SCEPTREPLUS

Final Report

Trial code:	SP 41
Title:	**A review of key current control measures for plum rust (*Tranzschelia discolor*) in the UK and overseas.**
Crop	Plum
Target	Rust (*Tranzschelia discolor*)
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Organisation:	RSK ADAS Ltd.
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ORETO Number: **(certificate should be attached)**	N/A

I the undersigned, hereby declare that the work was performed according to the procedures herein described and that this report is an accurate and faithful record of the results obtained

26 February 2019

Date

Authors signature

Summary

Introduction

Rust fungi cause major damage to many UK crops, including plums. Management of plum rust has always been a challenge, relying on a limited number of plant protection product active ingredients. Where these actives have been withdrawn, growers are left in a vulnerable position with few plant protection product options. This occurred recently through the loss of Systhane 20 EW (myclobutanil), the only rust-specific fungicide available. Financial impact to UK plum production was estimated at £1.0million if the disease was not controlled adequately with 10% yield loss (from AHDB gap analysis, 2016).

This document reviews current and potential management techniques and plant protection products for plum rust (*Tranzschelia discolor*) to identify plant protection options that may be useful for growers following assessment.

Summary

This document contains a review of potential management techniques and plant protection products for rust (*T. discolor*) in plum (*Prunus* spp.). It covers cultural practices to limit rust infection, and management using conventional chemical fungicides and biological-based plant protection products (PPPs), to inform the design of any efficacy trials to be undertaken in the SCEPTREplus project. It is an expert review that uses key papers to highlight possible approaches. The main conclusions are:

- There have been few recent studies on plant protection products (PPP) or cultural control of plum rust (*T. discolor*).
- Rust caused by *T. discolor* is an economically important diseases on plums and many other stone fruit, such as peaches and almonds.
- Early season triazoles-based fungicide foliar sprays appear to be the most effective way of controlling plum rust. Approaches involving biological-based biopesticides PPP have been reported, so may be worth investigating further in experimental work.
- The use of resistant or 'tolerant' plum rootstocks may play a role in reducing levels of plum rust in commercial orchards.
- Plum rust infections may be systemic, which would move the focus of management from prevention of infection, to inoculum-reducing strategies, but research in this area is limited, and requires further investigation.
- Cultural control methods such as leaf litter removal, and pruning to create an open canopy have been evaluated by some researchers, and are approaches worth exploring as part of an integrated management strategy.
- Information on the timing of *T. discolor* infective spore release throughout the season is currently unknown, but would be of great use to growers as it relates to when spray treatments would be most effective.

Next steps

The review has identified three disease management approaches that could be pursued:

1. Trials to evaluate ‘new’ PPPs, both conventional chemical fungicide and biofungicide treatments (such as hexaconazole, difenoconazole, and thyme, clove and citronella oil) on UK *T. discolor* spore germination, and on infected plum trees.
2. Evaluation of new resistant or ‘tolerant’ plum cultivars available to the UK industry.
3. Exploration and integration of cultural control methods, using both existing and those taken from other crops.
4. Explore the value of monitoring and forecasting– what is feasible and how would it be useful to growers.

Take home message:

Future management of plum rust will need to rely on an integrated pest management (IPM) approach which combines the latest information on plum rust epidemiology with cultural control methods and utilises both conventional chemical fungicides and biofungicides applied at appropriate timings where needed. Further work needs to be undertaken on all of these aspects before robust strategies for plum rust control can be recommended. New potential control treatments for plum rust were identified and could be tested next year in screening trials on young plum trees.

Background

In the UK, controlling rust in plums has become a top priority following the loss of key conventional chemical products, in particular myclobutanil (Systhane 20 EW). This coincides with the fruit industry aiming to move towards an integrated disease management approach, utilising resistant cultivars, crop husbandry and biopesticides. Rust in commercial plum orchards is caused by the fungus *Tranzschelia discolor (*not to be confused with the closely related *Tranzschelia pruni-spinosae*, which infects blackthorn/sloe), see Table 1 for distinctions.

The origin of the majority of the plums grown in the UK and northern Europe are *Prunus* x *domestica*, a variable group of plants of hybrid parentage involving *Prunus spinosa* (native European blackthorn or Sloe) which show some resistance to rust and *Prunus cerasifera* var. *divaricata*, native to Eastern Europe and central Asia, which show tolerance to rust. Within this already variable group, three main subgroups are noted: *P. domestica* ssp. *domestica* (common plum) – highly susceptible; *P. domestica* ssp. *interstitia* (damsons, bullaces, mirabelles); and *P. domestica* ssp. *italica* (greengages) – all relatively resistant (most but not all, show some intermediate rust symptoms). All are closely related and can cross-pollinate freely, resulting in countless intermediate forms (pers. comms. with J. Arbury, curator of RHS Wisley plum collection). Japanese plums (*Prunus salicina*), the predominant cultivar grown in Japan, China, the USA, Spain and Australia (Guerra Velo et al., 2010) also have a certain degree of resistance to *Tranzschelia* spp.

Table 1. Plum rust *Tranzschelia discolor* and *Tranzschelia pruni-spinosae* and their associated hosts. Information from the British Mycological society (Henderson, 2000, Price, 1980, Wilson and Henderson, 1966).

Fungus	**Host**	**Latin name**	**Alternate host**
Tranzschelia discolor	Common plum	*P. domestica* subspp*. domestica*	*Anemone coronaria*
	Damson, bullace and mirabelle	*P. domestica* subspp*. institia*	
	Greengage	*P. domestica* ssp*. italica*	
	Cherry plum, myrobalan	*P. cerasifera* var. *divaricata*	
	Japenese plum	*P. salicina*	
Tranzschelia pruni-spinosae	European blackthorn/Sloe	*P. spinosae*	*Anemone ranunculoides*

This review was undertaken to evaluate current control measures for plum rust in the UK and worldwide. A range of academic (25) and commercial (11) resources were reviewed, using the search terms ‘Tranzschelia discolor’, ‘plum’, ‘prunus’, ‘rust’ and ‘stone fruit’ in Web of Science, ResearchGate and Google Scholar, alongside consultations with industry experts including the curator of the RHS plum collection, independent top fruit advisors, growers, and a UK fruit tree propagator. For the purpose of this report, literature on *T. discolor* will be the main focus, but where relevant, work on *T. pruni-spinosa* will also be included.

Disease symptoms

Plum rust results in the development of yellow speckling on the upper leaf surface, following a period of asymptomatic/latent development after initial spore infection. The length of time between initial spore infection, and development of symptoms is unknown, due to the lack of research in this area. The yellow speckling corresponds with pale brown raised dots on the underside of the leaf, which are spore-producing pustules. Young leaves often become puckered, distorted and heavily infected; older leaves are not as susceptible, but may become necrotic and shrivel. Leaf spotting and pustules tend to be much more visible on varieties with lighter coloured leaves, and do not affect twigs or fruit in plum.

Rust pustules can pepper the leaf surface, or merge to form larger individual pustules (Figure 1). The pale brown pustules produce a mass of spores. Towards the end of the season, black specks start to appear on the underside of the leaf, which contain resting spores that overwinter on the fallen leaves. Depending on the time of year, plum leaves may show brown, both brown and black, or solely black pustules. Foliar symptoms depend on the disease pressure throughout the season, and could also be due to the local humidity/temperature around individual leaves, or the cultivar.

