Powdery mildew management – inoculum sources and control

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Introduction

Currently the focus of powdery mildew management programs is to prevent disease development on vines during the growing season so that the crop has very little or no disease at harvest and is acceptable for wine production. Generally these programs provide only partial control of over-wintering sources of disease (primary inoculum) each season. An important assumption is that primary inoculum is always likely to be present, especially in vineyards with a history of disease, and fungicide sprays will need to be always applied to prevent primary infection and spread of disease.

Good control of powdery mildew on the crop can be achieved successfully when sprays with the right fungicides are correctly applied at the right times (Hall and Wicks 2008). In particular, sprays of fungicides with high efficacy should be applied to protect vine foliage and the crop when the latter are most susceptible and the risk of infection is high. This occurs when pathogen activity is high and favourable weather conditions occur (i.e. from early season to pre-bunch closure). In most control programs, 5–8 sprays are applied each season.

Research over the last 2–3 decades has increased understanding of disease biology, the use of chemicals (e.g. fungicide efficacy, spray timing, spray application efficiency) and of vine cultural practices (e.g. canopy management) for the management of powdery mildew (Emmett 2005). As a result, there is substantial scope to increase the efficiency of disease management by controlling sources of powdery mildew in the vineyard as well as the development of disease on vines and the crop each season. But to do this, we need a smarter, longer term approach to powdery mildew management. This approach requires understanding of the sources of powdery mildew in vineyards each season, of influencing factors and the best ways to change current management practices.

Powdery mildew cycle in vineyards

The grapevine powdery mildew fungus or pathogen, *Erysiphe necator* (syn. *Uncinula necator*), over-winters either inside infected buds or as cleistothecia (microscopic fruiting bodies) harbouring on vine bark or leaf litter. In spring, infected buds produce diseased shoots (flag shoots). Wind-blown spores (conidiospores or conidia) produced on the flag shoots cause primary infections that produce powdery mildew colonies and initial symptoms of disease on adjacent young vine foliage. Powdery mildew colonies can also be produced on young vine foliage in spring from primary infections caused by spores (ascospores) released from over-wintered cleistothecia. The powdery mildew colonies produce further wind-blown spores (conidia) that cause secondary infections and spread the disease through the vineyard.

While the vine development cycle is annual [i.e. one growing season (spring, summer, autumn) plus dormancy (winter)], the cycle of the powdery mildew pathogen (i.e. an epidemiological season or 'epi-season') takes two growing seasons. The latter includes a period of primary inoculum development (first vine growing season) followed by a period of disease development from the over-wintered inoculum (second vine growing season).

Each epi-season overlaps with the next so that development of primary inoculum for the next season is occurring at the same time as the development of disease from primary inoculum produced in the previous season. Generally the powdery mildew epi-season can be divided into eight periods ('epi-periods', EP) in relation to pathogen activity as shown in Table 1 (P.A. Magarey and M. Moyer pers. com.).

Key factors influencing development and survival of over-wintering powdery mildew inoculum in vineyards

Infection of buds, survival of infected buds and flag shoot formation

Bud age

Grapevine bud susceptibility to internal infection is related to bud age. In studies of bud infection (Rumbolz and Gubler 2005, Emmett 2006), young green buds on shoots with up to six leaves were most susceptible, especially buds on shoots with 3–6 leaves. Buds on shoots with 1–6 leaves were aged 1–16 days when grown in the glasshouse at 25°C (Emmett 2006).

During bud infection, the powdery mildew fungus grew on the surface of young buds (Figure 1A) and appeared to enter the bud interior through a gap between the overlapping bud scales. Infection was established inside buds within three weeks of bud exposure to powdery mildew spores (inoculation) under favourable conditions.

Table 1. Powdery mildew 'epi-periods' and main primary pathogen or disease activities in relation to stages of the grapevine growth cycle.

Epi-period (EP) number	Grapevine growth cycle		Primary pathogen/ disease activity
	Number	Stage (E-L number*)	
1	1	Budburst (E-L 4) to flowering (E-L 23)	Bud infection
2	1	Flowering (E-L 23) to harvest (E-L 38)	Disease dispersion/expansion
3	1	Harvest (E-L 38) to leaf fall (E-L 47)	Cleistothecium formation
4	1	Dormancy (E-L 1)	Inoculum survival over winter
5	2	Budburst (E-L 4) to flowering (E-L 23)	Disease initiation (primary infection)
6	2	Flowering (E-L 23) to harvest (E-L 38)	Disease spread (secondary infection)
7	2	Harvest (E-L 38) to leaf fall (E-L 47)	Declining disease spread (decreased secondary infection)
8	2	Dormancy	Completion of disease cycle

* E-L number = Grapevine growth stage number according to the modified Eichhorn and Lorenz system (Coombe 1995).

