The significance of selection of infection model and climatic parameters on the operation and benefits of a primary apple scab warning service

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Abstract

An examination of primary apple scab infection period data for Orange and Batlow, NSW indicated that the model currently used (modified Jones) would detect over 90 percent of the infection periods determined using the MacHardy and Gadoury model, and over 85 percent of those determined using the Schwabe model. Where the determinations of the modified Jones model differed from those of the other two models, conditions were usually marginal for hours of wetness or temperature was low.

Scab warning services in NSW are operated using Reuter Stokes Apple Scab Predictors which are programed with the Jones model. These units have been found to provide reliable field indications of apple scab infection conditions over a seven year period, and have the advantage of requiring very little operator interpretation.

An examination of the climatic parameters used in the modified Jones model showed that the wet period is usually the major component and that the periods of high humidity or intermittent dry periods usually contribute less than 20 percent of the total period.

Infection periods at Orange averaged 11–13 days apart, and 8–9 days apart at Batlow. The average length of the infection periods was about 30 h at both centres. This indicates that the currently recommended practice for apple scab control, based on regular application of protectant fungicides at 7–10 day intervals, supplemented with curative sprays when required following infection warnings (i.e., a 'strategic' approach), is providing reliable disease control using a minimal number of applications.

Introduction

Apple scab (*Venturia inaequalis* Cke. Wint.) is the major apple disease in most areas of Australia and apple scab warning services are conducted in the principal apple growing districts to aid in disease control (Penrose *et al.* 1985).

For thirty years the criteria used to determine infection conditions (duration of surface wetness and temperature) were based on those determined by Mills (Mills and La Plante 1951). However in recent years Mills' model has been modified. These modifications include an allowance for the diurnal periodicity of ascospore discharge (Penrose *et al.* 1985, MacHardy and Gadoury 1989); an extension of the wet period when the relative humidity is high (Jones *et al.* 1980, 1984); or an index calculated by multiplying the duration of the wet period by the temperature (Schwabe 1980). Because the choice of model used for determining infection periods may have a bearing on whether a scab warning is issued, a study was made of the consequences of the use of several models using weather data collected for Orange and Batlow over the period 1983–1989.

One of the benefits claimed for a scab warning system is the ability to time the application of fungicide sprays more efficiently, using post-infection curative fungicides rather than protectant fungicides applied on a calendar basis. The usefulness of this approach will depend on the frequency of infection periods and the expected interval between infections. Therefore an examination was made of the average interval between infections at Orange and Batlow and the effect this would have on implementing a disease control program.

Material and methods

Weather data

Weather data was collected using Apple Scab Predictors (ASP) manufactured by Reuter-Stokes, Inc, Cleveland, Ohio, USA. Units were located at Orange (1983–89) and Batlow (1984–89) NSW to monitor wet and dry bulb temperature and periods of wetness. The predictors monitor the sensors at one minute intervals and compute infection periods using the Jones *et al.* (1980) model.

Information is provided on:

- time and date of initiation of infection (irrespective of whether this proceeds to become an infection period or not),
- temperature averaged over the whole infection period,
- scab level determined from a modified Mills' model,
- total infection period duration comprising:
  - wet period duration
  - cumulative dry period duration
  - high humidity period duration.

All further calculations used in the various models in this study are based on the data collected by the ASPs and cover the period September 1 to November 30 each season.

Infection models compared

A.i) Jones' model – ASP

Jones *et al.* (1980) defined an infection period as that period from the commencement of rain to the time at which the relative humidity (RH) drops below 90 percent. Wet periods are added together if the wetness sensor becomes wet again within 8 h from the time RH falls below 90 percent, and the predictions are based on the Mills table (Mills and La Plante 1951). No allowance is made for the diurnal periodicity of ascospore discharge (Brook 1969). These infection periods are those reported by the ASP.

A.ii) Jones' model modified locally

As above, but total infection period duration was reduced by the number of hours from commencement till 0600 hrs, where initiation occurred between 1800 hrs and 0600 hrs.

B. MacHardy model

MacHardy and Gadoury (1989) concluded that infection by ascospores requires a 3 h shorter duration of wetness than that determined by Mills. They also reduced the infection period by the number of hours from commencement till 0700 hrs where initiation occurred between 1800 hrs and 0700 hrs. To be consistent with our local practice, I have reduced the period by the number of hours to 0600 hrs, rather than 0700 hrs in these calculations and added intermittent wet periods until 8 h continuous dryness occurs, as determined by the ASP.