Within commercial production, if susceptible varieties of plum do not receive suitable fungicide applications as part of a programme, rust pustules may often be seen throughout the year. In England, plum rust symptoms are usually first reported in July, however, 2018 was a hot dry year, and first sightings were delayed until August. In Turkey, pustules on plum leaves are often first sighted in June (Erincik et al., 2016).

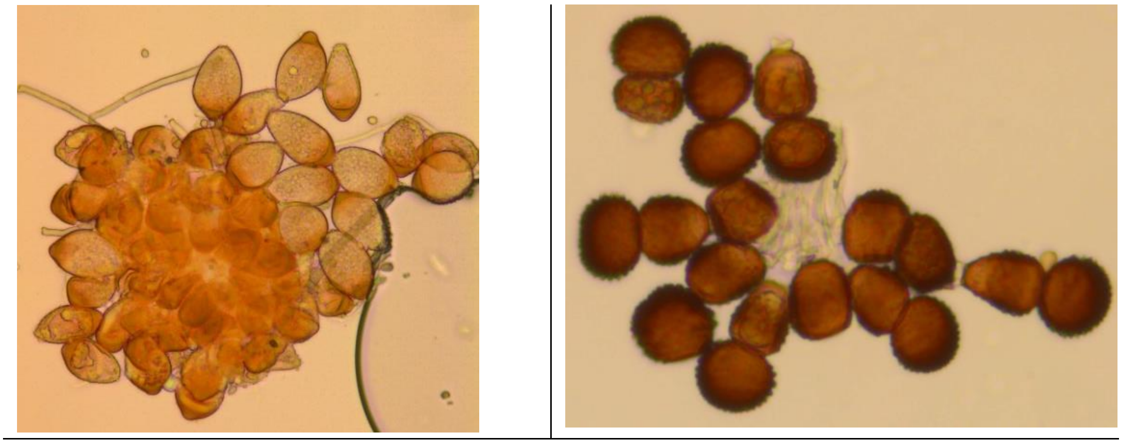
Figure 1. Brown pustules of plum rust on leaves caused by *Tranzschelia discolor* (left). Young plum tree with yellow speckling rust symptoms (right).

Early season infections are most damaging as photosynthetic capacity of leaves is reduced, and defoliation is premature, resulting in decreased carbohydrate production for the remaining year, and consequently a substantially reduced fruit production the following year. Severe rust on stone fruit can also cause a long-term decline in tree vigour (Horsfield, 2014).

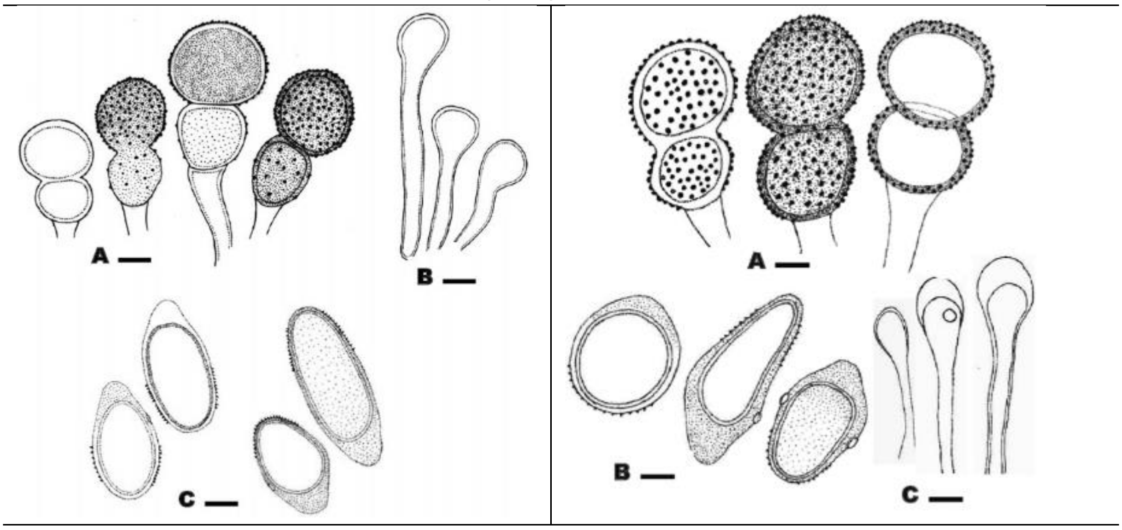
Life cycle of *Tranzschelia discolor*

Understanding the life cycle and conditions that favour *T. discolor* infection in commercial plums is essential in order to target fungicide applications and reduce disease progression.

Rust fungi are parasites that require living hosts and although they do not tend to rapidly kill host tissue, severe infections can cause plant tissue to collapse and die, leading to premature defoliation. Rust species have complex life cycles, with as many as five reproductive stages, and infections are often systemic. Some rusts also require an alternate host to complete their life cycle, including *T. discolor* and the majority of the *Tranzschelia* rusts (Scholler et al., 2018).



Ruth D'urban Jackson, RSK ADAS Ltd (2018)



T. discolor Fiaz et. al. (2017) *T. pruni-spinosae*

Figure 2. *Tranzschelia discolor* at x40, (top-left) urediospores: ellipsoid or ovoid, 20-40 x 10-19µ, wall thickened and dark orange at conical apex, and (top-right) teliospores: 2-celled, dark brown, coarsely verrucose, 30-45 x 18-25, deeply constricted at septum and readily fracturing Line drawings of *T. discolor* (bottom-left) bar = 8µ and *T. pruni-spinosae* (bottom-right) bar = 10µ. A – teliospores, B – paraphyses, C – urediospores (Fiaz et al., 2017).

Scientific literature indicates *T. discolor* to have four life-cycle stages, with different spore-producing structures (Figure 3). The first two stages; spermogonia (abbreviated to O) and aecia (I) involve the poppy anemone *A. coronaria,* and the latter two; uredinia (II) and telia (III), occurring on plum, *Prunus domestica* (Scholler et al., 2018). During the course of this review, the author observed *T. discolor* urediospores and teliospores, taken from a commercial plum orchard in Oxfordshire (Figure 2). In the UK only the teliospore (III) and urediospore (II) stages have been observed (Wilson and Henderson, 1966), and research on plum rust has been minimal over the last 50 years. However, recent work on the Tranzschelia rusts found that "Tranzschelia spp. do not host-alternate in certain regions, where no aecial host population is available", so it could be possible that UK T. discolor does not use an alternate host. Mitotic production of uredia (II) has been documented for *T. discolor*, and to date there are 87 telial and 11 aecial hosts documented (Scholler et al., 2018).

Depending on the country, *T. discolor* rust symptoms tend to appear on the secondary host *A. coronaria* in April-May. Once inside the leaf, the fungus becomes systemic, moving throughout the plant. The fungal mycelium moves down to the corm, where it is thought to remain over the following winter (Scholler et al., 2018). Numerous white spore producing structures (aecia) form on the leaves, causing them to constrict and twist, and interfere with flower production (Fawaz, 2018). From here, aeciospores are then dispersed and go on to infect plum leaves, forming brown uredia on the underside of leaves from June/July onwards, depending on the region (Wilson and Henderson, 1966).

