Review of potential control strategies for major pests in organic apple and pear production, with application in IPM orchards

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Abstract

Growers of organic tree fruit can have difficulty controlling pests and diseases that are more easily supressed in conventional orchards by chemical synthetic insecticides and fungicides. In recent decades, there has been a move towards growing organic produce from pome fruit varieties not originally cultivated for organic production (e.g., Gala), to meet retailer/consumer demand. This inevitably makes crop protection in organic orchards more challenging as modern varieties are often less tolerant to pests. In addition, there have been substantial changes to plant protection product (PPP) approvals in recent years resulting in fewer conventional PPPs (CPPPs) available for Integrated Pest Management maintained orchards.

Conversely, organic management of fruit trees has adapted many practices that may be applicable and successfully implemented in conventionally grown crops, but which may not currently be fully utilised by conventional growers.

This report will be useful for both organic and conventional tree fruit growers interested in adopting more environmentally sustainable practices in orchards in the future.

We review organic practices used worldwide, with a focus on those that could be incorporated into conventional UK apple and pear production. The topics cover cultural control (soil health, cover crops, avoiding harmful practices, crop varieties, canopy maintenance), biological control (natural enemies, introduced biological control, viruses, entomopathogenic fungi and nematodes, parasitoids, semiochemicals), physical control (netting and barriers, waste removal, foliar applications) and pest modifications (sterile insect technique, self-limiting genes, genetic modifications). We conclude by highlighting areas that require more investigation and practices used in other crops that could be adapted for tree fruit.

Introduction

The incentive for growers to adopt organic methods has been driven by consumer attitudes and an increased awareness of the impacts that some agricultural practices have on the environment (Basha et al., 2015). However, organic agriculture typically produces 8-25% lower yields than conventional production (Lesur-Dumoulin et al., 2017), and in apple specifically ~48% reduction in fruit production has been recorded compared with conventional IPM orchards (Samnegård et al., 2018). There are also concerns that fully organic systems will not meet the increasing demand for our expanding populations (De Ponti et al., 2012, Connor, 2013, Raviv, 2010, Reganold and Wachter, 2016). Whilst there are many positive impacts associated with organic agriculture, such as increased biodiversity in cropping areas (Dib et al., 2016, Wyss and Pfiffner, 2006), there is an economic and societal requirement for a balance between high yields, low waste and an ability to meet increasing demands on decreasing land area

(Connor and Mínguez, 2012). Organic production, as of 2017, covers 69.8 million hectares worldwide, with only 1.6% of all temperate fruit grown organically (Willer and Lernoud, 2019). Apple comprised 40% of organic temperate fruit production in 2017; the largest proportion of all temperate fruit, with pears accounting for 10% (Willer and Lernoud, 2019). In 2018, the UK market production of apples (dessert and culinary) and pears was 300.6 and 26.6 thousand tonnes, imports 372 and 120 thousand tonnes, and exports 22 and 2 thousand tonnes, respectively. The provisional projection for total UK apple and pear yield for 2019 was 313.8 thousand tonnes (Table 1); with 19 and 1 thousand tonnes of apples and pears estimated to be exported respectively (Department for Environment, Food and Rural Affairs (Defra), 2018). The full impact of leaving the European Union on UK fresh produce production and trade is unclear, but the area of culinary apples and pears grown in the UK has grown year-on-year since 2010. It is expected that if there is a reduction in European trading there will be an increase in consumer demand for ‘home grown’ produce, which would promote an increase in UK grown crops (Benton et al., 2019).

Table 1. Data collected by the Office for National Statistics on behalf of Defra on the projected apple and pear production values projection for 2019, based on 2018 data. Accessed May 2020.

	2019 Projection		
	Area grown (Hectares)	**Yield** (Thousand tonnes)	**Value** (£ Million)
Dessert Apples	6,292	206.5	140.8
Culinary Apples	2,638	79.9	42.0
Cider Apples & Perry Pears	7,010	170	24.4
Pears	1,515	27.4	22.8

An increase in the area of apple and pear grown, coupled with recent and rapid changes in PPP approvals, also threatens the pome fruit industry, with fewer new products introduced onto the market. The loss of organophosphates and some pyrethroid and neonicotinoid foliar sprays over recent years has resulted in a resurgence of key pests and diseases in apple and pear orchards. There have been additional yield losses due to fruit damage caused by sporadic pests that would subsequently have been suppressed by broad-spectrum products (Cross et al., 1999b), e.g. damage by forest bug *Pentatoma rufipes* (L.) (Powell, 2020). Further PPP withdrawals, such as thiacloprid in 2021, are expected to coincide with an increase in intermittent pests such as weevils, capsids and aphids. As more broad-spectrum PPP lose approval (Hillocks, 2012), growers need to adapt and be receptive to alternative methods for achieving control of pests in fruit.

Within this review we discuss organic strategies that can be exploited within conventional apple and pear orchards in the UK. The review includes results from AHDB funded projects and international peer-reviewed publications. Note that some methods may not yet be approved for use in the UK and a BASIS qualified advisor should be consulted for advice.

Organic control of arthropod pests

Introduction to pest control

Pest pressure in organic orchards can result in high yield losses, which may be difficult to estimate. For pests that cause direct damage to fruit, growers are able to identify the quantity of crop lost (for example losses due to codling moth *Cydia pomonella* (L.)). However, not all damage is easily identifiable and actual losses may be much higher than estimated (Culliney, 2014). For example, some pest damage can be overlooked as natural plant phenology, i.e., after egg laying, female apple fruit weevil, *Tatianaerhynchites aequatus* (L.), severs the stem of developing apple fruitlets causing them to fall to the ground, coinciding with June-drop. Other pests, like pear sucker, *Cacopsylla pyri* (L.), reduce plant health by feeding on leaves and overwintering buds, causing subsequent yield reductions. However, the presence of a pest in an orchard does not necessarily result in crop loss. For example, the occurrence of aphids may not equate to crop damage, depending on aphid species, aphid abundance, climate, and availability of natural enemies (predators and parasitoids). The loss of broad-spectrum foliar applications over recent years has resulted in a resurgence of key pests and a surge in minor pests, which were coincidentally controlled by these treatments. In addition, there are some invasive species (identified in AHDB project TF *223 Improving integrated pest and disease management in Tree Fruit*) that are likely to be a future threat to the industry and need control options to prevent yield loss, for example brown marmorated stink bug (Powell et al., 2020).

This report focuses on new prospects for achieving effective pest control in apple and pear orchards, particularly through biological, physical and cultural control methods and use of behaviour-modifying 'semiochemicals'. Many of these methods integrate with strategies within other classifications of control, such as cover crops in cultural control with the natural enemies they attract to enhance biological control. The control strategies discussed are organic methods which can be adopted within IPM programmes and in some cases, substitute or complement CPPPs. The main take-home messages are summarised at the end of each section, and we highlight key gaps in knowledge where further research is needed.

Cultural control

Cultural control aims to prevent or discourage pest populations by optimizing growing parameters and improving plant health and husbandry (Peshin et al., 2009). It can have a crop and/or surrounding habitat focus. Many of the techniques are implemented prior to planting and are applicable in both organic and conventional orchards. This section summarizes cultural management techniques used and the key pests they deter.

Soil health and properties

The characteristics and health of orchard soils can dictate the occurrences of pests within a crop and vary between farm and location. Prior to establishing an orchard or new planting it is beneficial to identify the soil type and properties. This will give an indication of qualities such as drainage, soil composition and soil quality which may affect fruit production after orchard establishment (Zhang et al., 2011). Soil health is a vital factor in pest management in both organic and conventional crop production. However above- and below- ground management are rarely combined in 'ecologically based pest management' approaches (Zehnder et al., 2007). Higher soil fertility and organic matter content has been linked to lower pest pressure, but excessive nutrient levels can have adverse effects by promoting excessive growth which, in apple and pear, will be targeted by aphid species (Altieri and Nicholls, 2003). In pear, high nitrogen levels were found to result in higher pear sucker *Cacopsylla pyricola* (Foerster) numbers which coincided with longer branches and a greater number of leaves (Daugherty et al., 2007). These examples demonstrate the precarious balance between soil properties and pest equilibrium. Soil fertility can be enhanced by using cover cropping (see below) which is linked to increased tolerance of pests and diseases by trees (Altieri et al., 2005). Soil properties at planting sites should be analyzed to determine the most appropriate amendments.

Cover crops

Prior to tree planting, cover crops can be used to protect the soil and amend soil properties including nitrogen, disease reduction and organic matter. In addition, wildflower mixes should be considered for the long-term management of orchards to provide habitat for beneficial insects including pollinators as conservation biological control (CBC) can be implemented in and around orchards to encourage the establishment of beneficial insects (Simberloff et al., 2013, Bugg and Waddington, 1994). Cover crops alter nutrient levels in soil and it is generally considered that healthy soils result in healthy plants, more tolerant to pests and diseases than those which grow in poor soils (Altieri et al., 2005, Altieri and Nicholls, 2003). However, not all cover crops are beneficial; some increase soil fertility above optimum levels (Lim et al., 2011). In an organic pear orchard with a ground cover of the legume, hairy vetch, *Vicia villosa* Roth, the K content was higher than control plots, but plots covered with barley, *Hordeum vulgare* L., or rye, *Secale cereale* L., had lower K than the uncovered control plots (Oh et al., 2012). Varieties of apple and pear may have different nutritional needs, which should be considered before planting cover crops. For example cv. Comice pears are frequently deficient in Mg (Hart et al., 1997) and so barley and hairy vetch would be incompatible as lower Mg levels occurred in plots covered with these species (Oh et al. (2012). Common vetch, *Vicia sativa* L. as a cover crop, caused a 'sharp increase' in soil nitrate in the spring and increased soil organic matter following decomposition of cuttings (Sánchez et al., 2007). During this time, there was also an increase in total number of soil nematodes and, although no predatory species were collected, high nematode numbers indicate good carbon flow within an orchard soil (Ferris and Bongers, 2006). These researchers also attributed the increase in nematode numbers to the increase in soil organic matter from leaving grass trimmings to break down naturally, providing a free nutrient top-up during the season. In another study (cv. Royal Gala), soils that were high in organic matter did not require the addition of N fertilizers as nutrition was naturally provided by the decaying process (Bould and Jarrett, 1962). Where white clover was sown as a cover crop, in Cox and Worcester orchards, high yields were attained compared to cover crops of rye or timothy grasses. The latter enabled more nitrate and phosphate up-take by the trees (Bould and Jarrett, 1962). Soil nutrition has also been linked to a plant's ability to recover after damage has been inflicted by pests. For example, on Brassica plants, defoliation caused by the small white butterfly, *Pieris rapae* (L.) caterpillar was twice as high in poor soil than in quality soil and plants grown in quality soil recovered within two weeks of the caterpillars being removed (Meyer, 2000).

