AHDB

Alternative control strategies for disease in organic apple and pear production

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Background

Apple and pear are important tree fruit commodities globally. In 2018, over 86.14 million tonnes of apples and 23.73 million tonnes of pears were produced (FAOSTAT 2020). In the UK and mainland Europe, there is currently ongoing consumer and environmental concern regarding over-reliance on chemical pest and disease control. This has resulted in increased chemical withdrawals and legal use restrictions continuing each year.

The European Commission (2020) defines organic farming as an agricultural method that aims to produce food using natural substances and processes. They state organic farming tends to have a limited environmental impact as it encourages 1) the responsible use of energy and natural resources; 2) the maintenance of biodiversity; 3) preservation of regional ecological balances; 4) enhancement of soil fertility; and 5) the maintenance of water quality.

European Union regulations on organic farming were designed to provide a clear structure for the production of organic goods across the EU. This is to satisfy consumer demand for trustworthy organic products whilst providing a fair marketplace for producers, distributors and marketers. All organic food and drink sold in the EU must meet the EU Organic Regulation, shown by the green leaf logo (Figure 1).

Figure 1. ***The EU Organic Regulation green leaf logo.***

There are several approved organic control bodies in the UK including Organic Farmers & Growers CIC (GB-ORG-02), Organic Food Federation (GB-ORG-04), Soil Association Certification Ltd (GB-ORG-05), Biodynamic Association Certification (GB-ORG-06), Quality Welsh Food Certification Ltd (GB-ORG-13), and OF&G (Scotland) Ltd (GB-ORG-17). It is a requirement that the identifying code of the certifier must be used when labelling certified organic products, for example 'Organic Certification: GB-ORG-01'. The name, initials or logo of the certifier can also be used in addition to the code. As an incentive to encourage the adoption of organic tree fruit production in the UK, the UK government offer country stewardship grants for organic tree fruit production and conversion of tree fruit orchards to organic production.

In the UK, the Agriculture and Horticulture Development Board (AHDB) funded SCEPTRE and SCEPTREplus projects 'Research for sustainable plant protection products for use in horticulture'. These projects were set up to test sustainable plant protection products for use on high priority disease, pest and weed problems in horticulture and ornamental production (https://ahdb.org.uk/SCEPTREplus). The projects also support the approval of products, and help to develop integrated pest and disease management programmes for the industry. The projects are run with a consortium of scientific researchers and biological control consultants from the University of Warwick, ADAS, NIAB Cambridge, NIAB EMR, Biorationale Ltd and AHDB.

The Apple Best Practice Guide is hosted on the AHDB website. When first published, it thoroughly covered the key diseases in UK apple production, with much of the information still relevant today (AHDB 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g) . However, some of the information needs updating, particularly concerning alternative products for disease control in organic orchard systems. The AHDB funded this desk study to review viable alternative control methods relevant to organic production of apple and pear.

This review aimed to provide novel and alternative control methods that will aid both organic and conventional growers. It will also identify areas for further research.

The key diseases of organic UK apple and pear production and their alternative controls that will be covered in this review include apple scab, European canker, powdery mildew, apple replant disease (ARD) and brown rot/blossom wilt. Invasive pathogens not yet present in the UK, and the effects of climate change on apple and pear diseases are also discussed.

Summary of main findings

Apple scab

- Orchards with a mix of scab susceptible and scab resistant cultivars have lower scab lesion numbers when compared to monocultures.
- A number of biocontrol agents and plant extracts show activity against scab, but don't offer reliable control.

Apple canker

- Orchards planted in early winter tend to develop fewer cankers than those planted in spring, with the exception of Gala which appears to be less influenced by planting date.
- The biological soil amendment, Trianum G (*Trichoderma harzianum*), has been shown to decrease the incidence of canker in newly planted apple orchards, but is not currently approved for use on apples. Soil incorporated plant growth promoting rhizobacteria (PGPR) have had a similar effect.
- Pruning out cankers and prompt removal of heavily infected trees is currently the most effective control method.
- Growers can reduce the speed of infection by optimising the amount and timing of application of nitrogenous fertilisers and irrigation.

Apple powdery mildew

- In conventional apple production, where combined with conventional fungicides in weekly spray programmes, switching between alternative products such as Cultigrow, Mantrac, Trident, SB Invigorator and Wetcit, can achieve similar levels of control to a routine 7-day conventional fungicide programme. It is not known what effect these products have on their own.

Apple replant disease (ARD)

- Soils of orchards with apple replant disease have been shown to have a reduced presence of arbuscular mycorrhizal fungi (AMF).
- Planting new trees in the inter row of previous orchards can help to avoid ARD.
- Planting more vigorous cultivar/rootstock combinations and rootstocks dissimilar to those previously planted, can be effective in reducing ARD development.

- Brassicaceous amendments of soils have increased tree growth and reduced replant disease relative to trees without the amendment.

Brown rot

- The biofungicide Boni Protect (*Aureobasidium pullulans*) is now approved for use on apples and pears and offers protection against brown rot.

Potential invasive pathogens

- *Xylella fastidiosa* is currently the greatest threat to UK pear production, affecting the water conducting tissues of the tree, causing wilting and tree death.

Effects of climate change

- The trend towards warmer higher annual temperatures in the UK favour the incidence and spread of the bacterial pathogens *Erwinia amylovora* and *Xylella fastidiosa*.

Apple and pear scab

Apple and pear scab is the most economically important disease of apple and pear worldwide. Scab on apple is caused by the fungus *Venturia inaequalis*, and on pear by *Venturia pyrina*. Much is known about the infection process and disease cycle, including the role of the overwintered sexual stage on dead leaves on the orchard floor, and the secondary infection of fruit and leaves by the asexual stage (Berrie 2019; MacHardy 1996; Burchill et al. 1965). Particularly in organic orchards, mycelia and conidia can overwinter in buds and twigs of the host tree and go on to produce new inoculum in spring. All the main varieties grown in the UK are susceptible, especially Gala (Berrie 2019).

