Development of an Infection Model for Botrytis Bunch Rot of Grapes Based on Wetness Duration and Temperature

J. C. Broome, J. T. English, J. J. Marois, B. A. Latorre, and J. C. Aviles

First and third authors: graduate research assistant and professor, Department of Plant Pathology, University of California, Davis, CA 95616; second author: associate professor, University of Missouri, Columbia, MO 65211; fourth and fifth authors: professor and research assistant, Facultad de Agronomía, Pontificia Universidad Católica de Chile, Casilla 306-22 Santiago, Chile.

This research was supported by a grant from NEOGEN Corporation, the Exporters Association of Chile, and an Organization of American States Fellowship given to J. C. Broome.

Accepted for publication 25 August 1994.

ABSTRACT

Broome, J. C., English, J. T., Marois, J. J., Latorre, B. A., and Aviles, J. C. 1995. Development of an infection model for Botrytis bunch rot of grape based on wetness duration and temperature. Phytopathology 85:97-102.

Grape berries were dipped in conidial suspensions of *Botrytis cinerea* and incubated for 4, 8, 12, 16, or 20 h of wetness at temperatures ranging from 12–30 C. Berries were infected after 4 h of wetness at all temperatures tested. Incidence of berry infection increased with increasing wetness duration at all temperatures. A multiple regression model described the logit of infection as a function of the interaction of wetness duration and temperature (R^2=0.75). This model was incorporated into an in-field environmental monitoring station and evaluated for two seasons on Thompson Seedless table grapes in the central valley of Chile. Applications of captan (3.2 kg/ha a.i.) or vinclozolin (1 kg/ha a.i.) were made according to the Botrytis model or a standard phenological spray program that consisted of four sprays (at bloom, cluster thinning, veraison, and preharvest) plus additional sprays after major rain events. Disease incidence and severity at harvest were similar whether applications were made according to a standard program (six to nine applications in 1991–1992, four to five in 1992–1993) or according to the Botrytis model (two to four applications in 1991–1992, zero to five in 1992-1993). In some vineyards, postharvest disease was significantly less when sprays were made according to the Botrytis model recommendations compared with the standard spray program.

Botrytis bunch rot, caused by *Botrytis cinerea* Perf.:Fr., is an important disease of grapes (*Vitis vinifera* L.) worldwide. The disease can be severe when prolonged periods of moisture coincide with preharvest berry ripening. Bunch rot can be controlled by canopy manipulations that enhance air flow around grape clusters, resulting in conditions unfavorable for *B. cinerea* (6–9,15). For example, on wine grapes in California, which often are supported on a vertical or divided trellis, leaves in the fruit zone are removed to reduce bunch rot development (8). In the event of prolonged rain, the effectiveness of canopy manipulations is reduced. Under such conditions, fungicide applications may be needed.

In Chile, most table grape vines are trained onto overhead arbors. Fruit in these canopies experience high humidity, low temperatures, and low light infiltration: conditions conducive to bunch rot (7). In Chile it is common for table grape growers to make 8–10 fungicide applications a year for control of Botrytis bunch rot. Benzimidazole resistance has been reported widely and there is evidence of resistance to dicarboximides (5).

Recently, research efforts have resulted in the development of models that relate the effects of environmental variables to diseases caused by *Botrytis* spp. (2,11,17,18), and a few models have been used to provide fungicide spray recommendations for control of these diseases (3,14,17). Typically the models have used in-field environmental monitoring stations that warn when conditions conducive to sporulation or infection occur, based on temperature, wetness duration, relative humidity, and crop phenology.

The objective of this study was to develop a model to characterize the infection response of inoculated grape berries in relation to wetness duration and temperature. This model was then validated and refined for two seasons in commercial table grape production vineyards in Chile.

MATERIALS AND METHODS

Model development. Mature table grape (cv. Red Seedless) berries were cut from clusters with short stem segments attached. The capstem end of each berry was dipped in molten paraffin (Parowax, Amoco) to seal the point of stem attachment and to prevent desiccation of fruit during the course of the experiment.

Berries were inoculated with conidia of two isolates of *B. cinerea* obtained from diseased grape berries in California. Conidia were produced after 7–14 days of culture growth on potato-dextrose agar (Difco) in the dark at room temperature. Conidia were suspended in sterile, deionized water by adding water to culture plates and gently rubbing the agar surface with a glass rod. Suspensions of conidia were poured through four layers of sterile cheesecloth to remove mycelial fragments and vortexed gently to disperse spores. Density of conidial suspensions of each isolate were determined with a hemacytometer (Reichert) and adjusted to 10^4 conidia per milliter of water and then combined before inoculation.