Many insects converge on cover crops within cultivated areas and it is their establishment on these hosts that attract and sustain predators and parasitoids (Altierr and Schmidt, 1986). Using immune-marker techniques, which employed marking natural enemies with egg white protein, which could be detected later using a specific immunoassay, it was confirmed that beneficial insects move between cover crops and pear trees. In field trials conducted by Horton et al. (2009), 17-29% of predators collected on pear trees were marked, indicating they had either migrated from or previously visited the immune-marker treated cover crop. These predators included species from Heteroptera (*Anthocoris* sp.), Coccinellidae (ladybirds), Chrysopidae (lacewings), and Araneae (spiders), common natural enemies in UK orchards. This topic is investigated in more detail in the 'Natural enemies' section of this review.

Variety

Varietal choice is a primary consideration in preventing pest damage to tree fruit. However, cultivar plantings are often driven by markets, retailer demands and producer organization variety requirements. A reliance on varieties that are high yielding but more susceptible to pests, is a barrier to reducing the reliance on PPPs. Variety choices vary with location and growers should seek advice from their agronomists on optimum cultivars for their soil types and climate. There are some apple scion varieties, such as Florina and Prima that have been found to be less susceptible to aphids including rosy apple aphid, *Dysaphis plantaginea* (Passerini), and green-apple aphid, *Aphis pomi* De Geer (Kutinkonova 2016). Rosy apple aphid resistance is linked to the presence of hydroxycinnamic acids, which are common in cider apple varieties. These acids protect the fruit skin from UV (Berrueta et al., 2018) and crosses between varieties that are high in hydroxycinnamic acids with those with attractive eating characteristics, could increase the availability of tolerant cultivars.

Marker assisted breeding has identified genetic markers associated with resistance to rosy apple aphid (Dapena et al., 2007), green-apple aphid (Stoeckli et al., 2008), and leaf-curling aphid *Dysaphis devecta* (Walker) (Roche et al., 1997). These markers should be used in the selection of future cultivars, although there is a lack of research. Woolly apple aphid is effectively controlled by varietal resistance in many New Zealand bred cultivars which, are developed for a temperate climate, and may be appropriate for the UK. These varieties include Geneva, Willie Sharp, and Korichnoe Polosatoje G01-104 (Sandanayaka et al., 2005). AHDB co-funded CTP studentship project "*Resistance and susceptibility in interactions between apple and woolly aphids*" focuses on specific populations of woolly apple aphid and commercial varieties actively grown in the UK. The project aims to identify candidate genes and mechanisms of woolly apple aphid resistance in apples. It will also aim to better understand woolly apple aphid genetic diversity and life cycle in the UK and identify how some clones of woolly apple aphid are able to overcome resistance genes in apple. Ultimately, the project aims to 'stack' resistance genes to give durable resistance to this resistance-breaking aphid.

In pear, resistant varieties can be selected to suppress pear sucker (*C. pyri* and *C. pyricola*) (Berrada et al., 1995, Puterka et al., 1993). The profile of polyphenolic secondary metabolites within pear leaves has been associated with resistance to pear sucker. Increases in these compounds are linked to the plant's self-defence mechanism against pathogens and UV, which in turn increases fitness (FotirićAkšić 2015). Microsatellite markers associated with resistance to pear-bedstraw aphid, *Dysaphis pyri* (Boyer de Fonscolombe), and QTL markers associated with pear sawfly (*Caliroa cerasi* (L.)) and pear blister mite (*Eriophyes pyri* (Pagenstecher)) resistance have also been identified in European pear varieties and can be searched for early in the screening of varietal development (Evans et al., 2008, Brewer et al., 2018).

Rootstocks also affect pest susceptibility. Although there are some apple rootstocks resistant to woolly apple aphid, such as 'Northern spy' (developed at East Malling Research) (Cummins and Aldwinckle, 1983), there is very little literature to indicate that they are widely used for this purpose (Orpet et al., 2019c). AHDB co-funded CTP studentship project '*Combining root architecture, root function and soil management to improve production efficiency and quality of apples*' aims to increase the knowledge surrounding root architecture in rootstocks through genetic techniques. Although this is not directly related to pest management, advances in the understanding of how genetic techniques can be used to better understand phenotypic traits is a welcomed advance in rootstock development. At the time of writing, there were no conclusive reports of pear rootstocks that are promising at promoting pest resistance. Known resistance promotors should be integrated into future apple and pear breeding programmes to aid the identification of pest resistant or tolerant cultivars of both scion and rootstock.

The classical breeding of new apple and pear varieties is an extremely long process, often taking decades, but the integration of marker-assisted breeding techniques could reduce the time from concept to commercialization while also promoting resistance to key pests and diseases (Bell, 2019, Brewer and Volz, 2019, Evans et al., 2008, Howard et al., 2018, Laurens et al., 2018). In AHDB project TF 211 (*Resources for future breeding of apple utilizing genome-wide selection*), work to identify methods of breeding in apple aimed to select for high fruit quality and high pest and disease resistance. The study reported several unexploited, known varieties, resistant to pests, which could be used as mother trees. The report highlighted that many desirable traits, like pest resistance, are not common in modern varieties, which supports the need for crossing with heritage cultivars. It concluded that the use of genome-wide selection could drastically reduce the time taken to develop a new variety. However, there is very little exploitation of marker assisted fruit-breeding which is usually attributed to the cost and expertise needed for such research (Laurens et al., 2018).

Cultivar phenology can also affect the level of susceptibility of a fruiting tree to pest insects by avoiding synchrony of vulnerable stages with the emergence or arrival of pests (Briggs and Alston, 1967). In apple, later developing, susceptible varieties, suffer less from rosy apple aphid as bud burst occurs after egg hatch and the neonates cannot feed (Minarro and Dapena, 2008). However, in pear, a preference for the more advanced stages of leaf emergence was found for egg-laying, winter morph, pear sucker even when resistant and susceptible varieties were available. It appears that while there are resistant and susceptible pear varieties to the summer morph, the winter morph is influenced more by the phenology of the trees than by the variety (Stuart et al., 1989). This indicates that there is an element of choice in the summer morph establishment and if several varieties are grown in close proximity, growers are more likely to observe infestation on specific varieties. However, if this variety is removed, it is likely that pear sucker would disperse to the next most attractive variety. Growers will know for their particular farms which pests are prevalent, and cultivar phenology should be taken into account to mitigate the impacts.

Canopy maintenance

Pruning tree canopies changes environmental conditions such as humidity, temperature, airflow and light penetration (Nath et al., 2019). Dhillon and Thakur (2014) concluded… "The crux of the canopy management lies in the fact, as to how best we can manipulate the tree vigour to utilize natural resources efficiently for improving productivity and quality". In addition to rootstock selection, pruning techniques and nutrient inputs, tree canopy architecture can also be controlled through genetic manipulation. Key genes involved with branching and growth can be used in marker assisted breeding of future varieties (Baldi et al., 2013). Physical training of fruit trees reduced pest and disease pressure in French orchards (Franck et al., 2007). Centrifugal training of pear and apple trees promoted a reduction in aphid species and scab incidence, attributed to the ability of predators to gain access to the pests along with a reduction in disease promoting humidity (Simon et al., 2006, Simon et al., 2007). General pruning and manual canopy maintenance can be used for existing varieties and plantings. Growers can combine methods such as pruning and applications of nitrogen to reduce excessive growth, which will be prone to aphid damage (Massimino Cocuzza, 2019).

In young orchards, aphid colonies can be effectively controlled by the removal of curled leaves, which contain the fundatrix (founding) aphid during blossom. This method does not require skilled labour and has been found to be extremely effective (C. Nagy, unpublished). Aphid colonies are tended by ants as part of a mutualistic relationship. Ants defend aphid colonies against predators in exchange for the honeydew that aphids secrete, although this relationship is not observed in all aphid species (Yao, 2014). Those aphid colonies that establish on lower and middle shoots of the tree are more accessible to ants as they can locate them earlier in the season compared to colonies on peripheral shoots. In older orchards, pruning of excess growth (the suckers) around the central tree zone can prevent aphid colonies establishing and forces them out onto the more natural enemy exposed areas of the tree. This makes it harder for the ants to locate them making the colony more accessible to aerial predators (see natural enemies' section for more detail). Figure 1 below shows the central growth that should be removed to promote aphid control; rosy apple aphid damage to the foliage can be reduced by 50% compared to an unpruned control (C. Nagy, unpublished).

There is little literature on both apple and pear canopy management for other pest reduction, but an increase in fruit yield is evident. Apple trees are normally managed to have less dense canopies to improve light and air flow for higher fruit yields and better fruit colouration (Wünsche and Lakso, 2000, Corelli and Sansavini, 1989). By removing canopy, not only is light penetration and airflow increased but opportunities for pest insects to hide from larger predators is reduced. Birds, predominantly tit species (family Paridae), have been well documented in predating on a range of pests in apple and pear orchards

(Solomon et al., 1976), particularly caterpillars during the bird nesting season, and are linked to a reduction in pest occurrence and increase in crop yield (García et al., 2018, Kirk et al., 1996, Peisley et al., 2016, Mols and Visser, 2002, Mols and Visser, 2007). Growers could further enhance numbers of Paridae on their farms by providing appropriate nesting habitat and nest boxes (Mols and Visser, 2007, Peisley et al., 2016). While some bird species can cause direct damage to apple and pear, mainly blackbirds and starlings, they generally attack near-ripening fruit (Dawson and Bull, 1970) and can be deterred with bird scarers or netting (see below). Visual inspections by crop walkers and agronomists may also benefit from thinning tree canopy resulting in quicker detection of pests and timely control within the orchard. In addition, the coverage of plant protection products such as entomopathogenic viruses and bio-protectants, is improved by good canopy management (Cross et al., 2003, Xu et al., 2006).

