A computer-based simulator for rational management of grapevine downy mildew (*Plasmopara viticola*)

P.A. Magarey[1], M.F. Wachtel[1], P.C. Weir[1], and R.C. Seem[2]

[1]South Australian Department of Agriculture, Research Centre, P.O. Box 411, Loxton, S.A. 5333, Australia.

[2]New York State Agricultural Experiment Station, Cornell University, Geneva, N.Y. 14456-0462 USA.

Summary

A computer-based simulator of the epidemiology of *P. viticola* is nearing completion. The simulator comprises a series of models each of which describe a phase in the life cycle of downy mildew. Detailed verification and validation is still required but tests of the accuracy of disease prognoses to date, have shown the simulator is encouragingly accurate. A completed simulator has potential as a decision-aid for Australian vineyard managers to rationalize existing fungicide spray programs. It is expected that fewer sprays will be required to achieve cheaper and better downy mildew control with less chemical hazard to the environment and reduced risk of pathogen tolerance to post-infection fungicides. A simulator for *P. viticola* would be a module in a series which could provide a practical management tool for most diseases and pests of Australian viticulture.

Introduction

A variety of economic, technological, and social pressures will continue to influence the way diseases of grapevines in Australia are managed (Magarey 1990). These include the cost of crop loss from disease, the increasing cost of chemical controls, changes in viticultural production technology and the consequent changes in risk of disease. Others include the advent of new diseases or of strains resistant to fungicides. In addition changes within the chemical industry with fewer products and increased demand for consumer and environmental safety are likely. Kable (1991) has reviewed these and other issues which will continue to contribute to the need for improved disease management practices in Australian viticulture.

These pressures influence vineyard managers in their approach to the control of the major foliage diseases of Australian viticulture viz. downy mildew (*Plasmopara viticola*) and powdery mildew (*Uncinula necator*).

Downy mildew and attempts to control it, cost Australian viticulture in excess of $13m. ($230 ha^{-1}) in dry seasons when most vineyard managers regularly apply at least three fungicide sprays (Magarey 1990). Often disease control measures are ineffective and un-necessary sprays are applied, some even in the absence of disease. In wet seasons, total loss exceeds $47m. ($835 ha^{-1}) because the application of controls costing near $14m. ($240 ha^{-1}), is not timed according to disease risk. The result is un-necessary yield loss, un-necessary cost and use of chemicals, and uncertainty about the effectiveness of controls.

A major reason for this is 'insurance spraying' i.e. the application of fungicides when the crop is considered 'at risk' but when that risk is not accurately known. Calendar-based or vine growth-based spray schedules often lead to fungicide application when the risk of disease is low and to poorly timed sprays when disease risk is high.

To illustrate this Figure 1 shows a typical example of a wet season spray program. Eight pre-infection protectant fungicide sprays were applied. Two were timed too early before the first infection period while others were either applied too soon before an infection period or applied after an infection period when the fungicide was ineffective. An efficient management strategy would have incorporated a post-infection fungicide immediately after the first two infection periods. This would have prevented development of the epidemic for the season and crop loss from downy mildew would not have occurred. Importantly it would have reduced the need for any additional sprays.

So far neither cultivar resistance nor biological control of *P. viticola* have been developed to control downy mildew in Australia. However in recent years increases in knowledge of disease epidemiology and the increased availability of computer technology, have facilitated the development of an alternative management procedure. That procedure will provide grapegrowers with day to day assessments of the risk of disease and offer disease management alternatives.

One aim of such alternative management procedures is to reduce the use of chemicals. This reduction will be increasingly important as environmental and consumer safety issues gather momentum but it can only be achieved for downy mildew by correctly timing fungicide sprays. Knowledge of the specific conditions needed for infection can be used to provide advice on when disease risk is high. This can lead to fungicides being timed to ensure excellent disease control with fewer spray applications and with reduced costs and environmental impact (Magarey 1985). The risk of pathogen tolerance to fungicides developing, as has occurred in Europe (Cohen and Coffey 1986), will also be reduced.