C. Schwabe model

Schwabe (1980) developed an index to determine primary scab infection periods, where light infection is said to occur when the average temperature (°C) × wetness period (h) is in the range 100–149. In my study intermittent wet periods were added and multiplied by the average temperature, as determined by the ASP. Schwabe's index figures are also reduced by the number of hours till 0600 hrs where initiation occurs between 1800 hrs and 0600 hrs, in line with his recommendations to measure length of wet period from dawn in orchards with low ascospore potential. Although Schwabe suggests adding wet periods till 16 h dryness occurs I have used the data from the ASP and wet periods have been added till 8 h dryness occurs.

Analysis of infection periods

Using data recorded by the ASP, but modified as above where wetness commenced during the period 1800 hrs and 0600 hrs, the duration of infection periods (in hours) for September, October and November each year were calculated and the mean infection period and range over the season noted.

The intervals, in days, between initiations (i.e., where wetness has caused the ASP to begin recording a potential infection period, whether this leads to an infection period or not) and the interval between actual infection periods, as recorded above, were calculated for the September, October and November months each season and the mean and range determined.

The duration of the parameters which comprise an infection period determined by the ASP i.e., wetness, intermittent dry periods till 8 h continuous dryness occurs, and the period where humidity exceeds 90 percent, were calculated for the months of September, October and November each season, and the mean and range over the long term recorded, as was the total number of initiations compared with initiations commencing at night, to examine the relative importance of these factors in the composition of an infection period.

Results

Comparison of infection models

Over the six or seven year period, depending on the location, the four models examined averaged similar numbers of infection periods (Table 1) however, within individual years the choice of model affected the number of infection periods recorded. The Jones model recorded the most infection periods, although in 1988 and 1989 at Orange, the ASP, which uses Jones' model, failed to record a number of marginal periods, which after manual calculation and allowance for night initiation, were recorded with the modified Jones model. The reason for this discrepancy is not known. In spite of requiring 3 h less wet duration MacHardy's model recorded less infection periods than the modified Jones model in most years, which indicates that most infection periods are not marginal, and 3 h less wetness would not have affected the decision to issue a scab warning in the majority of instances.

Although the MacHardy model on average recorded less infection periods than those recorded by the modified Jones model, a number of infection periods were recorded, both at Orange and Batlow, which were not detected using the modified Jones model (Table 2). Such differences are due to the fact that the modified Jones model can be made up of lengthy high humidity periods but only short wet periods.

Schwabe's model recorded an average of 10 percent more infection periods than the modified Jones model at Batlow, but the same number at Orange (Table 1). An examination of the extra infection periods recorded by either MacHardy's or Schwabe's models (Table 2), showed that most were marginal for wet period duration (when compared with Mills' figures), and many occurred at low temperatures where the Mills' model becomes less definite.

Analyses of infection periods

The mean number of infection periods re-

Table 1. Apple scab primary infection periods determined using different models.

Location and Year	Total No. infection periods per season and model: Jones i) ASP (1)	Jones ii) ASP modified (2)	MacHardy (3)	Schwabe (4)	No. of occasions (5) where ASP (modified) failed to detect infection period compared with: MacHardy	Schwabe
Orange						
1983	15	12	7	10	0	1
1984	9	7	7	8	0	1
1985	13	11	11	11	0	0
1986	12	10	8	10	0	0
1987	12	8	7	9	2	2
1988	6	4	5	7	1	3
1989	6	9	5	5	0	0
Mean	10	9	7	9	0.4	1.0
Batlow						
1984	11	11	9	10	0	0
1985	11	10	10	11	0	1
1986	13	10	10	11	0	1
1987	8	9	7	7	1	1
1988	14	9	8	10	1	3
1989	13	10	11	14	4	7
Mean	12	10	9	11	1.0	2.1

l) Infection periods recorded by ASP – includes wet, intermittent dry, and high humidity periods. **2)** As for (1), reduced by the number of hours from initiation to 0600 hrs when wetness commences between 1800 hrs and 0600 hrs. **3)** Wet period compared with Mills' figure less 3 h adjusted for night initiation as for (2). **4)** Wet period (h) x °C, adjusted for night initiation in (2). **5)** See Table 2.