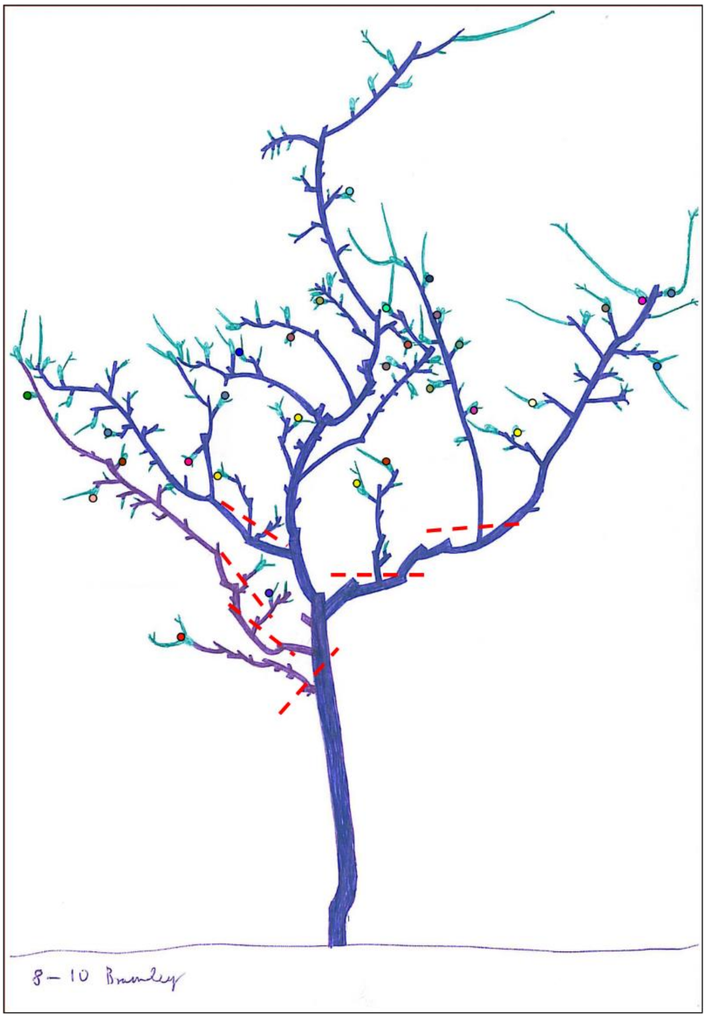

Figure 1. Visualisation of the growth to be removed to reduce rosy apple aphid colonies by disrupting the ant-aphid mutualistic relationship. Red lines indicate which growth should be removed. Coloured circles display aphid fundatrices occurring at different times. Illustration by C. Nagy

Key points for growers on cultural control

- Soil testing pre-planting will give insight into soil quality, organic matter, and nutrient composition which may affect fruit production.
- The use of cover cropping can improve organic matter in the soil and increase pest and disease tolerance.
- Cover crops should be compatible with cultivar and soil type.
- Avoid spraying harmful PPP during key life stages of natural enemies.
- Growers should avoid or minimise practices such as deep-tillage, excessive vehicle movement and herbicide applications that could be damaging to soil-dwelling beneficial insects.
- Pest resistant scion and rootstock choices are available, and phenology of cultivar can also result in lower pest pressure.
- Consider fruit variety selections based on the location and known pest incidence. Choices should be made depending on the key pests of the site.

- Pruning the canopy or altering tree architecture to increase light penetration and airflow will reduce pest occurrence by increasing exposure to predators, unfavourable abiotic factors and agronomists.

Biological control

The term biological control covers a wide range of topics. In this review, we focus on the use of natural enemies, entomopathogenic fungi, nematodes, viruses, exploiting insect behaviour and genetic manipulation to gain pest control in apple and pear orchards in the UK. We also highlight practices that could cause harm to beneficial organisms.

Natural enemies

Unsprayed fruit trees support a large fauna of >2,000 arthropod species which include both pest, beneficial and benign invertebrates (Cross et al., 2015). Some pest species have become more prevalent in conventional orchards due to the sensitivity of natural enemies to PPPs. Pear sucker prevalence has increased over the past 30 years through insecticide resistance and repeated applications of insecticides also adversely affecting natural enemies (Cross et al., 1999a). However, effective control is achievable in orchards that support and promote a healthy and diverse predator network (Fountain et al., 2013, Vranken et al., 2014). As for many naturally occurring predators and parasitoids the habitat required to support a healthy and sustainable population in the areas surrounding orchards requires diverse flora and fauna to host them year-round, when cropping habitats cannot provide shelter and food. These can be in the form of cover crops within the orchard themselves and/or perimeter hedgerows and adjacent fields. These CBC methods should be tailored to encourage the beneficial insects required for pest control whilst minimizing buildup of other pests and diseases. There are many naturally occurring generalist predators that help suppress pest populations at different times of the year (Solomon et al., 2000).

The pirate bug, *Anthocoris nemoralis* (Fabricius), effectively suppresses pear sucker populations in orchards when chemical controls are removed (Solomon et al., 1989) and, along with *Anthocoris nemorum* (L.), are regarded as the most widely occurring predatory Heteroptera in both pear and apple respectively (Sigsgaard, 2004). Anthocorids are generalist predators known to feed on many other pests including the fruit tree red spider mite, *Panonychus ulmi* (Koch) and numerous aphid species (Sigsgaard, 2010). Floral resources including weeds are also known to sustain anthocorid populations when prey within the orchard is scarce (Sigsgaard and Kollmann, 2007). These wild hosts encourage anthocorids by supporting non-pest, prey species, such as aphids and plant hoppers on which anthocorids will feed. Traditional hedgerows support anthocorid species and can be established around orchards also benefiting other beneficial insects including earwigs (Happe et al., 2018). Hedgerows can enhance an area by "*providing water quality improvement, flood risk reduction, soil loss reduction (erosion), crop water availability, crop pest reduction, crop pollination improvement, shelter provision (crops and livestock), climate change mitigation and urban air quality*" (Wolton et al., 2014). Unbroken, they can act as vegetation pathways enabling the movement of pollinators and natural enemies across a landscape (Garratt et al., 2017). Hedgerow species, goat and grey willow (*Salix caprea* L. and *S. cinerea* L.), hawthorn (*Crataegus monogyna* Jacq.), and nettle (*Urtica dioica* L.) host anthocorids early in the growing season by providing prey species on which they feed (Cross et al., 2010). Although anthocorids can overwinter within orchards they generally emigrate into apple and pear from surrounding areas, but this can often be too late for adequate control. Growers can enhance this free, naturally occurring biocontrol in cropping areas by planting and enhancing the wild hosts of anthocorids in the vicinity of apple and pear orchards. This will promote a more fluid movement of predators between wild and cultivated plants, reducing the lag in predator establishment and pest suppression (Debras et al., 2000). As with many other generalist predators, anthocorids can be purchased commercially for release into orchards early in the spring when naturally occurring numbers are low.

Earwigs are generalist predators commonly found in apple and pear orchards and contribute to the suppression of pests. Unusually for insects, they care for their brood by tending the eggs and nymphs in nests and regurgitating food to 1st stage nymphs (Staerkle and Kölliker, 2008). They predate on a range of pests (TF 185, *genetic fingerprinting to identify prey of earwigs*) including aphids, midge larvae, moth larvae (Orpet et al., 2019a), and scale pests (Logan et al., 2017). When sticky bands were applied to the trunks of apple trees to prevent woolly apple aphid movement between the canopy and root areas of trees, researchers found an increase in aphid colony size (Orpet et al., 2019c). Sticky banding inadvertently prevented earwigs from reaching the colonies to predate the aphids. A similar bioassay found that 'Tanglefoot insect exclusion bands' increased woolly apple aphid infestation of new apple shoots by 20-25% in comparison to controls in which earwigs could access the colonies (Mueller et al., 1988). Additionally, earwigs are sensitive to many PPPs (Vogt et al., 2008; Fountain and Harris, 2015, AHDB project TF 196 *Investigation of the effects of commonly used insecticides on earwigs* and TF 220 *Further development of earwig- safe spray programmes for apple and pear*) sometimes with sublethal effects difficult to detect in orchards (Fountain and Harris, 2015). In soft fruit production, earwigs are regarded as a pest due to their omnivorous diet (Orpet et al., 2019a) but have not been found to cause direct damage to apple (Orpet et al., 2019b) and traces of apple were not detected in gut content analysis (AHDB TF 185). Earwigs are nocturnal foragers and spend the daylight hours hiding in crevices in bark or introduced structures that provide refuge, e.g. supporting canes and tree stakes. More recently, a commercial refuge has been made available to the UK market, 'Wignest' (Russell IPM), which provides shelter and a food attractant (Innovate UK Project No: 101403). Rolled-up corrugated cardboard within a bottomless plastic drinks bottle can provide a simplified refuge and can be supplemented with dried cat-food in cases when prey is scarce (Suckling et al., 2006). These commercial or homemade-equivalent devices are particularly beneficial in young orchards where trees have not yet formed naturally occurring shelters and can be used in a variety of orchards to help establish earwig populations (TF 223). Helsen et al. (2007) found that in orchards with more than 6 earwigs per refuge (50 refuges per orchard consisting of rolled corrugated cardboard within a bottle) on an infestation scale of 0-8, with 0 being no infestation and 8 being severe, woolly apple aphid infestation never exceeded level 3 (fewer than 5 small colonies per tree). In organic apple orchards releases of earwigs were made in trees heavily infested with apple aphid (Carroll and Hoyt, 1984); 5-6 earwigs were released per tree and provided with day refuges within the trees and straw floor covering to provide shelter for the ground dwelling nymphs. Aphid numbers subsequently reduced from >500 to 50 per tree within three weeks of earwig release. This greatly contrasted with the 3,000 and 2,000 aphids per tree in the earwig free and control plots, respectively (Carroll and Hoyt, 1984).

Growers can find further information on earwig life cycle, their benefits in orchards, how to monitor and enhance earwigs in apple and pear in the AHDB guide 'Earwig-friendly spray programmes in apple and pear crops'.

Hoverflies are a common visitor to many environmental niches and are found in both urban and rural habitats (Verboven et al., 2014). Their importance in providing economic, environmental and ecological services has become more widely recognized over recent years with increasing concerns related to pollinator decline (Rotheray et al., 2008, Garratt et al., 2016). There are a range of hoverfly species in apple and pear orchards that contribute to aphid control, in addition to contributing towards pollination (Rossi et al., 2006). Hoverflies use a combination of chemical volatiles to locate prey, some of which are emitted by the plant and some from the prey itself (Verheggen et al., 2008). Encouraging wild vegetation, in particular pollen- and nectar-rich species, and alternative food sources for predacious larvae, is vital to encourage hoverflies into the proximity of crops. Several studies have highlighted the association between alyssum, *Lobularia maritima* (L.), and hoverfly species and the subsequent reduction in aphids in crops (Gontijo et al., 2013, Hogg et al., 2011). The hoverfly, *Episyrphus balteatus* (De Geer), is a specialist predator of aphids and also an important pollinator of fruit crops (Hodgkiss et al., 2018, Hindayana et al., 2001). The larvae of the hoverfly are voracious predators capable of consuming large numbers of aphids even at low temperatures (15°C) (Dib et al., 2011, Wyss et al., 1999b), hence may be effective predators in the spring while pear and apple are in flower. Commercial hoverflies are now available for purchase and can be released to supplement naturally occurring hoverflies.