Dr Tom Passey of NIAB EMR recently studied 'Population genetics and epidemiological effects on *Venturia inaequalis* from mixed cultivar apple orchards'. This work recommended cultivar selection as key to scab control as current popular dessert cultivars do not allow for mass scale commercial organic growing as they are nearly all susceptible to scab, and would require new resistant varieties to come on to the market (Passey and Xu 2019). There is possibly more scope for organic growing in cider production.

The use of copper, even in low doses, has been reported as necessary to control scab in organic orchards (Berrie 2019). However, as of March 2020, there was no copper product with fungicide approval for use on organic apples and pears in the UK. At the time of writing, an application had been submitted by the AHDB for an emergency authorisation for the Certis copper hydroxide product, Funguran Progress, which is expected to be approved within the 2021 season.

Much work has been completed by NIAB EMR (the former East Malling Research, and HRI – EM) regarding scab and alternative control methods. A five-year Defra funded HortLINK project (2000-2004) entitled 'Varieties and integrated pest and disease management for organic apple production' was completed with a consortium of 11 research and industry organisations. The most feasible solution for reliable control in organic production reported was to grow resistant cultivars. More recently, another five-year project (2015-2019) entitled 'Improving integrated pest and disease management in tree fruit' funded by AHDB and with a consortium of four research organisations [NIAB EMR, ADAS, Natural Resources Institute (University of Greenwich), and University of Reading] included scab surveillance from a UK indicator orchard at NIAB EMR as part of the ten year VINQUEST project which involved 24 partners from 14 countries (Patocchi et al. 2020).

Alternatives to chemical control

Breeding for resistance

Patocchi et al. (2020) reported a way to achieve durable resistance, which is to pyramid multiple scab resistance genes in a cultivar. The most promising apple-scab resistance genes for developing cultivars with durable resistance to date are Rvi5, Rvi11, Rvi12, Rvi14 and Rvi15. The Apple Best Practice Guide (AHDB 2020a) states that most of the main culinary and dessert cultivars grown in UK are susceptible to scab. Studies have shown that orchards with a mix of scab susceptible and scab resistant cultivars have lower scab lesion numbers when compared to monocultures (Didelot et al. 2007; Bousset et al. 1997; Parisi et al. 1993). Although cultivar mixes have been shown to reduce scab in dessert apples, they usually provide an insufficient level of control for commercial production standards. The magnitude of cultivar mixture effect depends on disease pressure, climatic conditions, cultivar mix structure and orchard management (Berrie 2019).

Alternative products

There is an urgent need to develop alternative products, particularly biocontrol options, targeting specific stages of the pathogen lifecycle integrated with forecasting models (Berrie 2019). Biocontrol agents (BCAs) generally only reduce scab, rather than control it, and are therefore probably not effective enough for use during the growing season (AHDB 2020a). There may be more scope for use of BCAs post-harvest to encourage leaf rotting in the orchard, and hence to reduce ascospore production. The fungus *Cladosporium cladosporioides* was found to reduce spore production and severity of scab on leaves and fruit under orchard conditions (Köhl et al. 2015, 2009). However, like many BCAs, a reduction of disease after application of *C. cladosporioides* is not always seen.

Plant extracts have also been tested for scab control. One per cent populin isolated from black poplar (*Populus nigra*) has been reported to slow conidial germination of *V. inaequalis in vitro* as well as reduce scab on leaves and fruit (Bálint et al. 2014). The plant growth regulator prohexadione-ca has been reported to reduce scab incidence (Bazzi et al. 2003), by inducing host resistance (Bini et al. 2008). Extracts from the soapbark tree (*Quillaja saponaria*), orange peel, grapefruit seed, Mojave yucca (*Yucca schidigerra*), *Camellia oleifera,* and quinoa (*Chenopodium quinoa*) seeds, as well as potassium bicarbonate have been reported to have good protectant efficacy against *V. inaequalis* when applied at 1 % concentration (Jamar 2011). However, alternative methods of scab control are often not adopted by commercial growers, as the control they provide is often variable, and the number of applications required usually outnumbers that of conventional chemicals. As with conventional chemical controls, there is a chance that pathogens can develop resistance against these products.

Hygiene and cultural control

Hygiene and cultural control are key to reducing scab in organic production, particularly where susceptible varieties are grown. Scab inoculum that would overwinter on leaves and twigs on the orchard floor need to be removed in autumn to prevent infection in the spring and summer (Passey and Xu 2019). Pruning is another key strategy for scab reduction in organic production. Trees should to be pruned to remove the inoculum source on infected branches, encourage good air circulation in the orchard canopy, and encourage rapid drying of leaves and fruit after rain and dew (AHDB 2020a).

Scab monitoring and forecasting

It is not possible to monitor scab in the early part of the season as visual scab can take up to three weeks at low temperatures between infection and visual scab symptoms (Berrie and Holb 2014). Therefore, conventional control products are usually applied early in the season based on tree phenology and weather, rather than visible symptoms. Searches for an assessment of scab are still important, to check on inoculum levels at the start of and during the season and to determine the success of control measures (Berrie 2019).

There are apple scab warning systems such as Adem™ that are currently being used in a recoded version by Agrii (UK) Ltd, and have been used successfully to aid fungicide scheduling, resulting in reduced inputs (Berrie and Xu 2003). Metos® uses the Mills or Mills/MacHardy scab infection models (MacHardy 1996; Mills and LaPlante 1951). In the UK, scab warnings mainly based on the software program RIMpro (Aćimović and Rosenberger 2018) are provided by private companies at a cost. RIMpro incorporates weather forecast to assist on making decisions on treatment.

European canker of apple and pear

Neonectria ditissima is the most important canker pathogen of apple in Europe (AHDB 2020b). The key sites for pathogen entry into trees are through wounds such as leaf scars during the autumn leaf fall period, fruit-picking scars, pruning cuts and insect damage. In addition to cankers, the pathogen also causes fruit rots both pre- and post-harvest. Cankers serve as the overwintered form of the disease with the wood providing a perennial substrate on which the pathogen can survive throughout the year (Saville and Olivieri 2019).

