on temperature of codling moth habitats in apple orchards, *Entomol. Exp. Appl*. 118, 245–59.

Kumar, S., Neven, L. G., Zhu, H. and Zhang, R. (2015), Assessing the global risk of establishment of *Cydia pomonella* (Lepidoptera: Tortricidae) using CLIMEX and MaxEnt niche models, *J. Econ. Entomol*. 108, 1708–19.

Kwon, D. H., Kwon, H. K., Kim, D. H. and Yang, C. Y. (2018), Larval species composition and genetic structures of *Carposina sasakii*, *Grapholita dimorpha*, and *Grapholita molesta* from Korea, *Bull. Entomol. Res*. 108, 241–52.

Lacey, L. A. and Chauvin, R. L. (1999), Entomopathogenic nematodes for control of diapausing codling moth (Lepidoptera: Tortricidae) in fruit bins, *J. Econ. Entomol*. 92(1), 104–9.

Lacey, L. A. and Shapiro-Ilan, D. I. (2008), Microbial control of insect pests in temperate orchard systems: Potential for incorporation into IPM, *Annu. Rev. Entomol*. 53, 121–44.

Lacey, L. A., Arthurs, S., Knight, A. L. Becker, K. and Headrich, H. (2004), Efficacy of codling moth granulovirus: Effect of adjuvants on persistence of activity and comparison with other larvicides in a Pacific Northwest apple orchard, *J. Entomol. Sci*. 39(4), 500–13.

Lacey, L. A., Arthurs, S. P. and Headrick, H. (2005), Comparative activity of the codling moth granulovirus against *Grapholita molesta* and *Cydia pomonella* (Lepidoptera: Tortricidae), *J. Entomol. Soc. Brit. Columbia* 102, 79–80.

Lacey, L. A., Arthurs, S. P., Unruh, T. R., Headricks, H. and Fritts, R. (2006), Entomopathogenic nematodes for control of codling moth (lepidoptera: Tortricidae) in apple and pear orchards: Effect of nematode species and seasonal temperatures, adjuvants, application equipment, and post-application irrigation, *Biol. Control* 37, 214–23.

Lahm, G. P., Selby, T. P., Freudenberger, J. H., Stevenson, T. M., Myers, B. J., et al. (2005), Insecticidal anthranilic diamides: A new class of potent ryanodine receptor activators, *Bioorg. Med. Chem. Lett*. 15, 4898–906.

Lalancette, N., Belding, R. D., Shearer, P. W., Frecon, J. L. and Tietjen, W. H. (2004), Evaluation of hydrophobic and hydrophilic kaolin particle films for peach crop, arthropod and disease management, *Pest Manage. Sci*. 61(1), 25–39.

Landolt, P. J., Hofstetter, R. W. and Biddick, L. L. (1999), Plant essential oils as arrestants and repellents for neonate larvae of the codling moth (Lepidoptera: Tortricidae), *Environ. Entomol*. 28(6), 954–60.

Landolt, P. J., Suckling, D. M. and Judd, G. (2007), Positive interaction of a feeding attractant and host kairomone for trapping the codling moth (Lepidoptera: Tortricidae), *J. Chem. Ecol*. 33, 2236–44.

Larocque, N., Vincent, C., Belanger A. and Bourassa, J. P. (1999), Effects of tansy essential oil from *Tanacetum vulgare* on biology of obliquebanded leafroller, *Choristoneura rosaceana, J. Chem. Ecol*. 25(6), 1319–30.

Lawson, D. S., Reissig, W. H., Nyrop, J. P. and Brown, S. K. (1994), Management of arthropods on columnar apple trees using exclusionary cages, *Crop Prot*. 13(5), 346–56.

Lawson, D. S., Nyrop, J. P. and Reissig, W. H. (1997), Assays with commercially produced *Trichogramma* (Hymenoptera: Trichogrammatidae) to determine suitability for obliquebanded leafroller (Lepidoptera: Tortricidae) control, *Environ. Entomol*. 26(3), 684–93.

Li, M., Ekramirad, N. Radym A. and Adedeji, A. (2018), Application of acoustic emission and machine learning to detect moth infested apples, *Trans. ASABE* 37, 1–15.

Light, D. M. and Beck, J. J. (2010), Characterization of microencapsulated pear ester, (2*E*,4*Z*)-ethyl-2,4-decadienoate, a kairomonal spray adjuvant against neonate codling moth larvae, *J. Agric. Food Chem*. 58, 7836–45.

Light, D. M. and Beck, J. J. (2012), Behavior of codling moth (Lepidoptera, Tortricidae) neonate larvae on surfaces treated with microencapsulated pear ester, *Environ. Entomol*. 41(3), 603–11.

Light, D. M. and Knight, A. L. (2005), Kairomone-augmented mating disruption control for codling moth in Californian walnuts and apples, *IOBC/WPRS Bull.* 28, 300–3.

Light, D. M. and Knight, A. L. (2011), Microencapsulated pear ester enhances insecticide efficacy in walnuts for codling moth (Lepidoptera, Tortricidae) and navel orangeworm (Lepidoptera, Pyralidae), *J. Econ. Entomol*. 104(4), 1309–15.

Light. D. M., Knight, A. L., Henrick, C. A., Rajapaska, D., Lingren, B., et al. (2001), A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.), *Naturwissenschaften* 88(8), 333–8.