Ladybirds (Coccinellidae) are generalist predators common in both commercial crops and wild habitats. They are less prevalent in conventional than in organic apple (Wyss et al., 1999a). Larval predation of pests typically begins just before flowering, which coincides with PPP applications (Wyss et al., 1999a). Nettle (*Urtica*) is common on farms and, as a host to the nettle aphid *Microlophium carnosum* (Buckton), acts as a 'reservoir' to many beneficial natural enemies (Perrin, 1975). Populations of nettle aphid increase from late April (Perrin, 1975) which provide resources for biocontrols to establish while cultural control practices delay expansion of aphid colonies on trees. Over 100 insect species have been identified on the common nettle *U. dioica* including ladybirds, lacewings, hoverflies and parasitoids (Baverstock et al., 2011).

The control of aphids by a range of predators and parasitoids can be disrupted by aphid colonies being tended by ants in a mutualistic relationship. In the UK the common black ant, *Lasius niger* (L.) typically tends colonies of rosy apple and green apple aphid and has been observed defending aphids from parasitic wasps (Cross et al., 2015). In field experiments in both the UK and Hungary, the exclusion of ants from aphid colonies and the provision of ants with sugar feeders resulted in an increase in predation from naturally occurring predators, including hoverflies (Nagy et al., 2013, Nagy et al., 2015, Offenberg, 2001). As the ants are either prevented from reaching the aphids with the exclusion bands or supplemented with sugar feeders, they do not defend the colonies (exclusion) or reduce defending the colonies (sugar feeders) and, while many larger predators may not be deterred by the presence of ants, this enables smaller and typically younger predators to gain access to the aphids (Jay and Cross, 2016). Aphidiinae parasitic wasp species, in particular, are able to exploit undefended aphid colonies but, unfortunately, are not sufficient on their own to prevent economic damage (Cross et al., 1999a).

Introduced biological control agents

Inductive (augmentation) biological releases can be implemented in apple and pear orchards. Although historically applied in glasshouse or protected cropping (Solomon et al., 2000), releases of some predatory mites can be made outdoors. Inductive biological control involves the mass release of commercially-produced predators into a crop (Eilenberg et al., 2001). These are native species which would be naturally occurring in the orchard, but their mass release can rapidly increase pest control success. Large numbers can be introduced either as a preventive or curative treatment, although in the field, due to lower temperatures, it is recommended that preventive introductions are made. Predatory mites can be introduced to suppress a wide number of pest mites including two-spotted spider mite, *Tetranychus urticae* Koch (Amano and Chant, 1979), fruit tree red spider mite, *Panonychus ulmi* (Fitzgerald et al., 2007), apple rust mite, *Aculus schlechtendali* (Nalepa) (Strapazzon and Montà, 1988), and pear rust mite, *Epitrimerus pyri* (Nalepa) (Easterbrook, 1979). TF 219 (Control of two-spotted spider mite (*Tetranychus urticae*) on protected cherry using the predatory mite *Amblyseius andersoni* found that in a protected cherry orchard, *Amblyseius andersoni* (Chant) were recovered from trees throughout plots in which 'Gemini' sachets were deployed at one per 5 trees, demonstrating the mobility of these mites even in tree crops. Their mobility and predation resulted in low populations of two-spotted spider mite, not only in the treated trees, but even in untreated trees where no predatory mites were deployed.

Temperature range greatly influences the optimum timing of applications of biological controls and the recommendations of manufacturers should be heeded for optimum efficacy. For example, *Phytoseiulus persimilis* Athias-Henriot, used to suppress two-spotted spider mite, requires a temperature range of 15-28°C to successfully establish and actively predate (Skirvin and Fenlon, 2003). *P. persimilis* females consume, on average, 370 two-spotted spider mite eggs in their life time, with 320 of these while they themselves are egg laying within this temperature range (Laing, 1968). *A. andersoni* can be introduced to control two-spotted spider mite and fruit tree red spider mite and has a much wider temperature range than *P. persimilis*. *A. andersoni* is active between 6-40°C (AgroSciences, 2016) and consumes more adult spider mite than *P. persimilis*. However, the former has a lower rate of population expansion (Amano and Chant, 1977). *A. andersoni* is attracted to apple branches infested with fruit tree red spider mite, possibly as a response to the emission rates of volatile organic compounds from the trees influenced by pest pressure (Llusià and Peñuelas, 2001). These factors indicate plant volatile cues could be combined with pest volatiles to encourage or attract predatory mites to specific areas of a crop.

Growers can encourage the natural establishment of predatory mites by transferring leaf litter during the autumn from orchards with a high predator population density, or the growing tips from other crops such as strawberry or vines (Szabo and Penzes, 2013, Solomon, 1975). In addition, fabric bands can be tied round tree trunks during the summer months and then transferred during the winter to areas with low predatory mite populations (Sekrecka and Niemczyk, 2006). Fabric or cardboard bands can provide refuges for a wide range of predators in apple and pear orchards and can be left in the orchards to provide year-round shelter (Horton, 2004, Horton et al., 2002). This method is particularly beneficial in young orchards in which the trees have not yet developed the textured bark and naturally forming crevices which develop as the trees increase in age (Costes et al., 2003). Cardboard and fabric bands can also be utilized by pest species, including codling moth, and can act as an indicator for pest presence.

Avoiding practices harmful to beneficial insects

The addition of cover crops or floral resources can benefit substrate dwelling insects by improving drainage and soil structure. Earwigs, *Forficula auricularia* L., are a key predator in apple and pear orchards. They nest in burrows where eggs are laid and nymphs are reared by the parent female (Kölliker, 2007, Helsen et al., 1998). Kolliker and Vancassell (2007) found that the disruption of the nest or the death/exclusion of the female can cause the loss of the brood, reducing the numbers of nymphs emerging in the spring in field trials. Although brood-adoption has been observed in some cases with females 'adopting' orphaned nymphs, the survival is greatly reduced and is not expected to be a frequent occurrence in the field (Kolliker and Vancassel, 2007). Earwigs not only require soils with good drainage to prevent waterlogging of nests, but are also more prevalent in orchards with higher ground cover and minimal soil disturbance or compaction (Orpet et al., 2019a). To reduce soil compaction at vulnerable times in the earwig life cycle, growers would benefit by avoiding driving on headlands and alleyways during the winter and should avoid tillage. As females nest within the soil during winter and early spring (Lamb, 1976), growers should avoid deep tillage and prevent soil compaction by minimizing vehicular travel around orchards. It is possible that similar advice is appropriate for the main pollinators of apple, solitary ground nesting bees, but this requires further investigation. Although, in spring, it is often necessary to apply PPPs during flowering to protect blossoms from diseases, where possible this should be kept to a minimum.

Ground-dwelling Coleoptera such as ground beetles (Carabidae), are polyphagous predators also disrupted by tillage (Lys and Nentwig, 1991). In cereals, rotary tillage reduced carabid activity by 52% in comparison to a control (Shearin et al., 2014), and in carrot fields the presence of vegetation cover, as the result of no soil disturbance, promoted ground beetle presence (Boivin and Hance, 2003). Mechanical weeding may adversely affect soil invertebrates, including earwigs, and where possible should be kept to a minimum depth to reduce disturbance. However, larger more robust insects, such as carabid beetles, seem more tolerant of this method (Kromp, 1999) and for some invertebrates, e.g. spiders, such weed control is less detrimental than herbicide applications (Miñarro et al., 2009), which remove structure for web building and prey capture, as the re-generation of the vegetation takes longer when herbicides are applied. The impact on ground-nesting solitary bees, important pollinators of apple (estimated to be worth £51 million (Garratt et al., 2016)), has not been investigated. The application of compost or mulches to suppress weeds in apple and pear orchards may be a more appropriate management technique than both mechanical weeding and herbicide applications, but consideration of the source of mulch is needed as mulch treatment can affect the viability of weed seeds. In apple, composted poultry manure applications to the base of trees resulted in weed suppression and an increase in predators observed (Brown and Tworkoski, 2004). The timing of compost laying should be considered as new, excessive shoot growth could be attractive to leaf-dwelling aphid species and pear sucker. However, benefits can also result from compost application into the tree row including a reduction in woolly apple aphid *Eriosoma lanigerum* (Hausmann) and spotted tentiform leafminer, *Phyllonorycter blancardella* (Fabricius). Fungicide applications to alleyways and tree spacings can adversely affect ground-nesting bees, which use the bare ground for their nests. Although the majority of fungicides will have no measurable impact on bees, some can cause periods of inactivity while the bees 'recover' (Ladurner et al., 2008), or impair orientation and nest recognition (Artz and Pitts-Singer, 2015). To ensure ground-nesting bees are not exposed to toxins, harmful PPPs should be targeted ideally before nesting begins prior to apple blossom (Kolliker and Vancassel, 2007).

Viruses

Biological control agents can be applied as viruses or pathogens to control pests. Species-specific viruses are available to target codling moth and summer fruit tortrix moth, Adoxophyes orana (Fischer von Röslerstamm), both of which can cause crop damage in apple and pear orchards. These are granuloviruses within the baculovirus family (double-stranded DNA) (Gebhardt et al., 2014). The viruses cause caterpillar mortality (Glen et al., 1984) and to date have had no reported impacts on non-target insects of other pests or beneficials. In a typical year, summer fruit tortrix and codling moth have their first generations between May-July and summer fruit tortrix has a second generation between August-September. Codling moth also has a partial second generation in the UK. Larvae pupate on the ground in leaf litter and soil but also in bark crevasses or in splits in tree stakes and tree ties. Codling moth and summer fruit tortrix are resistant to many plant protection products (Bouvier et al., 2001, Charmillot et al., 2006, Franck et al., 2007, Kadoic Balasko et al., 2020, Salamin et al., 2007) a major driving factor in the development of commercial viruses. The application of the viruses are targeted to coincide with egg hatch and larval feeding on the surface of the apple to ensure uptake (Arthurs and Lacey, 2004). The timing of application is critical for viruses to have a significant impact. For codling moth, first applications typically occur at 111-139°C degree days (Lacey et al., 2008), which for the UK is usually during May, but applications can also be timed by monitoring adult populations with species-specific pheromone traps (Arthurs et al., 2005, Sekita et al., 1984).