A management system to accomplish this is being developed, based on a computerized simulation of grapevine downy mildew epidemiology. Preliminary reports have been published (Magarey *et al.* 1983, 1988). *Plasmopara viticola* is a pathogen for which much epidemiological research has been undertaken. This is mainly because of the severity of losses from downy mildew since its introduction to Europe in the late 1870s (Viennot-Bourgin 1981). Because of the availability of this epidemiological information and because *P. viticola* is a major pathogen in Australian vineyards only when well defined weather

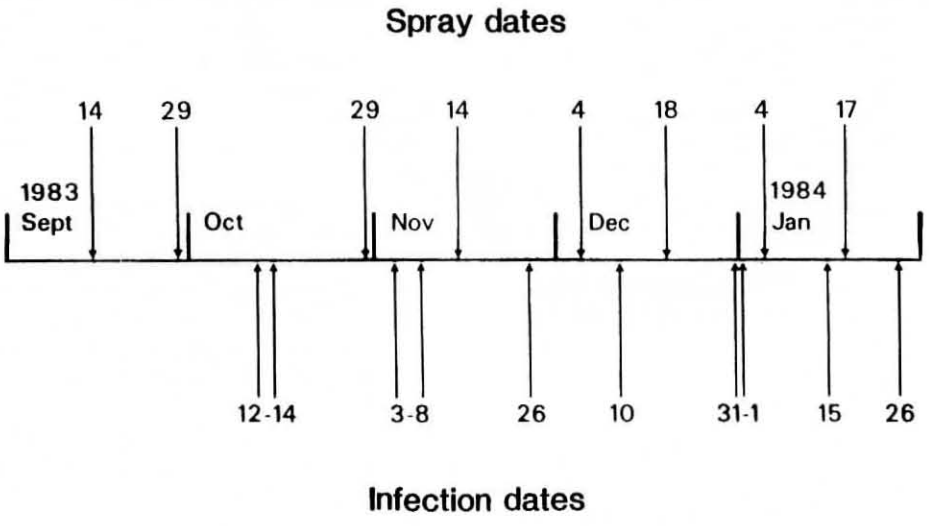

Figure 1. The relation of the date of downy mildew infection periods to the timing of fungicide spray applications in a typical schedule from the Riverland (near Loxton) South Australia. These events occurred in 1983/84 a high downy mildew risk season. Two appropriately timed post- infection fungicides (e.g. one each after 14th October and 8th November) could have effectively and efficiently prevented any subsequent disease and crop loss (see text).

events occur, it was the ideal candidate for initial developments with climate-data based modelling of grapevine disease epidemiology.

The Riverland of South Australia (near Loxton) was an ideal location to begin this task because the arid climate favoured only sporadic occurrence of downy mildew (McLean *et al.* 1984). That meant disease events usually would be discrete and easily discerned, an important aspect in evaluating a simulator.

Aim

The objective of this work was to improve the efficiency, effectiveness and safety of downy mildew disease control by the provision of reliable, computer-aided information with the potential to:

1. Improve disease control by better timing fungicide sprays when the risk of disease is high,
2. Reduce costs of disease control by reducing or eliminating fungicide sprays when the risk of disease is low or non-existent,
3. Reduce environmental pollution by minimizing the number of sprays needed for effective control,
4. Reduce uncertainty in disease management decisions by provision of reliable, timely disease management advice,
5. Reduce the risk of pathogen-tolerance developing to downy mildew fungicides by provision of sound anti-resistance management strategies.

Refinement of the understanding of downy mildew disease epidemiology was another expected benefit from construction of the simulator.

Methods and materials

Details of the epidemiology of *P. viticola* were compiled mainly from European literature. Useful data were obtained from Arens (1929), Muller and Sleumer (1934), Zachos (1959), Rafaila *et al.* (1968), Kable (1977), Blaeser and Weltzien (1977, 1978, 1979), Blaeser (1978), and Hill (1989) among others. These, together with Australian observations on the progress of *P. viticola* epidemics (Magarey and Wachtel-unpublished), provided a means by which the response of *P. viticola* to various environmental factors was described for each major phase in the pathogen life cycle (Figure 2).

Models of these relationships were devised and computerized initially in FORTRAN and now in TURBO C.

Results

Meteorological data collection

At present weather data from two different data logging systems can be easily processed by the simulator. They are the Campbell Scientific (Logan, Utah, USA) CR21® micrologger and the Northern Rivers Industrial Electronics (Lismore, NSW) Miser®. Both stations record, at 10 minute intervals, averaged dry and wet bulb temperatures (in a Stevenson screen), shaded canopy temperature, leaf wetness (with a wetness sensing grid) and the amount and intensity of rainfall (using a tipping-bucket rain gauge). Other types of logging systems can be used if the data format is modified to suit prior to accession by the simulator.