Lloyd, A., Hamacek, E, George, A., Nissen, R. and Waite, G. (2005), Evaluation of exclusion netting for insect pest control and fruit quality enhancement in tree crops, *Acta Hortic.* 694, 253–8.

Lo, P. L., Walker, J. T. S., Horner, R. M. and Hedderley, D. I. (2013), Development of multiple species mating disruption to control codling moth and leafrollers (Lepidoptera: Tortricidae), in New Zealand, *Plant Prot*. 66, 264–9.

Lo, P. L., Walker, J. T. S., Hedderley, D. I. and Cole, L. M. (2018), Reduction in leafroller (Lepidoptera; Tortricidae) abundance in orchards and vineyards 1976–2016 in Hawke's bay, New Zealand, *Agric. For. Entomol*. doi:10.1111/afe.12283.

Lombarkia, N. and Derridj, S. (2002), Incidence of apple fruit and leaf surface metabolites on *Cydia pomonella* oviposition, *Entomol. Exp. Appl.* 104(1), 79–97.

Lombarkia, N. and Derridj, S. (2008), Resistance of apple trees to *Cydia pomonella* egg-laying due to leaf surface metabolites, *Entomol. Exp. Appl.* 128(1), 57–65.

Lombarkia, N., Derridj, S., Ioriatti, C. and Bourget, E. (2013), Effect of a granulovirus larvicide, Madex, on egg-laying of *Cydia pomonella* L. (Lepidoptera: Tortricidae) due to changes in chemical signalization on the apple leaf surface, *Afr. Entomol.* 21(2), 196–208.

Lowery, D. T. and Smirle, M. J. (2000), Toxicity of insecticides to obliquebanded leafroller, *Choristoneura rosaceana*, larvae and adults exposed previously to neem seed oil, *Entomol. Exp. Appl*. 95, 201–7.

Luedeling, E., Steinmann, K. P., Zhang, M., Brown, P. H., Grant, J., et al. (2011), Climate change effects on walnut pests in California, *Global Change Biol*. 17, 228–38.

MacCollom, G. B. and Reed, E. M. (1971), A nuclear polyhedrosis virus of the light brown apple moth, *Epiphyas postvittana*, *J. Invert. Pathol.* 18(3), 337–43.

Machial, C. M., Ikkei, S., Smirle, M., Bradbury, R. and Isman, M. B. (2010), Evaluation of the toxicity of 17 essential oils against *Choristoneura rosaceana* (Lepidoptera: Tortricidae) and *Trichoplusia ni* (Lepidoptera: Noctuidae), *Pest Manag. Sci.*, 66, 1116–21.

MacLellan, C. R. (1973), Natural enemies of the light brown apple moth, *Epiphyas postvittana* in the Australian Capital Territory, *Can. Entomol*. 105(3), 681–700.

Magalhaes, L. C. and Walgenbach, J. F. (2011), Life stage toxicity and residual activity of insecticides to codling moth and oriental fruit moth (Lepidoptera: Tortricidae), *J. Econ. Entomol.* 104(6), 1950–9.

Magalhaes, L. C., Van Kretschmar, J. B., Barlow, V. M., Roe, R. M. and Walgenbach, J. F. (2012), Development of a rapid resistance monitoring bioassay for codling moth larvae, *Pest Manag. Sci*. 68, 883–8.

Maheswaran, G., Pridmore, L., Franz, P. and Anderson, M. A. (2007), A proteinase inhibitor from *Nicotiana alata* inhibits the normal development of light-brown apple moth, *Epiphyas postvittana* in transgenic apple plants, *Plant Cell Rep.* 26(6), 773–82.

Mani, E. and Wildbolz, T. (1977), The dispersal of male codling moths (*Laspeyresia pomonella* L.) in the upper Rhine valley, *J. Appl. Entomol.* 83(1), 161–8.

Margaritopoulos, J. T., Voudouris, C. C., Olivares, J., Sauphanor, B., Mamuris, Z., et al. (2012), Dispersal ability in codling moth: Mark-release-recapture experiments and kinship analysis, *Agric. Forest Entomol*. 14, 399–407.

Marko, V., Blommers, L. H. M., Bogya, S. and Helsen, H. (2008), Kaolin particle films suppress many apple pests, disrupt natural enemies and promote woolly apple aphid, *J. Appl. Entomol*. 132, 26–35.

Marko, V., Jenser, G., Muhalyi, K. Hegyi, T. and Balazs, K. (2012), Flowers for better pest control? Effects of apple orchard groundcover management on mites (Acari), leafminers (Lepidoptera: Scitellidae), and fruit pests, *Biocontrol Sci. Technol*. 22(1), 39–60.

Markwick, N. P., Docherty, L. C., Phung, M. M., Lester, M. T., Murray, C., et al. (2003), Transgenic tobacco and apple plants expressing biotin-binding proteins are resistant to two cosmopolitan insect pests, potato tuber moth and light brown apple moth, respectively, *Transgenic Res*. 12, 671–81.

Marliac, G., Penvern, S., Barbier, J.-M., Lescourret, F. and Capowiez, Y. (2015), Impact of crop protection strategies on natural enemies in organic apple production, *Agron. Sustain. Dev*. 35, 803–13.

Mastrangelo, T., Parker, A. G., Jessup, A., Pereira, R., Orozco-Dávila, D., et al. (2010), A new generation of X ray irradiators for insect sterilization, *J. Econ. Entomol*. 103, 85–94.