Field trials with viruses resulted in a 97% reduction in larvae in the shoots, 50-60% reduction in damage to fruit, and >81% mortality in larvae for tortrix (Peters et al., 1984), and >77% reduction in deep entry wounds for codling moth (Arthurs et al., 2005). The timing of pests' generations can also be effectively predicted with models which use local temperature data to predict larval hatching. RimPro (Relative Infection Measure Pro) takes temperature, rainfall and humidity data and applies them to simulation models which were developed for apple and pear in Europe (Wallhead and Zhu, 2017). This can then be used to make real-time decisions on pest control. Codling moth and apple sawfly, *Hoplocampa testudinea* (Klug) egg hatch can be predicted by RIMPro (Trapman, 2016, Trapman et al., 2008), but it is clear from the (lack of) literature that this is an underutilised resource for key pests in UK pear and apple.

As with conventional insecticides, resistance to viruses is a possibility as individuals with low tolerance will be removed from the population's genetic pool and offspring with a higher tolerance may inherit resistance to the virus and so over time the efficacy of the virus may decline. This occurred in populations of codling moth in southeast France to the CpGV-M strain of granulovirus, which has been used for the past 15 years, although new strains were isolated for renewed efficacy (Berling et al., 2009). Hence, resistance management is now implemented, alternating strains to mitigate virus resistance within codling moth populations. At the time of writing there were no other viruses approved for use in the UK on pests in apple and pear although there have been several baculovirus identified in other global lepidopteran pests (Lacey et al., 2007). In addition, the development of viruses for the control of other key pests would greatly benefit growers by increasing control options that are species-specific.

Entomopathogenic fungi and nematodes

Entomopathogenic nematodes and fungi can be effective strategies to target pests and can be used in combination with many other IPM and organic practices (Kaya and Gaugler, 1993). Both entomopathogenic fungi and nematodes are naturally occurring in the environment but formulated products containing different species or stains are produced commercially for optimum efficacy. Generally, they have a broad host range with no impact on vertebrates and require specific conditions to be effective.

Nematodes have traditionally been applied to control vine weevil *Otiorhynchus sulcatus* (Fabricius) (Bedding and Miller, 1981), and slugs (Grewal et al., 2005). Cross et al. (1999b) highlighted the use of nematodes applied to the soil as a strategy for controlling pests which spend some period of their life-cycle below ground, (e.g. weevils, tortrix moths, and codling moth). Apple sawfly is a common pest of dessert apple with varieties Discovery and Worcester being highly susceptible (AHDB Apple best practice guide). Controlling sawfly in organic orchards is challenging because most effective PPPs are not available for organic production. Adult sawfly emerges just before blossom but spends ~11 months of the year below ground in prepupal or pupal form (Vincent et al., 2019). Nematodes are typically applied to substrate (Divya and Sankar, 2009) often targeting pests in the soil, following CO_2 emitted by their hosts to locate them (Labaude and Griffin, 2018). Nematodes can also be applied to plant foliage. In field trials, where four foliar applications of *Steinernema carpocapsae* (Weiser) were applied to apple trees, secondary sawfly damage was reduced with 8% fruit damage compared to 27% in the untreated control (Vincent and Belair, 1992). When applying nematodes as a foliar application, growers should be aware that in-field conditions can make control variable (Wright et al., 2005).

Pear sawfly, *Hoplocampa brevis* (Klug) has a similar life cycle to apple sawfly, spending several months within the soil. Pear sawfly can be controlled with the nematode *Steinernema feltiae* (Filipjev), using both foliar and soil applications (Curto et al., 2007) but the optimum temperature for this nematode species can limit its effectiveness, becoming inactive when soil temperature is below 10°C. There are currently very few reports of pear sawfly causing economic losses in the UK. Rising average temperatures during the summer could increase incidence of this pest, as it is common in its native range of Asia and warmer European climates, like Italy (Fornaciari and Vergnani, 2006). The use of nematodes in warmer conditions could be considered as a control measure.

In AHDB project TF 223, *S. carpocaspsae* and *S. feltiae* were applied to codling moth larvae in a series of laboratory tests (Figure 2). At 50 and 100% field rates 62 and 100% mortality occurred in treated larvae, respectively. There is also evidence to show *S. carpocaspsae* and *S. feltiae* can be applied to reduce survival of codling moth larvae as a foliar application (Lacey et al., 2006) and woolly apple aphid as a spot treatment (Brown et al., 1992) in the field. However, the application of nematodes requires high moisture levels to ensure nematodes do not desiccate and are able to survive and reach target pests. While these studies highlight the ability of nematodes to target orchard pests the lack of uptake in organic pest control is surprising. Although there are several publications that have found nematodes to be effective in controlling pests, they are rarely used for control in orchards (Kaya and Gaugler, 1993). This may be because control is often difficult to quantify in a field setting.

Figure 2. Nematodes within codling moth larvae from TF 223

By 2020, 750 species of entomopathogenic fungi (EPF) had been identified that infect a wide range of invertebrate hosts from virtually all orders of insect (Mantzoukas and Eliopoulos, 2020). Almost all of these fungi infect the host through the cuticle and spores can be picked up from brief contact with an inoculated surface (Sookar et al., 2008). As with many control options discussed in this review, uptake of EPFs as a pest control tool in horticulture has been minimal (Litwin et al., 2020). This may be because EPFs do not kill the pest instantly and the pest may continue to feed and reproduce for some time, in comparison to CPPPs. Generally the processes of infection, once a host has come into contact with the EPF, can take between 7-14 days for symptoms and finally death to occur (Litwin et al., 2020). However, EPF spores are persistent in the environment, even when hosts are absent or when environmental conditions are unfavorable. Once hosts are available, EPFs have the potential to repeatedly cycle within the population providing season long inoculum (Shah and Pell, 2003) and organic growing environments typically have higher diversity and abundance of EPFs than conventional systems (Tkaczuk et al., 2019). While there are reports of detrimental impacts of PPPs on EPFs within laboratory trials (Litwin et al., 2020), Clifton et al. (2015) concluded that in the field it is negative impact of growing practices used in conventional growing such as tillage and soil disturbance that reduce EPF abundance.

Rust mites (Eriophyidae) are a common secondary pest in apple (*A. schlechtendali*), and pear (*E. pyri*) orchards, and while apple rust mite can be controlled with the predatory mite *Typhlodromus pyri* Scheuten, the hairless leaves of the pear tree offer no protection for *T. piri* (AHDB pear best practice guide). Both species are small (0.13-0.16 mm) and wind dispersed (Easterbrook, 1978). Effective Eriophyidae population suppression has been achieved by several strains of EPF on other crops by applying foliar applications in laboratory and field trials (Robles-Acosta et al., 2019), but to date only one study has been published on apple rust mite (Demirci and Denizhan, 2010), and there are no reports for EPF efficacy on pear rust mite. Ninety-eight percent mortality, 6 days after application of *Paecilomyces lilacinus* (Thom) to apple leaves, was observed in apple rust mite in laboratory bioassays (Demirci and Denizhan, 2010). However, higher humidity levels resulted in higher spore concentration than might be experienced in the field and hence applications after rainfall may be beneficial (as found by Yagimuma (2007)). Historically EPFs have more consistent efficacy when applied to target soil dwelling pests, due to the moisture required for sporulation (Cross et al., 1999b) but their efficacy as foliar applications has greatly improved within the last 5 years. Advances in formulation (Wu et al., 2020), microencapsulation (Wenzel Rodrigues et al., 2017), application technology, and application setting (i.e. in unprotected cropping) (Litwin et al., 2020) have greatly enhanced reliability and consistency over recent years. Growers would benefit from future research on the use and timing of applications to enhance control of key pest species using fungi and nematodes in apple and pear orchards.

Parasitoids

Parasitoids are insects whose larval stages feed, and eventually kill, an arthropod host (Godfray, 1994). Nematodes are often referred to as parasitoids, although the characteristics of true parasitoids include a four staged life cycle (egg, larva, pupa and adult), and after oviposition a parasitoid female will not re-locate the host. Parasitic wasps (Hymenoptera) are the most widely known parasitoids in which females have an elongated ovipositor enabling them to lay eggs in the host. Releases of parasitic wasps are a commonly used biological control strategy in soft-fruit, typically in protected growing systems, but natural parasitism does occur in orchards. The review by Cross et al. (1999a), over 20 years ago is still the most comprehensive report of European parasitoids of apples and pears and the pests they target. The authors highlight that although there is a wide range of parasitoids in orchards, their impact on pest populations is probably minimal as an individual species. However, multiple species may be more effective.

Apple sawfly is parasitized by *Lathrolestes ensator* (Brauns) of which females lay eggs during a two week period, targeting the 1st and 2nd instar larvae (Vincent et al., 2019). This is a very short window of opportunity and can easily be disrupted by poor weather conditions. In addition, due to the variation in flowering and fruit development time, varying rates of parasitism can occur on different cultivars (Cross and Jay, 2001) as a result of the tree phenology being either synchronized or miss-aligned with that of the parasitoid. Rates of parasitism by *L. ensator* also vary between orchards and the management techniques used within them. Generally parasitoid species richness is higher in organic orchards versus conventional or IPM orchards (Mates et al., 2012) due to the detrimental impact of chemical interventions (Cross et al., 1999a). However, occurrence of *L. enactor* was found to be lower in organic orchards in which sulphur applications were made while the parasitoid was in flight and were more common in orchards with sandy soils (Zijp and Blommers, 1993, Zijp and Blommers, 2002a).

Woolly apple aphids are a common pest in apple orchards worldwide, characterised by the wax 'wool' on the bark. They decrease plant health and can result in yield loss at high population levels. *Aphelinus mali* (Haldeman) is one of the more successful parasitoid species. Female wasps are capable of laying 85 eggs within a lifetime. However, *A. mali* is limited by temperature with slow reproduction rates below 25°C restricting parasitism of woolly apple aphid to the summer months (Mols and Boers, 2001). Quarrell et al. (2017) investigated the ability of *A. mali* to suppress woolly apple aphid populations aided by earwigs, which predate within the trees earlier in the season at cooler temperatures. They found that >14 earwigs per tree were required to suppress woolly apple aphid and where this level was not met >0.5 *A. mali* per tree were required to prevent 'severe' infestation. They concluded that where these levels of natural enemies occurred in conventional orchards, PPP may not be required to control woolly apple aphid.