Alternatives to chemical control

Breeding for resistance

Malus species and apple cultivars show variation in susceptibility to *N. ditissima* (Saville and Olivieri 2019; Ghasemkhani et al. 2016; Gómez-Cortecero et al. 2016; van de Weg 1989; Alston 1970). Resistance breeding is underway in global breeding programmes. However, enduring resistance to canker has not been demonstrated (Gómez-Cortecero et al. 2016). Currently, Amanda Karlstrom of NIAB EMR is investigating '*The genetic basis of resistance to Neonectria ditissima'.* Growing varieties tolerant to the disease is the most effective method of control, although, little is known regarding the genetic basis for quantitative resistance that exists in apple germplasm. The project aims to investigate the genetic component of resistance through studying resistance/susceptibility in a multi-parental population at multiple sites. Resistance in the population is being assessed in both wood and fruit to examine differences in resistance levels in different tissues. The data is being used to map quantitative trait loci (QTL) for canker resistance through a pedigree-based analysis. Candidate genes for resistance will be identified through transcriptome analysis of the moderately resistant variety 'Golden Delicious' and susceptible variety 'M9' during infection with *N. ditissima*.

Rootstock scion and cultivar selection

In the recently completed AHDB TF223 project, the effect of rootstock selection on Neonectria canker of Gala scions was tested after grafting on to fourteen rootstock selections, on two sites (one NIAB EMR, East Malling, Kent, the other at Poolhill, Newent, Gloucestershire). There was generally an inconsistent reduction in canker with the same rootstock cultivars across sites, suggesting other factors are at play. For example, the Geneva rootstocks in Kent had higher canker incidence, whereas the same rootstocks grown in Gloucestershire had lower canker incidence. The current BBSRC and industry funded CANKERLink project '*The role of endophytes in affecting European canker development on apple'* is investigating canker of several important commercial scion cultivars during early-winter planting and early spring the following year after cold storage (2ºC, frequent misting, trees in bundles). Results from the CANKERLink project have suggested site selection, scion cultivar selection, and endophyte assemblages likely have a larger effect on canker than the rootstock selection. Varieties tested included Gala, Kanzi, Jazz, Rubens, Golden Delicious, Grenadier and Braeburn. Braeburn and Grenadier had low canker number regardless of the time of planting, Gala had a moderate and similar number of cankers with both early winter and early spring planting. Considering canker across all three sites tested, all varieties, except Gala, had higher number of cankers with cold storage and spring planting vs early winter planting. It is unclear what the cause of this increase is, whether it be tree stress caused by the refrigerated storage period and/or infection during refrigeration as some of the trees already have latent and visible cankers when bundled together after lifting and placing in storage.

The role of endophytes

Endophytes have been reported to influence plants in several different ways including plant growth, resistance to abiotic stress and disease resistance (Busby et al. 2016; Bulgarelli et al. 2013; Bacon 1993). There are increasing numbers of patents of endophytic fungi being granted (Gokhale et al. 2017). PhD research by Dr Leone Olivieri with Royal Holloway, University of London entitled '*Understanding endophytes to improve tree health'* is in part looking at the endophyte assemblages in susceptible and more tolerant apple cultivars, and their potential role in resistance to canker. This work also forms part of the CANKERLink project. In CANKERLink a principal component analysis of fungal OTUs (operational taxonomic units) showed that data points cluster together mostly based on site/location and then cultivar. The Bray-Curtis indices echoed the results of the PCA analyses. There was little effect of rootstocks (more tolerant M116, more susceptible M9 337) on fungal endophyte assemblages.

Biological control agents

In the AHDB TF223 project, a soil amendment *Trichoderma harzianum* T-22 (Trianum G, Koppert Biological Systems) was added during the planting of newly established orchards. The product is marketed as a biofungicide for the reduction of soil-borne diseases such as *Pythium* spp*., Rhizoctonia* spp., *Fusarium* spp*.* and *Sclerotinia*. It is also marketed to promote plant growth, particularly root and aerial parts of the plant. The product reduced canker number in two of the three tested orchards in the 2019 assessments. A cost-benefit analysis of a newly planted orchard of 1,000 trees showed a financial benefit of >£1,050 over five years. Trianum G is currently only approved for use in permanent protection full enclosure situations, so cannot be used in commercial orchards.

Other biological soil amendments such as arbuscular mycorrhizal fungi (AMF) are increasingly being used to aid tree establishment. Cider apple trees inoculated with AMF had fewer cankers than un-inoculated trees (Berdeni et al. 2018). The AHDB TF223 project tested an AMF product consisting of a consortium of AMF species (*Funneliformis mosseae, Funneliformis geosporus, Claroideoglomus claroideum, Rhizophagus irregularis* and *Glomus microaggregatum*). An experimental plant growth promoting rhizobacteria (PGPR) product marketed by Plantworks containing a bacterial consortium (*Rhizobium* sp. strain IRBG74, *Bacillus amyloliquefaciens, B. megaterium, Derxia lacustris strain HL-12*) was also tested. In the 2019 assessments, two out of the three newly planted orchards, and the stoolbed at NIAB EMR showed an overall reduction in canker compared to the untreated control, suggesting this PGPR product has an effect on reducing canker. This can still translate to hundreds or thousands of pounds in financial benefits if the products are applied to newly planted apple trees and rootstock stoolbeds. There was also no effect on the tree vigour for any of the amendments compared to the unamended control, indicating there is no penalty, on this measure of tree growth, when applying these amendments.