Throughout the growing season, further cycles of infection occur as urediospores reinfect the same trees and those nearby resulting in more pustules and additional spores. Germination of urediospores for many rust fungi declines above 25^{o}C (Worapong et al., 2009), and in one study on *P. pruni-spinosae*, urediospores were found to tolerate low temperatures (2-3^{o}C) better than teliospores (original paper by (Blumer, 1960) in German, cited by (Scholler et al., 2018)). The effect of temperature on germination of *T. discolor* spores in the UK is not known. At the end of the season, when conditions are favourable, black specks can be seen. These contain resting teliospores which remain on fallen leaf litter throughout winter, and give rise to spores which infect *A. coronaria*, hence restarting the cycle.

Disease sources

The role of alternate hosts, and the primary inoculum spore type responsible for plum infection in the UK has been a source of debate, and remains partly unknown. In the south of England, UK, teliospores formed on bullace (*P. domestica* spp. *insititia*) were found to infect an anemone (Linfield and Price, 1983). Teliospores from plum leaf litter were also found to germinate from late December to form spores (basidiospores) which went on to infect *A. coronaria* (Price, 1980). However, there have been no reports of the occurrence of *T. discolor* aecidia on *A. coronaria* or other hosts in Britain, as they have been observed in Turkey, France, Italy and India (Fawaz, 2018), so this requires further investigation.

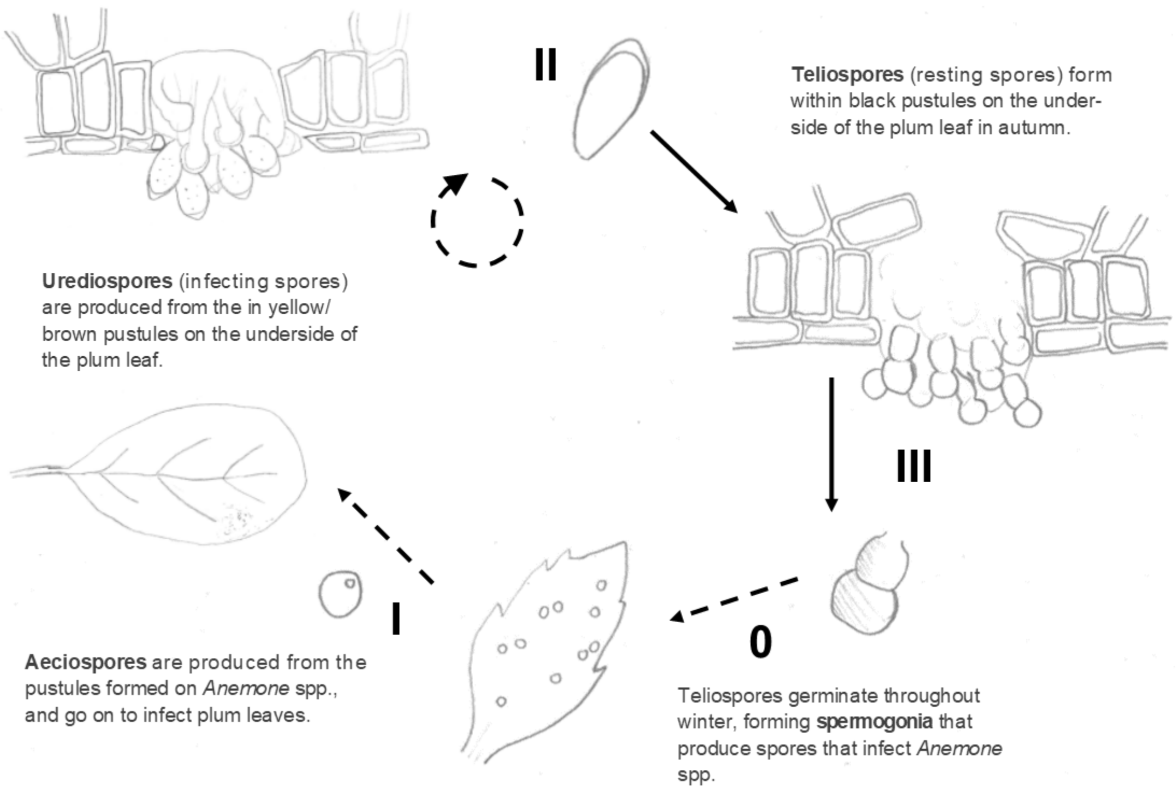


Figure 3. Probable life cycle of *Tranzschelia discolor* on cultivated *Prunus* spp. (image credit: Ruth D'urban-Jackson). In the UK, only the teliospore (III) and urediospore (II) stages have been observed, suggesting *T. discolor* potentially only cycles between the aforementioned two stages, without an alternate host – as indicated by dotted lines.

A thorough investigation into *T. discolor* in Australian almond orchards found infected leaf litter to be the primary inoculation source, with 27% of the urediospores viable at the time of new leaf emergence (Horsfield and Wicks, 2010). Almonds have the capacity to support *T. discolor* races that also infect *Prunus* spp. which is significant because, unlike plums, almonds don't completely defoliate over winter, so may provide an overwintering site for rust races for both crops (Kable et al., 1986). In addition it is possible that with recent milder winters delaying leaf drop and warmer springs, there is less of a time-gap between the old and new leaves in UK plum orchards. Late-developing urediospores on plum leaf litter, barks of stems, branches, shoots, or leaf scars, or in hedgerows (e.g. wild plum, damsons or bullace), may then be able to survive through the winter and remain viable to re-infect newly emerging leaves in UK orchards.

Recent work by Scholler et al. highlighted an interesting feature of the fungi life cycles. Amongst the rust fungi (Pucciniales) sister-species pairs that include host-alternating (heteroecious) and non-host-alternating (autoecious) species that share a common host are called correlated species. Work on the *Tranzschelia* genus found three pairs of correlated species, indicating that the evolution of these rust fungi can move from a heteroecious macrocyclic strategy to an autoecious microcyclic strategy (Scholler et al., 2018). This suggests that *T. discolor* urediospores can potentially survive the winter to reinfect newly emerging leaves in the spring without the need for an alternate overwinter host.

It is also interesting to note that although the alternate host for *T. discolor* is *A. coronaria*, it is not always confirmed as an inoculum source. For instance in California, *A. coronaria* is rarely found where stone fruit crops are grown, so it is not thought to provide the inoculum for initial spring infections (Mancero-Castillo et al., 2015).

We know *T. discolor* infection in *A. coronaria* to be perennial (Wilson and Henderson, 1966, Laura et al., 2015), so it could be that *T. discolor* infection is systemic in plum trees. This is important, as trees may remain infected, and continue to show symptoms each year, regardless of whether there is an inoculum source nearby. Therefore, control methods to reduce early season infection may be wasted efforts. The emphasis would then be to apply fungicides immediately after first symptoms to prevent secondary cycles of infection. With limited applications of conventional chemical fungicides and biological PPPs, this is an important point to consider.

Understanding where and under what conditions urediospores can remain viable over winter in the UK would aid cultural control measures in reducing primary inoculum levels at the beginning of the season, but if the pathogen is actually systemic, then control measures should be adjusted.