McCann, S. F., Annis, G. D., Shapiro, R., Piotrowski, D. W., Lahm, G. P., et al. (2001), The discovery of indoxacarb: Oxadiazines as a new class of pyrazoline-type insecticides, *Pest Manag. Sci*. 57, 153–64.

McDougall, S. J. and Mills, N. J. (1997), The influence of hosts, temperature and food sources on the longevity of *Trichogramma platneri*, *Entomol. Exp. Appl*. 83, 195–203.

McGhee, P. S., Epstein, D. L. and Gut, L. J. (2011), Quantifying the benefits of areawide pheromone mating disruption programs that target codling moth (Lepidoptera: Tortricidae), *Am. Entomol*. 57(2), 93–100.

Men, Q.-L., Chen, M.-H., Zhang, Y.-L. and Feng, L.-L. (2013), Genetic structure and diversity of a newly invasive species, the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) in China, *Biol. Invasions* 15, 447–58.

Merckx, T., Feber, R. E., Dulieu, R. L., Townsend, M. C. and Parsons, M. S. (2009), Effect of field margins on moths depends on species mobility: Field-based evidence for landscape-scale conservation, *Agric. Ecosyst. Environ*. 129, 302–9.

Miliczky, E. R. and Calkins, C. O. (2002), Spiders (*Araneae*) as potential predators of leafroller larvae and egg masses (Lepidoptera: Tortricidae) in Central Washington apple and pear orchards, *Pan-Pacif. Entomol.* 78(2), 140–50.

Miller, J. R. and Gut, L. J. (2015), Mating disruption for the 21st century: Matching technology with mechanism, *Environ. Entomol*. 44(3), 427–53.

Mills, N. (2003), Augmentation in orchards: Improving the efficacy of *Trichogramma* inundation, *in* van Driesche, R. (Ed.), *1st International Symposium on Biological Control of Arthropods*, USDA Forest Service, pp. 130–5.

Mills, N. (2005), Selecting effective parasitoids for biological control introductions: Codling moth as a case study, *Biol. Control* 34, 274–82.

Mills, N. (2013), Biological pest control in organic tree crops in the western U.S.: An overview. *Acta Hortic*. 1001, 105–10.

Mills, N. J., Pickel, C., Mansfield S., McDougall, S., Buchner, R., et al. (2000), *Trichogramma* inundation: Integrating parasitism into management of codling moth, *Calif. Agric*. 54(6), 22–5.

Mills, N. J., Beers, E. H., Shearer, P. W., Unruh, T. R. and Amarasekare, K. G. (2016), Comparative analysis of pesticide effects on natural enemies in western orchards: A synthesis of laboratory bioassay data, *Biol. Control* 102, 17–25.

Monteiro, L. B., Lavigne, C., Ricci, B., Franck, P., Toubon, J.-F., et al. (2012), Predation of codling moth eggs is affected by pest management practices at orchard and landscape levels, *Agric. Ecosyst. Environ*. doi:10.1016/j.agee.2011.10.012.

Mota-Sanchez, D., Wise, J. C., VanderPoppen, R., Gut, L. J. and Hollingworth, R. M. (2008), Resistance of codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), larvae in Michigan to insecticides with different modes of action and the impact on field residual activity, *Pest Manag. Sci*. 64, 881–90.

Mujica, V., Preti, M., Basoalto, E., Cichon, L., Fuentes-Contreras, E., et al. (2018), Improved monitoring of oriental fruit moth (Lepidoptera: Tortricidae) with terpinyl acetate plus acetic acid membrane lures, *J. Appl. Entomol*. 142, 731–44.

Mullinix, K., Isman, M. B. and Brunner, J. F. (2010), Key and secondary arthropod pest population trends in apple cultivated over four seasons with no insecticides and a legume cover, *J. Sustain. Agric*. 34, 584–94.

Mullinix, K., Brunner, J. F. and Isman, M. B. (2011), Apple leafroller (Lepidoptera: Tortricidae) populations and parasitism in an orchard managed with either a grass or alfalfa cover and without insecticides over four growing seasons, *Int. J. Fruit Sci*. 11(2), 99–110.

Murata, M., Nishimura, M., Murai, N., Haruta, M., Homma, S., et al. (2001), A transgenic apple callus showing reduced polyphenol oxidase activity and lower browning potential, *Biosci. Biotechnol. Biochem.* 65(2), 383–8.

Myers, C. T., Hull, L. A. and Krawczyk, G. (2006), Comparative survival rates of oriental fruit moth (Lepidoptera: Tortricidae) larvae on shoots and fruit of apple and peach, *J. Econ. Entomol*. 99(4), 1299–309.

Navarro-Roldan, M. A. and Gemeno, C. (2017), Sublethal effects of neonicotinoid insecticide on calling behavior and pheromone production of tortricid moths, *J. Chem. Ecol*. 43, 881–90.

Navarro-Roldan, M. A., Avilla, J., Bosch, D., Valls, J. and Gemeno, C. (2017), Comparative effect of three neurotoxic insecticides with different modes of action on adult males and females of three tortricid moth pests, *J. Econ. Entomol*. 110(4), 1740–9.

Negrisoli, C. R., Negrisoli, A. S. Garcia, M. S., Dolinski, C. and Bernardi, D. (2013), Control of *Grapholita molesta* (Busck 1916) (Lepidoptera: Tortricidae) with entomopathogenic nematodes (Rhabditida: Heterorhabditidae, Steinernematidae) in peach orchards, *Exp. Parasit*. 135, 466–70.