As buds aged, physiological changes to the outer bud scales appeared to prevent entry of the fungus and infection of the tissues inside buds. Age-related resistance to infection of the interior of buds started to appear in older buds of shoots with nine leaves.

After exposure to severe powdery mildew epidemics in the glasshouse, some buds aged up to 24 days on shoots of very susceptible vine cultivars (e.g. Verdelho) were infected sufficiently to produce flag shoots (Figure 1B) in the following season (Emmett 2006). Nevertheless, only relatively low numbers of over-wintered buds produced flag shoots (up to 12%), regardless of extensive exposure of the young buds to infection in the previous season.

Vine cultivar

Grapevine cultivars appear to differ in susceptibility to bud infection and flag shoot formation (Emmett et al. 2007). In separate glasshouse experiments, numbers of flag shoots produced from over-wintered buds exposed to similar post inoculation epidemics in the previous season on vines of Verdelho, Chardonnay and Sultana were 120, 33 and 2 per 1000 buds, respectively.

Historically, random field observations by the authors during research projects have indicated similar trends in the incidence of flag shoots in unsprayed vineyards of these cultivars. In contrast, incidence of flag shoots in vineyards of some other cultivars (e.g. Shiraz) appeared to be very low, indicating that these cultivars may have low susceptibility to bud infection.

Vine cultivar susceptibility to flag shoot formation appears to be mostly related to differences in the susceptibility of young tissues of powdery mildew infection. Studies by Rumbolz and Gubler (2005) showed that flag shoot formation from the over-wintered buds was related to severity of infection of the surface of the buds in the previous season.

Vineyards of cultivars with a high potential for flag shoot production are more likely to become severely diseased in the absence of adequate control measures because of the higher likelihood of early season primary infection and, as a result, more severe powdery mildew epidemics. Vineyards of these cultivars will require a higher level of management to prevent bud infection and flag shoot development than those of cultivars with low susceptibility.

Vine management

Winter pruning practices, can affect the incidence of over-wintering buds and flag shoots. As shoots extend during the growing season, young buds at the ends of shoots are susceptible to infection until they develop age-related resistance. Retention of these buds on vines in the following spring, however, is dependent on winter pruning practice. While buds at the ends of shoots may have been infected, many of these will be removed when shoots are pruned to keep only a selected number of basal buds for growth in the next season.

Some vine canopy and irrigation management practices may also reduce the production of new buds and/or increase the exposure buds to adverse environmental conditions that reduces their risk of infection, e.g. minimally pruned vines on low or restricted watering regimes.

Environment

Environmental conditions can affect the development of disease on young vine foliage, bud infection, the survival of infected buds and the formation and survival of flag shoots.

Prevalence of environmental conditions that favour infection and the spread of powdery mildew on young vine foliage (temperature 20–30°C, relative humidity 40–85%) will increase the risk of bud infection and potentially, flag shoot formation in the following season. In glasshouse trials (Emmett 2006), diffuse light and temperatures of 22–28°C when relative humidity was 65–85% were most favourable for the growth of powdery mildew on the surface of leaves, stems and buds.

Low temperatures during winter may reduce the survival of infected buds or the survival of the powdery mildew fungus in infected buds. The occurrence of low ambient winter temperatures (lower than −13°C) may account for the absence of flag shoots in some seasons and in some viticultural regions. Some examples of the latter are the Rheinhessen region in Germany (Hill 1990, Kast 2006), New York USA (Pearson and Gadoury 1987) and Eastern Washington USA (Grove 2004).

Spring temperatures during and following budburst may also influence the formation and survival of flag shoots. High temperatures and low relative humidity appear to affect spore formation on flag shoots, flag shoot survival and subsequently, the contribution of spores from flag shoots to disease epidemics. In preliminary growth chamber experiments with the vine cultivar Carignane (Rumbolz and Gubler 2005), more flag shoots developed on canes with infected over-wintered buds exposed to a day-time temperature of 22°C than those with temperature of 30°C. Hence, high spring temperatures in some seasons and regions may reduce flag shoot formation.

Formation and survival of cleistothecia

Vine cultivar

Vine cultivar susceptibility can affect disease severity and cleistothecium formation. Cleistothecia develop on diseased vine foliage mostly in late summer and autumn (Figure 1C). The formation of cleistothecia follows the convergence of compatible mating strains of the powdery mildew fungus. The amount of fungal growth on foliage (i.e. disease severity) governs the likelihood of convergence and cleistothecium formation (Gadoury and Pearson 1988, Gadoury and Pearson 1991).