Table 2. Data where Jones (modified) model failed to detect infection period recorded by MacHardy or Schwabe models.

Location and Date	Climatic Parameters (l): Temp °C	Wet period h (3)	Dry Period h	High Humidity Period h	Models (2): Mills Period h (4)	MacHardy Wet Period Required (5)	Schwabe Index (6)
Orange							
Nov 22 1984	7	14:40	0	2:30	21	-	102
Oct 15 1987	13	21:40 (9:40)	0	0	11	8	125
Oct 19 1987	8	16:50	0	0	18	15	134
Sept 2 1988	6	19:40	0	0	26	-	118
Nov 16 1988	5	27:10	0	0	>48	-	136
Nov 26 1988	10	12:30	0	0	14	11	125
Batlow							
Oct 23 1985	5	29:20	0	0	>48	-	147
Oct 31 1986	7	17:20	0	0	21	-	121
Nov 20 1987	15	11:20 (7:00)	0	0	10	7	105
Sept 12 1988	5	25:10 (21:10)	3:40	0	>48	-	105
Sept 27 1988	8	16:50	0	0	18	15	134
Oct 8 1988	6	19:50	0	2:00	26	-	119
Sept 17 1989	6	21:50	00:40	00:10	26	-	131
Sept 22 1989	9	11:20	0	3:30	15	-	102
Oct 5 1989	8	17:10	0	0	18	15	138
Oct 10 1989	6	18:10	0	0	26	-	109
Oct 13 1989	8	17:10	0	0	18	15	138
Oct 19 1989	9	18:10 (12:30)	0	0	15	12	113
Nov 11 1989	9	13:50	0	0	15	12	124

l) Data recorded by ASP. **2)** In some cases the modified Jones model recorded positive whilst MacHardy and Schwabe recorded negative, and hence the number of infections recorded in this table may not agree with Table 1. **3)** Figure in brackets is wet period after allowance for night initiation of infection period. **4)** Wet period duration required at this temperature for Mills' Infection period. **5)** Essentially Mills' period less 3 hours. **6)** Comprises wet period (h) x °C. Index between 100–149 indicates light infection.

Table 3. Mean duration of infection periods recorded by ASP, intervals between recording initiations and between infection period commencements.

Location	Season							Mean	Range over
	1983	1984	1985	1986	1987	1988	1989		6-7 years
Orange									
Mean duration of infection period[1] (h)									
Sept	26	73	44	56	27	40	36	37	14-103
Oct	23	34	37	20	21	–	19	26	11-58
Nov	43	21	25	37	27	22	42	31	14-64
Mean								31	
Mean interval between initiations[2] (days)									
Sept	3	4	7	8	10	8	6	7	1-21
Oct	5	10	6	4	4	4	4	5	1-23
Nov	4	6	5	8	6	8	3	6	1-20
Mean								6	
Mean interval between infection period commencements[3] (days)									
Sept	5	15	10	8	15	22	14	13	1-51
Oct	9	13	9	7	12	–	7	11	2->1 mo
Nov	11	14	5	10	6	25	3	11	1-33
Mean								12	
Batlow									
Mean duration of infection period[1] (h)									
Sept		44	23	60	33	31	75	44	18-78
Oct		23	25	38	25	24	33	28	14-89
Nov		15	32	49	18	30	19	27	12-83
Mean								33	
Mean interval between initiations[2] (days)									
Sept		4	5	4	5	4	4	4	1-17
Oct		6	4	4	4	7	3	6	1-16
Nov		8	7	10	4	5	3	6	1-14
Mean								5	
Mean interval between infection period commencements[3] (days)									
Sept		6	12	10	9	10	8	9	1-21
Oct		10	6	5	3	–	16	8	1-36
Nov		11	7	10	9	9	4	8	1-34
Mean								8	

(1) Duration (hours) of infection period recorded by ASP, after allowance for infections initiated during the night. **(2)** Period (days) between initiation of recording and next initiation, regardless of whether infection occurred. **(3)** Interval (days) between infection period commencements recorded by ASP, after adjustment for night initiation.
– no infection period recorded. All readings have been rounded up to the nearest hour.

corded using the modified Jones model averaged nine for Orange and ten for Batlow over the Sept.-November period (Table 1). However, at Orange the range over the seven year period examined varied from four to twelve, while the range at Batlow was from nine to eleven. The range over these periods using the MacHardy model was from five to eleven for Orange and from seven to eleven for Batlow.