Berries were immersed in the spore suspension up to the wax coating at the capstem end, placed over deionized water on a wire-mesh grid and misted without runoff with an atomizer. Inoculated berries were covered with a wet paper towel and maintained in plastic containers in the dark at constant temperatures of 12, 16, 20, 24, 28, and 30 C. At 4-h intervals, 30 berries were removed from a container kept at each temperature. The berries were dried in front of a fan (wind speed 8 m/s) and placed in new containers without water. All grapes were incubated for an additional 6 days at 22 C, and then transferred back to containers with deionized water for 24 h to establish high relative humidity. The next day, berries were evaluated for infection incidence on the basis of appearance of mycelium and conidia on berry surfaces. During the entire experiment, uninfected berries remained turgid with pedicles attached. The experiment was repeated three times.

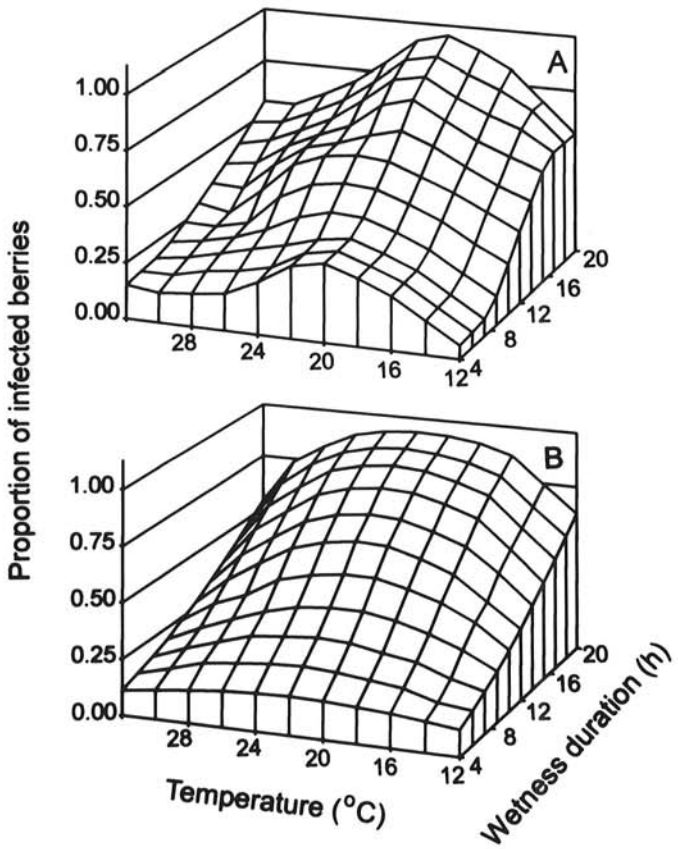

Fig. 1. The proportion of grape berries infected by *Botrytis cinerea* affected by wetness duration and temperature. Response surfaces were generated with SAS (Cary, NC) using the averages of three experiments. **A,** actual values; **B,** predicted values from Botrytis model.

The relationship of the incidence of berry infection to wetness duration and temperature was evaluated by multiple regression analysis. Incidence data were transformed with Gompertz and logit transformations and regressed on linear and quadratic combinations of wetness duration and temperature (2). In addition, the Analytis "beta" model, as described by Bulger et al (2) was evaluated. All models were evaluated for their descriptive potential by adjusted (R_a^2) and nonadjusted (R^2) coefficients of determination. Additionally, the statistic R^{*2} was computed to evaluate the goodness of fit of back-transformed values to observed disease values (2,4). Additional criteria for model suitability included significance of estimated coefficients, normality of residuals, and their patterns.

Model implementation. The multiple regression model was incorporated into an in-field environmental monitoring station (NEOGEN Corp., Lansing, MI). The monitoring stations measured temperature, hours of free moisture, rainfall, and relative humidity every 15 min, and recorded an hourly average of each. The Botrytis model initiated calculation of a disease index whenever leaf wetness was detected. To determine the relative risk of an infection period, logit values computed by the model were compared to parameter values that specified infection risk. Logit values of zero and below implied no risk, 0.01–0.5 implied low risk, 0.5–1.0 implied moderate risk, and 1.0 or greater implied high risk. A spray was advised as soon as either a moderate or high risk was indicated, even if the wet period continued. The calculation of a logit value was stopped if a dry period of greater than 4 h was recorded. If within the 4 h of a dry period a new wet period occurred then the accumulation of hours of wetness duration resumed, although the model does indicate that a split wet period occurred.