The AHDB SCEPTREplus consortium in association with NIAB EMR is currently completing a project SP68 *Testing efficacy of new plant protection products against apple canker pathogen N. ditissima.* This project will focus on testing alternative products to chemicals. Results of this work will likely be available in spring 2021, with experiments beginning in autumn 2020. Previous work on Biological Control Agents (BCAs) to control *N. ditissima* have shown varying results. Schiewe and Mendgen (1992) tested more than 700 isolates originating from apple trees and fruit. Only four bacterial and three fungal isolates reduced lesions on fruit incubated at 20 °C, however at 4 °C none of the isolates were effective. This variation in control of the pathogen was also observed by Walter et al. (2017) who tested a number of BCA products consisting of either individual strains or consortia of *Bacillus* spp. (*B. subtilis, B subtilis* var. *amyloliquefaciens*), *Pseudomonas putida, T. koningii,* and *T. harzianum.* They found that the tested BCAs did not provide adequate wound protection and were not recommended during harvest and leaf fall under high spore load conditions. Concerning applications of BCAs and pathogen inoculation, consideration needs to be given to the timing and number of applications of the BCAs, and inoculation with the pathogen, to observe any effect of the BCAs. The CANKERLink project is investigating some of the isolated fungal endophytes that show promise as BCAs. *In vitro* assays have shown reduced growth of *N. ditissima* when challenged with isolates of *Epicoccum* and *Aureobasidium. Epicoccum in planta* to test any effect of reducing canker, with results to date being unclear. Further testing is currently underway.

Hypoviruses and hypovirulent fungal strains have been used extensively in Europe with the chestnut blight pathogen *C. parasitica* for over 50 years, and may be a useful method for controlling *N. ditissima* (Rigling and Prospero 2018; Milgroom and Cortesi 2004; Peever et al. 2000). Transfection of *N. ditissima* with a mycovirus of *Cryphonectria parasitica* has been shown to successfully reduce growth of the fungus *in vitro* (Green 2005). However, in the same study, reductions in virulence of *N. ditissima* were not observed when tested in detached fruit assays. Further work testing the effects of strains infected with mycoviruses on other host tissues including active cankers on trunks and branches is needed. Hypoviruses and hypovirulent fungal strains have also been reported from apple pathogens including *Alternaria alternata* hypovirus 1 (AaHV1) isolated from the apple leaf spot pathogen *A. alternata* f. sp. *mali* (Li et al. 2019) in China, and *Valsa ceratosperma* hypovirus 1 (VcHV1) isolated from the apple dieback pathogen *V. ceratosperma* in Japan (Yaegashi et al. 2012).

Orchard management

Pruning out of cankers and prompt removal of heavily infected trees is currently the most effective and widely adopted practice due to a lack of alternative control measures (Saville and Olivieri 2019). Growth cracks in trees, particularly where branches divide or where they meet the trunk are another site of pathogen entry (Swinburne 1975). These growth cracks can be exacerbated by high nitrogen and irrigation inputs and subsequent rapid growth. Growers can reduce this risk by optimising the amount and timing of nitrogen rich fertilisers and irrigation.

Alterations to propagation methods in the nursery phase is another method to potentially reduce canker. Saville and Olivieri (2019) explain that the current Knipboom propagation technique involves the wounding of trees, hence increasing sites for pathogen entry. The use of alternative methods such as producing maiden trees is being used during the production of particularly canker susceptible varieties as there is less wounding of trees during this propagation process. Cold storage of nursery trees before planting in new orchards is another management factor that can affect canker. The CANKERLink project found that lifting nursery trees, cold storing over the winter period, and planting in spring can have the effect of increasing canker once trees are planted out in the orchard. Canker number was also strongly affected by scion variety, with Kanzi, Jazz and Rubens having higher canker number when refrigerated than Golden Delicious and Grenadier for example. However, this effect seems to be changing the longer the trees are in the orchard, likely due to increased numbers of infections from field-based inoculum over time.

Disease monitoring and forecasting

Inspection of orchards for cankers during winter pruning and for shoot dieback in spring and summer will give an indication of canker incidence. Orchards where 25% or more of the trees have cankers are considered high risk (Berrie 2019). Cankers resulting from infection of leaf scars the previous autumn will not usually become visible until the following spring, usually from blossom time onward (Berrie 2019). Weather is also an important factor with canker infection, particularly rainfall during key infection periods such as late blossom/petal fall for fruit infections and autumn leaf fall for leaf-scar infection. Early warning systems for canker include NECTEM contained in ADEM (Xu and Butt 1993), and a model developed in Chile by Latorre et al. (2002). The models are driven by weather data including temperature, rainfall, surface wetness duration, temperature and relative humidity. However, the models give information on infections that have already occurred and controls (even chemical) that are effective against *N. ditissima* are limited and none are curative in action (Berrie 2019).

Apple powdery mildew

Apple powdery mildew, caused by the fungus *Podosphaera leucotricha*, is one of the most important diseases of apple in the eastern UK, although less so in the west due to climatic conditions being less conducive (AHDB 2020f). The pathogen also infects pear and quince. All parts of the tree can be infected including fruit. The disease reduces yield and quality and repeated attacks over subsequent years weaken the tree. *Podosphaera leucotricha* is an obligate parasite and overwinters as mycelia in dormant buds infected during the previous growing season. Thus, in northern mainland Europe, the disease is not as serious, as the cold winters ≤–12ºC usually kill the overwintering inoculum (AHDB 2020f). Secondary infections then cycle in the canopy throughout the growing season, depending on weather conditions, and infect leaves, flowers and developing fruit (Amiri and Gañán 2019).

Alternatives to chemical control

BCAs, nutrients, silicon, elicitors, biostimulants, cultural control

Durable host resistance is recommended as key to powdery mildew control. However, the absence of total immunity in current commercial cultivars, and the ongoing risk of the pathogen overcoming host resistance requires an integrated management strategy (AHDB 2020f; Amiri and Gañán 2019). The AHDB Project TF 223 investigated the use of alternative control methods in programmes with conventional chemical fungicides. This integrated approach showed the benefit of reduced reliance on 7-day conventional fungicide programmes, while also giving the same level of mildew control by the end of July (mid-summer in the UK) for the two varieties tested (Gala and Braeburn). The alternative products incorporated into programmes included Mantrac Pro (a manganese based nutrient), SB Invigorator (various nutrients and plant products providing physical control), Trident (silicon, copper & zinc nutrients together in the formulation potentially producing an elicitor effect) and Crop Biolife (flavonoids that have elicitor and biostimulant effects). Application of the nutrient based products may boost tree health, with elicitor and/or biostimulant effects. As there were no 'chemical fungicide/conventional free' treatments in this experiment it is difficult to estimate what effects the alternative controls have on mildew when used on their own (without being rotated with chemical control products).