Conditions favouring disease development and spread

A critical feature of rusts is that they require a period when there is free water on the leaf surface in order for their spores to germinate (Scrace, 2000, O'Neill, 2002, Wedgwood and Robinson, 2016), with the length of time leaves are wet to be a major determinant of whether infection occurs (Kable et al., 1991). High relative humidity (>80%), rainfall and dew point also favour *T. discolor* rust development (Mancero-Castillo et al., 2015, Dicklow, 2013). Temperature is also important to germination, in the presence of free water, *T. discolor* urediospores in almond, germinate between 5-30^{o}C, with over 80% of spores germinating within 2 hours of incubation between 10-28^{o}C (Ellison et al., 1990). In Australia in a computer-based system was set up for the management of rust in French prunes, called the Prune Rust Infection Predictor (PRIP). This involved measurement of air temperature, rainfall and the presence of free water in tree canopies, to predict conditions for rust infection and disease severity (Kable et al., 1991). Online open source monitoring programmes that measure rainfall, humidity and day/night temperatures to report on the likelihood of disease development in crops such as potato - Blightwatch (AHDB, 2018), are available in the UK, but not for rust on plums. Further work is required to understand the environmental conditions conducive to plum rust infection and development before these online tools can be developed.

Control measures for plum rust must start as soon as first symptoms appear (Erincik et al., 2016) to ensure minimal disease progression. This is important as there are no curative products for plum rust, once leaves are infected. Once urediospores penetrate the leaf surface, rust pustules appear after 15-21 days (Erincik and Timur Döken, 2010), so fungicides should be targeted at this stage, to prevent further inoculum production, and further foliar infections. In Turkey, the greatest fungicide efficacy was found when applications were made immediately after the first foliar rust symptoms were observed on plum (Erincik et al., 2016).

Control strategies

1. Resistant varieties

The availability of rust-resistant plum varieties has been hampered by a poor state of knowledge regarding the host/pathogen interaction, an issue which is mirrored in the commercial production of *A. coronaria*, the alternate host, which also suffers when infected by *T. discolor*. Work investigating the transcriptome of *A.coronaria* infected with *T. discolor*, found amongst up-regulated genes, six which encoded proteins involved in the jasmonic acid signalling pathway that induced a systemic defence response in the host (Laura et al., 2015). It is not known whether this response to *T. discolor* is produced in *Prunus* spp. during infection.

Some resistant and 'tolerant' plum cultivars exist; the latter being those that form fewer rust pustules after initial inoculation and are less likely to defoliate prematurely. Plum tree rootstocks also differ in their susceptibility/tolerance to rust, so could present an option to help minimise damage caused by plum rust. Cultivar St. Julian A is very susceptible, whereas cultivar Wavit has been seen to tolerate rust in the UK (pers. comms with UK fruit tree propagator) so they could work well as candidate cultivars for resistance trials. Work on *T. discolor* in almond concluded that future focus should utilise artificial inoculation to screen cultivars for use as potential parents in breeding programmes (Horsfield and Wicks, 2014). The genes responsible for resistance to *T. discolor* in *Prunus* spp. are unknown, so this requires further study.

To investigate the relative susceptibility of different *Prunus* cultivars to rust, a visit to the RHS Wisley Plum collection was made on the 18th September 2018 by the author. The collection is the largest in the UK, containing 110 cultivars of plum (*P. domesticus*), damson (*P. domestica* subsp. *insitita*), gage (*P. domestica* subsp. *italica*), bullace (*P. domestica* subsp. *insititia* var. *nigra*) and other crosses. Rust symptoms were recorded along with other problems such as bacterial canker and shot-holing. Due to the unusually dry 2018 season in the UK, the appearance of rust symptoms were delayed and leaves which were severely coated in rust pustules, remained attached to the plant (but were judged to be close to detaching).

It was noted that rust symptoms were predominantly on younger leaves, suggesting they may be more susceptible to infection, or that climatic conditions conducive to rust outbreaks occurred late in the season, when new young leaves were emerging. It was also observed that in plum trees with severe infections, St. Julian A was the predominant rootstock, suggesting rootstocks might play a role in plum rust infection. Of the 110 cultivars, 97 showed some degree of rust symptoms (Appendix 4). Of those showing symptoms, 55 were suffering (or going to suffer) from severe premature defoliation, whilst others looked green and healthy, appearing to tolerate the rust. The disease pressure was high, with so many infective trees around, but thirteen cultivars were without rust symptoms:

Ferbleue, Guinevere, Anna Spath, Angelina Burdett and Beauty (plums), Merton Gage (gage), Mirabelle de Nancy, Golden Sphere (Damson & mirabells), Gypsy, Myrobalan, Poltava (cherry plum and myrobalans), Shiro (Japanese plum) and one unnamed tree. These were in line with previous observations by J. Arbury of the RHS (pers. comms).

Alongside using resistant cultivars, crop husbandry such as pruning is considered important in reducing disease pressure, as it reduces humidity in the canopy that favours spore germination and infection. Strategic pruning to control *T. discolor* in peach was explored in

Brazil, but it was found that rust lesions increased over time, regardless of pruning level (Rodrigues et al., 2008). Some plum cultivars have a more open canopy than others, which allows good air flow while others have dense, erect upright branches, which should be pruned or trained outward, to avoid heavily laden branches snapping under their own weight.

2. Conventional chemical fungicides

In the UK, currently approved conventional chemical fungicides for controlling plum rust are limited (Table 2). Certain key products are no longer available, such as Systhane 20 EW (myclobutanil) which was removed from use in September 2017 (LIAISON, 2018a), and used to be the primary fungicide for rust control in plum (Cross, 2014).

The Extension of Authorisation for Minor Use (EAMUs) programme provides certain options for UK growers. There was an EAMU for Indar 5 EW (fenbuconazole) which had some effect on plum rust, but this is no longer available (RedTractor, 2016). At the time of publication (HSE, 2018c) EAMU options include Regalis Plus (prohexadione), Signum (boscalid + pyraclostrobin) and Switch (cyprodinil + fludioxonil), but these are mostly used to control other fungal pathogens, such as *Botrytis cinerea* which also pose a threat to plum production. With a limit to the number of applications allowed as part of fungicide resistance management, control of rust is often not the primary approved use for these fungicides.

A lack of conventional chemical control can be an issue to growers, when they lack sufficient alternative management strategies. In work comparing organic to conventional plum orchards in Spain, defoliation occurred one month earlier in the organically managed orchard, largely due to differences in the severity of rust disease (Arroyo et al., 2013, A. García-Galavís et al., 2009). In the UK, fertilisers are advised to treat trees that are facing severe premature defoliation (RedTractor, 2016) as a way to counteract the decline in photosynthetic output, and the subsequent decrease in carbohydrate production to achieve reasonable yields,. However, the use on plum trees facing severe rust infection, and a decline in green leaf area, has not been investigated.

Table 2. Currently approved fungicide and biofungicide products available in the UK that have EAMUs on plum (October 2018).