Neven, L., Ferguson, H. J. and Knight A. (2000), Sub-zero cooling synchronizes post-diapause development of codling moth, *Cydia pomonella, Cryo Letters* 21(4), 203–14.

Neven, L. G., Kumar, S., Yee, W. L. and Wakie, W. (2018), Current and future potential risk of establishment of *Grapholita molesta* (Lepidoptera: Tortricidae) in Washington State, *Environ. Entomol*. 47 (2), 448–56.

Norelli, J. L., Jones, A. L. and Aldwinckle, H. S. (2003), Fire blight management in the twenty-first century - Using new technologies that enhance host resistance in apple. *Plant Disease*. 87(7):756–65.

Onstad, D. W. (2008), *Insect Resistance Management, Biology, Economics and Prediction*, Elsevier, Amsterdam, 305pp.

Padilha, A. C., Arioli, C. J., Boff, M. I. C., Rosa, J. M. and Botton, M. (2017), Traps and baits for luring *Grapholita molesta* (Busck) adults in mating disruption-treated apple orchards, *Neotrop. Entomol*. doi:10.1007/s13744-017-0517-z.

Panneton, B., Lacasse, B. and Theriault, R. (2005), Penetration of spray in apple trees as a function of airspeed, airflow, and power for tower sprayers, *Can. Biosys. Eng.* 47, 213–20.

Pasqualini, E., Villa, M., Civolani, S., Espinha, I., Ioriatti, C., et al. (2005a), The pear ester ethyl (*E,Z*)-2,4-decadienoate as a potential tool for control of *Cydia pomonella* larvae, preliminary investigation, *Bull. Insect*. 58, 65–9.

Pasqualini, E., Schmidt, S., Espinha, I., Civolani, S., Ioriatti, C., et al. (2005b), Effects of the kairomone ethyl (2*E*, 4*Z*)-2,4-decadienoate (DA 2313) on the oviposition behaviour of *Cydia pomonella*, preliminary investigations, *Bull. Insect*. 58, 119–24.

Pasquier, D. and Charmillot, P. J. (2003), Effectiveness of twelve insecticides applied topically to diapausing larvae of the codling moth, *Cydia pomonella* L., *Pest Manag. Sci*. 60, 305–8.

Pfannestiel, R. S., Unruh, T. R. and Brunner, J. F. (2010), Overwintering hosts for the exotic leafroller parasitoid, *Colpoclypeus florus*: Implications for habitat manipulation to augment biological control of leafrollers in pome fruits, *J. Insect Sci*. 10, a75.

Pluciennik, Z. and Olszak, R. W. (2010), The role of parasitoids in limiting the harmfulness of leafrollers in apple orchards, *J. Plant Protec. Res.* 50(1), doi:10.2478/v10045-010-0001-9 (accessed September 2018).

Porcel, M., Sjoberg, P., Swiergiel, W., Dinwiddle, R., Ramert, B. and Tasin, M. (2014), Mating disruption of *Spilonota ocellana* and other apple orchard tortricids using a multispecies reservoir, *Pest Manag. Sci.* 71(4), 562–70.

Pree, D. J., Whitty, K. J. and Van Driel, L. (1998), Resistance to insecticides in oriental fruit moth populations (*Grapholita molesta*) from the Niagara peninsula of Ontario, *Can. Entomol*. 230, 245–56.

Prokopy, R. J. and Croft, B. A. (1994), Apple insect pest management, *in* Metcalf, R. L. and Luckman, W. H. (Eds), *Introduction to Insect Pest Management*. Wiley, New York, NY, pp. 543–85.

Pronier, I., Pare, J., Wissocq, J.-C. and Vincent, C. (2002), Nucleopolyhedrovirus infection in obliquebanded leafroller (Lepidoptera: Tortricidae), *Can. Entomol*. 134, 303–9.

Pszczolkowski, M. A. and Brown, J. J. (2002), Prospects of monosodium glutamate use for enhancement of spinosad toxicity against codling moth neonates, *Phytoparasitica* 31, 283–91.

Pszczolkowski, M. A. and Brown, J. J. (2004), Enhancement of spinosad toxicity to *Cydia pomonella* neonates by monosodium glutamate receptor agonist, *Phytoparas.* 32(4), 342–50.

Pszczolkowski, M. A., Brunner, J. F., Doerr, M. D. and Brown, J. J. (2004), Enhancement of *Bacillus thuringiensis* with monosodium glutamate against larvae of obliquebanded leafroller (Lep.: Tortricidae), *J. Appl. Entomol.* 128(7), 474–7.

Pszczolkowski, M. A., Durden, K., Sellars, S., Cowell, B. and Brown, J. J. (2011), Effects of *Ginkgo biloba* constituents on fruit-infesting behavior of codling moth (*Cydia pomonella*) in apples, *J. Agric. Food Chem*. 59, 10879–86.

Puterka, G. J., Glenn, D. M. and Pluta, R. C. (2005), Action of particle films on the biology and behavior or pear psylla (Homoptera: Psyllidae), *J. Econ. Entomol*. 98(6), 2079–88.

Randall, P., Sholberg, P., Judd, G. and Cossentine, J. (2011), Acetic acid fumigation of fruit storage bins to control diapausing codling moth larvae, *HortSci*. 46(12), 1634–9.