Pruning and discarding infected shoots showing symptoms of primary mildew in early spring can reduce inoculum load. However this is labour intensive (Holb and Kunz 2016). Removal of alternate hosts from the site such as rose bushes can reduce inoculum loads (Amiri and Gañán 2019).

Disease monitoring and forecasting

Mildew is always present in the orchard and routine control measures are usually needed from around green cluster until vegetative growth ceases (AHDB 2020f). Podem™ is a PC-based system which gives warning of powdery mildew (Xu 1999). The model incorporates weather variables including rainfall, surface wetness duration, ambient temperature and ambient relative humidity. Data are recorded by a data-logger or weather station. The mildew model forecasts secondary mildew infection by combining effect of weather on spore production and dispersal, and subsequent colony development on young leaves, with varietal susceptibility and amount of mildew inoculum recorded in the orchard (low, moderate or high). Mildew risk is predictive as it forecasts the amount of sporulating mildew in 3-4 days. The index of mildew risk generated can then be used to assist in decision-making and mildew management.

Apple replant disease (ARD)

Apple replant disease (ARD) occurs when new trees are planted into the same soil where apple trees were previously grown (Mao and Wang 2019; Winkelmann et al. 2019). Symptoms include stunted growth, shortened branch internodes, smaller and lighter green leaves, root tip necrosis, reduced root biomass, reduced yield, reduced fruit size and weight, discolouration of fruit skin, altered fruit aroma and tree death (Xu and Berrie 2018; Mao and Wang 2019). Profitability of an orchard can be reduced by up to 50% during the orchard's lifetime if ARD is present (van Schoor et al. 2009). The recent establishment of apple fruit wall production systems planted into soil previously planted with apple, has resulted in ARD problems in the years after tree establishment and subsequent reduced financial returns (Xu and Berrie 2018).

It is now generally accepted that ARD is primarily caused by a number of pathogens in a disease-complex, with severity influenced by site factors including environment and soil of individual sites (Tilston et al. 2020; Xu and Berrie 2018). Every known biotic factor associated with ARD does not need to be present to cause the disease, and the relative importance of each factor may vary greatly from site to site. Several microbial pathogens are implicated in the ARD complex including oomycetes (*Phytophthora cactorum*, *Pythium irregulare*), fungi (*Thelonectria* (formerly *Cylindrocarpon*) *lucidum, Fusarium* sp., *Ilyonectria sp., Rhizoctonia* sp.) and nematodes (*Pratylenchus* spp.) (Hewavitharana et al. 2020; Mao and Wang 2019; Nyoni et al. 2019; Ceustermans et al. 2018; Mazzola et al. 2009; Jaffee et al. 1982). Deakin et al. (2019) found an AMF operational taxonomic unit (OUT) with reduced abundance with ARD trees, suggesting a reduced presence AMF in soil with ARD affected trees. Microbes that are present in replant free soil have also been implicated in the growth of healthy trees. These include *Bacillus* sp., *Streptomyces* sp., *Pseudomonas* sp. and *Chaetomium* sp. (Nicola et al. 2017). In addition to biotic factors, abiotic factors such as soil fertility, degraded soil structure, residual herbicide activity, and phytotoxicity of plant roots have been linked to the disease (Hewavitharana et al. 2020).

Alternatives to chemical control

Cultural control

Cultural control such as planting position, crop rotation, rootstock selection, addition of organic amendments and soil water management have been recommended to treat ARD (Hewavitharana et al. 2020; Deakin et al. 2019; Mao and Wang 2019; Xu and Berrie 2018; Meints and Toma 2017). Soil replacement has also been considered as effective in smaller scales, but is not feasible on a commercial scale (Meints and Toma 2017).

Planting position

Soil microbial community structure of apple orchards has been shown to differ greatly between tree stations and inter-row grass aisles, even when within metres of each other (Deakin et al. 2018). Planting new apple trees in the inter-row is seen as one of the simplest non-chemical methods to control ARD (Kelderer et al. 2012; Rumberger et al. 2004). This avoids areas where infection and infestation by ARD agents is highest. However, if trees are planted in the grass inter-row, care needs to be taken to control weeds as competition at the early tree establishment stage may cause more damage than ARD itself (Xu and Berrie 2018).

Crop rotation

Crop rotation in ARD affected soil can be used effectively to reduce ARD symptoms. A five-year plus crop rotation to a non-woody crop is reported to reduce pressure from ARD causing organisms (Hewavitharana et al. 2020). However, other crops can host ARD pathogens, therefore crop rotation is not a guaranteed strategy. Pan et al. (2017) found short-term rotation with *Allium fistulosum* mixed with *Trichoderma* could alleviate ARD. Mao and Wang (2019) recommended a mixed cropping system with spring onions leading to lower populations of disease causing fungi such as *Fusarium oxysporum.*

Rootstock selection

Rootstocks are reported to differ in tolerance to ARD, particularly the Geneva series, while the Malling (M) and Malling-Merton (MM) are reported as susceptible (Leinfelder and Merwin 2006). Planting more vigorous variety/rootstock combinations and rootstock genotypes more dissimilar to the one previously planted are recommended on known ARD affected sites (Xu and Berrie 2018). Deakin et al. (2019) found that replanting trees with a rootstock genotype different from the previous one, can be effective in reducing ARD development, and that susceptibility to ARD is likely to be genetically controlled. The production of ARD free rootstocks in the propagation phase is important. If ARD agents are present during propagation, they can then be easily transported to new sites through the nursery supply chain.