Model validation. Validation of the infection model was done in commercial table grape vineyards in the central valley of Chile from 1991–1993 (between latitude 33–35 S and longitude 70–72 W). Vineyards were located at Buin, Donihue, Olivar, and Rancagua in the 1991–1992 season, and at Colina, Donihue, and Olivar in 1992–1993. Vines of table grapes (cv. Thompson Seedless) were supported on an overhead arbor 2 m in height and spaced at 4 × 4 m (except at Buin where the vines were spaced at 3.5

TABLE 1. Estimated regression coefficients and coefficients of determination for the incidence of infection of grape berries (cv. Thompson Seedless) by *Botrytis cinerea* in response to various wetness durations and temperatures[v]

Model estimate	Regression coefficients[w]			
	Expt. 1	Expt. 2	Expt. 3	Combined data[x]
Variable intercept[y]	−3.120543 (0.3254)	−2.418956 (0.2450)	−2.325320 (0.2223)	−2.647866 (0.1837)
W	−.498932 (0.1312)	−.124354 (0.1800)	−.121506 (0.0906)	−.374927 (0.798)
WT	0.080563 (0.0125)	0.041555 (0.0155)	0.026772 (0.0090)	.061601 (0.0075)
WT^2	−0.001988 (0.0001)	−0.001142 (0.0001)	−0.000638 (0.0001)	−0.001511 (0.0002)
Coefficients of determination[z]				
R^{2z}	0.83	0.88	0.71	0.75
R_a^2	0.81	0.86	0.67	0.74
R^{*2}	0.86	0.87	0.70	0.78

[v] Wetness durations examined were 4, 8, 12, 16, or 20 h and temperatures examined were 12, 16, 20, 24, 28, or 30 C.

[w] Values are estimates of coefficients. Values in parentheses are standard deviations of estimates.

[x] Analysis was run on the means of the three experiments.

[y] Estimated coefficients b_1, b_2, and b_3 correspond to the y-intercept, W, WT, and WT^2 respectively; W is the wetness duration (h) and T is the temperature (C).

[z] R^2 is the coefficient of determination, R_a^2 is the adjusted coefficient of determination, and R^{*2} is the coefficient of determination of relations of back-transformed values of predicted disease incidence and observed values.

× 3.5 m). Vines had been winter pruned to 15–24 canes per vine with 15–30 buds per cane depending on location.

At each vineyard, disease was evaluated on vines treated with captan (3.2 kg/ha a.i.) or vinclozolin (1 kg/ha a.i.) according to either a spray program based on warnings of the Botrytis model or a standard program that consisted of applications at full bloom, manual cluster thinning, veraison, harvest, and after major rain events. Treatments were established in a split plot randomized complete block design with three replicate plots per location. Spray program was the main plot, and fungicide was the sub-plot. Each plot was 5 rows wide by 20–40 vines in length. The Botrytis model provided spray advisories on an hourly basis. Each unit was checked by the vineyard manager every 2–3 days for spray advisories and fungicides were applied as soon as possible after a warning was made. All fungicide applications were made by the grower with a commercial spray rig. In the second season, 1992–1993, unsprayed controls were included at each location; however, at Donihue the control vines were not correctly placed within appropriate replicate blocks and were not included in the statistical analysis.

Botrytis bunch rot incidence and severity were evaluated at first appearance, veraison, and harvest. One hundred clusters per replicate plot were evaluated for disease incidence (the average number of diseased clusters) and disease severity (the average number of diseased berries per cluster).

A postharvest rating of disease was obtained for two 8.2-kg boxes of grapes per replicate that had been treated as if for export. After harvest, whole clusters were fumigated with approximately 0.5% SO_2 for 20 min, hand cleaned, and sorted in the packing line. Grapes were packed with an "Uvas Quality" SO_2 pad (Nipo S.A.C., Chile) that releases SO_2 in two phases, a fast release that provided 2,000 ppm SO_2 for 4 days, and a slow release that provided 5–10 ppm SO_2 for up to 60 days. Boxes of grapes were precooled for 12 h and stored for 20 days at 0 C. At the end of this period, the SO_2 pad was removed, and the grapes were incubated for 3 days at 20–25 C (to imitate marketing time) before evaluation of postharvest disease incidence and severity.

A *B. cinerea* disease potential assay was performed at veraison and harvest. For each replicate plot, 100 non-surface-sterilized berries, with pedicle attached, were placed on waxed wire-mesh grids in a humid chamber with 1 cm of water on the bottom to maintain the humidity at > 95%. The number of berries sporulating with *B. cinerea* after 7 days was recorded.