Regier, J. C., Brown, J. W., Mitter, C., Baixeras, J., Cho, S., et al. (2012), A molecular phylogeny for the leaf-roller moths (Lepidoptera: Tortricidae) and its implications for classification and life history evolution, *PLoS ONE* 7, e35574. doi:10.1371/journal.pone.0035574.

Reyes, M. and Sauphanor, B. (2008), Resistance monitoring in codling moth: A need for standardization, *Pest Manag. Sci.* 64,945–53.

Reyes, M., Franck, P., Charmillot, P. J., Ioriatti, C. and Olivares, J. (2007), Diversity of insecticide resistance mechanisms and spectrum in European populations of the codling moth, *Cydia pomonella*, *Pest Manag. Sci.* 63, 890–902.

Reyes, M., Franck, P., Olivares, J., Margaritopoulos, J., Knight, A. L., et al. (2009), Worldwide variability of insecticide resistance mechanisms in the codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), *Bull. Entomol. Res.* 99, 359–69.

Ricci, B., Franck, P., Toubon, J. F., Bouvier, J. C. and Sauphanor, B. (2009), The influence of landscape on insect pest dynamics: A case study in southeastern France, *Landsc. Ecol.* 24, 337–49.

Ricci, B. R., Franck, B. P., Bouvier, J. C., Casado, D. and Lavigne, C. (2011), Effects of hedgerow characteristics on intra-orchard distribution of larval codling moth, *Agric. Ecosyst. Environ.* 140, 395–400.

Riddick, E. W. and Mills, N. J. (1994), Potential of adult carabids (Coleoptera: Carabidae) as predators of fifth-instar codling moth (Lepidoptera; Tortricidae) in apple orchards in California, *Environ. Entomol.* 23(5), 1338–45.

Riedl, H. (1995), Laboratory evaluation of mineral oils for control of codling moth (Lepidoptera: Tortricidae), *J. Econ. Entomol.* 88(1), 140–7.

Riedl, H., Croft, B. A. and Howitt, A. J. (1976), Forecasting codling moth phenology based on pheromone trap catches and physiological time models, *Can. Entomol.* 108, 449–60.

Rodriguez, M. A., Bosch, D. and Avilla, J. (2011), Resistance of Spanish codling moth (*Cydia pomonella*) populations to insecticides and activity of detoxifying enzymatic systems, *Entomol. Exp. Appl.* 138(3), 184–92.

Roush, R. T. and Tabashnik, B. E. (Eds) (1990), *Pesticide Resistance in Arthropod*, Chapman and Hall, New York, NY, 303pp.

Sackett, T. E., Buddle, C. M. and Vincent, C. (2005), Effects of kaolin on fitness and behavior of *Choristoneura rosaceana* (Lepidoptera: Tortricidae) larvae, *J. Econ. Entomol.* 98(5), 1648–53.

Sackett, T. E., Buddle, C. M. and Vincent, C. (2007), Effects of kaolin on the composition of generalist predator assemblages and parasitism of *Choristoneura rosaceana* (Lep., Tortricidae) in apple orchards, *J. Appl. Entomol*. 131(7), 478–85.

Sarvary, M. A., Nyrop, J. and Reissing, H. (2010a), Effects of natural enemies and host plants in wild and orchards habitats on obliquebanded leafroller (Lepidoptera: Tortricidae) larval survival, *Biolog. Control* 55, 110–17.

Sarvary, M. A., Nyrop, J., Reissing, H. and Gifford, K. M. (2010b), Potential for conservation biological control of the obliquebanded leafroller (OBLR) *Choristoneura rosaceana* (Harris) in orchards systems managed with reduced-risk insecticides, *Biolog. Control* 40, 37–47.

Sauphanor, B. and Bouvier, J. C. (1995), Cross-resistance between benzoylureas and benzoylhydrazines in the codling moth, *Cydia pomonella* L. *Pest Manag. Sci.* 45, 369–75.

Sauphanor, B., Cuany, A., Bouvier, J. C., Brosse, V., Amichot, M., et al. (1997), Mechanism of resistance to deltamethrin in *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), *Pest Biochem. Physiol.* 58, 109–17.

Sauphanor, B., Brosse, V., Monier, C. and Bouvier, J. C. (1998a), Differential ovicidal and larvicidal resistance to benzoylureas in the codling moth, *Cydia pomonella*, *Entomol. Exp. Appl.* 88, 247–53.

Sauphanor, B., Bouvier, J. C. and Brosse, V. (1998b), Spectrum of insecticide resistance in *Cydia pomonella* (Lepidoptera: Tortricidae) in southeastern France, *J. Econ. Entomol.* 91, 1225–31.

Sauphanor, B., Brosse, V., Bouvier, J. C., Speich, P., Micoud, A., et al. (2000), Monitoring resistance to diflubenzuron and deltamethrin in French codling moth populations (*Cydia pomonella)*, *Pest Manage. Sci.* 56, 74–82.

Sauphanor, B., Berling, M., Toubon, J. F., Reyes, M., Delnatte, J., et al. (2006), Carpocapse des pommes, Cas de résistance au virus de la granulose en vergers biologiques, *Phytoma* 590, 24–7.

Sauphanor, B., Franck, P., Lasnier, T., Toubon, J. F. and Beslay, D., et al. (2007), Insecticide resistance may enhance the response to host-plant volatile kairomone for the codling moth, *Cydia pomonella*, *Naturwissen.* 94(6), 449–58.

