A multifaceted approach to grape Botrytis disease management

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Introduction
Monoculture often creates inherent disease problems. Many of these diseases can be difficult to control, especially when the organism establishes in host material and/or in alternate hosts. Initially, satisfactory control can be obtained through the use of chemicals. Over time, however, this becomes difficult because of pathogen resistance, environmental concerns such as spray drift and chemicals reaching non-target areas (soil and water supplies), as well as economic concerns.

Botrytis is one of the most important diseases of wine-grapes in New Zealand, and its control has traditionally relied on fungicides applied at specific phenological stages regardless of the risk of infection. Hence, when the risk of infection is low, fungicides have been used unnecessarily. A multifaceted approach to disease management may be a more appropriate strategy to manage grapevine diseases. This requires the adoption of one or more strategies to suit the specific conditions of host, plant and environment. This approach needs to use a combination of control and management options, such as the use of chemicals on a ‘need to’ basis in alternation with biological control systems, soft fungicides, host (vine) modifications, improved soil health to encourage the defence system of the plants, and management options which discourage the pathogen.

An understanding of the pathogen and its interaction with the host and environment is crucial for suitable strategies to be developed. This will identify the infection risks, so that suitable control systems can be targeted when needed, to reduce infection and subsequent disease epidemics. An understanding of Botrytis disease epidemics is also important to enable effective and cost efficient strategies. This includes identification of the various infection pathways and their importance to the development of the epidemic.

An integrated disease management system (IDMS) is an integral part of a multi-faceted approach to disease management, which aims to manage diseases by targeting fungicides on a ‘need to’ basis, i.e. targeting fungicides only when disease is present, and the vine is at a susceptible stage of growth for infection. This has both economic benefits (as fungicide and application costs would be reduced), and also environmental benefits (such as reduced fungicide usage and added value to grapes and wine).

This paper outlines the development of Botrytis disease epidemics, gives an understanding of how Botrytis infects the vine through several infection pathways, and outlines the importance of these various pathways. Management strategies to minimise/control Botrytis are discussed, with particular emphasis on the development of an IDMS which uses computer software to assist disease control.

Understanding the development of Botrytis disease epidemics
Once infection occurs, Botrytis disease epidemics develop according to the amount of inoculum, and the weather. Both these driving forces lead to an inoculum-driven or weather-driven epidemic. Hence, any disease control or management system needs to initially identify the driving force of the epidemic, i.e. is it inoculum- or weather-driven? (Figure 1).

Inoculum-driven disease epidemics
In regions where weather is always conducive for disease (i.e. frequent wet periods in conjunction with high humidity), the amount of primary and secondary inoculum becomes the driving force for the epidemic. Simulation of an inoculum driven disease epidemic (Figure 2) shows two disease epidemics commencing with 5 and 30 propagules of primary inoculum. Both will have the same rate of increase but different amounts of disease at any given time (assuming other variables remain the same for the two epidemics).
In this situation where the epidemic is inoculum driven, it is important to minimise the amount of primary inoculum present at the beginning of the season. This can also include inoculum on alternate hosts such as weeds and senescing plant parts. A ny control or management strategy should be directed at minimising carry-over of inoculum from one season to the next. It is equally important to minimise the secondary inoculum from alternate hosts and other vineyards.

A suitable control/management strategy for an inoculum driven epidemic would be to provide constant protection against Botrytis. The control measures will depend on individual options, i.e. chemical, integrated, organic, or sustainable. Even when primary inoculum is minimised, protection needs to be provided against infection from secondary inoculum.

Weather-driven disease epidemics
In regions where weather is not conducive to disease most of the time, weather becomes the driving force of the epidemic, and the level of primary and secondary inoculum becomes less important (assuming all the other variables remain the same). In this situation the rate of the disease epidemic development is strongly influenced by weather variables.

In a simulated study, (Figure 3), a season commencing with 20 propagules of primary inoculum can have 50–100% disease at the end of the season, depending on when and how frequently conducive weather conditions occur (as well as vine susceptibility to disease at various growth stages). Even when there are 40 propagules of primary inoculum, the final amount of disease can be less compared to 20 initial propagules of primary inoculum depending on conducive weather during the season.

In the case of weather driven epidemics, there is the opportunity to develop cost effective control systems using any chemical, integrated, organic or sustainable means.

