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Powdery mildew (PM) afflicts vineyards worldwide. Eastern North America has the dubious distinction of being home to this disease, and we cannot grow grapes here without controlling it. Although our climate is different from that in the western U.S., the fungus responds similarly to environmental factors and control treatments in both areas. While certain management details may vary among regions, all control programs employ the same basic principles. Within this context, I'd like to discuss:

- The fundamental biology of the disease;
- When the crop is most susceptible to infection;
- The basics of the fungicides that are used in control programs.

Biology

The PM fungus overwinters either within infected buds, which germinate to form mildewed "flag shoots" in the spring; or as minute fruiting bodies (cleistothecia) that lodge in the bark on the vine. They then release unique spores (ascospores) to infect new foliage and young clusters in the spring. The subsequent spores (conidia) produced on infected tissues are the same as those produced on flag shoots, so further spread throughout the season is the same regardless of the initial source of infection. Of course, any program that provides good disease control on the fruit and foliage during one growing season will limit the production of both cleistothecia and flag shoots that perpetuate PM the following spring.

Although cleistothecia do require at least a brief rain to release their ascospores, neither these spores nor the conidia require moisture in order to germinate and cause infection. Therefore, the primary factor that controls the spread of PM is temperature. Table I summarizes work conducted at the University of California, Davis, in the 1950s, showing the number of days from the time that a spore lands on a leaf until it forms a mildew colony producing new spores capable of disease spread.

Table I – Effect of temperature on spread of powdery mildew

Temp. (°F)[a]	Days
48	25
54	18
59	11
63	7
74–86	5–6
90	not active

[a]Constant temperatures

These data are extremely useful in formulating spray strategies, and are the "guts" of the current UC Davis risk index that has been used so effectively in California over the last few years. Note that whereas the fungus can multiply rapidly when temperatures are in the mid-60s to mid-80s, it is inactive while temperatures remain above 90†F. In fact, some spores and colonies are killed after relatively short exposures above 95†F, a fact that also is accounted for by the risk index.

Another environmental factor that influences development of PM is relative humidity (RH), although just how important a role it plays remains unclear. In multiple tests on Riesling seedlings, we've shown that disease severity increases progressively to a point of doubling as the RH increases from 39% (the lowest level that could be tested) up to an optimum near 85% to 90%. (Rain or condensation on the leaves and fruit are detrimental to disease development).

A model that guides control programs in German vineyards incorporates humidity as one of its determining factors, and recent work at UC Davis has provided further evidence that humidity affects the development of this disease. Although not as influential as temperature, higher humidities do increase the risk of PM. Thus, coastal regions appear to face a "double whammy," with both temperature and humidity remaining highly favorable for PM throughout much of the season.

Crop susceptibility

Powdery mildew is a disease of young, juvenile tissues. Leaves are highly susceptible to infection while they are expanding, but become resistant soon after they're fully expanded. Similarly, recent research by colleagues at Cornell has shown that berries are highly susceptible from bloom until shortly after fruit set, but become much more resistant afterwards.

Although fruit on very susceptible varieties, such as Chardonnay, may not become highly resistant until more than five weeks after bloom (much earlier than previous literature has indicated), severe berry infections appear to develop only when they are initiated during the first few weeks after flowers open. Emphasizing this point, repeated fungicide trials have demonstrated that sprays applied from the start of bloom until two or three weeks later are responsible for the lion's share of PM control on the berries. Conversely, significant berry infection at harvest can almost always be traced back to a problem with the control program during this early post-bloom period.

Now for the fine print:

1. In climates such as that of the northeastern U.S., most flowers tend to open within a few days of each other. "Bloom" is relatively easy to define, as are the specific times when berries are highly susceptible to infection and when they start to acquire significant resistance. However, in climates such as that of

California, particularly in certain locations and/or years, flowers may open over a much longer period of time, resulting in some berries acquiring age-related resistance at a time when others are still young and highly susceptible. This can extend the “danger period” in any given vineyard.

2. In the northeastern U.S. climate, infections that occur about four weeks post-bloom (near bunch closure, when berries are in their final stage of susceptibility) produce few visible symptoms. However, such infections are visible with magnification, and appear to provide an entry point for bunch rot and other spoilage microorganisms.

The message is simple: Unless temperatures are consistently high enough to shut down the disease, the critical time to control PM on the fruit is from the start of bloom until a few weeks later. The key is to maintain good protection through bunch closure. Although this is certainly not the only time to spray for PM, it is when you should use your best PM fungicides and do the best possible job of applying them. There will be times when you need to take shortcuts in various operations during the season, but don’t short-cut your disease control program during this critical period.