Soil amendments

Application of organic amendments such as arbuscular mycorrhizal fungi (AMF), plant growth promoting rhizobacteria (PGPR), brassicaceous amendments, biochar, seaweed and fermented organic materials, have been reported as remedies for ARD. Current research is focusing on identification of biological alternatives to improve the health of soil and in turn aid tree growth and productivity. The application of plant growth promoting rhizobacteria (PGPR) to apple trees has shown to significantly increase yield, tree growth, and nutrient content of leaves (Aslantaş et al. 2007; Pirlak et al. 2007). AMF have been found to increase resistance to *Neonectria ditissima* (Berdeni et al. 2018). However, in the same study AMF was not found to consistently alter leaf nutrients, growth, phenology or fruit and flower production. AMF application appears to affect the soil microbiome differently in organic and conventional orchards, with organic orchards having higher richness of AMF when compared to conventional soils (Purin et al. 2006). Apple seedlings grown with AMF have also been reported to grow better in the presence of lesion nematodes (*Pratylenchus penetrans*) (Ceustermans et al. 2018).

The use of brassicaceous amendments have also shown results in organic orchards. At an organic-certified orchard in Washington State, USA, an experiment testing the addition of brassica seed meals (*Brassica juncea: Brassica napus*) in a 1:1 ratio with soil planted to M26 rootstock/Gala scion trees performed as well in terms of ARD control and vegetative growth of trees as those cultivated in fumigated soil (Mazzola and Brown 2010). Brassicaceous based soil amendments used in conjunction with rootstocks have been shown to reduce nematode populations (Mazzola et al. 2009). Wang and Mazzola (2019) found brassica seed meal applications increased tree growth and reduced replant disease relative to trees without the amendment added. They also found a reduction of replant disease using rootstocks G.41 and G.210 in addition to the brassica seed-meal soil treatment. However, brassica-based green materials, AMF and PGPR incorporated into soils may only be active against fungal pathogens not oomycetes (Xu and Berrie 2018).

The use of biochar has mixed results. Wang et al. (2014) reported ARD was reduced through activation of antioxidant enzymes, decreased lipid peroxidation, and reducing phenolic acid content of soil. However, Khorram et al. (2019) found the addition of biochar (and compost) did not increase yield and fruit quality due to a limited ability to suppress ARD, although there were other benefits such as improved soil quality (nutrient content, decreased bulk density) and increased plant growth. Seaweed organic fertilisers have been found to reduce ARD through promoting apple seedling growth and increasing soil enzyme activity (Wang et al. 2016). Fungal community profiles were found to be different when higher amounts of seaweed were added (40 g seaweed per kg of soil). Differences were observed compared to when lower amounts of seaweed were added (0, 5, 20g seaweed per kg of soil) (Wang et al. 2016). The addition of fermented organic materials has been reported to reduce ARD. Zhang et al. (2012) tested two fermentation methods to produce organic material, one aerobic generating solid compost and the other anaerobic generating fermented fluid. In a pot experiment using apple seedlings planted in new cropping soil, ARD soil, ARD soil+solid compost added, and ARD soil+fermented fluid added, the ARD+fermented fluid was found to be superior to ARD+solid compost for reducing the disease, and the ARD+fermented fluid had a higher bacterial content than both the ARD+solid compost, and the new cropping soil.

Anaerobic soil disinfestation (ASD) is a variation of organic amendment addition, where granular or liquid plant extracts are added to the ARD infected soil, and covered for 3-4 weeks (Xu and Berrie 2018). The temperature of the soil subsequently increases, and the abundance of beneficial bacteria increases. Herbie 82® is a product used for ASD and has been shown to increase vigour of plants grown in ARD infected soil and covered with film for 3-4 weeks (Mancini et al. 2014). However, the use of ASD products in the UK would likely need Chemical Regulation Division (CRD) approval before commercial use.

Cranfield University and NIAB EMR based PhD candidate Chris Cooke is currently studying '*Understanding resilience of soil beneficials to combat apple replant disease (ARD)'.* The key aims of the research include long-term trials with biological amendments (PGPR, AMF), microbiome population/soil functionality analysis of rhizosphere of amended trees, synthetic microbiome work to test resilience of beneficials in orchard soils and climate change stress (temperature, water potential, carbon dioxide) applied to bulk soil, and model plants to predict climate impact on soil populations and function with ARD onset. The results of this project will provide some working biological solutions for organic apple and pear growers to combat ARD.

Soil water management

Soil water management including improving water infiltration into soil, reducing compaction and improving soil structure through addition of organic matter, has also been recommended to treat ARD. Limiting periods of soil saturation and selecting sites with good drainage is essential (Hewavitharana et al. 2020). Oomycetes in the ARD complex can disperse between trees if the soil is saturated. Saturated soil also aids in the dispersal and subsequent infection of roots by oomycetes. Reducing periods of soil saturation will reduce oomycete dispersal and subsequent disease problems.

Brown rot and blossom wilt

Brown rot is one of the most important causes of rot of stored apples and pears whilst also causing significant losses in the orchard pre-harvest. In the UK, brown rot of apple and pear are caused by *Monilinia fructigena* and *M. laxa* (Table 2). There are brown rot quarantine pathogens not currently present in the UK including *Monilinia fructicola* and *Monilinia polystroma.* Both *M. fructicola* and *M. polystroma* have been detected in mainland European countries and have a high risk of introduction in the UK (CABI 2020a; Holb 2019).

Table 2. Species of *Monilinia* causing rot, canker, and wilt diseases of apple and pear in the UK (AHDB 2020c, 2020d; Holb 2019)**.**

Host	***M. fructigena***	***M. laxa***
Apple	Fruit rot (common and destructive); black apple; canker	Blossom wilt (*M. laxa* f.sp. *mali*); canker; black apple (rare); fruit rot (rare)
Pear	Fruit rot	Blossom wilt caused by *M. laxa* f.sp. *mali*; fruit rot (rare)

Pre-harvest losses to brown rot in organic pome-fruit orchards up to 45% have been reported, while yield loss in unsprayed orchards can range from 50-90% (Holb 2019; Berrie and Holb 2014; Holb 2007). Post-harvest losses, particularly from *M. fructigena* can be up to 22% (Holb 2019; Berrie and Holb 2014).