The timing of applications depends on when infections occur, and/or on the most conducive stages of vine susceptibility to infection.

An important factor to consider when developing disease management strategies is the various infection pathways and their importance in the epidemic.

An understanding of how Botrytis infects the vine through various infection pathways
Botrytis has many pathways of infection. The inoculum for these pathways comes from two sources—primary and secondary. Primary inoculum—carried over from the previous season—is mainly found in infected canes, buds, petioles, rachii, and alternate hosts.

Secondary inoculum is inoculum produced as a result of primary infection in grape vines and alternate hosts.

Initial infection of the grapevine can occur through primary and secondary inoculum sources. Primary infection can take place at any time during the season depending on the susceptible nature of the vine and the presence of conducive environmental conditions. Figure 4 shows the various stages of the grapevine which are conducive to infection.

Leaf infection
Under normal circumstances leaves do not get infected unless they are damaged through various means such as frost, trimming, wire lifting, hail, insect damage, etc. Leaves have their own active defence mechanisms which prevent infection. The potential risk from infected green leaf tissue on the disease epidemic is very low. However, when a leaf is senescing the defence mechanisms weaken and the leaf material becomes conducive to infection. These infections can provide a continual source of inoculum for infection of flowers and aborted and maturing berries. It is therefore important that leaf litter be removed from canopies. The best way to minimise leaf litter in canopies is to have an open canopy to allow litter to fall—this can be achieved by appropriate canopy management.

Flower infection
Grape flowers are very susceptible to infection both through the stigma and the thallus (base of the ovary) regions of the flower. Senescing flower parts are also ideal infection sites for Botrytis. Once flower parts become infected, the infection can proceed to the developing ovary and remain quiescent, manifesting itself once véraison commences. Various pheno- nolic compounds present in the developing berry at high concentrations help to contain this latent (quiescent) infection until the berry starts ripening (when phenolics and Resveratrol start declining and sugar levels start increasing).

The inoculum for flower infections can come from various sources, including primary inoculum from cane and bud infections, infected petals and rachii (Figure 5). Botrytis spores from alternate hosts can also contribute to flower infection.

The progress of the latent infection is very dependent on weather conditions once véraison is reached. Overcast conditions associated with high temperature and high humidities encourages sporulation, whereas warm sunny days can delay sporulations and the progress of infections within berries. Once berries start sporulating, they can provide inoculum for other berry infections.

The importance of flower infections in relation to final Botrytis levels depends on the amount of infection pressure during the flowering period. If more than one infection peri-

Figure 3. Disease epidemics influenced by weather
Figure 4. Disease epidemics influenced by weather
od occurs during flowering, it is important to provide adequate protection during this time. However, this will also depend on the amount of inoculum present during the flowering period.

A detailed study was undertaken in Marlborough in 1997/98 to determine the amount of infestation and infection of Botrytis from various sources such as flowers, berries, bunch trash, and leaf trash at both prebunch closure and véraison (Balasubramaniam et al. 1998). From this, the potential infection risk was determined.

Infestation and infection of Botrytis on flowers was low at most of the five sites assessed, suggesting that the flower infection pathway is not important in Marlborough when it is dry during the flowering period. Hence, in regions such as Marlborough where dry conditions during flowering often occur, (and the potential infection risk is low), it is possible to avoid the flowering sprays. In those sites where there were open canopies, the potential infection risk actually declined between prebunch closure and véraison, because of microclimate modification which was less favourable for pathogenic activity. Under conducive conditions for Botrytis development however, flower infections may be important where infestation is high, contributing to latent infections which may appear post véraison. Hence, it is important to provide adequate protection against Botrytis in this situation.

**Berry infection**

Under normal circumstances grape berries become susceptible to infection once the berries start softening (véraison). However, under extremely high infection pressures, young berries at less than 5°Brix can be infected.

**Berry infection pathway**

Inoculum for berry infection can come from various sources, e.g. sporulations on leaf litter (senesced), flower debris, aborted berries, infected berries, and other sources (Figure 6).