Effects of spray program and fungicide on disease incidence and severity were analyzed with a general linear model (SAS, Cary, NC) as a split plot design with spray program as main plot, and fungicide as sub-plot. Mean separation was performed with planned orthogonal contrasts. Disease severity values were arcsine $\sqrt{x}$ transformed before analysis.

RESULTS

Model infection. Grape berries were infected by *B. cinerea* over a range of temperatures from 12–30 C. At all temperatures, infection occurred after only 4 h of wetness and varied from about 9% at 12 C to 37% at 20 C (Fig. 1). Disease incidence increased with increasing wetness duration at each temperature. After 24 h of wetness, maximum disease incidence varied from 54% at 30 C to over 90% at 12–20 C. Infection of berries also occurred at 32 C, but disease incidence after 24 h was less than 10% (data not shown). Variation of disease with environment was described best by the model: $\ln(Y/(1-Y))=b_0 + b_1W + b_2WT + b_3WT^2$ where $\ln(Y/1-Y)$ is logit of disease incidence, Y is the proportion of diseased host, W is the wetness duration (h), and T is tempera-

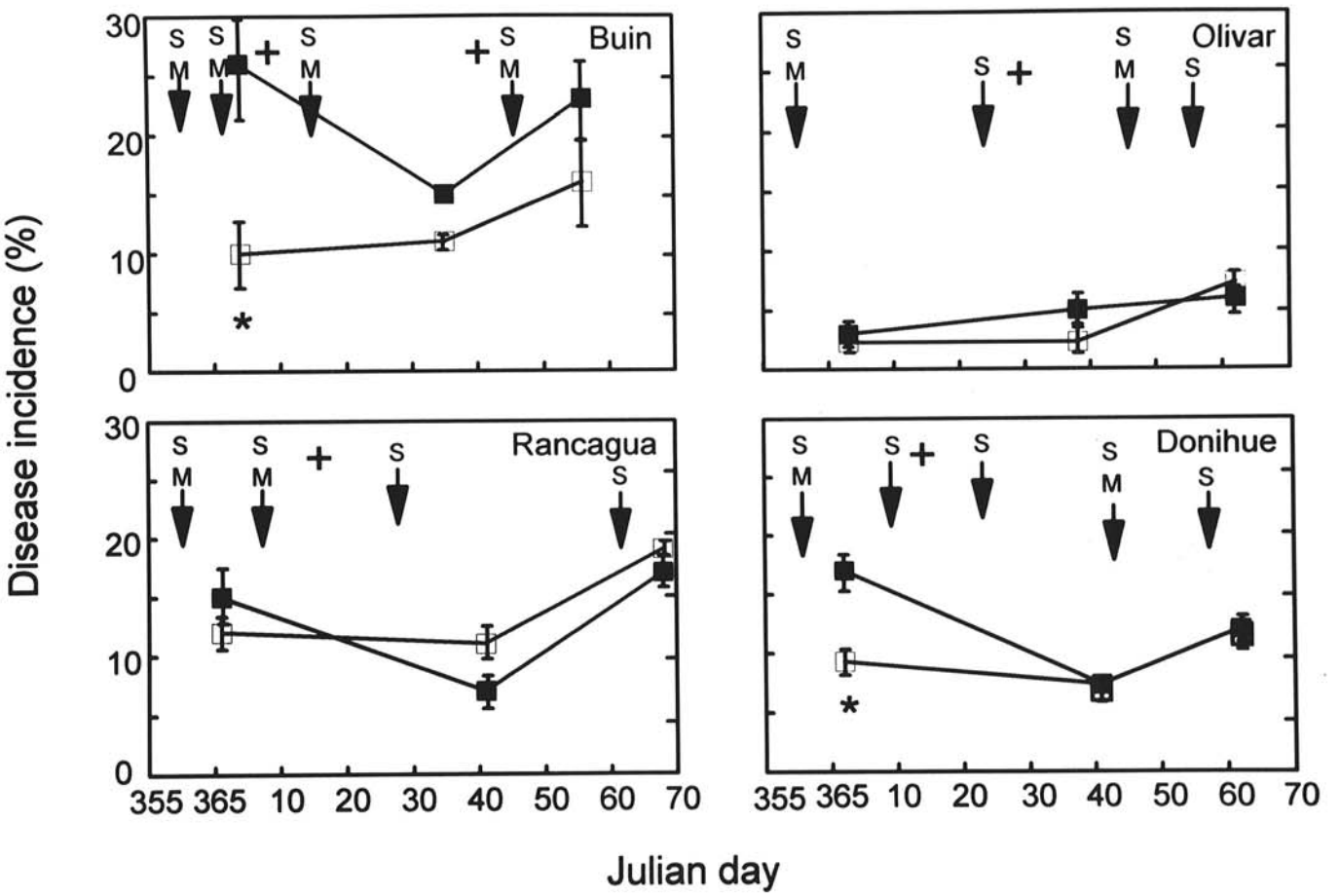

Fig. 2. Incidence of Botrytis bunch rot at Buin, Donihue, Olivar, Rancagua, 1991–1992. Fungicide applications (arrows) made based on Botrytis model (M), or according to standard program (S). ■ Botrytis model; □ Standard. Vertical bar indicates the standard error of the mean. * Indicates at that date the means of disease incidence are significantly different at $P > 0.05$ as determined by planned orthogonal contrasts. + Indicates date of manual removal of infected berries.

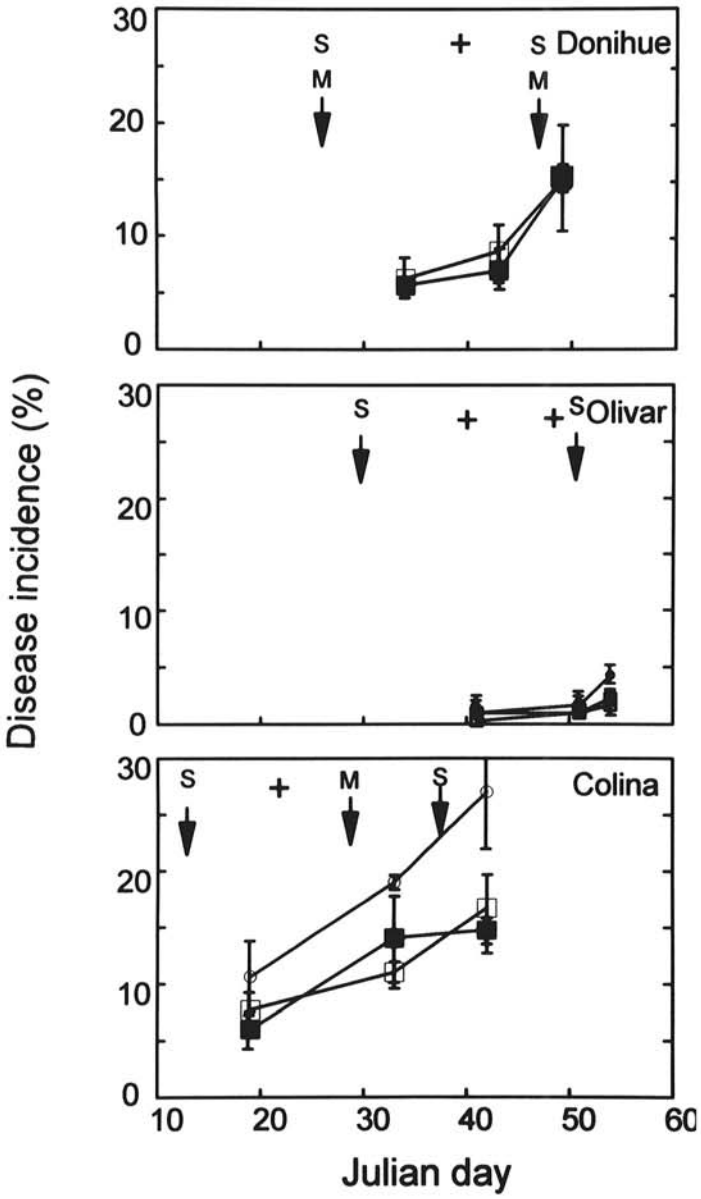

Fig. 3. Incidence of Botrytis bunch rot at Colina, Donihue, Olivar, 1992–1993. Fungicide applications (arrows) made based on Botrytis model (M), or according to standard program (S). ■ Botrytis model; □ Standard; ○ Control. Vertical bar indicates the standard error of the mean. * Indicates at that date the means of disease incidence are significantly different at $P > 0.05$ as determined by planned orthogonal contrasts. + Indicates date of manual removal of infected berries.

ture (C).