Sauphanor, B., Severac, G., Maugin, S., Toubon, J. F. and Capowiez, Y. (2012), Exclusion netting may alter reproduction of the codling moth (Cydia pomonella) and prevent associated fruit damage to apple orchards, *Entomol. Experi. Appl.* 145(2), 134–42.

Schmidt, S., Tomasi, C., Pasqualini, E. and Ioriatti, C. (2008), The biological efficacy of pear ester on the activity of granulosis virus for codling moth, *J. Pest Sci.* 81, 29–34.

Schumacher, P., Weber, D. C., Hagger, C. and Dorn, S. (1997a), Heritability of flight distance for *Cydia pomonella*, *Entomol*. *Exp. Appl.* 85, 169–75.

Schumacher, P., Weyeneth, A., Weber, D. C. and Dorn, S. (1997b), Long flights in *Cydia pomonella* L. (Lepidoptera: Tortricidae) measured by a flight mill: Influence of sex, mated status and age, *Physiol. Entomol*. 22, 149–60.

Sciarretta, A. and Trematerra, P. (2006), Geostatistical characterization of the spatial distribution of *Grapholita molesta* and *Anarsia lineatella* males in an agricultural landscape, *J. Appl. Entomol*. 130, 73–83.

Severac, G. and Romet, L. (2008), Alt'Carpo, une alternative efficace, *Phytoma* 612, 16–20.

Sharma, R. R., Reddy, S. V. R. and Jhalegar, M. J. (2014), Pre-harvest fruit bagging: A useful approach for plant protection and improved post-harvest fruit quality – a review, *J. Hortic. Sci. Biotechnol.* 89(2), 101–13.

Sial, A. Q. and Brunner, J. F. (2010), Toxicity and residual efficacy of chlorantraniliprole, spinoteram, and emamectin benzoate to obliquebanded leafroller (Lepidoptera: Tortricidae), *J. Econ. Entomol.* 103(4), 1277–85.

Sial, A. A. and Brunner, J. F. (2012), Selection for resistance, reversion towards susceptibility and synergism of chlorantraniliprole and spinetoram in obliquebanded leafroller, *Choristoneura rosaceana* (Lepidoptera: Tortricidae), *Pest Manag. Sci.* 68, 462–8.

Silva-Brandao, K. L., Silva, O. A. B. N. E., Brandao, M. M., Omoto, C. and Sperling, F. A. H. (2015), Genotyping-by-sequencing approach indicates geographic distance as the main factor affecting genetic structure and gene flow in Brazilian populations of *Grapholita molesta* (Lepidoptera, Tortricidae), *Evol. Appl.* 8(5), 476–85.

Simon, S., Lauri, P. E., DeFrance, H. and Sauphanor, B. (2006), Does manipulation of fruit-tree architecture affect the development of pests and pathogens? A case study in an organic apple orchard, *J. Hortic. Sci. Biotechnol.* 81 (4), 765–73.

Simon, S., Sauphanor, B. and Lauri, P.-E. (2007), Control of fruit tree pests through manipulation of tree architecture, *Pest Technol*. 191, 33–7.

Smirle, M. J., Lowery, T. and Zurowski, C. L. (2002), Resistance and cross-resistance to four insecticides in populations of obliquebanded leafroller (Lepidoptera: Tortricidae), *J. Econ. Entomol*. 95(4), 820–5.

Smirle, M. J., Lowery, D. T. and Zurowski, C. L. (2003), Susceptibility of leafrollers (Lepidoptera: Tortricidae) from organic and conventional orchards to azinphos-methyl, spinosad, and *Bacillus Thuringiensis*, *J. Econ. Entomol.* 96, 879–84.

Sofu, M. M., Er, O., Kayacan, M. C. and Cetisli, B. (2016), Design of an automatic apple sorting system using machine vision, *Comput. Electron. Agric.* 127, 395–405.

Song, B., Jiao, H., Tang, G. and Yao, Y. (2014), Combining repellent and attractive aromatic plants to enhance biological control of three tortricid species (Lepidoptera: Tortricidae) in an apple orchard, *Florida Entomol*. 97 (4), 1679–89.

Sonka, S. T. and Coaldrake, K. F. (1997), Cyberfarm: What does it look like? what does it mean? *Am. J. Agric. Econ.* 78, 1263–8.

Sparks, T. C. and Nauen, R. (2015), IRAC: Mode of action classification and insecticide resistance management, *Pest. Biochem. Physiol.* 121, 122–8.

Stelinski, L. L., Gut, L. J., Haas, M., McGhee, P. and Epstein, D. (2007), Evaluation of aerosol devices for simultaneous disruption of sex pheromone communication in *Cydia pomonella* and *Grapholita molesta* (Lepidoptera: Tortricidae), *J. Pest Sci.* 80, 225–33.

Stelinski, L. L., Il'Ichev, A. L. and Gut, L. J. (2009), Efficacy and release rate of reservoir pheromone dispensers for simultaneous mating disruption of codling moth and oriental fruit moth (Lepidoptera: Tortricidae), *J. Econ. Entomol.* 102(1), 315–23.

Stoeckli, S., Mody, K. and Dorn, S. (2008), Influence of canopy aspect and height on codling moth (Lepidoptera: Tortricidae) larval infestation in apple and relationship between infestation and fruit size, *J. Econ. Entomol.* 101(1), 81–9.