Most of the berry infections referred to in this section are those occurring in ripe berries from véraison onwards. Infected flower debris in close contact with the ripening berry can easily infect those berries. Also, remnants of flowers still attached to the pedicel of the berry can infect through the point of attachment. Such infections are easily recognisable through the infection progressing from the pedicel end. Botrytis spores can also infect through the lenticels and cracks in the berry skin. All these infections can proceed within the berry resulting in sporulations which contribute to secondary infections of the berries. However, the rate of progress of an infection within a berry depends on environmental conditions following infection. Sunny, warm and dry (high vapour pressure deficits) conditions slow the rate of progression of disease within infected berries. Warm, wet and humid conditions can reduce the incubation periods and increase the rate of disease.

The 1997/98 study (Balasubramaniam et al. 1998) of the importance of berry infestation and infection to the development of the epidemic showed that this infection pathway is only important when regions experience frequent wet, warm and humid conditions from véraison until harvest. In regions where these conditions are infrequent, suitable control measures are needed only when necessary.

**Flower and leaf debris infection pathway**

Flower debris, aborted berries, and leaf litter are important sites for Botrytis infections, especially those trapped in the canopy (Figure 7). Some flowers (caps) do not fall off and hence remain trapped within the developing bunches. Under conducive conditions, these caps and aborted berries can be infected, and in turn infect developing berries. A finer bunch closure, sprays cannot easily penetrate the bunches to provide protection to developing bunches. Infections arising from this infection pathway are often detectable through bunches that rot from the inside out. When infection risks are high and frequent during the post bunch closure period, even young berries with low sugars (<5°Brix) and high phenolic levels can be infected.

The 1997/98 study (Balasubramaniam et al. 1998) showed that flower and leaf debris were potentially the most important source of secondary inoculum. One of the most important ways of reducing the potential infection risk from flower...
and leaf debris is to remove trash, which is not practical on a large scale. However, modifying the canopy micro-climate by leaf plucking and vine trimming is a practical option to minimise the infection risks.

A clear example of the benefit of canopy modification by leaf plucking Sauvignon Blanc vines three weeks after flowering is shown in Figures 8 and 9. Leaf plucking had a significant effect on reducing the incidence (Figure 8) and severity (Figure 9) of Botrytis. This was more significant than the removal of trash by hand. This suggests that canopy microclimate modification which helps to minimise conditions conducive to infection may play a more important role in some years compared to the presence of debris in the canopy.

In summary, if it is possible to identify the various pathways of infection that prevail in your vineyard and their importance within a season, it is then possible to target those pathways which have the most impact on the Botrytis epidemic.

Developing Botrytis management strategies using knowledge of the pathogen, host and environment

Once an understanding is gained of how Botrytis epidemics develop, what the various infection pathways of the pathogen are and their importance, as well as knowledge about the vine (e.g. stages of susceptibility to infection) and the environment, appropriate and cost-effective management and control strategies can be developed. Modification of any one of these components can assist with minimising disease infection risks. Some of the factors that can be influenced within each component are listed below:

Environmental conditions
1. Site selection. A Botrytis spreads more rapidly in wet conditions, selecting low rainfall areas or those areas where rain is not predominant during the véraison to preharvest period would reduce the infection risk.
2. Sites in regions where there is a high vapour pressure deficit will minimise relative humidity, and hence be less conducive to the spread of Botrytis compared to regions with high humidity.
3. Wind. Even in areas where it often rains, wind can help to dry the canopy quicker, thereby minimising the potential risk from infections which rely on sustained moist conditions.