The duration of infection periods over the periods examined are given in Table 3. The means were similar for both Orange and Batlow, of around 30 to 40 hours, but the range varied from 11 to 103 hours.

The interval between initiations, i.e., the commencement of a wet period recorded by the ASP, was around 5–7 days at Orange and 4–6 days at Batlow, but the range tended to be greater at Orange (1 to 23 days) than Batlow (1 to 17 days). The interval between infection period commencements was about 11–13 days at Orange and 8–9 days at Batlow, with a range for Orange from 1 to 51 days and 1 to 36 days at Batlow.

An analysis of the composition of infection periods in Tables 4 and 5 shows that approximately one third of wet period initiations occur at night (1800–0600 hrs), both at Orange and Batlow.

As a component of the ASP infection period the duration of the wetness period was generally about four times longer than either the intermittent dry periods or the high humidity period, and therefore either of these latter factors contributed only around 20 percent to the total duration of a calculated infection period.

The range of duration of wetness period, dry period and high humidity period varied greatly from season to season.

Discussion

In comparison with our practice of using a modification of the Jones *et al.* (1980) model, the selection of other models for apple scab infection periods affected the number of warnings which would have been issued by an apple scab warning service. The use of the MacHardy and Gadoury (1989) model would have resulted in fewer warnings on average, but some additional warnings in some years. The Schwabe (1980) model would have resulted in 10 percent more warnings at Batlow, than those determined using our existing system, but the same average number at Orange. At both locations, the Schwabe model indicated light infection periods which were not recorded using the modified Jones model. Schwabe (1980) indicates that normally no control measures should be necessary after a light infection period (index 100–149).

The practice of discounting the number of hours from initiation of wetness till daylight when infection commences during the night is also suggested by MacHardy and Gadoury (1989) and Schwabe (1980) and results in fewer warnings being issued. The need to make such an allowance for the diurnal periodicity of ascospore discharge is supported by the experimental work of MacHardy and Gadoury (1989).

Schwabe's (1980) index agrees generally with the MacHardy and Gadoury (1989) model, but at low temperatures (below 5°C) where the Mills table requires in excess of two days for infection, the Schwabe index would only require 20 h wetness (5°C × 20 h), whereas the MacHardy and Gadoury (1989) model would require 45 h.

Nowacka and Cimanowski (1985) compared the Jones *et al.* (1980) model with that of Mills (Mills and La Plante 1951). They found that the Jones model was more reliable since Mills model failed to detect some critical periods which caused infection of potted trees. However in their paper, whilst they state that either ascospores or conidia were trapped during each infection period, they do not differentiate between the two spore types in their results. MacHardy and Gadoury (1989) have indicated that conidia require a longer wet period than ascospores to cause infection.

The scab warning services conducted at Orange and Batlow over the six and seven year periods of the study used the warnings provided by the ASP, modified for infections which began at night. This approach was convenient and did not result in any apparent commercial disease control failures and has the advantage over using other weather stations in that the unit is self contained and access to a computer is not required for interrogation of the instrument. Further, only one calculation is required, and this is only required when infection is initiated during the night.

The examination of the components of infection periods at Orange and Batlow show that the wet period is usually the major component. Intermittent dry periods comprise less than 20 percent of an infection period, this discrepancy is not critical in most cases.

The extension of Mills wet periods by the

Table 4. Means of various infection parameters determined by ASP for Orange (1983-89).

Parameter	Season							Mean	Range[1]
	1983	1984	1985	1986	1987	1988	1989		
Total No. of initiations									
Sept	11	9	4	2	3	6	6	6	2-11
Oct	8	3	5	10	7	2	7	6	2-10
Nov	7	5	5	4	5	4	3	5	3-7
Mean								5.6	
No. of initiations commencing at night [2]									
Sept	6	4	4	0	2	4	3	3	0-6
Oct	5	1	0	3	3	0	4	2	0-5
Nov	3	1	2	2	3	3	0	2	0-3
Mean								2.3	
Duration of wet period (h)									
Sept	14	19	23	40	20	19	16	22	1-69
Oct	14	26	19	14	13	10	8	15	1-38
Nov	16	12	24	28	13	18	22	19	2-46
Mean								18.7	
Duration of dry period (h)									
Sept	2	5	10	6	6	5	6	6	0-14
Oct	1	6	2	1	2	6	6	3	0-14
Nov	1	1	2	4	3	0	9	3	0-20
Mean								4-0	
Duration of high humidity period (h)									
Sept	5	7	13	11	2	6	6	7	0-31
Oct	2	3	7	3	3	3	4	4	0-16
Nov	4	4	1	6	4	0	11	4	0-22
Mean								5.0	

(1) Range of recordings by ASP over 7 years.
(2) Wet period commencing between 1800 hrs and 0600 hrs.