In the UK, brown rot of apple and pear fruit by *M. fructigena* is mainly dependent on the presence of wounds caused by biotic and abiotic wounding agents. In contrast, *M. laxa* can infect both healthy and wounded fruit. The incidence of brown rot in organic orchards is significantly higher due to higher levels of pest injury (Holb and Scherm 2007), whilst late ripening cultivars show more severe brown rot than earlier ripening cultivars (Holb and Scherm 2007, 2008).

Alternatives to chemical control

Cultural control

Sanitary measures and hygiene are effective at reducing or eliminating sources of *Monilinia* inoculum. Primary infections occur from overwintered infected blossoms, twigs, fruit, spurs and branches (Holb 2019). Removal of infected material should be made whenever signs of the disease occur. Insect control is also key as the wounding they cause can create pathogen entry sites. AHDB (2020c) recommends cultural controls including pruning of cankers in winter; removing mummies during pruning and together with those under the tree, throw into the grass alley where they can be macerated by mowing; remove infected fruit as soon it appears in summer and throw into the alley for maceration; remove waste fruit from early pollinator varieties and throw in the alley to be macerated so they are not a source of inoculum for the main orchard variety; use early varieties as pollinators; at harvest, selectively pick fruit so only healthy appearing fruit is placed in the bin to reduce incidence of brown rot in store; and to avoid damage to fruit, especially at harvest.

Host resistance

Host resistance varies between cultivar, with physiological characters such as fruit with thicker skin, low cracking susceptibility, higher acidity and higher phenolic content correlated with reduced disease. However many of these characters are also associated with poor marketing quality (Holb 2004; Byrde and Willets 1977). Brown rot is also dependent on the stage of fruit maturity, with mature fruit being more susceptible than immature fruit (Holb 2019; van Leeuwen et al. 2000; Xu and Robinson 2000).

Biological control

The apple fruit surface has been reported as excellent as a source of naturally occurring antagonists against postharvest fruit decay (Janisiewicz and Korsten 2002). Both endophytic and epiphytic fungi have been reported as having inhibitory effects on *Monilinia* spp. of apple. The endophytic yeasts *Schwanniomyces vanrijiae*, *Galactomyces geotrichum*, *Pichia kudriavzevii, Debaryomyces hansenii*, and *Rhodotorula glutinis* were found to inhibit *M. fructigena* when inoculated on to apple fruit as well as in culture (Madbouly et al. 2020). The epiphytic fungi *Aureobasidium pullulans* (Boni Protect), *Epicoccum purpurascens* [*Epicoccum nigrum*], *Sordaria fimicola*, and *Trichoderma polysporum* isolated from apple leaves and applied individually or in mixtures to wounded apples, were also found to give good protection from *M. fructigena* (Falconi and Mendgen 1994). In addition to yeasts and fungi, bacteria are reported as biocontrol agents and there is much more evidence of the biocontrol activity of bacteria against *Monilinia* diseases of stonefruit, particularly *Bacillus* spp. (Carmona-Hernandez et al. 2019; Gotor-Vila et al. 2017; Yánez-Mendizábal et al. 2011; Pusey 1989).

University of Reading and NIAB EMR based PhD candidate Sophia Bellamy is currently studying '*Biocontrol as a key component to manage brown rot disease on cherry'.* Brown rot and blossom wilt of cherry in the UK is caused by *Monilinia laxa.* The biocontrol agents being tested are UK strains of *Aureobasidium pullulans* (Boni Protect), a yeast-like fungus, and the bacterial species *Bacillus subtilis* (Rungjindamai et al. 2013). These biological control agents may have effectiveness on *Monilinia* diseases of apple and pear. However, experiments would need to be completed to confirm this.

Physical control

Several methods of physical control are used to reduce disease caused by *Monilinia* spp. particularly post-harvest. These include controlled atmosphere (CA) storage, hydro-cooling, hydrair-cooling, heat, hot water brushing, UV-light and other forms of radiation (Holb 2019).

CA conditions will not prevent infection of fruit in store although the composition of the atmosphere can influence the degree of rotting (AHDB 2020e). Ultra-low oxygen conditions below 1% have been shown to nearly eliminate brown rot of apple caused by *M. fructigena*, compared to 18-35% in conventional storage (Holb et al. 2012). With the apple cultivar Cox CA conditions that are low in oxygen and high in carbon dioxide are more conducive to rotting than low oxygen only (AHDB 2020e). Cox apples for medium or long-term storage should be kept in low oxygen and low carbon dioxide conditions particularly where there is a history of rot problems.

After harvest fruit is usually hydro-cooled down to 0-3ºC. However the cooling water can harbour pathogen propagules (Holb 2019). Hydrair-cooling is another cooling method where cold air is used instead of water and reduces the risk of pathogen transmission. Post-harvest hot-water treatment of fruit is another method used to reduce storage rots. The method is reported to work through a heat shock-induced antimicrobial response rather than a direct killing of fungal inoculum. Hot-water treatment of freshly harvested apple fruit for 3 min at 50–52°C has been found to give high efficacy against most storage rots including *Monilinia* spp.. Shorter exposures for <30 seconds at 55–60°C also provided good control. In an earlier study by Maxin et al. (2012), significant reductions in the incidence of fruit rot caused by *M. fructigena* was achieved by incubation periods of 3 min at 50–54°C (dipping) and 20 or 25 seconds at 55°C (rinsing), followed by up to 100 days cold-storage at 2°C and 14 days at 18°C.

Radiation is a more recent method used for brown rot control. When applied post-harvest, the method heats and disinfects the fruit. Low hormetic doses of ultraviolet light (254 nm, UV-C) have been reported to reduce postharvest decay of Golden Delicious apples caused by *Monilina* spp. (Stevens et al. 1996), while gamma irradiation has also been reported to reduce fungal development and rot of apple caused by *M. fructigena* (Marcaki 1998).

Disease forecasting

A disease warning system for *M. fructigena* in organic apple production has been developed (Holb et al. 2011; Holb 2009). The model is coupled with a disease management strategy and insect control.