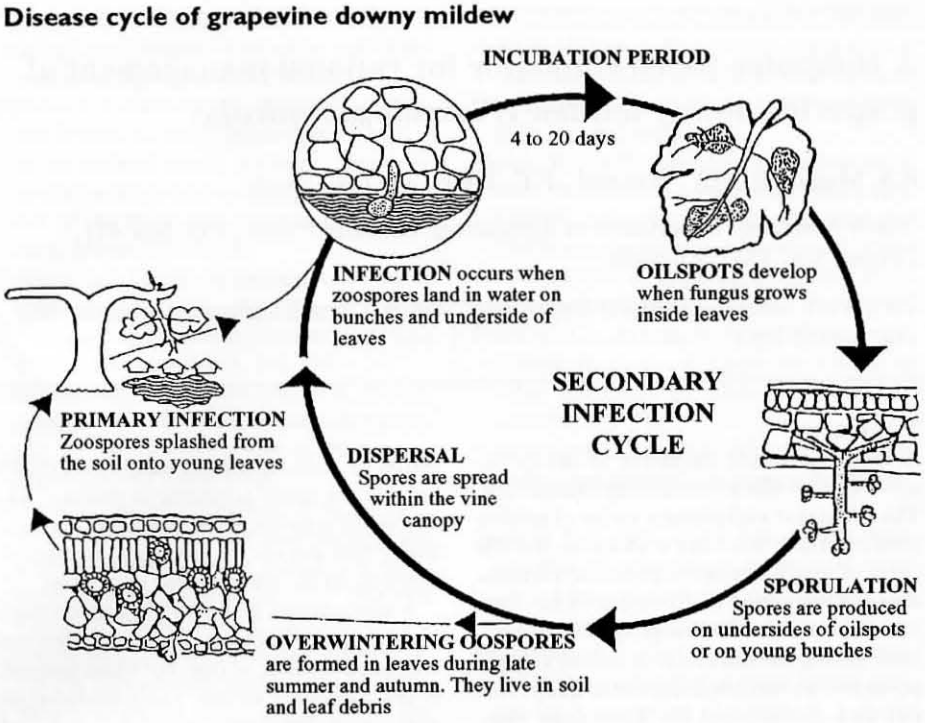

Figure 2. A schematic life cycle of grapevine downy mildew (*Plasmopara viticola*).

The models that form the simulator (Figure 3) process the meteorological data to produce a disease forecast for the vineyard from which the meteorological data were collected.

An outline of disease epidemiology and the derivation of the models which comprise the simulator follow.

The models

1. Primary Infection. Primary infection, the soil-to-canopy spread of inoculum, initiates the disease each season. In the vineyard, oospores, the source of overwintering inoculum, require sufficient duration of soil wetness and adequate temperature to germinate and release zoospores in the soil or into the atmosphere.

The zoospores must then be dispersed to wet foliage. Sufficient duration of foliage wetness is required with adequate temperature to enable the germination of encysted zoospores and growth of germ-tubes through stomates, to initiate infection. The model of primary infection assumes viable and mature oospores are present.

The broad criteria of a minimum of 10 mm rainfall within any 24 h period (to allow for sufficient soil wetness and pooling of water to splash inoculum to the foliage) while the minimum temperature remains at or above 10°C, are used to signal primary infection, which may occur at any time throughout the season. A more detailed set of criteria with a graded evaluation of data is to be included to ascribe risk of infection when conditions are marginal. The likelihood of primary infection is calculated from a soil and leaf wetness pre-conditioning factor, a crop growth susceptibility factor and a temperature/time factor. The model will evaluate conditions with temperatures as low as 8°C and rainfall as low as 6 mm. Some interaction to include vineyard irrigation is included. The broad criteria of the primary infection model were derived from European experiences (Kable 1977). The more detailed criteria were derived from observations of the occurrence of disease in Australian vineyards (Magarey and Wachtel - unpublished data).

2. Incubation Period. Once infection is initiated the mycelia of *P. viticola* proliferate within foliage tissue and eventually disrupt normal cell function. From 4 - 20 days after infection, depending on prevailing temperature, yellow oilspots develop at infection sites on leaves. These oilspots are the distinctive vineyard symptoms of downy mildew. The bunches may also be affected but usually only after the disease spreads.