Stoeckli, S., Hirschi, M., Spirig, C., Calanca, P., Rotach, M. W., et al. (2012), Impact of climate change on voltinism and prospective diapause induction of a global pest insect *Cydia pomonella* (L.), *PLoS ONE*, 7, e35723.

Suckling, D. M., Gibb, A. R., Burnip, G. M. and Delury, N. C. (2002), Can parasitoid sex pheromones help in insect biocontrol? A case study of codling moth (Lepidoptera: Tortricidae) and its parasitoid *Ascogaster quadridentata* (Hymenoptera: Braconidae), *Environ. Entomol*. 31(6), 947–52.

Suckling, D. M., Stringer, L. D., Baird, D. B., Butler R. C., Sullivan, T. E. S., et al. (2014), Light brown apple moth (*Epiphyas postvittana*) (Lepidoptera; Tortricidae) colonization of California, *Biol. Invasions* 16, 1851–63.

Sun, X. and Barrett, B. A. (1999), Fecundity and fertility changes in adult codling moth (Lepidoptera: Tortricidae) exposed to surfaces treated with tebufenozide and methoxyfenozide, *J. Econ. Entomol*. 92, 1039–44.

Sun, X., Barrett, B. A. and Biddinger, D. J. (2000), Fecundity and fertility reductions in adult leafroller exposed to surfaces treated with the ecdysteroid agonists tebufenozide and methoxyfenozide, *Entomol. Exp. Appl.* 94, 75–83.

Tasin, M., Demaria, D., Ryne, C. Cesano, A., Galliano, A, et al. (2008), Effect of anti-hail nets on *Cydia pomonella* behavior in apple orchards, *Entomol. Exp. Appl*. 129, 32–6.

Thistlewood, H. and Judd, G. J. R. (2003a), Movement and dispersal of codling moth, *Cydia pomonella*, in rural and orchard areas, *IOBC/WPRS Bull.* 26, 111–16.

Thistlewood, H. and Judd, G. J. R. (2003b), Area-wide management of codling moth, *Cydia pomonella*, at very low densities, *IOBC/WPRS Bull.* 26(11), 103–9.

Thomas, D. D., Donnelly, C. A., Wood, R. J. and Alphey, L. S. (2000), Insect population control using a dominant, repressible, lethal genetic system, *Science* 287(5462), 2474–6.

Thompson, G. D., Dutton, R., and Sparks, T. C. (2000), Spinosad – a case study: An example from a natural products discovery programme, *Pest Manag. Sci*. 56, 696–702.

Trematerra, P., Gentile, P. and Sciarretta, A. (2004), Spatial analysis of pheromone trap catches of codling moth (*Cydia pomonella*) in two heterogeneous agro-ecosystems, using geostatistical techniques, *Phytoparasitica* 32, 325–41.

Trimble, R. M. and Vickers, P. M. (2000), Evaluation of border sprays for managing the codling moth (Tortricidae: Lepidoptera) and the apple maggot (Tephritidae: Diptera) in Ontario apple orchards, *J. Econ. Entomol.* 93(3), 777–87.

Trimble, R. M., El-Sayed, A. M. and Pree, D. J. (2004), Impact of sub-lethal residues of azinphos-methyl on the pheromone-communication systems of insecticide-susceptible and insecticide-resistant obliquebanded leafrollers *Choristoneura rosaceana* (Lepidoptera: Tortricidae), *Pest Manag. Sci.* 60, 660–8.

Tyson, R., Thistlewood, H. and Judd, G. J. R. (2007), Modelling dispersal of sterile male codling moths, *Cydia pomonella*, across orchard boundaries, *Ecol. Mod.* 205, 1–12.

Undorf-Spahn, K., Fritsch, E., Huber, J., Kienzle, J., Zebitz, P. W., et al. (2012), High stability and no fitness costs of the resistance of codling moth to *Cydia pomonella* granulovirus (CpGV-M), *J. Invert. Path.* 111, 136–42.

Unruh, T. R. (1998), From Russia with love: New predators and parasite for control of tree fruit insect pests, *Proc. Wash. Hortic. Assoc.* 94, 42–9.

Unruh, T. R. and Lacey, L. A. (2001), Control of codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae), with *Steinernema carpocapsae*: Effects of supplemental wetting and pupation site on infection rate, *Biol. Control* 20, 48–56.

Unruh, T. R., Knight, A. L., Upton, J., Glenn, D. M. and Puterka, P. J. (2000), Particle films for suppression of the codling moth (Lepidoptera; Tortricidae) in apple and pear orchards, *J. Econ. Entomol.* 93, 737–43.

Unruh, T. R., Pfannenstiel, R. S., Peters, C., Brunner, J. F. and Jones, V. P. (2012), Parasitism of leafrollers in Washington fruit orchards is enhanced by perimeter plantings of rose and strawberry, *Biol. Control* 62, 162–72.

Unruh, T. R., Miliczky, E. R., Horton, D. R., Thomsen-Archer, K., Rehfield-Ray, L., et al. (2016), Gut content analysis of arthropod predators of codling moth in Washington apple orchards, *Biol. Control* 102, 85–92.

Vail, P. V., Tebbets, J. S., Mackey, B. E. and Curtis, C. E. (1993), Quarantine treatments: A biological approach to decision-making for selected hosts of codling moth (Lepidoptera; Tortricidae), *J. Econ. Entomol.* 86(1), 70–5.