Example product and MAPP number	Active ingredient and fungicide group	FRAC code	Approved status for plums	Renewal date of UK product registration
Amylo X (17978)	*Bacillus amyloliquefaciens* subsp. *plantarum* strain D747	44	EAMU 20180469	30 September 2027
Calcium hydroxide*	Calcium hydroxide	-	-	Unstipulated
Cuprokylt (17079)	Copper oxychloride	M1	EAMU 20181815	28 November 2018
Prestop (17223)	*Gliocladium catenulatum* strain J1446	-	EAMU 20152773	30 September 2019
Serenade ASO (16139)	*Bacillus subtilis* strain QST 713	44	EAMU 20182354	29 February 2020
Signum (11450)	Boscalid + pyraclostrobin (Carboxamide + strobilurin)	7 + 11	EAMU 20102109	31 July 2021
Switch (15129)	Cyprodinil + fludioxonil	9 + 12	EAMU 20103092	30 April 2021
Teldor (11229)	Fenhexamid	17	EAMU 20031866	9 September 2099

* Product approved in Europe as a Basic Substance (EuropeanCommission, 2018).

This table has been collated using information from the Health and Safety Executive (HSE) website (pesticides.gov.uk) and from product labels and supplier technical leaflets. Important – regular changes occur to the approval status of plant protection products, arising from changes in the legislation or for other reasons. For the most up to date information, please check the HSE website or with a professional supplier or BASIS-qualified consultant, as information could have changed since the publication of this review.

FRAC – Fungicide Resistance Action Committee

EAMU – Extension of Authorisation for Minor Use

Recent work in Turkey on plum rust evaluated a range of conventional chemical fungicides, including triazoles, strobilurins, benzimidazoles, and chlorothalonil at standard rates, under both glasshouse and field experiments (Table 3). In glasshouse experiments, the strobilurin group of fungicides did not show efficacy when applied after inoculation, but did exhibit some activity in the field experiments. Here all fungicides provided better control over the season and significantly reduced premature leaf fall when applied immediately after rust pustules (uredinia) were first observed (Erincik et al., 2016). It was also noted that rust severity was low throughout May, but dramatically increased in the early June, leading them to suggest that mid-May was the optimal time to commence fungicide sprays against rust. This work highlights the importance of identifying the most effective time to spray. Many conventional chemical fungicides were effective as early applications (up to 7 days after inoculation) but when applied later (i.e. late in the season) at the time of secondary infections, most fungicides did not result in control of rust.

Work on *T. discolor* rust in peach also found the timings of treatments to be a significant factor in reducing disease (Soto-Estrada et al., 2003), in particular after stem lesion detection, and the occurrence of rainfall.

Difenoconazole was shown by Erincik et al., (2016) to provide some curative effect against plum rust, so products such as Amistar Top (difenoconazole + azoxystrobin), which is registered in the UK for use on protected and outdoor strawberry, should perhaps be considered for an EAMU (HSE, 2018a). An EAMU (20182671) was recently approved (2 October 2018) for Amistar Top for use against rust on selected herbs (HSE, 2018b). Hexaconazole and tebuconazole also showed activity; the former is not currently approved for use as a plant protection product in the EU (EuropeanCommission, 2016), and the latter used to be available for use on plums in the UK as a pruning paint until 31 August 2015 (LIAISON, 2018b).

In Australia, Luna Sensation (Fluopyram + trifloxystrobin) is available for use on stone fruit (Bayer, 2018), but in the UK, this fungicide only has approval for use on strawberry. Trifloxystrobin was found to be highly effective in controlling rust in prune trees in northern Israel, alongside the standard treatment of alternating myclobutanil + mancozeb (Reuveni, 2000). With the loss of myclobutanil (Systhane 20 EW) in the UK, having a similarly effective fungicide, such as trifloxystrobin could be useful to growers. However, trifloxystrobin was not as effective against *T. discolor* as it used to be, in work by Erincik et al., where strobilurin fungicides performed worse than the azole group of fungicides.

Information provided by the University of Florida Extension services (Mancero-Castillo et al., 2015) and the University of California (Adaskaveg et al., 2015) lists products for controlling *T. discolor* on peaches, such as azoxystrobin and pyraclostrobin + fluxapyroxad, which could be potential candidate actives for UK plum rust control (see Table 3). Appendix 1 and 2 contains full extension service information respectively.

Work evaluating fungicides against rust in almonds found the most effective protective fungicides to be azoxystrobin, pyraclostrobin + boscalid and pyraclostrobin + metiram, which were at least effective as registered fungicides such as chlorothalonil. Propiconazole was less effective than other fungicides, when applied as a protective spray programme (Horsfield, 2014). This work also found that post-infection fungicide sprays, applied during the latent phase of *T. discolor* provided 50-100% inhibition of uredia production.

Table 3. Range of fungicide efficacies for control of rust on stone fruit in Turkey, Australia and the USA.

Country (crop)	**Location**	**Treatment timing**	**Treatments**	**Relative efficacy***
Turkey (plum) (Erincik et al., 2016)	Glasshouse (controlled environment)	Pre-inoculation	All fungicides (as below)	++++
		Applied any time post-inoculation	Strobilurins (azoxystrobin and trifloxystrobin) and benzimidazoles (thiophanate-methyl and carbendazim)	-
		Applied post-inoculation (up to 7 days after)	Triazoles (tebuconazole, difenoconazole, flusilazole and hexaconazole)	++++
Turkey (plum)	Field	Early season (at primary infection stage)	All fungicides (as above)	++++
		Late season (at secondary infection stage)	All fungicides (except hexaconazole)	- (Provided no apparent benefit in preventing secondary infections and premature leaf fall later in the season)
			Hexaconazole	+++ (Provided satisfactory control: 89% less disease than untreated control).
Florida, USA (peach) (Mancero-Castillo et al., 2015)	Field	All season	Sulphur	++
			Chlorothanil	+++
			Captan	+++
			Azoxystrobin	++++
			Tebuconazole	++
			Tebuconazole + trifloxystrobin	+++
			Fenbuconazole	++
			Difenoconazole + cyprodinil	++++
			Pyraclostrobin + fluxapyroxad	++++
			Penthiopyrad	++
Australia (stone fruit) (Bayer, 2018)	Field	All season	Fluopyram + trifloxystrobin	++++
Australia (almond) (Horsfield, 2014)	Field	All season	azoxystrobin	+++
			Pyraclostrobin + boscalid	+++
			Pyraclostrobin + metiram	+++
			propiconazole	+

*Efficacy ratings range from +, slightly effective to ++++ highly effective, standardised from information from the respective sources.

It is worth noting that of the conventional chemical actives discussed, the following are candidates for substitution (EuropeanCommission, 2015).

- Cyproconazole
- Cyprodinil
- Difenoconazole
- Dimoxystrobin
- Fludioxonil
- Propiconazole
- Tebuconazole

3. Biopesticides

There is potential for the use of biopesticides to control rust in plums, with existing approved products including Amylo X (*Bacillus amyloliquefaciens* subsp. *plantarum* strain D747), Prestop (*Gliocladium catenulatum* strain J1446) and Serenade ASO (*Bacillus subtilis* strain QST 713), see Table 2.