The model of incubation period, which is temperature dependent, uses the polynomial

$$y = 42.0 - 3.6x + 0.1x^2 - 0.0005x^3$$

where y = incubation period (days) and x = temperature (°C), to describe the rate of growth of *P. viticola* within leaves and hence the date of appearance of oilspots. The variable, average temperature is operative between 8-35°C and is processed for each 10 minute interval after (primary or secondary) infection. The polynomial was derived from data from Muller and Sluemer (1934), Zachos (1959) and Rafaila *et al.* (1968), and incorporated modifications by Magarey and Wachtel (unpublished data).

Initial predictions of the date of oilspot appearance are based on historical median daily temperatures (34 years' data from Loxton) and are retrieved from a look-up table. They are then progressively updated using the 10

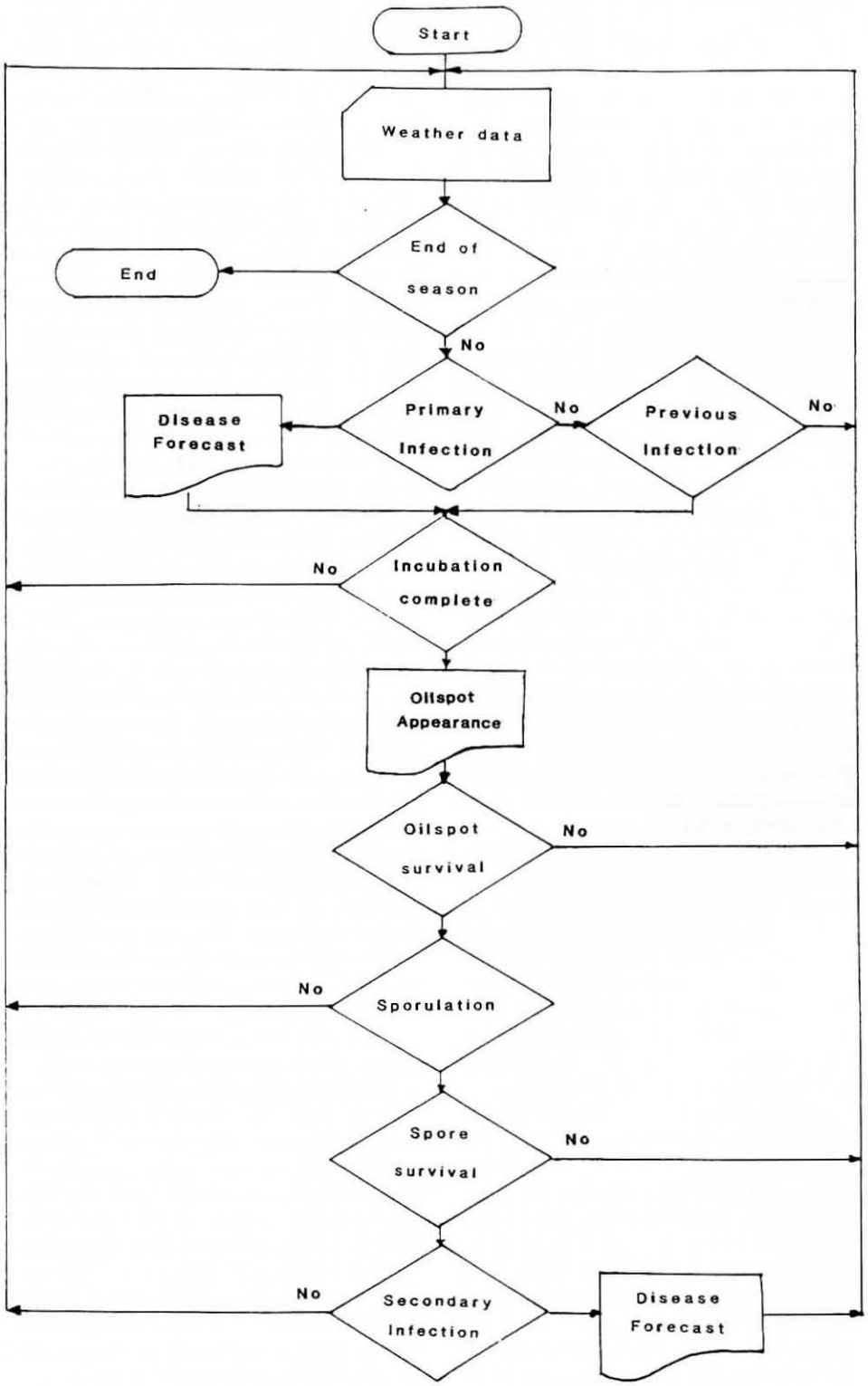

Figure 3. Flow chart of the simulator of epidemiology of grapevine downy mildew (*Plasmopara viticola*).

minute average temperatures from the current meteorological data.