Several weevil species are damaging in apple and pear orchards including pear blossom weevil *Anthonomus spilotus* Redtenbacher, apple bud weevil *Anthonomus pyri* Kollar, and apple blossom weevil *Anthonomus pomorum* (L.) (Morris et al., 2017). While there are associated parasitoids, mainly from the

Pteromalidae family (Hymenoptera), because the weevils have only one generation per year, the population increase of the parasitoids is limited. In addition, due to the long underground life stages of these weevils, the opportunity of parasitism to occur is time restricted to the adult stage of the weevil. However, *Centistes delusorius* (Foerster), hibernates within apple blossom weevil adults as a larvae and pupation occurs in late spring with adult parasitoids emerging to coincide with the emergence of weevil adults (Zijp and Blommers, 2002b). As discussed in previous sections, floral margins provide food (pollen and nectar) and shelter for parasitoids (Bianchi and Wäckers, 2008) which may promote the rate of parasitism of weevil species.

Codling and tortix moths (primarily, summer fruit tortrix *A. orana*, and tree fruit tortrix *Archips podana* (Scopoli)) can be targeted by parasitoids at juvenile stages (egg, larvae and pupa) but many attempts to employ this method have been unsuccessful in Europe. This has been attributed to the, generally, high CPPP input associated with these moths. As low populations of these pest species result in economic damage, growers typically employ chemical applications timed for adult moth flight to prevent egg hatch and subsequent fruit damage even at low pest population numbers. As parasitoids are sensitive to chemicals the two methods are not complementary. However, in organic orchards, parasitoids (both native and introduced) have a positive effect on pest control (Cross et al., 1999a). Anecdotally, in project TF 223, 50% of samples of tortrix larvae from chemically untreated plots were parasitized by various parasitoid species but it is estimated that in the field 10-20% parasitism is more common in tortrix species (Balázs, 1997). In Swedish apple orchards, following the withdrawal of azinphosmethyl (a broad-spectrum product applied to target codling moth), population densities increased for summer fruit and fruit tree tortix but no increase in damage was seen (Sjöberg et al., 2015). Although several factors were thought to contribute to this response, the use of more selective CPPPs appears to have had a positive impact on predation and parasitism. Parasitoids are used very successfully in New Zealand to target codling moth, where augmented releases of some species made up to 50 years previously are now identified in crops in which they have not been recently released (Davis et al., 2018). Before parasitoids such as *Ascogaster quadridentata* Wesmael can be augmented to control codling and tortrix moths in the UK, growers need to evaluate their ability to reduce CPPP applications for these species and employ other organic control options.

One of the main issues with the use of parasitoids is the registration process of non-native species, which are often associated with invasive pests. As the introduction of alien species can severely disrupt native ecosystems, careful consideration is needed before they can be released (Tingley et al., 2018). There is often a lag between pest detection and parasitoid release due to the difficulties in the approval process as approvals are often sought after a pest has established in a newly invaded area. However, researchers in New Zealand have driven the process to obtain approval for the production and release of the Samurai wasp *Trissolcus japonicus* (Ashmead), a specialist parasitoid of the brown marmorated stink bug (BMSB) *Halyomorpha halys* (Stål). This invasive species originally from Asia has extended its range to include America, and Europe aided by international trade. It is not only a pest of an extensive list of crop species but also invades homes causing an unpleasant odor, hence the 'stink bug' name (Zhu et al., 2012). By having this approval in place, if the pest is detected in New Zealand, releases of the wasp can be made immediately; parasitoids are more likely to have an impact at low host populations. Researchers have also evaluated the possible impacts of this species on native stink bugs (Charles et al., 2019), and how it will interact with the environment (Avila and Charles, 2018). Although the UK does not have an approval in place for the samurai wasp, it indicates that a proactive approach is possible.

Key points for growers on biological control

- To encourage natural enemies into orchards, alternative hosts should be available to support natural enemies when pest availability in the orchard is low. Alternative hosts can be incorporated into hedgerows, floral margins and alleyways.
- Growers should consider which beneficial insects they wish to attract and base choices of alternative hosts on this or use generalist hosts, such as nettles, which attract a range of natural enemies.
- Refuges for predators, such as earwigs, can be deployed in orchard trees and should be a priority in newly established orchards that do not have the natural refugia of older, more established trees.
- Commercially produced predatory mites can be introduced with timed releases to help suppress two-spotted spider mite and fruit tree red spider mite.
- Applying biological controls is dependent on environmental conditions and it is key to release according to manufacturer's instructions to gain the best efficacy.
- The timing of application of species-specific viruses for codling and tortrix moths is crucial for their efficacy and pheromone traps and prediction models can be used to target timing.
- Entomopathogenic nematodes are dependent on moisture for their efficacy and, while foliar applications can be made, soil application for pests with a soil-dwelling life-stage are optimum.
- Entomopathogenic fungi could be considered for rust mite control in pear and apple.

- Several species of parasitoid will contribute to the reduction of a pest. Consider providing pollen and nectar sources and reducing chemical inputs to enhance orchard populations.

Semiochemicals

Semiochemicals produced by insects enable inter- and intra-specific communication (Thomson et al., 1999). Sex pheromones have been, to date, the most widely investigated and exploited semiochemicals for pest monitoring and control. However, other pheromones, such as alarm, trail and aggregation pheromones have also been identified for many species (Norin, 2007). The ability to synthetically produce semiochemicals has enabled their exploitation for pest monitoring and control because they are target specific and have minimal impact on non-target species. (Witzgall et al., 2010). Once pheromones have been identified (Cork et al., 1990) and successfully synthesized, they can be use in pest monitoring and control strategies including mass trapping and mating disruption (Reddy and Guerrero, 2010). Monitoring using pheromones provides an accurate and localised approach which is often species-specific and used to make real-time crop protection decisions (Hall et al., 2012).

Semiochemicals for pest control

Pheromone monitoring traps are also a useful tool to aid growers in the detection of new, invasive species. They can be deployed in habitats known to be favourable to the pest, saving time and resources on physical searches. Apple and pear are two brown marmorated stink bug (BMSB) host plants and direct feeding damage to the fruits causes high yield losses if not controlled (Leskey et al., 2012, Rice et al., 2014). BMSB aggregate in human dwellings during the winter and the aggregation pheromone, which is produced to attract other individuals, has been identified and synthesized for use in pheromone trapping. Pheromone traps are used to aid monitoring in countries which do not yet have the pest (Vandervoet et al., 2019; Powell et al., 2020) and have been used for detection within AHDB project TF 223. In West Virginia, a recently invaded area, researchers have been investigating trap catch thresholds, trap position, and resulting economic damage (Short et al., 2017). In apple orchards, two black, pyramid traps baited with BMSB pheromone, were deployed one at the edge of the orchard and one in the centre with both checked weekly. It was found that if an effective PPP was applied following capture of 1 to 10 BMSB individuals within a week, there was a significant reduction in damage to fruit compared to trap catches of 20 individuals per week or an untreated control. Unfortunately, there are no organic products currently available to target BMSB to be used in conjunction with threshold monitoring. However, due to the severity of this pest, which was identified in pheromone traps in 2020 in the UK (Powell et al., 2020), there is a real need to develop alternative, biological, and organic control products.

The use of species-specific aggregation pheromones and/or plant volatiles in mass traps to attract both sexes in soft fruit has been developed over the past twenty years and is used to combat some of the key pests such as strawberry blossom weevil *Anthonomus rubi* (Herbst), European tarnished plant bug *Lygus rugulipennis* Poppius (Cross et al., 2000, Fountain et al., 2014, Baroffio et al., 2018, Wibe et al., 2014), and raspberry beetle (Woodford et al., 2003). However, the application of mass trapping in pome fruit is not common practice. It would be beneficial to develop mass trapping for insects with aggregation pheromones, e.g. weevil species.

There are three species of gall forming midge associated with tree fruit where the female sex pheromone has been identified and synthesized. These include: apple leaf midge, *Dasineura mali* (Kieffer) (Cross et al., 2009a), pear leaf curling midge, *Dasineura pyri* (Bouché) (Amarawardana et al., 2007) and pear midge, *Contarinia pyrivora* (Riley) (Amarawardana et al., 2008). The sex pheromones for these species are used to monitor population levels and to time PPP applications (Cross et al., 2009b). Apple leaf midge first generation adult emergence from pupation is monitored with a synthetic loaded sex pheromone dispenser in red delta traps with sticky card inserts (Cross et al., 2009a). Trap design and colour is also key to the effectiveness of monitoring systems. Pheromone trapping is combined with economic thresholds of crop damage. For apple leaf midge, a trap catch of 30 midges per trap per week would trigger the application of a PPP. Species-specific pheromone traps have also been employed in a mass trapping strategy to reduce apple leaf midge damage. In orchards where mass traps were deployed at 500 traps per hectare, monitoring traps captured 96% fewer midges compared to untreated areas (Suckling et al., 2007). In a separate trial, larvae in leaf shoots were reduced by 48% in comparison to an untreated control and fruit infestation was extremely low with only 1 in 200 apples with signs of midge in the calyx (Lo et al., 2015).

Pheromones can also be deployed without trapping devices for effective pest control. Codling moth is one of the most damaging insects in apple and pear crops, worldwide, and has insecticide resistant populations (Pajač Živković et al., 2019), which have driven the development of several organically approved control strategies. Mating disruption is an area-wide management practice that exploits the insects' mate finding behaviour. This system works by flooding the treated area with species-specific female sex pheromone preventing males from locating the females and subsequent mating (Miller et al., 2010). First proposed in the 1960's (Rothschild, 1981) mating disruption use began commercially in the 1990's with varying levels of success (Knight, 2008). Since then, mating disruption has evolved and become extremely successful for several moth species; however, it has limitations and knowledge gaps (Cardé and Minks, 1995, Suckling, 2000, Lance et al., 2016). For codling moth, a dispenser is loaded with a synthetic formulation of the female sex pheromone. These can either be in the form of a device impregnated with the pheromone known as passive dispenser, applied as a regular aerial spray, or via a timed-release aerosol ('puffer'). The passive dispensers are distributed within the orchards at high densities, typically between 200-3,000 units per hectare depending on manufacturer (Benelli et al., 2019) and are labour-intensive to deploy and collect in at the end of the season (Kong et al., 2014). Aerosol dispensers can be timed to release pheromone at specific times to coincide with the female's natural pheromone release, 'calling,' behaviour, which for codling moth occurs at dusk. These aerosols are deployed at a much lower density per hectare, typically 2-4, depending on manufacturer (Benelli et al., 2019). McGhee et al. (2014) concluded that to provide the same atmospheric saturation as the passive mating disruption technique, 5 aerosol units per hectare would be needed. Pheromones can act to 'camouflage' calling females, but also as false trail following, diverting the male moths away from females (McGhee et al., 2014). In addition, exposure to high quantities of sex pheromones can result in male olfactory receptors becoming non-functional, preventing further detection of sex pheromones; synthetic or natural. Codling moth mating disruption development and implementation is covered in detail by Knight et al. (2019). The approach may also be combined with Sterile Insect Technique (see below).