This model explained a large proportion of the variation in disease incidence, as indicated by the adjusted and nonadjusted coefficients of determination (Table 1). When data from all experiments were analyzed, R^{*2} was 0.78. Estimates of values for coefficients b_0, b_2 and b_3 were significant ($P < 0.05$) in all experiments. However, estimates for b_1, the coefficient for wetness duration, were significant at this level only in experiment 1 and when data from all three experiments was combined. Random patterns of residuals were observed in all models fit to the logit transformed data.

Variation of disease in relation to wetness duration and temperature was described less satisfactorily by models based on the Gompertz transformation or the Analytis model. These models were rejected either because of low coefficients of determination or because of severe departure of residuals from randomness. Also, among experiments, the variables selected for inclusion in these models were not as consistent as those selected with the logit-transformed data.

Model validation. Fungicide applications applied according to the Botrytis model were effective for both seasons, which in comparison had very different weather and levels of disease. Moreover, disease control was equal to or better than the control obtained with the standard spray program (Figs. 2 and 3, Table 2).

During the 1991–1992 season, rainfall was above average. At the first appearance of disease on Julian day 1, 1992, at Olivar and Rancagua, there was no difference in disease incidence between the two spray programs; at Donihue and Buin, grapes treated according to the Botrytis model had significantly greater disease incidence than grapes treated according to the standard program ($P > 0.05$)(Fig. 2). By harvest, however, disease control was similar in plots at all four vineyards treated with fungicides according to either the Botrytis model or the standard spray program. The model program required a total of only 3.5 sprays per vineyard compared with 7.0 per vineyard for the standard program (Table 3). At the Olivar vineyard, use of the model resulted in a 67% reduction in the number of fungicide applications compared with the standard program, and equivalent disease control was obtained.

In general, the 1992–1993 season had fewer rain events and less Botrytis bunch rot was observed in vineyards than in the 1991–1992 season. There was no significant difference in disease control in relation to spray program for any of the ratings done at any of the three vineyards (Fig. 3). Disease was first observed on Julian days 19, 33, and 41 at Colina, Donihue, and Olivar, respectively. At Colina, disease incidence and severity of the untreated grapes were significantly greater ($P < 0.05$) at preharvest and at harvest compared to treated grapes. At Olivar, no sprays were applied in the Botrytis model treatment despite early season warnings (Table 4). An average of 3.0 sprays per vineyard were applied in the Botrytis model treatment, compared with 4.7 per vineyard in the standard program (Table 4).

TABLE 2. Effect of spray program on postharvest disease incidence and severity of Thompson Seedless table grapes in Chilean vineyards

		Disease incidence (%)			Disease severity (%)		
Season	Location	Standard program[v]	Model spray program[w]	Control[x]	Standard program[v]	Model spray program[w]	Control[x]
1991–1992	Buin	8.7 a[y]	11.0 a		0.04 a[z]	0.08 b	
	Donihue	5.0 a	18.0 a		0.04 a	0.13 a	
	Olivar	8.1 a	2.4 b		0.07 a	0.01 a	
	Rancagua	12.3 a	8.4 a		0.10 a	0.07 a	
1992–1993	Colina	6.4 a	1.7 b	9.6 c	0.04 a	0.01 a	0.09 b
	Donihue	3.9 a	6.3 a	5.1	0.05 a	0.03 b	0.04
	Olivar	2.9 a	5.2 a	7.5 a	0.02 a	0.04 a	0.09 a

[v] Standard spray program received fungicide applications at bloom, manual cluster thinning, veraison, and preharvest, and after major rain events.
[w] Model spray program received fungicide applications only when indicated by the model.
[x] Control vines did not receive any fungicide applications.
[y] Means for disease incidence for the same season and location followed by different letters are significantly different by orthogonal contrasts, $P < 0.05$.
[z] Means for disease severity for the same season and location followed by different letters are significantly different by orthogonal contrasts, $P < 0.05$.

Postharvest disease incidence and severity in 1991–1992 at Buin and Rancagua were the same regardless of spray program used (Table 2). However, at Olivar, there was a 53% reduction in postharvest disease with use of the Botrytis model versus the standard spray program ($P = 0.06$). In contrast, at Donihue, grapes treated according to the Botrytis model had significantly greater postharvest disease than the standard program–treated grapes.

In 1992–1993, at Colina, there was a reduction in postharvest disease when the Botrytis model was followed compared with the standard spray program (Table 2); 2.5% of clusters treated according to the model became diseased (severity rating of 0.015%) compared with 6.2% of clusters treated according to the standard program (severity of 0.04%). The vines that were not treated the entire season had 9.6% diseased clusters (0.10% severity), which was significantly greater than either the model or the standard program treatment ($P < 0.05$).