Vakenti, J. M., Cossentine, J. E., Cooper, B. E., Sharkey, M. J., Yoshimoto, C. M., et al. (2001), Host-plant range and parasitoids of obliquebanded and three-lined leafrollers (Lepidoptera: Tortricidae), *Can. Entomol.* 133, 139–46.

Valentine, B. J., Gurr, G. M. and Thwaite, W. G. (1996), Efficacy of the insect growth regulators tebufenozide and fenoxycarb for lepidopteran pest control in apples, and their compatibility with biological control for integrated pest management, *Aust. J. Exp. Agric.* 36(4), 501–6.

Varela, L. G., Welter, S. C., Jones, V. P., Brunner, J. F. and Riedl, H. (1993), Monitoring and characterization of insecticide resistance in codling moth (Lepidoptera: Tortricidae) in four western states, *J. Econ. Entomol*. 86(1), 1–10.

Vickers, R. A. (1997), Effect of delayed mating on oviposition pattern, fecundity and fertility in codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), *Aust. J. Entomol.* 36, 179–82.

Voudouris, C. C., Sauphanor, B., Franck, P., Reyes, M., Mamuris, Z., et al. (2011), Insecticide resistance status of the codling moth *Cydia pomonella* (Lepidoptera: Tortricidae) from Greece, *Pest. Biochem. Physiol.* 100(3), 229–328.

Vreysen, M. J. B., Robinson, A. S. and Hendrichs, J. (2007), *Area-wide Control of Insect Pests: From Research to Field Implementation*, Springer, Dordrecht, The Netherlands.

van der Geest, L. P. S. and Evenhuis. H. H. (Eds), (1991), *Tortricid Pests: Their Biology, Natural Enemies and Control*, Elsevier, Amsterdam, The Netherlands, 808pp.

Waelti, H. (1992), Should we use plastic bins? *Tree Fruit Postharvest J.* 3, 14–17.

Walker, K. R. and Welter, S. C. (2001), Potential for outbreaks of leafrollers (Lepidoptera: Tortricidae) in California apple orchards using mating disruption for codling moth suppression, *J. Econ. Entomol*. 94(2), 373–80.

Waltz, E. (2015), Nonbrowning GM apple cleared for market, *Nat. Biotechnol.* 33(4), 326–7.

Wang, S., Birla, S. L., Tang, J. and Hansen, J. D. (2006), Postharvest treatment to control codling moth in fresh apples using water assisted radio frequency heating, *Postharvest Biol. Technol.* 40, 89–96.

Wearing, C. H. and Hokkaner, H. M. T. (1994), Pest resistance to *Bacillus thuringiensis*: Case studies of ecological crop assessment for Bt gene incorporation and strategies of management, *Biocontr. Sci. Technol.* 4, 573–90.

Weddle, P. W., Welter, S. C. and Thomson, D. (2009), History of IPM in California pears – 50 years of pesticide use and the transition to biologically intensive IPM, *Pest Manag. Sci.* 65, 1287–92.

Whitaker, K. and Middleton, S. (1999), The profitability of hail netting in apple orchards, *Aust. Agric. Res. Econ.* 43, 1–15.

Willett, M. and Westigard, P. H. (1988), Using horticultural spray oils to control orchard pests, *Pacific Northwest Coop. Ext. Bull*. 328, Corvalis, OR.

Willett, M. J., Neven, L. and Miller, C. E. (2009), The occurrence of codling moth in low latitude countries: Validation of pest distribution reports, *HortTech.* 19(3), 633–7.

Witzgall, P., Stelinski, L. L., Gut, L. J. and Thomson, D. (2008), Codling moth management and chemical ecology, *Annu. Rev. Entomol.* 53, 503–22.

Xu, K. (2013), The next generation biotechnology for apple improvement and beyond: The CRISPR/CAS9 story, *N. Y. Fruit Quart.* 21(4), 19–22.

Xu, X., Wu, P., Thorbek, P. and Hyder, K. (2006), Variability in initial spray deposit in apple trees in space and time, *Pest Manag. Sci.* 62, 947–56.

Yamada, H., Parker, A. G., Oliva, C. F., Balestrino, F. and Gilles, J. R. L. (2014), X-ray-induced sterility in *Aedes albopictus* (Diptera: Culicidae) and male longevity following irradiation, *J. Med. Entomol.* 51, 811–16.

Zhang, B.-C. (1994), *Index of Economically Important Lepidoptera*, CAB International, Wallingford, UK, 599pp.

Zheng, Y., Qiao, X., Wang, K., Dorn, S. and Chen, M. (2015), Population genetics affected by pest management using fruit-bagging: A case study with *Grapholita molesta* in China, *Netherlands Entomol. Soc. Entomol. Experi.* 156, 117–27.

Zijlstra, C., Lund, I., Justesen, A. F., Nicolaisen, M., Jensen, P. K., et al. (2011), Combining novel monitoring tools and precision application technologies for integrated high-tech crop protection in the future, *Pest Manag. Sci.* 67, 616–25.

Zingg, D., Kraaz, I., Wandeler, H. and Zuger, M. (2012), Madex twin, a new *Cydia pomonella* granulovirus isolate for the control of both codling moth *Cydia pomonella* and oriental fruit moth *Grapholita molesta*, *Proceedings of the 15th Ecofruit International Conference on Organic Fruit Growing*, Hohenheim, Germany, 20–22 February 2012, pp. 187–93.