Azadirachtin (Margosa extract), garlic extract and citronella are approved plant extracts for use in the UK. Work elsewhere has investigated the use of plant oils against rust fungi, which showed some efficacy in certain crops, for inhibiting urediospore germination. One example, on coffee rust (*Hemileia vastatrix*) found essential oils to inhibit germination of urediospores with increasing concentrations, in particular the oils of thyme, clove and citronella (concentration 1000µL L^{-1}), with citronella showing the most pronounced inhibition (Pereira et al., 2012). These essential oils may be considered for future work in plum rust, as *H. vastatrix* is part of the same order (Puccinales) as *T. discolor*. Other work, investigating the use of essential oils on Teak rust (*Olivea neotectonae*) control, found noni (*Morinda citrifolia*) and lemongrass oils to completely inhibit *O. neotectonae* urediospore germination at 4000µL L^{-1}, however phytotoxicity was noted on the coffee seedlings at 2000µL L^{-1} and 1500 µL L^{-1} respectively (Arguelles Osorio et al., 2018). There are no reports in the literature regarding effect of essential oils on germination of *T. discolor* urediospores, and this could therefore be a promising approach for further work.

Table 4. Essential oils with activity against coffee rust (Pereira et al., 2012) and teak rust (Arguelles Osorio et al., 2018).

Product	Rate	Rust control?	Phytotoxicity
Thyme oil	1000µL L^{-1}	Yes	None
Clove oil	1000µL L^{-1}	Yes	None
Citronella oil*	1000µL L^{-1}	Yes	None
Noni oil	2000µL L^{-1}	Yes	Yes
Lemon grass oil	1500µL L^{-1}	Yes	Yes

* UK approved bioherbicide

Phosphites also offer potential control of rust, as they have been shown to stimulate defence responses in horticultural crops (Gómez-Merino and Trejo-Téllez, 2015) through induction of host resistance. Copper phosphite has also been found to reduce severity of rust in peach (Kowata et al., 2012).

4. Cultural management

Cultural management approaches to reduce plum rust inoculum sources include: reducing Prunus leaf litter on the ground, in the nooks of branches, cutting back hedgerows with other *Prunus* spp. that may have infected leaves attached longer into winter/spring, and in Europe avoiding having nearby *A. coronaria* secondary host plants (*A. coronaria* not yet confirmed as a source of inoculum in the UK). A common management measure in apple orchards for reducing fungal inoculum (such as for apple scab) is to flail or use urea to break down leaf litter, a major site for over wintering spores (Sundin and Irish-Brown, 2018). In work done in the USA, urea applied to leaf litter in November reduced the number of ascospores trapped (in spore traps) by 50%, and by 66% when applied in April (Sutton et al., 2000). However, in Northern Ireland, total removal of leaf litter did not significantly reduce scab disease incidence (Mac Antsaoir et al., 2010), with the authors suggesting that the much higher rainfall in that region (compared to other European countries) made even the heightened hygiene insufficient for suitable disease management. Regardless of the orchard cleanliness in autumn, missing the first fungicide application in spring always reduced yield. No information was found on the efficacy of removing plum leaf litter in the UK for control of rust.

Hedgerows are sometimes used as pollinators for plum orchards, but they may also provide over-wintering protection for urediospores (pers. comms. with J. Allen - fruit advisor) so investigating this as a potential inoculum source could add to our understanding of *T. discolor* epidemiology in the UK.

Discussion

This review has discussed the complexity of *T. discolor* rust infection on plums, highlighted our lack of a clear understanding of its life cycle and epidemiology, and identified potential current and new control measures for it. Some measures growers can take on immediately, whilst others require further work in order to fully understand.

Two areas in particular need to be addressed, to develop robust plum rust management strategies. If inoculum sources (e.g. leaf litter or infected alternate hosts) are the primary cause of infection each year, then efforts to reduce these should be investigated.

However, if plum rust is found to be systemic, then fungicide applications should be targeted early in the season at the first signs of infection in order to minimise further disease development (and subsequent premature defoliation and reduced photosynthetic output). The importance of spray timings was frequently discussed, but there are currently no rust-specific products available for use on plum in the UK. Work in Turkey, Brazil, Australia, and information from the USA extension programmes has highlighted potential PPPs, including hexaconazole, azoxystrobin, fluopyram plus trifloxystrobin. Other work on inhibition of rust spore germination highlighted potential plant oil products such as thyme and clove oil, both of which are active substances going for approval at EU level. Products that are close to market or have authorisation on other crops, would be ideal candidate products for plum rust screening trial work.

Further work:

Findings from this review have highlighted a number of gaps in our knowledge of *T. discolor* on plums in the UK. Further work is required to:

- Identify weather conditions that result in first appearance of plum rust symptoms.
- Confirm timings of *T. discolor* spore dispersal in the UK, via urediospore traps.
- Confirm whether *T. discolor* exhibits an aecial life phase on the secondary host *A. coronaria* (or other plant) in Britain or if the pathogen is microcyclic and confined to urediospore and teliospores stages, thus not requiring an alternate host.

- Confirm whether infection by *T. discolor* in plum trees is systemic. Potentially through using PCR primers, as work has already studied the transcriptome of *A. coronaria* when infected by *T. discolor*.
- Test potential fungicides and biopesticides in efficacy trial work against *T. discolor*, such as those in Table 3 that have potential to be registered for use on plum in the UK. Trials could be conducted on young plum trees (e.g. with 10 leaves) under protection, using inoculation via spore spray. This would enable uniform disease pressure and ensure correct climatic conditions for disease emergence (overhead misting to ensure spore germination, and shelter to ensure initial inoculation is not washed off by rain).
- Compare susceptible and tolerant plum rootstocks, such as St. Julian A and Wavit respectively. Results could then inform growers of rootstocks that could be used in an integrated management programme.

Preliminary list of candidate products to control plum rust

Difenoconazole*	Pyraclostrobin + fluxapyroxad	Citronella oil**
Tebuconazole*	Pyraclostrobin + boscalid	Thyme oil
Azoxystrobin	Trifloxystrobin + fluopyram	Clove oil
Trifloxystrobin	Penthiopyrad	Orange oil
		Spear mint oil

* Actives are currently on the EC’s list of candidates for substitution (as of December 2018).
** All oils listed are approved in the EU.

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Appendix 1:

Table extract from the University of Florida Extension (Mancero-Castillo et al., 2015). Suggested fungicide options organized by efficacy for peach rust management, their application rates, effectiveness, re-entry intervals (REI) and Pre-harvest intervals (PHI). Effectiveness ratings range from +, slightly effective to ++++ highly effective.