3. Oilspot Survival. The ability of oilspots to sporulate varies with oilspot viability. To calculate oilspot viability and to determine when oilspots die, an equation from Hill of Germany (personal communication) was modified to reduce the viability of oilspots to zero after 50 days in ideal conditions. The viability factor is reduced at a rate inversely correlated with saturation vapour pressure deficit (SVPD) (Magarey and Wachtel, unpublished data).

4. Sporulation. Given adequate temperature, humidity (as measured by SVPD), and darkness, mycelia of *P. viticola* will sporulate through stomata on the underside of oilspots. The model of sporulation predicts the formation of sporangia if oilspots are present and average temperature is at least initially ≥13° C for a minimum of 4 dark hours while the SVPD of the canopy is ≤1.3 mb. Darkness is defined as the onset of civil twilight as calculated by a separate subroutine. Civil twilight is when stars are just visible and on a clear evening when the light intensity declines to 3.55 lux. This routine which can be utilized for any given latitude and longitude, was initially provided by J. Luck, Division of National Mapping, Department of National Development and Energy. It was converted for CSIRONET by V.A. Drake, CSIRO Division of Entomology, Canberra, ACT.

Once initiated sporulation may continue if the above conditions continue and temperature is ≥11°C. The intensity of sporulation, called sporulation factor (range 0-1), is determined by a function of temperature and time. The sporulation model was derived from the data of Blaeser (1978), Blaeser and Weltzien (1978), Hill (1989), Pearson and Seem (personal communication), and Magarey and Wachtel (unpublished).

The sporulation factor is stored in the simulator for use later to establish an estimate of infection severity.

5. Spore survival. Sporangia of *P. viticola* are dispersed by wind and rainsplash with dispersion peaks occurring during rapid changes in humidity e.g. at sunrise. Sporangia survival depends on the prevailing temperature and humidity.

The model that describes spore survival decreases the number of viable sporangia as calculated by the hyperbolic function

$$y = 22.5/x$$

where y = sporangial survival (days) and x = SVPD (mb). The equation was derived from the data of Blaeser (1978) and Blaeser and Weltzien (1978). The dispersal of sporangia is assumed automatic and complete by noon of the day of sporulation. Blaeser's limit of 6 h survival of sporangia at 29° C is assumed. The output of this routine is a survival factor (range 0-1) based on the proportion of sporangia surviving. This factor is updated if further sporulation events occur and is stored for use later to help establish an estimate of infection severity.

6. Secondary Infection. The spread of inoculum from primary infection sites to cause second generation infection in the canopy, i.e. the spread from leaf to leaf or leaf to bunch, is called secondary infection. Sporangia require suitable combinations of temperature and leaf wetness to germinate and release zoospores which infect foliage as described for primary infection.

The model of secondary infection determines if viable spores are present (from the spore survival routine) and calculates the severity of infection, using accumulated degree-hours while leaves are continuously wet. The severity of infection is scaled from 0- 1.0 for degree hours between 45 and 71 based on data from Blaeser and Weltzien (1977) and Blaeser (1978).

7. Disease Forecast. This model provides a forecast of disease severity by adding the infection severity rating to the spore survival factor and scaling the outcome to produce estimates that range from no disease through

trace, light, moderate, to severe.

Discussion

The simulator of *P. viticola* has been designed to provide disease forecasts based on vineyard weather data. Predictions of disease events to date using data from several seasons have been encouragingly accurate. For instance from 1980 when construction of the simulator began, the season with the most number of infection periods (nine) was 1983-84. In that season the single primary infection and all secondary infections observed in an unsprayed vineyard at Loxton were correctly indicated by the simulator. Of the nine predicted dates of oilspot appearance, oilspots appeared within one day of prediction on five occasions. On each other occasion oilspots were predicted prior to the date of their detection, likely due at least in part, to insufficient frequency of surveys for disease. This level of accuracy typifies that achieved in subsequent seasons to 1990/91. In 1990/91 the weekly processing of data from in-vineyard weather stations at five locations near Loxton, and at Nuriootpa (SA), in the Hunter Valley and at Pt. Macquarie (NSW) was begun. Although initial data management problems with the interstate sites and dry conditions impeded evaluation of the simulator, to mid-season downy mildew infection periods were not predicted. This was consistent with disease surveys which did not detect any oilsopts.