Fungicides

Sulfur is a traditional material with two major positives: it’s cheap and effective. Furthermore, it’s been used to control PM around the world for nearly 150 years, with no development of resistance. However, because sulfur acts largely through the vapor phase, its activity is temperature-sensitive. Conventional wisdom says that sulfur is relatively inactive at cool temps below 65†F, and can be phytotoxic at temperatures above 85† to 90†F. Although sulfur products have been used effectively under such “suboptimal” conditions, these potential limitations should be recognized.

DMI fungicides do not inhibit spore germination, but attack the fungus during its early growth stage within the plant. Thus, they provide only limited residual or protective activity, but do provide significant post-infection activity. This probably explains why they were once so effective under extended spray intervals; that is, when new (unprotected) leaves developed after one spray and became infected, control was provided by the post-infection activity of the next spray. However, their activity is declining in many parts of the world, due to increasing levels of resistance developed by the PM fungus.

For this reason, very few New York growers still rely on the DMIs for PM control during the critical bloom through fruit-set period. Nevertheless, DMI fungicides have remained useful components in many control programs, and it is beneficial to consider how resistance to these materials develops and what you can do to minimize resistance in order to maintain their utility.

Resistance to some fungicides (such as Benlate, Topsin-M, Vangard) follows an “all or nothing” model. That is, nearly all individuals in the fungal population are highly susceptible to the materials when they are first introduced, but a few are virtually immune to any amount of it. These individuals build up very quickly once enough sprays are applied to kill off the susceptible population, and because the resistant population is completely unaffected by the fungicide, control failures can occur suddenly if the weather turns in the disease’s favor.

In contrast, resistance to DMI fungicides follows a “shades of gray” model. In this case, no individuals are immune, but response to the fungicides is very dose-dependent: an individual that is completely inhibited at one dose may be only partially inhibited at a lower dose. Furthermore, individuals within the pathogen populations vary widely in their susceptibilities to the materials, showing a typical bell-shaped curve with respect to the distribution of their sensitivities. That is, most individuals will require an “average” dose for control. Decreasing proportions will require progressively lower or higher doses to achieve the same level of control.

It is important to recognize that fungicide rates are set by experimentation (usually on populations with little previous exposure to related materials), and that economic and regulatory pressures encourage labeling of the lowest rates that will provide full control of about 98% or 99% of the “baseline” population.

However, once such a fungicide (or group) has been introduced and applied repeatedly, the most sensitive members of the population get eliminated, leaving only those that require a “full” rate, along with the original few that were only partially controlled by that rate. If the dose is then reduced — either intentionally or through poor spray coverage — many such individuals become capable of growing to variable extents. Although they may be at least partially controlled by each spray, they gradually build up to damaging levels. Eventually, the fungicide “just doesn’t work as well as it used to.”

For powdery mildew, this “creeping” loss of control typically happens more quickly in regions where many generations or disease cycles occur every year (moderate summers) versus those with shorter periods of fungal activity (long, hot summers).

Based on the above, there are a few simple rules to minimize development of resistance to DMI fungicides and thus maintain their usefulness into the future:

1. Always use full labeled rates with excellent spray coverage. Remember, the fungus doesn’t react to the rate in the tank, only to the rate on the vine.
2. Limit the seasonal use of these materials (we recommend a maximum of three applications per season).
3. Use these fungicides early in the season or to maintain a clean vineyard later, but do not use them to clean up a PM epidemic that’s gotten out of hand. (The larger the PM population, the better the chance for selecting resistant individuals when you spray the fungicide.)

The three principles were tested in New York during the 1996 and 1997 seasons, in a commercial vineyard of the hybrid cultivar Seyval (Chardonnay parentage). A buildup of the DMI-resistant segment of the PM population had resulted in Bayleton giving poor control by the early 1990s and the performance of Rally (sold as “Nova” in the eastern U.S.) was just starting to slip.

Various fungicide programs were imposed, using six spray applications at 14-day intervals beginning two weeks pre-bloom and continuing through veraison. By varying both the application rate of Rally and the rotational pattern with sulfur, we examined a number of combination strategies:

- Rally at our recommended rate of 4oz/acre versus 50% of that rate;
- Three sprays each of Rally and sulfur compared to six of Rally only;
- Rally in the first three sprays, before disease was apparent, compared to the last three sprays, after significant PM was visible.

Disease was rated before harvest, and 40 individual mildew colonies from each treatment were tested in the lab to determine their resistance status. In this way, we could calculate not only the total disease control, but also the control of the resistant portion of the population in each treatment.

The results in Table II demonstrate that the three theoretical anti-resistance principles actually work under real world conditions. In this particular case, limiting Rally to three applications per season in rotation with sulfur, using the material before the disease was well established, and maintaining our recommended rate of 4oz/acre provided the best total disease control and the least selection of resistant mildew individuals.