Material	FRAC Code (2015)	Rate/Acre	Effectiveness[z]	REI/PHI	Remarks
sulfur	M2	18 lbs./100 gal	++	24 hrs./0 days	
Chlorothanil					
Bravo Weather Stik	M5	3–4 pts.	+++	12 hrs./do not apply after shuck split	Chlorothalonil provides 14–21 days of scab control. Chlorothalonil is not labeled for use after shuck split, but can be used after harvest. **Chlorothalonil and captan are severe eye irritants.** Although the restricted-entry interval expires after 12 hours, **for 7 days after use, entry is permitted only when the following safety measures are provided:** 1. At least one container designed specifically for flushing eyes must be available in operating condition at the mandatory WPS-required decontamination site. 2. Workers must be informed, in a manner they can understand: • that residues in the treated area may be highly irritating to their eyes. • that they should take precautions, such as refraining from rubbing their eyes, to keep the residues out of their eyes. • that if they do get residues in their eyes, they should immediately flush their eyes using the eyeflush container that is located at the decontamination site or using other readily available clean water. • how to operate the eyeflush container.
Bravo Ultrex WDG		2.8–3.8 lbs.			
Equus 720 or ECHO 720		3–4 pts.			
Captan					
Captan 50W	M4	4–6 lbs.	+++	24 hrs./0 days	
Captan 80WDG		2.5–3.75 lbs.			
Captec 4L		2–3 qts.			
Azoxystrobin					
Abound	11	9.0–15.5 fl. ozs.	++++	4 hrs./0 days	
Tebuconazole					
Tebuzol 45DF	3	4 oz.	++	12 hrs./0 days	For peaches only, 9.0–15.5 fl. ozs. can be used for scab control. For scab, begin applications at petal fall and continue at 7–14 day intervals per label. Do not apply more than two sequential applications of Group 11 fungicides before alternation with a fungicide that
Orius 20AQ		10.75–17.2 oz.			
Tebuconazole plus **trifloxystrobin**					
Adament 50 WG	3 + 11	4–8 oz.	+++	12 hrs./24 hrs.	
Fenbuconazole					
Indar	3	2 oz.	++	12 hrs/0 days	
Difenoconazole plus **cyprodinil**					
Inspire Super	3 + 9	16–20 fl. oz.	+++	12 hrs/0 days	
Pristine	11 + 7	10.5–14.5 oz	++++	12 hrs/0 days	
QoI/SDHI mix: **pyraclostrobin** plus **fluxapyroxad**					
Merivon Xemium	11 + 7	4–6.7 fl oz	++++	12 hrs/0 days	Under certain conditions, mixtures of Merivon Xemium with adjuvants, additives and/or other products may cause crop injury, particularly to fruit within two weeks of harvest. DO NOT use Merivon Xemium with: • Emulsifiable concentrate (EC) or solvent-based formulation products. • Crop oil concentrate (COC), methylated seed oil (MSO) adjuvants.
penthiopyrad					
Fontelis	7	14–20 fl oz	++	12 hrs/0 days	

[z]Effectiveness ratings range from +, slightly effective, to ++++, highly effective.
The use of trade names in this publication is solely for the purpose of providing specific information. UF/IFAS does not guarantee or warranty the products named, and references to them in this publication do not signify our approval to the exclusion of other products of suitable composition. All chemicals should be used in accordance with directions on the manufacturer's label.

Appendix 2:

Table extract from the University of California IPM extension service – Pest Management Guidelines (Adaskaveg et al., 2015).

Common name (Example trade name)	Amount to use	REI‡ (hours)	PHI‡ (days)
UPDATED: 9/15			
Compare treatments · Calculate emissions · Protect bees			
When choosing a pesticide, consider its usefulness in an IPM program by reviewing the pesticide's properties, efficacy, application timing, and information relating to resistance management, honey bees, and environmental impact. Not all registered pesticides are listed. Always read the label of the product being used.			
SULFUR TREATMENTS			
A. WETTABLE SULFUR# MODE-OF-ACTION GROUP NAME (NUMBER[1]): Multi-site contact (M2) COMMENTS: Do not apply within 3 weeks of an oil application.	18 lb/100 gal water	See label	See label
B. WETTABLE SULFUR# . . . PLUS . . . LIQUID LIME SULFUR# MODE-OF-ACTION GROUP NAME (NUMBER[1]): Multi-site contact (M2) COMMENTS: Do not apply within 3 weeks of an oil application.	Label rates	See label	See label
C. LIQUID LIME SULFUR# MODE-OF-ACTION GROUP NAME (NUMBER[1]): Multi-site contact (M2) COMMENTS: Do not apply within 3 weeks of an oil application.	6 gal/100 gal water	See label	See label
D. SULFUR DUST# MODE-OF-ACTION GROUP NAME (NUMBER[1]): Multi-site contact (M2) COMMENTS: Do not apply within 3 weeks of an oil application.	50 lb/acre	See label	See label
STEROL INHIBITOR FUNGICIDES			
A. TEBUCONAZOLE (Elite 45WP) MODE-OF-ACTION GROUP NAME (NUMBER[1]): Demethylation inhibitor (3) COMMENTS: Do not apply more than 3 lb/acre per season.	4–8 oz/acre	120 (5 days)	0
B. PROPICONAZOLE (Bumper, Tilt) MODE-OF-ACTION GROUP NAME (NUMBER[1]): Demethylation inhibitor (3) COMMENTS: Maximum of 2 preharvest sprays.	4 fl oz/acre	12	0
C. METCONAZOLE (Quash) MODE-OF-ACTION GROUP NAME (NUMBER[1]): Demethylation inhibitor (3) COMMENTS: Do not make more than 3 applications per season.	3.5–4 oz/acre	12	14
STROBILURIN FUNGICIDE			
A. AZOXYSTROBIN (Abound) MODE-OF-ACTION GROUP NAME (NUMBER[1]): Quinone outside inhibitor (11) COMMENTS: Do not apply more than two applications before alternating with a fungicide that has a different mode of action group number.	12–15.5 fl oz/acre	4	0
B. TRIFLOXYSTROBIN (Gem 500SC) MODE-OF-ACTION GROUP NAME (NUMBER[1]): Quinone outside inhibitor (11)	3.8 oz/acre	12	1