Therefore any factor that decreases disease severity will reduce the density and number of cleistothecia formed on vine foliage (Gadoury and Pearson 1988). This includes grapevine cultivar susceptibility. Magarey et al. (1997) recorded higher disease severity and incidence of cleistothecia on foliage of grapevine cultivars with high powdery mildew susceptibility (e.g. Chardonnay) than on less susceptible cultivars (e.g. Sultana). At budburst in the following season, densities of cleistothecia that over-wintered on vine bark were also higher on susceptible vine cultivars (e.g. Chardonnay, 5,000–20,000 per kg bark) compared to less susceptible cultivars (e.g. Sultana 100–2000 per kg bark).

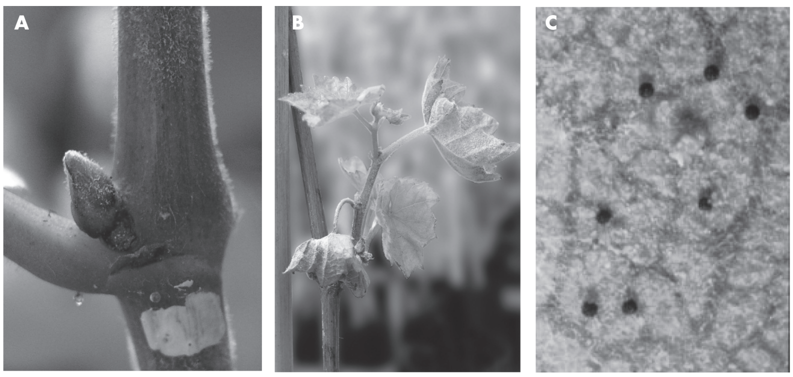

Figure 1. A. Growth of the powdery mildew fungus on a young bud. **B.** A flag shoot produced from an infected bud on a Verdelho vine. **C.** Powdery mildew cleistothecia on a diseased leaf in autumn. (Photos: R.W. Emmett and T. Hunt, DPI Vic.).

Vine management

Vine management can also influence disease severity and cleistothecium formation. Management practices (vine trellising, pruning, irrigation) can affect amounts of and periods of production of new foliage on vine canopies.

During studies of the effects of vine canopy management on powdery mildew development (Emmett et al. 2005), less disease developed on minimally pruned vines than on mechanically hedged and cane pruned vines in some field trials. The environment in the canopy of minimally pruned vines appeared to be less favourable for disease development. While minimally pruned vines had more shoots, these shoots were shorter and were in more open canopies than those on mechanically hedged and cane pruned vines.

Furthermore, from berry set onwards, shoot extension and the production of new foliage was lower on minimally pruned vines than on mechanically hedged and cane pruned vines, especially when vines were water stressed during summer. On minimally pruned vines, the rate and amount of powdery mildew development was often lower in late spring and summer, apparently because of the higher amount of older foliage with age-related resistance. The lower number of cleistothecia over-wintering on and beneath minimally pruned vines than on and beneath cane pruned vines in some trials was a likely consequence of the less extensive development of powdery mildew on the foliage of minimally pruned vines in the previous season (Emmett et al. 2005).

Environment

Rain during late winter appears to reduce cleistothecium survival. In mid to late autumn, mature cleistothecia fall or are washed off diseased foliage and are caught on vine bark where they survive through the winter. Some cleistothecia remain attached to leaves and persist in leaf litter on the vineyard floor where they also survive if conditions are favourable. Cleistothecia that fall onto soil do not appear to survive.

When mature and pre-conditioned cleistothecia on the bark of vines are thoroughly wet, they release ascospores. This occurs when rains or irrigations exceed 2.5 mm at temperatures exceeding 10°C (Gadoury and Pearson 1990). Favourable rains during late winter (exceeding 2.5 mm) when temperatures are at least 10°C may therefore promote ascospore release before budburst. This is likely to be the main reason why populations of mature cleistothecia on vine bark often decline during winter (Magarey et al. 1997, Moyer et al. 2008).

Long-term management of powdery mildew in vineyards

Rationale

A fundamental aim of the long term management of powdery mildew in vineyards is to break the powdery mildew cycle by preventing the development of inoculum (infected buds, cleistothecia) that will over-winter and be the source of disease in the following season. This particularly applies to vineyards with a history of disease.