In laboratory studies, conducted by Verheggen et al. (2008), the presence of a synthetic aphid pheromone in cages containing prey, resulted in an increase in foraging behaviour and oviposition by female hoverflies. In AHDB funded project TF 218 (*Increasing hoverfly populations in apple orchards for control of apple aphids*), several volatiles and blends were successful in attracting hoverflies, and other beneficials, including common green lacewings, *Chrysoperla carnea* (Stephens), into cropping areas. Methyl salicylate identified from a range of plants which are under attack by herbivores has been used to attract hoverflies and lacewings into apple orchards in TF 218 and was also found to be effective in attracting lacewings (James, 2003), ladybirds and *Orius* (James, 2005) into hop gardens.

Semiochemicals can be deployed as repellents, deterring pests away from a crop or even disrupting behaviour (Abd El-Ghany, 2019). These disrupting cues can be based on a range of volatiles including alarm pheromones and even repellent plants, inter-cropped within the orchard. The common green capsid, *Lygocoris pabulinus* (L.) has historically been an infrequent pest on apple and pear (Fountain et al., 2014) although along with other mirid species is expected to be more frequent in the future. Groot et al. (2001) identified the female alarm pheromone of the common green capsid and virgin females housed in a monitoring trap in combination with the alarm volatile caught only 1 male over a 30-day period, in comparison to the female alone treatment that caught 36 males. It seems that in the presence of the alarm pheromone, hexyl butanoate, male common green capsids are less attracted to the females, which would reduce mating success and subsequent population development. Similarly, research in AHDB SF 156 has identified and demonstrated repellence of *L. rugulipennis* in conventionally- and organically-grown strawberry crops with a reduction in mirid presence in the crop and reduced fruit damage of up to 80%. In a follow-on project, *Lygocoris pabulinus* was successfully repelled from commercial raspberry crops reducing fruit and foliar damage (AHDB SF 174).

Aromatic plants emit volatiles that have the potential to attract and/or repel a wide range of pest species. Where ageratum (*Ageratum houstonianum* Mill.), French marigold (*Tagetes patula* L.), and summer savory (*Satureja hortensis* L.) were planted in organic orchards, there was a reduction in summer fruit tortrix moths within organic apple orchards (Song et al., 2014). In these orchards, there was also an increase in parasitic wasps and diverse natural enemies to target other species. French marigold, ageratum and basil (*Ocimum basilicum* L.) also reduced spirea aphid (*Aphis spiraecola* Patch) infestation on apple by 35%, 29% and 38%, respectively in comparison to an untreated control. These plants act as a deterrent to the pest and an attractant to their parasitoids (Souza et al., 2018) and predators. Similarly, coriander (*Coriandrum sativum* L.) promoted lacewing oviposition in strawberry tunnels (Hodgkiss et al., 2019).

Apple blossom weevil is one of the most damaging pests in organic apple and can attack pear (AHDB apple best practice guide). Synthetic walnut tree (*Juglans regia* L.) volatiles had a deterrent effect on apple blossom weevil in laboratory studies (Collatz and Dorn, 2013), but this research was not extended into pest control options. Pear blossom weevil, pear bud weevil (*Anthonomus spilotus* Redtenbacher) and apple bud weevil, are also minor pests of pear (Morris et al., 2017). Pheromones have been identified for *Anthonomus* pests on other crops, e.g. cotton boll weevil (*Anthonomus grandis* Boheman) (Dickens, 1989), pepper weevil (*Anthonomus eugenii* Cano) (Eller et al., 1994) and strawberry blossom weevil (*Anthonomus rubi* Herbst) (Innocenzi et al., 2001), indicating that volatile communication and detection is well preserved in this family. For this reason, it would be beneficial to identify the pheromones of orchard weevils to better monitor and exploit pheromones for control.

Semiochemicals to attract ('pull') pests away from the crop can be combined with repellent volatiles to 'push' the pest from the area in a system known as 'push-pull' which could exploit synthetic or natural volatiles. Semiochemicals can also be employed to pull natural enemies into the vicinity and target the pest (Abd El-Ghany, 2019, Xu et al., 2018). This system is used effectively by subsistence farmers in Africa, the first area to employ this method, to control stem borer species (Lepidoptera) in maize. There are several reports of the use of this system in vegetable and field crops (Cook et al., 2007), but its uses in fruit crops are limited. The implementation of this method in apple and pear would require little additional research prior to testing for some pests. As there are semiochemicals associated with several pests such as midges and tortrix species there is an opportunity to exploit pheromones and plant volatiles to attract and deter pest insects and pull natural enemies into apple and pear orchards.

Key points for growers on semiochemicals

- Pheromone traps are accurate indicators of pest phenology and should be used to make real-time decisions on whether control is needed and when to time control applications, such as viruses or bioprotectants.
- Pheromone traps could be exploited in the future for mass trapping some orchard pests.
- Mating disruption is an area-wide control strategy for codling moth. It can be deployed via timed aerosol puffers or slow-release dispensers.
- Synthetic volatiles can be deployed to attract beneficial insects and/or deter pests from an area. Inter-planting with aromatic plants can also deter pests and encourage natural enemies.
- Push-pull strategies could be tested for some pests immediately where associated semiochemicals have been identified.

Physical control

Physical pest control can be time-consuming and costly to implement in apple and pear orchards, but physical barriers generally reduce pest pressure by preventing pest migration into orchard trees and consequently fruit damage.

Netting and physical barriers

Netting of fruit trees has become common practice for stone fruits over recent years, especially with the introduction of spotted wing drosophila, *Drosophila suzukii* (Matsumura), in cherry (Mazzi et al., 2017). The netting or mesh is normally erected prior to pest occurrence in the orchards and physically prevents the pest from reaching the developing fruit. Netting apple and pear has historically been used to protect fruit from damage from environmental conditions such as sunburn, hail damage and high winds (Mupambi et al., 2018) but is infrequently used for pest control. In pear and apple, many lepidopteran, sawfly and weevil pests spend a proportion of their life-cycle within the soil meaning trees would need to be netted with minimal or no soil accessibility or as individual rows rather than whole-orchard netting (Alaphilippe et al., 2016). To do this, nets would have to encase the canopy and be closed around the main trunk to be effective. In France netting has been successfully used within field trials to reduce fruit damage by codling moth by 91% in comparison to an un-netted control (Sauphanor et al., 2012). It is speculated that the reduction occurs via disrupting mating (by preventing moths from flying over the canopy to find mates) rather than suppressing oviposition. Fruit damage from mirids and birds was also reduced, however woolly and rosy apple aphid species can increase in prevalence (Alaphilippe et al., 2016), presumably because insect-excluding mesh creates a microclimate beneficial to aphids and/or prevents their main natural enemies from reaching trees (e.g. earwigs, hoverflies, ladybirds etc.). In continental Europe, netting has been successfully used to prevent BMSB damage to apple, to levels lower than insecticide treated plots. Authors also state that predator and parasitoid numbers were not reduced using this technique (Candian et al., 2020). BMSB, has not yet been confirmed as having a breeding population in the UK, but AHDB project CP 197 has been developing rapid DNA-based identification to aid in distinguishing BMSB life stages (eggs, nymphs and adults) from those of common UK stink bug species.

Waste removal

The life cycle of some key pear and apple pests has a soil phase. Weevil, sawfly and lepidopteran pests can pupate in the soil beneath trees after migrating from the dropped fruitlets and foliage to the soil. For example, apple fruit weevil females sever the petiole of developing fruitlets once an egg has been laid. The larvae can then gain access to the soil for pupation. In soft and stone fruit, it has become common practice to remove all waste fruit from the crop and the floor and then treat the fruit to prevent re-infestation of spotted wing drosophila (Bal et al., 2017, Noble et al., 2017). Currently this has not been adopted in pome fruit management, presumably due to the high labour input needed to implement it successfully.

In some cases, growers have combined apple and livestock farming and used either sheep or pigs to graze on dropped fruit. With sheep grazing there have been reports of increased levels of N, C, and P (Landi et al., 2017) (see section on soil health and properties) which can be beneficial or detrimental depending on cultivar. There are varying levels of success reported but overall reductions in codling moth and tortrix damage the following season have been observed; pigs typically remove between 90-100% of dropped fruit (Buehrer and Grieshop, 2014, Nunn et al., 2007). Buehrer and Grieshop (2014) identified a significant reduction in oriental fruit moth larvae in dropped fruit and significantly reduced codling moth and oriental fruit moth damage to fruit the following year in pig-grazed orchards, compared to untreated controls. There are many associated costs with implementing livestock grazing in orchards including fencing, animal husbandry and licencing. Livestock can cause extensive soil disturbance which could have impacts on ground-nesting/dwelling organisms and may open areas for solitary bees. The choice of livestock, breed and age should be carefully considered to prevent tree damage (more detail and case studies are in Grieshop (2019)).