Host considerations
1. Host resistance. The breeding of disease resistant varieties will provide another avenue for minimising disease within the vine. This is a viable option with the availability of many genetic tools and the ability to undertake genetic manipulation. However, in existing vineyards replanting with resistant varieties may take many years, and the adoption of such a practice may not be immediate.
2. Host modification. Many modifications to the host may be made to minimise the micro-climate effect within the canopy which is conducive to disease infections. Some of these are already being practised, such as an open trellis type (e.g. Scott Henry), leaf plucking, and vine trimming. Leaf plucking has mainly been done during the pre véraison period, but for maximum benefit for disease control, there is a need to leaf pluck even earlier. Californian studies by Doug Gubler (pers. com.) indicate that it is possible to leaf pluck one to two weeks after fruit set, thereby exposing the developing bunches to maximum sunlight. This practice enables the epidermal cells of the developing berry to thicken and suberise, thus making it difficult for fungal mycelium to penetrate the cell walls. However, exposure of white varieties may increase the phenolic compounds in the berries which are not desirable in white wine. Therefore a balance needs to be drawn in relation to the benefits of early leaf plucking and the amount of phenolic compounds in white wine grapes. Early leaf plucking, however, is very desirable in red wine grapes.
3. Cluster architecture. Most grape varieties have a tight bunch cluster which creates a bunch microclimate, and it is often difficult for sprays to penetrate and provide protection to those berries which are within the bunch and in tight contact with one another. Opening up the cluster through breeding practices will assist better penetration of chemicals or control practices, and also enable modification of the bunch microclimate.
4. Host defence mechanisms. In addition to some of the defence mechanisms discussed above, it is possible to induce resistance in vines to diseases. Studies with other crops suggest that by using certain natural compounds, plant extracts, and other chemicals it is possible to activate the defence mechanisms in plants.
5. Nutritional management of the host can also minimise infection risks. Overseas studies have shown that high nitrogen levels can increase bunch stem necrosis (Keller and Koblet 1995; Christensen and Boggero 1985), which increases the susceptibility of vines to Botrytis infection through damaged tissues.
6. Improving the health of the vine through improved soil health will activate the vine's own defence mechanism, providing added protection from disease. This is a new and exciting area of research which is currently being undertaken in Marlborough.
Pathogen considerations
Many traditional control measures have been targeted solely at the pathogen. Unfortunately, disease-causing organisms have the ability to mutate and adjust to the environment for their survival. Thus, it is important to adopt more than one control measure to try and overcome this pathogen resistance, and minimise Botrytis levels within the grapevines. There are many control measures available (Table 1).

These control measures are mainly applied during the season, while out-of-season control is rarely practised. If the objective is to minimise the carry-over of inoculum and reduce the amount of primary inoculum available for starting a disease epidemic, it is important that out-of-season control measures be adopted. Some of the measures include removal and destruction of diseased tissue by either burning or composting. It is also possible to mulch a lot of the diseased tissue, and use biocontrol agents to reduce inoculum levels. However it is often difficult to control the endophytic disease problems within canes which have been laid down for the following season. Initial studies with chemicals applied during the pre-bud burst period are effective in inactivating Botrytis sclerotes, but the cost-effectiveness of this measure needs to be determined. An alternative is to use suitable biocontrol agents during the pre-bud burst period to inactivate these sclerotes on canes. It is also possible to identify the potential risks involved with disease epidemics during the early stages of vine growth. An assessment of background Botrytis populations when the new shoots are between 12 cm and 15 cm long would provide early information on the potential risks. It may be necessary to plan a suitable control strategy based on this to minimise the risk.

It is possible to mix and match the various control methods to develop a strategy suitable for individual vineyards. If disease pressures are low, there is always the option of minimising sprays by targeting spray applications. Targeting sprays involves identifying those phenological growth stages that are conducive to infection, determining if there is a high infection risk during that period, and selecting the most appropriate means of control for that particular stage. For example, if a high risk potential is identified through the monitoring of background pathogen population in the 15 cm shoot growth stage, then the application of a suitable biological control agent either at that time or prior to flowering would assist in minimising potential infections. However if the risks are low in the early stages, then an infection risk based program could be adopted during flowering. The use of forecasting or infection modelling could then be used to identify infections during the flowering period and a spray of either chemical, biological, natural products or soft fungicides applied (Table 1).

The use of an integrated disease management system to assist disease control
An integrated disease management system involves mixing and matching more than one control measure to achieve in-season and out-of-season control. By targeting control measures on a need-to basis, diseases can be successfully controlled.

A three-year study in Marlborough, New Zealand (Balasubramaniam et al. 1996, 1997 and 1998) has clearly shown that it is possible to minimise the amount of fungicides used for Botrytis control by targeting fungicide applications on a need-to basis in response to infection modelling. Further reductions in disease have been brought about by combining leaf plucking with fungicide targeting. Improved air flow through the canopy also allows faster drying of moisture, and hence reduces Botrytis spread. In this instance the leaves were plucked on either side of the bunches when the berries were pea size to

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<td><strong>Cultural control</strong></td>
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<td>Destroying diseased tissue</td>
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<td>Mulching</td>
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<td>Composting</td>
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<td>Removal of senescent tissue</td>
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<td>Air blasting canopy</td>
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<td>Leaf plucking</td>
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<td><strong>Soft fungicides</strong></td>
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<td>Bicarbonate of soda</td>
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<td>Neem oil</td>
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<td>JMS Stylet oil</td>
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<td>Hydrogen peroxide</td>
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enable them to acclimatise through cytological changes. This assisted in further reduction in disease levels at harvest.