Prevention of bud infection is therefore of primary importance. This will prevent flag shoot formation and primary infection from spores produced on flag shoots early in subsequent season(s). Prevention of primary infection will, in turn, prevent disease development during vine growth and the late season formation of cleistothecia.

Thorough application of management practices (e.g. intensive spraying) to prevent inoculum development through at least 2–3 consecutive growing seasons should ensure that there is little or no over-wintering inoculum in the vineyard. If this is achieved, little if any powdery mildew will develop. Subsequently, the intensity of spraying could then be reduced to a level required to keep the vineyard free of disease.

Risks

Practices to eliminate the sources of powdery mildew in vineyards may be compromised if:

(1) Fungicide spray application is inadequate and does not prevent infection and disease development, and/or

(2) Powdery mildew spores are blown into the vineyard from neighbouring diseased vineyards. The risk of the latter is high if an adjacent diseased vineyard is very close (0–100 m) but declines substantially with increasing distance (Gadoury et al. 1997). The risk is decreased further on vine cultivars with low disease susceptibility. The risk of disease spread from an adjacent diseased vineyard is also unlikely to occur before the critical pre-flowering period.

Spray strategies

Spray programs to prevent bud infection

Fungicide sprays should be applied at regular intervals to prevent infection of the surface and interior of susceptible young buds that will be retained on vines for growth in the following season.

Spraying with protectant fungicides should commence at 30–50% budburst when susceptible buds appear and continue until all of the buds that will be kept for the next season have aged sufficiently (24 days) to become resistant to infection.

Spray intervals are determined by shoot growth rate. In most seasons and regions, adequate protection of new vine growth is achieved when sprays are applied every 10–14 days.

The length of the 'window for bud infection' that will need to be covered by the spray program is related to the number of buds per shoot that will be retained after the vine is pruned in winter. A diagrammatic representation of bud susceptibility to infection in relation to vine growth stage, vine pruning system and levels of powdery mildew spores produced from cleistothecia and flag shoots for vineyards in the Sunraysia and Riverland districts is presented in Table 2.

For vines that will be pruned to spurs, each with 2–3 buds, sprays of protectant fungicides will need to be applied at 30–50% budburst and when shoots have 5 and 10 leaves. In the Sunraysia and Riverland districts, these sprays will need to be applied at 0, 2 and 4 weeks after budburst.

However, for vines that will be pruned to canes, each with 15–16 buds, sprays of protectant fungicides will need to be applied for a longer period, i.e. at 30–50% budburst, when shoots have 5, 10, 13-14 and 16 leaves (pre-flowering) and at berry set. In the Sunraysia and Riverland districts, these sprays will need to be applied at 0, 2, 4, 6, 8 and 10 weeks after budburst.

Use of sprays of fungicides or mixtures of synergistic fungicides with some systemic (translaminar) activity may increase the effectiveness and efficiency of spray programs to prevent bud infection. For example, the application of a systemic fungicide at 2 weeks after budburst with some ability to eradicate newly established infections within buds could reduce or avoid the need to apply a spray at or just after budburst.

In glasshouse trials, Emmett et al. (2007) observed differences in the efficacy of DMI (demethylation inhibiting) and morpholine fungicides on flag shoot formation after their application to young shoots of Verdelho vines at 2 or 4 weeks after inoculation with powdery mildew in the previous season. Penconazole (Topas®, Syngenta Crop Protection) applied at two weeks after inoculation and a tank mixture of spiroxamine (Prosper®, Bayer CropScience) with tebuconazole (Folicur®, Bayer CropScience) applied at four weeks after inoculation, reduced flag shoot formation by 50% and 62%, respectively.

In conventional spray programs for prevention of disease development on the crop, sulphur fungicides are widely used early in the season (e.g. when shoots have 5 and/or 10 leaves) while fungicides with translaminar activity (e.g. DMI, morpholine or strobilurin fungicides) are applied mostly in the period from when shoots have 10 or 15 leaves to when berries are 6–7mm diameter.

In intensive spray programs to prevent bud infection, DMI and/or morpholine fungicides could be used earlier in the season (e.g. from when shoots have 5 leaves) to ensure that infections are not established in buds when they are young and most susceptible. Strategies for managing resistance to selected fungicides (AWRI 2008) should be considered during planning of these spray programs.

Spray programs to prevent spread of disease and cleistothecium formation

Spray programs that prevent disease development on the surface of vine foliage and on bunches (disease severity) during the vine growing season will prevent cleistothecium formation towards the end of the season.