Continued detailed validation of the simulator in additional wet seasons and in other viticultural regions of Australia, is essential to ensure the disease status reports and disease forecasts are accurate. Teng (1981) provides some useful guidelines on what this validation requires. To achieve this, disease and weather data must be collected from the Riverland and other viticultural regions in Australia. This is a matter of high priority for Australia-wide application of the simulator and any other developed for powdery mildew, *Botrytis* or *Phomopsis* etc.

Further development of the simulator and especially associated data management software, including automatic error checking and data quality control routines, are also required. The model describing primary infection is the most naive portion of the simulator. The factors governing oospore release, zoospore dispersal and infection e.g. soil wetness, rainsplash and leaf wetness, are ill-defined and therefore primary infection is crudely modelled.

We are currently addressing the compounding effects of irrigation and rainfall, but the intensity of rainfall has not been taken into account. Although some infections associated with irrigation have not been predicted, generally the model has been designed to over-predict primary infection as a safeguard until better epidemiological data are available.

A model to predict first occurrence of disease each season has been developed by Stryzik (1983). This is being evaluated in detail in New York, USA (Seem, unpublished data) but more data are needed on the conditions that govern the primary infection processes.

The incubation model is a most important component of the simulator. This is because the predicted date of oilspot appearance is critical to decisions made by vineyard managers in determining the correct timing of fungicide sprays. The precision of predictions to date has been suitable for commercial use of the simulator. A table of median daily temperature for Loxton (SA) is used to predict incubation periods for the Riverland. A separate table for each viticultural region in Australia is needed and the collection of these data ought commence immediately to allow validation of the simulator in these other regions.

The sporulation and spore survival models have functioned well but the capacity of oilspots to sporulate, declines with time. More data on this rate of decline are required. The model of secondary infection ignores periods of intermittent leaf wetness and more information on the effect on the infection process of short dry periods is also required.

Whilst some of the aforementioned deficiencies need to be overcome by the collection of data and experimentation, the recent appointment of a programmer to incorporate additional modifications should lead to improved ease of use of the simulator particularly with regard to the input of weather data for processing. In addition improved accuracy of the predictions of disease occurrence and severity are expected.

A completed simulator would provide vineyard managers with a real-time statement of disease risk. It would also advise the predicted date of oilspot appearance and provide menu driven access to a fungicide list that could be used to advise of disease management alternatives. Pre-infection fungicides must be applied before the weather events trigger disease, and have a more limited place in this system than do post-infection (curative) fungicides.

The simulator is designed for use with post-infection fungicides which would be applied when and only when a high risk of disease is predicted. Better control of grapevine downy mildew could be achieved more cheaply, with less uncertainty for the vineyard manager. By combining prognoses of disease with accurate vineyard disease survey techniques (Seem *et al.* 1985), effective management of downy mildew is possible. Further economic and environmental savings could be made by reducing fungicide applications when the risk of disease was low and when disease control measures were not needed. This would also reduce the risk of pathogen tolerance to post-infection fungicides such as metalaxyl, one of the phenylamide group (Cohen and Coffey 1986).

It is anticipated that at least one fungicide spray application for downy mildew (costing \$19 ha^{-1}) of an assumed average of three, could be saved if sprays were correctly timed in a dry season. Additionally the associated improvement in disease control achieved, could lead to a 5% reduction in the assumed average crop loss (\$178 ha^{-1}) caused by downy mildew during an average Australian season (Magarey *et al.* - unpublished data). Similar savings could be expected in a wet season like 1983/84, when an average of six sprays were applied for the control of downy mildew and crop loss was assumed to average near \$600 ha^{-1}. This would lead to an annual saving for Australian viticulture of between \$2m. and \$4m. if sprays were applied on a more rational basis. The discussion in the text associated with Figure 1 would suggest that two or more sprays could be saved and most crop loss prevented in wet seasons. Of course not all grapegrowers could or would adopt this new approach to control, but even assuming a low rate of adoption, the total savings for Australian viticulture in wet seasons could range between and probably would exceed \$3m. and \$7m. (Magarey *et al.* - unpublished data).