Table 5. Means of various infection parameters determined by ASP for Batlow (1984-89).

Parameter	Season						Mean	Range[1]
	1984	1985	1986	1987	1988	1989		
Total No. of Initiations								
Sept	8	2	7	6	7	5	6	2-8
Oct	5	7	9	6	5	11	7	5-11
Nov	4	4	2	4	6	7	5	2-7
Mean							6.0	
No. of initiations commencing at night [2]								
Sept	1	0	4	4	3	2	2	0-4
Oct	3	2	1	2	1	5	2	1-5
Nov	2	1	0	1	2	3	2	0-3
Mean							2.0	
Duration of wet period (h)								
Sept	33	11	23	20	20	31	23	1-83
Oct	18	22	27	17	12	17	19	1-71
Nov	11	30	27	8	20	15	19	2-55
Mean							20.3	
Duration of dry period (h)								
Sept	6	5	1	3	2	3	3	0-16
Oct	1	2	2	4	3	2	2	0-12
Nov	2	2	2	4	4	3	3	0-9
Mean							2.7	
Duration of high humidity period (h)								
Sept	4	5	3	5	2	11	5	0-43
Oct	0	1	3	1	6	2	2	0- 13
Nov	1	3	8	3	3	3	4	0-24
Mean							3 . 7	

(l) Range of recordings by ASP over 6 years
(2) Wet period commencing between 1800 hrs and 0600 hrs

duration of high humidity as in Jones model will have much the same effect on determining the infection period as reducing the wetness requirement by 3 h as suggested by MacHardy and Gadoury (1989) and is in agreement with the work of Preece and Smith (1961) who observed that hours of 90 percent or more relative humidity after rain could be substituted for hours of leaf wetness on the Mills' table.

Variations in drying rate within trees and within orchards and across the districts served by the NSW apple scab warning services, suggest that one should err on the side of conservatism and these variations may outweigh the variations based on the selection of the scab infection model. Therefore because of the ease of use, the ASP (Jones) model modified for the diurnal nature of ascospore release, is supported for field use and has proved adequate over the past seven years.

Manktelow *et al*. (1989) point out that infection period monitoring and forecasting help indicate infection risks and permit informed decisions on the need for fungicides and the type of fungicide used. Beresford *et al*. (1989) found that in all regions of New Zealand, monitoring of infection periods could improve disease management through better timing of curative sprays. They found however that in Auckland and Nelson there was little scope to deviate from the standard program of 7–10 day application of protectant fungicides because the expected interval between infection periods is less than 7–10 days.

The fact that infection period commencements are about 8–9 days apart at Batlow, and 11–13 days apart at Orange, and that the average duration of an infection period at these two centres is approximately 30 hours, would suggest that the current recommendations of protectant sprays applied at 7–10 day intervals during spring would be an appropriate approach to disease control and provide protection of newly emerging growth. This would not be markedly reduced over the long term by a switch to curative control (Penrose 1989).

The average duration of infection periods of 30 h suggests that if the whole orchard could be sprayed within 24 h of the cessation of the infection period, a curative fungicide with a kickback period of at least three days would be required. The extreme variation in the duration of the infection period (up to 103 hours) means that even a curative fungicide with a five day kickback period may not be adequate to provide control in some seasons. Prolonged wet periods associated with long infection periods may also make it difficult to use spray machinery in the orchard within the available kickback period.

The regularity of wetness at approximately six day intervals may reduce some of the effectiveness of protectant fungicides by washing them off and therefore lessening the length of the protective period.

This assessment of the operation of the Apple Scab Warning Service in NSW has confirmed that the current approach to determining infection criteria are adequate and that the recommended 'strategic' disease control program of protectant sprays applied on a regular basis backed up with curatives when required (Penrose 1989) should provide disease control reliability with minimal number of fungicide applications.

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