In addition to the visual disease assessments made in the plots and the postharvest assessments, humid chamber ratings of detached berries were carried out for each location at harvest. Over both years, disease incidence in detached berries reflected disease levels observed in the vineyards. At Olivar in 1992–1993, however, grapes treated according to the Botrytis model had a significantly higher incidence of infected berries compared with grapes that received the standard fungicide treatment (3.2 versus 0.3%). Early in the growing season, two spray alarms were not responded to at this location.

TABLE 3. Fungicide application dates and environmental data for the Botrytis model and standard spray programs, 1991–1992, Chilean vineyards of Thompson Seedless table grapes

	Botrytis model warnings[v]				Fungicide application dates	
Location	Date	Hours wet	Av. temp.	Risk	Model[w]	Standard[x]
Buin						23 Nov.
						13 Dec.
	25 Dec.	30:45*[y]	13.6	Severe	27 Dec.	27 Dec.
	31 Dec.	16:45*	15.4	Severe	4 Jan.	4 Jan.
					17 Jan.[z]	17 Jan.[z]
	13 Feb.	4:15	15.0	Moderate	13 Feb.	13 Feb.
Donihue						
					17 Nov.	17 Nov.
						23 Nov.
	29 Nov.	9:45	12.4	Severe	29 Nov.	29 Nov.
						11 Dec.
	25 Dec.	16:00*	14.8	Severe	26 Dec.	27 Dec.
						7 Jan.
						23 Jan.
	9 Feb.	13:00*	15.1	Severe	11 Feb.	11 Feb.
						27 Feb.
Olivar						
	9 Nov.	8:45	12.0	Severe		
						26 Nov.
						18 Dec.
	25 Dec.	16:30*	14.9	Severe	26 Dec.	26 Dec.
						24 Jan.
	10 Feb.	7:15*	13.8	Severe	11 Feb.	11 Feb.
						25 Feb.
Rancagua						
					16 Oct.	16 Oct.
						24 Nov.
	10 Dec.	23:00*	6.0	Severe	11 Dec.	11 Dec.
	25 Dec.	17:15*	14.5	Severe	26 Dec.	26 Dec.
	1 Jan.	4:00	13.1	Moderate	2 Jan.	2 Jan.
						31 Jan.
						6 Mar.

[v] Dates of and average temperatures during Botrytis model wetness periods. Infection risk is considered none if the logit value was < 0, low if it was 0.01–0.5, moderate if it was 0.50–1.0, and severe if it was >1.0.
[w] Fungicide applications based on Botrytis model.
[x] Standard fungicide program included sprays at bloom, manual thinning, veraison, preharvest, and after major rain events.
[y] Asterisk indicates recorded wetness was connected to a rain event.
[z] Application made due to disease, after infected berries removed.

DISCUSSION

The model developed based on logit-transformed disease incidence values adequately predicted grape infection by *B. cinerea* based on temperature and wetness duration. In laboratory experiments, Nelson (12) previously evaluated the effect of wetness duration and temperature on grape-berry infection by *B. cinerea*, but he frequently maintained the berries under conditions of high relative humidity (>90%) after the wet period. For example, Nelson observed that more than 90% of berries kept wet for only 3 h became diseased when incubated at 91% relative humidity at 12 C (13). These conditions would be equivalent to a vapor pressure deficit of about 0.11 kPa. The experimental approach used in this study used lower relative humidity during the post–wet period. Incubating dried berries at the initial wet period temperatures would have exposed them to different vapor pressure deficits, with perhaps variable influences on infection. To avoid this situation, berries were dried completely in rapidly moving air and maintained at 22 C. Vapor pressure deficits under these conditions were more than 0.5 kPa, which we consider sufficient to prevent further infection. Under these conditions, an interactive effect of wetness duration and temperature was observed; the potential for confounding effects of high humidity during postinfection incubation was reduced.

Infection occurred after 4 h at 12–30 C. Although this period of time is very short, Kosuge and Hewitt (10) showed that it is sufficient for accumulation of exuded sugars that stimulate germination of conidia of *B. cinerea*. Increases in disease incidence beyond 4 h of wetness reflected the influences of temperature on infection processes.