In vineyards with a history of disease, the thorough application of sprays of protectant fungicides commencing at budburst and continuing until pre-bunch closure, when berries are at least pea size (6–7mm), will be required in the first 2–3 seasons to prevent primary infection by spores from cleistothecia and/or flag shoots and subsequent spread of disease.

Sprays for the prevention of bud infection (as described above) and sprays that are normally applied to prevent disease development on the crop each season (i.e. sprays from when shoots have 5 leaves until pre-bunch closure) are necessary parts of this program.

In addition, the vineyard should be monitored after bunch closure. If disease appears because of poor spray application or spread from adjacent diseased vineyards, further sprays (at two week intervals) will be required to ensure that no cleistothecium development occurs before leaf fall.

The application of a high volume spray of sulphur and synertrol oil to vine trunks and cordons at advanced woolly bud when temperatures are at least 15°C for rust mite control (Bernard et al. 2003) may also reduce cleistothecium survival and the risk of powdery mildew primary infection early in the season. Drenching of vine bark during this spray may reduce populations of over-wintering cleistothecia by promoting conditions that favour release of their spores before budburst (Emmett 2003).

Spray programs to prevent re-appearance of disease

Powdery mildew will not develop in a vineyard without over-wintering inoculum, unless it is re-introduced into the vineyard on infected planting material or as spores blown or carried into the vineyard from neighbouring diseased vineyards during the growing season, as noted previously.

If there is a risk of re-introduction, the vineyard should be regularly monitored to detect early signs of disease. If the disease re-appears, a spray program should be applied again for disease control and to prevent inoculum production.

Alternatively, a minimal, relatively inexpensive spray program supplemented by monitoring could be applied to the vineyard each season to prevent re-appearance of disease. This program could include a sulphur spray when shoots have 5 leaves, monitoring when shoots have 10 and 13–14 leaves, a spray with a DMI fungicide at pre-flowering and at berry set, a sulphur spray when berries are pea size, followed by further monitoring if required as proposed by Emmett (2006).

Adjustment of spray programs on cultivars with low susceptibility

Grapevine cultivars that do not produce flag shoots should not require fungicide sprays to prevent bud infection. While little is known of the relationships between susceptibility to bud infection and/or flag shoot formation and cultivar susceptibility to disease in the field, cultivars with low to very low field disease susceptibility are unlikely to produce flag shoots. Spraying vines of these cultivars to prevent bud infection is unlikely to be worthwhile economically. Prevention of disease development and cleistothecium formation on vines of these cultivars is also likely to be achieved using spray programs that are less extensive than those required for more susceptible cultivars.

More research is required to increase knowledge of vine cultivar susceptibility to bud infection and flag shoot formation.

Key messages

The long-term efficiency of powdery mildew management in vineyards can be increased substantially by preventing the development of over-wintering sources of disease, i.e. infected buds and cleistothecia.

To break the epi-season (two growing season cycle) of powdery mildew, prevention of bud infection is most important because it

Table 2. Grapevine bud susceptibility to infection by powdery mildew in relation to vine growth stage, vine pruning system and levels of powdery mildew spores produced from cleistothecia and flag shoots for vineyards in the Sunraysia and Riverland districts (Emmett 2006).

Growth stage	0-5 leaves	6-10 leaves	11-15 leaves	PF-F	Bset 2-3mm	Berries 4-7mm	PBC-BC	Veraison
Weeks after BB	**0-2**	**3-4**	**5-7**	**8-9**	**10**	**11-13**	**14-15**	**16-17**
Primary inoculum								
Spores from cleistothecia								
Spores from flag shoots								
Bud susceptibility								
Spur pruned								
Cane pruned								
Minimally pruned								

PF-F = Pre-flowering to flowering; Bset = Berry set; PBC-BC = Pre-bunch closure to bunch closure; BB = Budburst.
Shading: Pre-flowering to flowering stage outlined by rectangle; Higher levels of primary inoculum (spores from cleistothecia or flag shoots) represented by darker grey shading; Higher bud susceptibility (bud susceptibility level x number of susceptible buds) represented by darker grey shading.

will prevent primary infection from spores produced on flag shoots early in subsequent season(s). This, in turn, will prevent disease development during vine growth and late season formation of cleistothecia.

Thorough application of well-timed early season sprays over 2–3 consecutive seasons can prevent bud infection and the formation of cleistothecia. When this is achieved, vineyard monitoring and low input spray programs with fewer sprays and less expenditure on chemicals and fuel will be needed to prevent re-appearance of the disease.

Cultivar potential for flag shoot production, vine pruning practice and selection of fungicides are important considerations when designing spray programs to efficiently control sources of primary inoculum in vineyards.

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