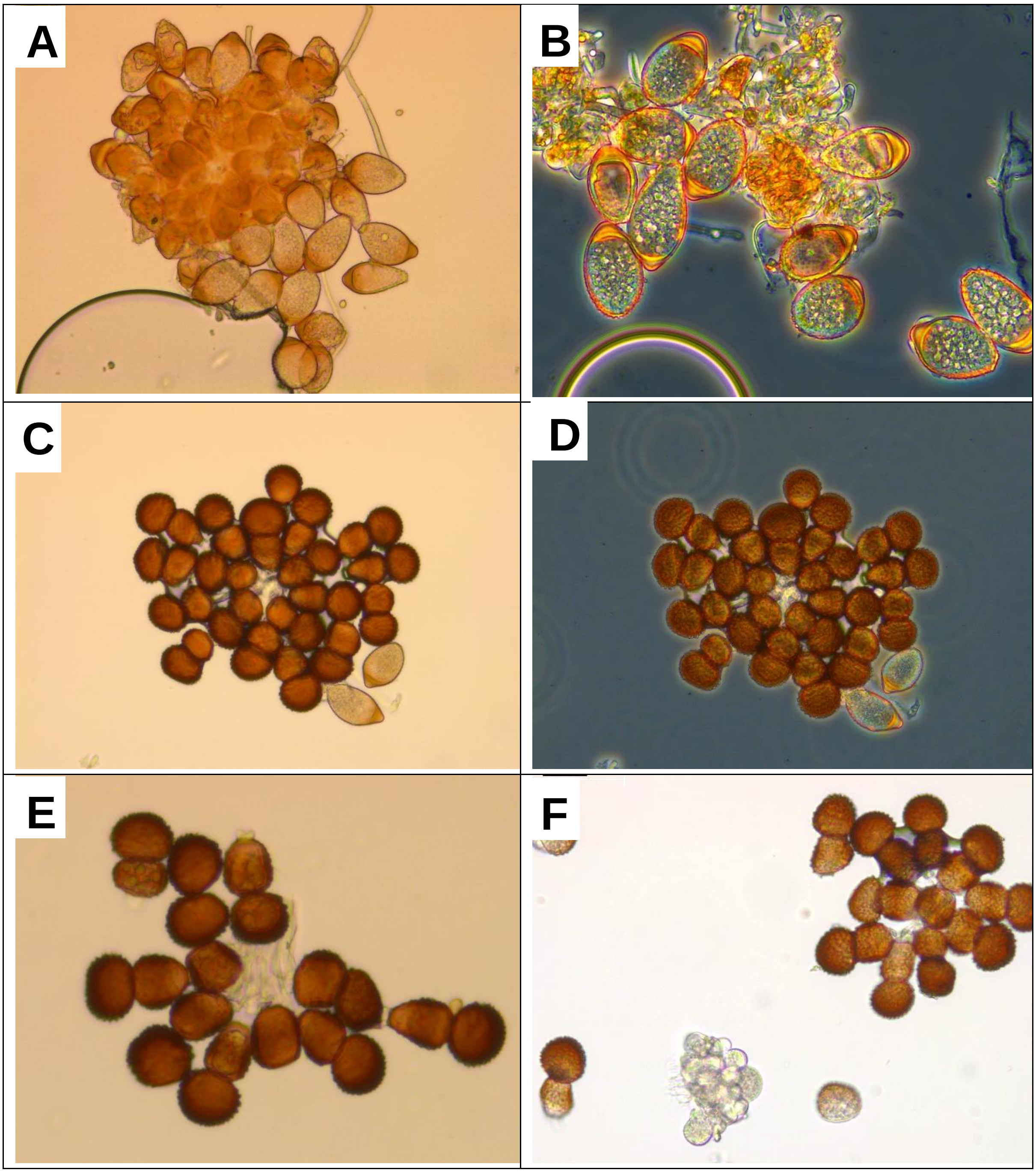
‡ Restricted entry interval (REI) is the number of hours (unless otherwise noted) from treatment until the treated area can be safely entered without protective clothing. Preharvest interval (PHI) is the number of days from treatment to harvest. In some cases the REI exceeds the PHI. The longer of two intervals is the minimum time that must elapse before harvest.

\# Acceptable for use on organically grown produce.

1 Group numbers are assigned by the Fungicide Resistance Action Committee (FRAC) according to different modes of actions (for more information, see http://www.frac.info/). Fungicides with a different group number are suitable to alternate in a resistance management program. In California, make no more than one application of fungicides with mode of action Group numbers 1,4,9,11, or 17 before rotating to a fungicide with a different mode of action Group number; for fungicides with other Group numbers, make no more than two consecutive applications before rotating to a fungicide with a different mode of action Group number.

Appendix 3:

Images of *T. discolor* sampled from plum leaves in England 2018. Magnification x40 images of *Tranzschelia discolor* spores. Urediospores (A) in phase contrast (B), cluster of teliospores with two urediospores bottom right (C) in phase contrast (D), and the darker brown teliospores (E and F).



Appendix 4:

Table of plum cultivars at RHS Wisley (courtesy of Jim Arbury, 2018). Green highlighted cultivars showed no rust symptoms at assessment by ADAS (Ruth D'urban-Jackson & Janet Allen) on 18th September 2018 of individual trees of each cultivar.

Name	Rust Present?	Defoliated?
Bradley's King	Yes	No
Merryweather	Yes	Yes
Farleigh	Yes	No
Prune	Yes	No
Westmorland	Yes	No
White Damson	Yes	Yes
Shepards Bullace	Yes	No
Langley Bullace	Yes	No
White Bullace	Yes	No
Fludes Damson	Yes	Yes
Marjories seedling	Yes	No
Coe's Golden Drop	Yes	Yes
Crimson Drop	Yes	No
Haganta	Yes	No
Guinevere*	No	No
Jojo	Yes	Yes
Severn Cross	Yes	No
Zwetsche Large	Yes	Yes
Zwetsche Bohemian	Yes	No
Zwetsche No 11	Yes	Yes
Ferbleue*	No	No
Warwickshire Drooper	Yes	Yes
Giant Prune	Yes	No
Laxton's Cropper	Yes	Yes
Anna Spath*	No	No
Late Muscatelle	Yes	Yes
Verity	Yes	Yes
Valor	Yes	Yes
Victory	Yes	Yes
Delma	Yes	Yes
Jefferson	Yes	Yes
Allgrove's Superb	Yes	Yes
Royal de Vilverde	Yes	Yes
Laxton's Ideal	Yes	Yes
Edward's	Yes	No
Stanley	Yes	No
Kirke's	Yes	Yes
Laxton's Olympia	Yes	Yes
Laxton's Delicious	Yes	No
White Magnum Bonum	Yes	No

Lawson’s Golden	Yes	Yes
Merton Gage*	No	No
Pershore	Yes	Yes
Cox’s Emperor	Yes	Yes
Queen’s Crown	Yes	Yes
Jubileaum	Yes	Yes
Victoria	Yes	Yes
Laxton’s Jubilee	Yes	Yes
Reine Claude Violette	Yes	No
Autumn Compote	Yes	Yes
Old Greengage	Yes	Yes
Lindsey Gage	Yes	No
Willingham gage	Yes	No
Cambridge Gage	Yes	No
Bryanston Gage	Yes	No
Brahy’s Greengage	Yes	Yes
Washington	Yes	No
Guthrie’s Late Green	Yes	No
Laxton’s Supreme	Yes	No
Laxton’s Delight	Yes	No
Swan	Yes	No
WJ 7	Yes	Yes
Excaliber	Yes	No
Reeves	Yes	Yes
Bountiful	Yes	Yes
Monsieur Jaune	Yes	Yes
Early Transparent	Yes	Yes
UNAMED	No	No
Yakima	Yes	Yes
Angelina Burdett*	No	No
Dittisham Ploughman	Yes	Yes
Utility	Yes	No
Anita	Yes	Yes
Belgian Purple	Yes	Yes
Belle de Louvain	Yes	Yes
Avalon	Yes	Yes
Heron	Yes	Yes
Flotow	Yes	No
Mallard	Yes	No
Count Althann’s Gage	Yes	No
Shiro*	No	No
Violetta	Yes	Yes
Meritaire	Yes	Yes
Brandy Gage	Yes	No
Blue Tit	Yes	No
Blue Rock	Yes	Yes

Prince Englebert	Yes	No
Oullin's Gage	Yes	No
Imperial Gage	Yes	Yes
Stanwick	Yes	No
Czar	Yes	Yes
Opal	Yes	Yes
Edda	Yes	No
Mirabelle de Nancy*	No	No
Mirabelle de Nancy 1510	Yes	No
Mirabelle de Nancy 1725	Yes	No
Mirabelle de Metz 2778	Yes	No
Golden Sphere*	No	No
Gypsy*	No	No
Poltava*	No	No
Early Laxton	Yes	Yes
River's Early Prolific	Yes	Yes
Beauty*	No	No
Herman	Yes	Yes
Myrobalan*	No	No
Magna Jensen	Yes	No
Carlsen Skiod	Yes	Yes
Sanctus Hubertus	Yes	Yes
Stint	Yes	Yes
Bonne de Bry	Yes	Yes
Total trees	**110**	
Total with rust	**97**	
Total without rust	**13**	