The construction of dummy weather data sets that cause the simulator to predict various levels of infection, would encourage user acceptance and provide tests of effective function of the simulator. Such a data set would also be useful for use as a teaching aid for educational institutions. Individuals or groups of grapegrowers, district advisers and students could evaluate different methods of disease management and compare the cost of various fungicide treatments. The test data could be used to perform sensitivity analyses of the effects of various weather events on the simulator output. These analyses are useful because they can demonstrate to the user the particular influence of aspects of vineyard microclimate on different disease processes and their influence on the disease levels forecast. Management strategies could then be constructed to reduce the in-vineyard influence of these factors. For example a more aerated canopy structure that led to less leaf wetness events may be subject to less risk of infection.

An additional use of a validated simulator is in the classification of Australian (and later world) grapegrowing regions according to predicted annual risk from downy mildew. By processing historical weather data from present or proposed viticultural areas, disease prognoses could be generated and the regions classified accordingly. McLean *et al.* (1984) attempted this for several viticultural regions in Western and South Australia using daily weather records and crude operation of the models described above.

Already as a result of publicity associated with development of the simulator, some Riverland grapegrowers have begun to modify their disease management strategies by spraying for downy mildew only when disease risk is high. In this dry inland region (McLean *et al.* 1984), fewer fungicide sprays have been applied. This has been the result of advice that more frequently assisted grapegrowers to decide when not to spray than when to spray. This change in grower practice provides optimism for the adoption of the completed simulator into Australian viticulture.

A 24 h telephone service called "Horticulture Hotline" has been established in Mildura

by the Victorian Department of Agriculture to provide grapegrowers with advice of prognoses and disease management alternatives for downy mildew among other diseases and pests of grapes.

A completed simulator of downy mildew offers potential for incorporation into a broader decision-aid information (expert) system that includes most major diseases and pests of Australian viticulture. A simulator of light brown apple moth is in commercial operation in vineyards near Mildura (Madge and Stirrap 1991), and development of a simulator of powdery mildew is underway in a joint Victorian Department of Agriculture - South Australian Department of Agriculture project based at Irymple, Victoria (Emmett *et al.* 1990). Simulators for other viticultural pathogens are planned (Kable 1991).

These developments are being overviewed by a group of plant pathologists and entomologists who form the Australian Disease and Pest Management Co-ordination Group (Magarey 1990). The objective of this group is to co-ordinate and rationalize the use of human and physical resources in the development and implementation of improved disease and pest management practices in Australia. The development of a simulator of *P. viticola* is a typical example of this approach.

Collaboration between the Australian and overseas researchers will be further enhanced through meetings such as the International Workshop on Downy Mildew of Grapevines, in Geneva, New York, U.S.A. in 1991. This will improve the efficiency of resource use and the speed with which the downy mildew simulator will be completed for practical use in Australian vineyards.

Acknowledgements

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References

Arens, K. (1929). Untersuchungen über Keimung and Zytologie der Oosporen von *Plasmopara viticola* und physiologische Untersuchungen an *P. viticola* unter besonderer Berücksichtigung der Infektionsbedingungen. (Investigation of the germination and cytology of oospores of *Plasmopara viticola* and physiological investigation of *P. viticola* with specific regard to the requirements for infection). *Jahrbuch für wissenschaftliche Botanik* 70, 57.

Blaeser, M. (1978). Untersuchungen zur Epidemiologie des Falschen Mehltaus an Weinreben, *Plasmopara viticola* (Berk. et Curt., ex de Bary) Berl. et de Toni. (Investigation into the epidemiology of grapevine downy mildew *Plasmopara viticola* (Berk. et. Curt., ex de Bary) Berl. et de Toni). Diss., Univ. Bonn.

Blaeser, M. and Weltzien, H.C. (1977). Untersuchungen über die Infektion von Weinreben mit *Plasmopara viticola* in Abhängigkeit von der Blattnässedauer. (Investigation of the infection of grapevine with *Plasmopara viticola* in relation to leafwetness). *Meded. Fac. Landbouww. Rijksuniv. Gent* 42, 967-976.

Blaeser, M. and Weltzien, H.C. (1978). Die Bedeutung von Sporangienbildung, -ausbreitung und -keimung für die Epidemiebildung von *Plasmopara viticola*. (The significance of sporulation, dispersal and germination of sporangia of *Plasmopara viticola*). *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz* 85, 155-161.