A doping an integrated disease management approach also enables the substitution of natural products, soft fungicides and biological control systems in place of chemicals. However, it is important to identify what type of substitution can be made based on the risk potential.

The key to disease control is management. Management does not necessarily mean bringing about 100% control, rather, it means maintaining diseases at, or below, set economic threshold levels. Endeavouring to bring about 100% control can contribute to long-term problems through mutations within pathogen populations which constantly strive to adjust to the changing environment. Strategies to suit individual vineyard needs and philosophies can be developed.

Using a computer software program in an integrated disease management system to identify suitable spraying times for managing diseases

The development of a computer software program is an integral part of the integrated disease management system. This software is at present being used successfully by Marlborough grapegrowers.

The decision support software program has four modules, viz. weather, infection, spray coverage, and disease progress. The four modules are displayed on the computer screen as five windows (Figure 10). The first window from the bottom displays the temperature as hourly averages and rainfall as hourly totals. The weather data can be obtained from different logging sites, which makes it possible to analyse weather data from various sites.

The second window is the wetness sensor window. It is possible to access and display wetness data from sensors placed in the field. There are various sensors that are used in the field for detecting surface wetness of plant organs. These include leaf wetness sensors, flower wetness sensors, and bunch wetness sensors which represent various stages of berry growth. Sensors can be selected depending on the growth stage of the vine, and displayed in this window. The leaf wetness sensor data is displayed when the sensor detects wetness 50% of the time within an hour. However, it is possible to change this criteria within the software to represent the actual wetness of the organ that is being sensed.

The third window of the display relates to the Botrytis infection model. Whenever the surface of the organ being sensed is wet, the model begins running. It uses the algorithms developed through research on infection criteria, i.e., the interaction between pathogen, temperature and wetness. The infection model is cumulative for each hour, and builds until an infection threshold is reached, when the display turns red to indicate that all the criteria for infection have been met. When an infection period has occurred, the end user can decide to spray if that infection coincides with a conducive growth stage.

When a spray is applied, the information can be entered into the spray entry module. The fourth window displays the information on spray application. For each type of spray, the duration for which the spray will remain active is displayed, with days on the horizontal axis, and the percentage cover on the crop on the vertical axis. If a fungicide has a ‘reach-back’ effect (i.e. a curative effect if applied immediately post-infection) this is displayed as red bars for the duration of the reach-back period. A spray degradation component has been built into this window, whereby the percentage cover declines over time due to sunlight and crop growth effects. This degradation model is based on anecdotal information, and research on spray degradation would be valuable in this particular component.

If it rains, there is a rapid decline in the effectiveness of spray

Figure 10. Various display windows of the decision support system software
coverages. In combination with information from the infection window, the spray coverage window, and the growth stage of the crop, it is possible to decide if another spray needs to be applied in response to two or more infection periods following in close proximity.

The fifth window displays disease progress information. Disease incidence monitored at weekly intervals is entered into the database, and this information is displayed in a line graph. It is possible to have two treatment factors represented in this graph to compare the effectiveness of a modified spray program with a standard (conventional) spray program. All five windows can be displayed on the computer screen at any one time, the decision support system enables one to monitor the effectiveness of spray programs in suppressing disease development in response to infection periods or disease thresholds. While the disease progress is based on actual information, further research is required to simulate disease progress using current weather, pathogen and host information. This will enable the prediction of disease status, and the effectiveness of disease management systems.

This IDMS has proved to be cost effective, efficient and environmentally suitable. The integrated disease management system and the infection models need to be tested and validated for other grape growing areas of the world before it can be recommended for use in those regions.

Conclusions
A multi-faceted approach to disease management will enable growers to make sound decisions which are based on host, pathogen and environmental considerations. This will result in a more effective use of chemicals in combination with alternative strategies, which will be more environmentally friendly and cost effective.

References