Potential effects of invasive pathogens not currently present in the UK

Xylella fastidiosa currently represents the largest exotic pathogen threat to UK horticulture including pear and currently a transient detection on apple (Jeger et al. 2018; Mehta and Rosato 2001). The pathogen is a xylem limited fastidious bacterium and can be transmitted asymptomatically (Baldi and La Porta 2017), making detection ever more challenging. Taxonomically, *X. fastidiosa* is composed of six subspecies (Denancé et al. 2019). Since 2013, various cases have been reported in Europe (Italy, France, Germany and Spain) on large ranges of host plants including pear, olive trees, grapevines and ornamentals (EPPO 2020; Su et al. 2014; Mehta and Rosato 2001). The detection of *X. fastidiosa* in Puglia, southern Italy, represented the first confirmed detection in Europe. The introduction pathways of *X. fastidiosa* into Asia or Europe are unclear. However, EPPO member countries e.g. France, the Netherlands and Switzerland, have intercepted *X. fastidiosa* several times on ornamental coffee plants imported from South America (EPPO 2020).

Xylella fastidiosa mainly survives and causes disease in warmer climates. Of the known European outbreaks, *X. fastidiosa* sub species *multiplex* detected in Corsica, mainland France, mainland Spain and Portugal, in a small area of southern most Tuscany, and in nursery stock on the Spanish Balearic Islands, is of most concern to the UK. This subspecies is able to survive in cooler climates and affect a wide range of hosts, including many native broadleaved trees such as oak (Defra 2020). The current epidemic in Europe has mainly occurred in warmer areas such as Puglia in southern Italy, southern mainland France and Corsica, mainland Spain and the Balaeric Islands, and Portugal. The largest probability of introduction to the UK is via infected plants imported through the horticultural trade.

Once established, the pathogen is transmitted by sucking insects including spittlebugs, leaf hoppers, sharp shooters, frog hoppers and cicadas (Jeger et al. 2018). The widespread meadow spittlebug for example, is responsible for transmitting the disease in Italy (Santoiemma et al. 2019; Cornara et al. 2017).

Valsa spp. are severe pathogens of apple in locations including sub-saharan Africa and East Asia (China, Japan and Korea) (Li 2019; CABI 2014). In China, there have been four epidemics of the disease since the 1940s with almost all of the apple orchards destroyed in the 1980s (Li 2019). In 2008, disease incidence was up to 85% in some regions (Cao et al. 2009). The species of *Valsa* isolated from apple and pear in China have been identified with molecular and morphological data as three species *Valsa mali, Valsa piry* and *Valsa malicola. Valsa mali* was reported to cause 90% of apple canker in China, while *V. malicola* was only found to be a weak pathogen of apple. It is currently unknown what impact the Asian species of *Valsa* would have on apple and pear in the UK, particularly under a warming climate.

Effects of climate change

Since the industrial revolution and particularly since the 1980s, there has been an overall upward trend in global average temperature including the UK (Met Office 2020) . The UK summer of 2018 was provisionally the equal warmest on record when compared to the 1981 to 2010 average, with monthly mean temperatures 1.8 °C above average in June, 2.2 °C above in July, and 0.3 °C above in August (Met Office 2018) . These increases in temperature are closer to the optimum temperatures of bacterial pathogens including *Erwinia amylovora* and *X. fastidiosa* and increases the probability of infection.

Climate change is likely to have an impact on the range of pathogens that would normally not be able to survive UK winters or are of lower incidence due to the cooler UK climate. A key example is fireblight caused by *Erwinia amylovora*. Currently this disease is only of sporadic concern in the UK and mainly affects pear. Fireblight risk is greatest when temperatures exceed 18ºC and there is rain. Disease development occurs between 5-30ºC with an optimum temperature of 27ºC (AHDB 2020g).

In vitro and in planta studies on grapevines by Feil and Purcell (2001) showed temperatures between 25 and 32°C critical for the epidemiology of Pierce's disease, because of its rapid growth rate at these temperatures, whereas temperatures below 12 to 17°C and above 34°C may affect the survival of the pathogen in plants.

The range and severity of *X. fastidiosa* also depends on the distribution and biology of insect vectors whose biology and reproduction are often influenced by temperature.

Climate change may also affect the physiology and epidemiology of established pathogens of apple and pear in the UK. In an apple orchard, Bannon et al. (2009) observed an increase of airborne *M. fructigena* conidia counts with higher temperatures in both of the two years sampled, which can be related to the development of the fungus. With apple powdery mildew, warmer winters will result in greater survival of overwintered primary inoculum and allow more infections to occur (AHDB 2020f). The fungal family Botryosphaeriaceae are geographically and ecologically cosmopolitan and contain many plant pathogens including those that cause canker and fruit rot of apple and pear (CABI 2020b, 2020c; Bertetti et al. 2012; Phillips et al. 2013). These fungi cause disease mainly in warmer climates. Higher temperatures may favour infection from these pathogens.

Higher temperatures and more extreme weather conditions have an impact on tree health and potentially make them more stressed and susceptible to pathogens. For example, the number of chilling hours directly affects temperate tree flowering and fruit set (Ramírez and Kallarackal 2015). Although the absolute number of frost days in Europe is declining, warmer winters also lead to earlier blossom time of trees, which in turn can lead to increased risk of frost days after blossom (Pfleiderer et al. 2019).

The exact consequences of climate change are difficult to predict due to the changeable nature of the weather and the amount of greenhouse gasses released by human activity. However, a warming planet may favour range expansion of pathogens and pests, while increasing plant stress and susceptibility.

Conclusions

Organic farming and non-chemical control methods are becoming more important in UK horticulture and worldwide due to regulatory bodies banning or restricting the use of chemical pesticides and consumer demands for safer food products free from pesticide residues. These changes are often difficult for growers who have traditionally employed these chemical based control methods. However, organic disease controls are generally more sustainable long term as they often have fewer negative effects on the environment and on human health. There is innovative research past and present that can be applied to concurrently provide economic efficiency, environmental sustainability and the supply of safe nutritious food.

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