Particle films

Particle films are mineral in composition and coat the target crop in a barrier which disrupts insect behaviour and protects fruit from damage (Glenn and Puterka, 2005). Most films consist of kaolin, a white clay substance that has high reflectance that can be easily washed from fruit prior to sale. Kaolin films have been used successfully for the season-long control of olive fruit fly compared to an insecticide treated grove, which was only protected while the last spray persisted (Saour and Makee, 2004). For boll weevil, cotton plants treated with kaolin yielded 2.4 and 1.4 times more cotton than an untreated control and cotton treated with an insecticide (Showler, 2002). On pear, the application of kaolin to control pear sucker was investigated by Saour et al. (2010). They found a reduction in nymph density on kaolin-treated trees, which continued for season-long suppression. An increase in pear yield was also obtained from the treated trees. Pear sucker was also reduced by 75% in trees treated with kaolin within TF 181 (*Exploiting semio-chemicals, conservation biocontrol and selective physical controls in integrated management of pear sucker*) and had been suggested as a pre-bud burst application to control early season sucker. In warmer climates, the use of particle films has been found to reduce leaf-roller damage to leaves and heat stress in apple (Thomas et al., 2004). In the Netherlands, kaolin was effective in reducing several key pest species including apple blossom weevil; numbers reduced by 51% (Marko et al., 2008). However, a disruption of earwigs and parasitoids was also observed and woolly apple aphid and rosy apple aphid incidence increased in the treated plots (Marko et al., 2008). It would be beneficial to further investigate the timing and application methods of particle films to gain optimum pest control whilst not disrupting natural enemies.

Key points for growers on physical control

- Installing insect mesh barriers can reduce damage by codling and tortrix moths and is effective against brown marmorated stink bug. More work is needed on the economics of netting systems and side effects of insect mesh in tree fruit (e.g., environment, disease, and natural enemies).
- Mesh installation should be timed to optimise visitation to blossom by pollinating insects.
- Livestock grazing can be an effective way to remove dropped waste fruit from the orchard floor and has been linked to a reduction in fruit damage.
- There are associated costs with grazing that may outweigh the level of control, but it is a viable option for livestock farmers with orchards.
- Applications of particle films can be incorporated into control programmes to deter pests.

Foliar application of products

Non-chemical PPPs registered for use in organic production vary widely in their modes of action and efficacy but should be considered within IPM programmes. Some act as plant strengtheners to promote a natural tolerance to pests and some deter pests by coating the trees in an unattractive material.

FLiPPER, consisting of fatty acids, has be identified as a promising option against several midge species (SCEPTREplus SP38) while being safe to several predators and parasitoids (AHDB, Apple best practice guide). FliPPER has an EAMU approval for use on apples and can be used to target apple leaf midge and aphid species. The application of FLiPPER should be made within 24 hours of apple leaf midge monitoring traps reaching trap threshold, as discussed in the 'Semiochemical' section.

Bitter ash, *Quassia amara* L., extract has been used as a natural pesticide in developing countries for many years (Latum and Gerrits, 1991). In Europe, bitter ash extract, produced by boiling wood chips of the plant, has reduced apple sawfly infestation in several investigations. Apple sawfly infestation can be reduced by 50%, when the equivalent of 3.5 kg per hectare of bitter ash chips were boiled down and applied in field trials (Psota et al. (2010). Applications of 12 kg per hectare at different stages of apple tree and pest phenology resulted in a significant 3-10% reduction in damage compared to an untreated control, but there was no difference in damage when applied at petal fall or applied to coincide with egg hatch of apple sawfly (Neupane, 2012). Finally, Kienzle et al. (2006) found a greater efficacy of apple sawfly control at 6 g per hectare of bitter ash extract when mixed with 1.5 L per hectare of a wetting agent. The use of plant extracts and botanical insecticides could greatly increase the number of products against pests in many crops and there is extensive evidence of their efficacy in the literature (see Tembo et al. 2018). However, it is clear that the regulatory process in some countries, including the UK, is preventing the commercialisation of these products (Isman 2020) and this lack of accessibility may be preventing their uptake in pest control.

Plant strengtheners are 'borderline' products that do not fall within the plant protection product category or that of a plant fertiliser, but may enhance a plant's resistance to harmful organisms (Torre et al., 2013). Generally they affect the physiology and cellular structure of the target plant and improve abiotic and biotic stress responses (du Jardin, 2015). Garlic, *Allium sativum* L*,* contains organosulfur compounds and is used in traditional medicines for its antimicrobial properties (Ross et al., 2001). As a plant strengthener, it increased tomato fruit yield by 67% in field crops and reduced fungal growth in laboratory tests (Mulugeta et al., 2020). It may also have insecticidal properties as demonstrated with mosquitoes (Singh and Singh, 2008).

Macroseaweed extract applied to apple cv. Jonathan, stimulated tree growth with a 20% increase of leaf area compared to the untreated control and delayed the storage disease 'Jonathan spot' up to 60-days after harvest (Soppelsa et al., 2018). In some crops there has been a positive correlation between the use of plant strengtheners and an increase in parasitoid attraction into the crop. Initially, research on BTH [benzo (1,2,3) thiadiazole-7-carbothioic acid S -methyl ester] applied to maize crops to induce disease resistance, found that treated plants infested with caterpillars were more attractive to the parasitoid, *Microplitis rufiventris* Kukujev (Sobhy et al., 2014). In addition, when BTH was applied to cotton with damage caused artificially or by the caterpillar, this resulted in an increase in attraction of parasitoid wasps (Sobhy et al., 2015).

Key points for growers on foliar applications

- Foliar applications can control pests by causing direct mortality, by deterring them from the orchard and strengthening the plant.
- FLiPPER is a promising product found to control a range of midge species and application timing is key.
- Plant extracts are used as a natural pesticide in developing countries but the registration process in the UK may prevent this method from being exploited.

Pest modifications for future control

Sterile insect technique (SIT) is a species-specific method successfully used to suppress a range of pest insects, primarily those that threaten human and agricultural health. Traditionally SIT involves mass rearing the target insect, sterilization of males by radiation, and mass release of sterilized males into the target insect population. Mating between wild females and sterile males produce no offspring, reducing the next generation's population. The Okanagan-Kootenay Sterile Insect Release (OK SIR) programme in British Columbia is the longest running area-wide SIT program targeting codling moth (Thistlewood and Judd, 2019). Established in 1992, the OK SIR programme has also highlighted issues associated with this method such as the need for it to be applied in an area-wide approach rather than small scale. The combination of SIT and mating disruption, discussed above, within the OK SIR programme resulted in no damage being detected after two years of implementing the combination of control methods and no larvae or adult moths being caught after four years (Judd and Gardiner, 2005). In this experiment 15-20% of the insecticide-treated orchards had detectable levels of codling moth at the end of the four-year period.

An alternative to radiation SIT is release of transgenic insects carrying lethal self-limiting genes. Such insects can be mass produced on a diet containing a suppressor of the self-limiting gene. Once released into the wild target population, the lack of suppressor results in mortality of offspring produced between the self-limiting insects and wild counterparts prior to reaching the adult stage of the lifecycle (Alphey and Bonsall, 2018, Jin et al., 2013). The self-limiting trait can also be sex-specific. For olive fruit fly *Bactrocera oleae* (Gmelin), this technique has proven more effective than mass release of sterile males, assumed to fail due to the misalignment of mating rhythms between wild and laboratory reared individuals or reduced fitness of treated males. In research by Ant et al. (2012) olive fruit flies carrying a female specific (fs) self-limiting gene were found to have no reduction in fitness, which is often associated with traditional SIT methods. Weekly releases of fs self-limiting gene carrying males in cage trials resulted in population collapse within 10 weeks of initial releases into cages.

The 'incompatible insect technique' has been developed for Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) control, where sterilisation is achieved by infection with the bacterium *Wolbachia* (Zabalou et al., 2009). Hosts carrying strains of *Wolbachia* may suffer from sex-dependent mortality of offspring, feminization (resulting in only female offspring emergence), or an incapability between individuals preventing fertilization during reproduction (Zhang et al., 2015).

Genetic manipulations can also be made to shift the sex ratio of pest species in favour of males. The process results in a reduction in female offspring and therefore reduced reproduction (Schliekelman et al., 2005). This can either be implemented by a male favouring allele of which males carrying this allele will only sire male offspring or the result of genetically female offspring being phenotypically male. While some of these genetic methods have been applied to important agricultural pests, there is still a need to reduce costs associated with the processes which would make them more accessible for 'every-day' use (Scott et al., 2018). These genetic techniques are not currently approved for use in the UK but the technology and knowledge is available for further development and testing should it gain support for use in the future.

Future research

Throughout this review we have summarised areas of research that could be investigated in the future to aid organic apple and pear growing. The topics that we, as researchers, believe to be worthy of investigation and that would benefit growers and the environment are listed below.

Cultural control

- Resistant variety development and marker assisted breeding for both rootstock and scion.
- Canopy maintenance and the impact on pest pressure, natural enemies, and yield.

Biological control

- Impacts of inductive biological control in unprotected trees and the establishment of habitats to support these natural enemies (both wild and introduced).
- Development of species-specific viruses to target key pests.
- Application and efficacy of nematodes to control pests with a long period below ground such as weevils and sawfly.
- Efficacy of entomopathogenic fungi to target orchard pests focusing on timing of application possibly with pheromone traps, development models based on degree days, or tree phenology.
- The identification of aggregation pheromones and female attracting semiochemicals associated with orchard pests including weevil species for the development of mass trapping.
- Identification of repellent cues for orchard pests to develop 'push-pull' strategies.

Physical control

- Efficacy of netting on crop damage from tortrix moths and impact of other pests.
- Livestock grazing and waste removal of fruit to reduce subsequent pest populations.
- Foliar applications in replicated field trials for key and minor pests in apple and pear.

Pest modifications

- Genetic and physical modification of multi-generation pest insects and their application in the field to reduce subsequent populations.

Conclusions

While there are many organic control options available to control pests in apple and pear in the UK, several methods need to be combined for suppression below economic thresholds. Where in conventional orchards, a broad-spectrum insecticide may potentially eliminate many pests with one application, organic practices may require several, accurately timed applications and the integration of several control methods. For some control options there may be an increase in labour requirements in installation, monitoring, and regular deployment. However, through employing these techniques, growers will build more resilient and sustainable year-on-year control strategies rather than short-term fixes with fast-acting PPPs alone. To achieve this, more regular and accurate monitoring with a greater understanding of pest/natural enemy lifecycle and biology is required, coupled with information on the appropriate timing and environmental conditions for optimum efficacy of each approach for success.

This review has highlighted current and future non-chemical plant protection options, which are appropriate for commercial organic and IPM orchards. We have also highlighted areas where there are obvious gaps in knowledge that could be researched and further exploited for future pest control options. It is clear from these gaps that the foundations for future research are well established, but revenue is needed to fully explore their efficacy under different orchard scenarios. There is also a lack of uptake from growers for some of the more effective methods, but this may be due to the availability of other, easy, low-cost options. It is promising that there are many organic pest control options available for apple and pear growers and that there are pioneering growers willing to test and demonstrate implementation and efficacy.

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