Table II: Effect of rate, timing, and number of myclobutanil sprays on control of powdery mildew and the selection of resistant fungal isolates (cv. Seyval, Finger Lakes, NY)

Treatment, rate/Acre	Timing[1]	% Control, 1996		% Control, 1997	
		Total[2]	Resistant[3]	Total[2]	Resistant[3]
Check	—	0	*0*	0	*0*
Rally, 4 oz	1 – 6	76	*51*	84	*59*
Rally, 2 oz	1 – 6	40	*18*	49	*29*
Rally, 4 oz Microthiol, 4 lb	1 – 3 4 – 6	81	*88*	80	*81*
Microthiol, 4 lb Rally, 4 oz	1 – 3 4 – 6	44	*n.d.*	52	*40*
Rally, 2 oz Microthiol, 4 lb	1 – 3 4 – 6	12	*0*	61	*64*

[1] Spray timing: 1 = 2 wk pre-bloom; 2 = 5% cap fall; 3 = 1st post-bloom (+14 days); 4 – 6 = 2nd, 3rd, 4th post-bloom (14-day intervals).

[2] % Control, total = % control on cluster surface relative to that on the unsprayed checks (checks had 45% and 68% surface area infected in 1996 and 1997, respectively).

[3] % Control, resistant = % control on cluster surface of DMI-resistant fungal individuals relative to that on unsprayed checks.

The strobilurin fungicides (Abound, Flint, and Sovran, plus additional materials still under development) appear to be the most important new group of fungicides since introduction of the DMIs. Because the "strobies" are likely to become increasingly important in grape disease management, it's worthwhile to understand how they work. These are excellent protectant fungicides, providing their best activity when present on the foliage or fruit before a spore lands and tries to infect. They also provide some post-infection control against PM, although it is less reliable and possibly more dangerous in terms of future resistance development.

Additionally, the strobies show significant "anti-sporulant" activity. That is, when applied after infection has occurred but before symptoms develop, they may allow lesions to form but inhibit the production of new spores from those lesions. This is a particularly significant attribute, since it limits the infectious agents responsible for continued disease spread.

Resistance warning

The risk of fungal pathogens developing resistance to the strobies appears to be high. To date, strobilurin resistance has followed the Benlate (all or nothing) model, i.e, most resistant isolates are virtually immune to the fungicides and multiply with impunity if they are not controlled by some other material, such as by tank-mixing with sulfur. Therefore, it will be critical to manage these materials carefully in order to

maintain their effectiveness over time.
Minimize the number of annual applications (cost should encourage that!), use in strict rotation with other fungicide groups, and don't spray a strobie as an emergency "rescue" treatment if PM gets out of control.

Alternative fungicides

The PM fungus is different from all other fungal pathogens of grapes in that it grows primarily on the surface of infected tissues. Thus, it is vulnerable to topical applications of various materials that do not control other diseases, whose causal organisms are embedded within the tissues and not exposed to such treatments.

"Alternative" products that are labeled for PM control on grapes include various oils, potassium salts (monopotassium phosphate, potassium bicarbonate), and dilute solutions of hydrogen peroxide. In extensive tests with one such material — monopotassium phosphate — we've found that it provides virtually no protective or residual activity, i.e., no control when sprayed on plants that were inoculated with the PM fungus one to 10 days later. In contrast, we've found significant eradicative and anti-sporulant activity when it was thoroughly applied one to seven days after inoculating with the fungus.

Similarly, we've gotten much better activity in field trials when plants were sprayed every seven days (numerous post-infection "hits") compared to every 14 days with twice the rate (same amount of fungicide per season, but only half as many "hits").

I suspect that this scenario (a quick knockdown with little or no protection against subsequent infections) is applicable to some of the other "alternatives" (such as bicarbonates, oils, and hydrogen peroxide), and that they'll need to be applied on a more frequent basis than traditional fungicides. Of course, such activity as there is assumes complete coverage of the leaves and fruit, which often is problematical.

Take-home messages

- The period of PM activity is determined by temperature. Extended periods greater than 90†F will arrest its development, whereas growth is "explosive" at temps in the mid-60s to mid-80s.
- Although less important than temperature, high humidity promotes disease development and low humidity reduces it.
- Grape berries are highly susceptible to PM from flowering until shortly after fruit set, and serious disease losses are a result of control failures during this time. This is when attention should be most sharply focused on control (best materials and application techniques) if temperatures are at all favorable to the disease.
- Although DMI fungicides remain effective in many vineyards, their efficacy has been compromised by resistance in many locations. Limited-use, conscientious choices of rates, and thorough application techniques should be implemented in order to maintain their usefulness.
- New strobilurin fungicides are extremely effective against PM, but their use should be limited for resistance management purposes. Two applications during the flowering and/or early post-flowering period have provided superior control of fruit infections while also providing supplementary control of Botrytis.

- PM is uniquely susceptible to topical applications of numerous alternative products (oils, potassium salts, hydrogen peroxide). However, these appear to act primarily as temporary eradicants, with little or no protective activity against new infections.