Blaeser, M. and Weltzien, H.C. (1979). Epidemiologische Studien an *Plasmopara viticola* zur Verbesserung der Spritzterminbestimmung. (Epidemiological studies to improve the control of grapevine downy mildew (*Plasmopara viticola*). *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz* 86, 489-498.

Cohen, Y. and Coffey, M.D. (1986). Systemic fungicides and the control of Oomycetes. *Annual Review of Phytopathology* 24, 311-338.

Emmett, R.W., Magarey, P.A., Madge, D.G. and Wicks, T.J. (1990). Computer simulation of grapevine powdery mildew. Proceedings of the 7th Australian Wine Industry Technical Conference, Adelaide, August 13-17th, 1989, Abst. 5. p235.

Hill, G.K., (1989). Effect of temperature on sporulation efficiency of oilspots caused by *Plasmopara viticola* (Berk. & Curt. ex de Bary) Berl. & de Toni in vineyards. *Viti. Enol. Sci.* 44, 86-90.

Kable, P.F. (1977). Practical management of crop diseases. Winston Churchill Memorial Trust Report. N.S.W. Dept. of Agriculture, Agricultural Research Centre, Yanco, N.S.W.

Kable, P.F. (1990). Crop disease management with fungicides - an overview. *Plant Protection Quarterly* 6, 19-28

Madge, D.G. and Stirrat, S. (1990) Use of day degree model to predict generation events for Light Brown Apple Moth (*Epiphyas postvittana* Walker) on grapevines. *Plant Protection Quarterly* 6, 39-42.

Magarey, P.A. (1985). A disease management system for viticulture. An insight into tomorrow's technology for disease control. *Annual Technical Issue. Australian Grapegrower and Winemaker*. 22(256), 6-7.

Magarey, P.A. (1990). Systems for managing diseases and pests of grapevines. Proceeddings of the 7th Australian Wine Industry Technical Conference, Adelaide, 13-17th August 1989, 136-141.

Magarey, P.A., Maelzer, D.A., Kable, P.F., Woods, P., Wicks, T.J. and Wallace, H.R. (1983). A management system for grapevine downy mildew in Australia - its conception. Abst. No. 292., Abstracts of Papers, 4th International Congress Plant Pathology. Melbourne, Australia. 17-24th August, 1983.

Magarey, P.A. and Weir, P.C. (1988). A simulator for better management of downy mildew. *Australian Grapegrower and Winemaker*. 25 (292), 47.

McLean, G.D., Magarey, P.A., Wachtel, M.F. and Dry P.R. (1984). A climatic evaluation of the question: Could grapevine downy mildew develop in Western Australia? Advances in Viticulture and Oenology for Economic Gain. Proceedings of the 5th Australian Wine Industry Technical Conference, Perth, W.A., 29th Nov.-1st Dec. 1983, 249-260.

Muller, K. and Sleumer, H. (1934). Biologische Untersuchungen über die Peronosporakrankheit des Weinstockes, mit besonderer Berücksichtigung ihrer Bekämpfung nach der Inkubationskalendermethode. (Investigation of the biology and control of Perenospora disease of grapevines, with special consideration of the incubation calendar method). *Landwirtschaftliche Jahrbucher* 79, 509-576.

Rafaila, C., Sevcenco, V. and David, Z. (1968). Contributions to the biology of *Plasmopara viticola*. *Phytopathologische Zeitschrift* 6, 328-336.

Seem, R.C., Magarey, P.A., McCloud, P.I. and Wachtel, M.F. (1985). A sampling procedure to detect grapevine downy mildew. *Phytopathology* 75(11), 1252-1257.

Stryzik, S., (1983). Modele d'etat potentiel d'infection. Application a *Plasmopara viticola*. *Association de Co-ordination Technique Agricole*, Maison Nationale des Eleveurs, Paris, France. pp.1-46.

Teng, P.S. (1981). Validation of computer models of plant disease epidemics: A review of philosophy and methodology. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* 88(1), 49-63.

Viennot-Bourgin, G. (1981). History and importance of downy mildews. Ch. 1. pp.1-15 in the Downy Mildews, Ed. D.M. Spencer. Academic Press, London.

Zachos, D.G. (1959). Recherches sur la biologie et l'epidemiologie du mildiou de la vigne en Grece. (Investigation of the biology and epidemiology of grapevine downy mildew in Greece). *Annales de l'Institute phytopathologique Benaki* 2, 193.