In this study, the infection conditions of mature grape berries by *B. cinerea* were similar to those described for infection of

TABLE 4. Fungicide application dates and environmental data for the Botrytis model and standard spray programs, 1992–1993, Chilean vineyards of Thompson Seedless table grapes

	Botrytis model warnings[u]				Fungicide application dates	
Location	Date	Hours wet	Av. temp.	Risk	Model[v]	Standard[w]
Colina	9 Nov.	18:00*[x]	13.9	Severe	13 Nov.	13 Nov.
	18 Nov.	8:30	11.7	Moderate	21 Nov.	
	26 Nov.	6:15	12.1	Moderate	26 Nov.	26 Nov.
						3 Dec.
						13 Jan.
	28 Jan.	4:30	11.5	Moderate	29 Jan.	
						10 Feb.
Donihue[y]	9 Nov.	17:15*	14.8	Severe	12 Nov.	12 Nov.
	18 Nov.	7:45	13.3	Moderate	19 Nov.	
						23 Nov.
						2 Dec.
	6 Dec.	10:00	12.7	Moderate	7 Dec.	
	25 Dec.	4:15	12.0	Moderate	29 Dec.	
	22 Jan.	4:45	14.4	Moderate	26 Jan.	26 Jan.
						15 Feb.
Olivar[z]	9 Nov.	17:30*	14.2	Severe		28 Nov.
	26 Nov.	4:45	13.0	Moderate		19 Dec.
						29 Jan.
						20 Feb.

[u] Dates of and average temperatures during Botrytis model wetness periods. Infection risk is considered none if the logit value was < 0, low if it was 0.1–0.5, moderate if it was 0.50–1.0, and severe if it was > 1.0.
[v] Fungicide applications made based on Botrytis model.
[w] Standard fungicide program included sprays at bloom, manual thinning, veraison, preharvest, and after major rain events.
[x] Asterisk indicates recorded wetness was connected to a rain event.
[y] At Donihue, alarms occurred on 11/30/92 and 1/7/93 but no applications were made, and grapes were unprotected from previous applications.
[z] At Olivar, alarms occurred on 11/9/92 and 11/26/92, however no applications were made.

strawberry flowers (2), black spruce seedlings (18), and Cabernet Sauvignon grapes (11) by *B. cinerea*, and onion leaves by *B. squamosa* J. C. Walker (17). The effect of increasing wetness duration on increased *B. cinerea* incidence also was observed in these other studies. With the Cabernet Sauvignon model (11) at 20 C, 50% of the grape berries were infected within 12 h of wetness, which is very similar to our Botrytis model. Similarly, the coefficient for the quadratic WT^2 interaction term was negative for the strawberry and spruce models. Negative coefficients also were observed in models describing infection of sweet cherry and peach (1) by *Monilinia fructicola* (G. Wint.) Honey. Within the environmental ranges of those studies and in the present experiments, such negative coefficients tended to dampen the rate of increase of $\ln(Y/1-Y)$ with increasing wetness duration. This is a result of disease incidence approaching its maximum value of 1.

Over two seasons, the fungicide program based on model warnings proved to be effective in controlling disease. Botrytis bunch rot at harvest was similar in plots that received the model treatment or the standard program. Moreover, vines treated according to the Botrytis model received 34–67% and 0–100% fewer applications of fungicides than vines treated according to the standard program, in 1991–1992 and 1992–1993, respectively. During 1991–1992, at the first disease rating there was more disease in the model-treated grapes than in the standard-program grapes at Buin and Donihue. At Buin, however, the grower was slow to respond to the warnings, and on two occasions delayed applying the fungicide for 2–4 days after significant rain events. In addition, at Donihue and Buin, the Botrytis model was installed a month later (23 November 1991) than at the other two locations and earlier infection events in the first season could have been missed at these locations. However, by the end of the first season (1991–1992) and for all of the second season (1992–1993) adequate disease control was obtained at all locations in the model-based and standard-spray programs.

The fungicides currently available for Botrytis bunch rot control are not known for having postinfection activity. Captan and vinclozolin, the fungicides employed in this study, are considered contact materials with postinfection activities of 24 and 36 h, respectively. Captan inhibits spore germination, whereas vinclozolin inhibits germ tube elongation. Both fungicides, however, provided similar and adequate control when used with the Botrytis model. Only captan data were reported here to facilitate presentation of the model's performance. Use of the model with a fungicide with longer postinfection activity could result in improved disease control.

The model was developed with mature grape berries, and its applicability for providing early season warnings for protection of either floral tissue or immature berries needs further research. For example, in 1992–1993 at Olivar, no fungicides were applied in the model treatment after early season infection periods occurred; yet disease control at harvest was similar in the model treatment, the standard program, and the untreated control. However, the humid chamber infection evaluations showed that there were a greater number of infected berries in the untreated grapes, suggesting that the pathogen was active during the periods when the model signaled spray warnings. Nair and Allen (11), working with Cabernet Sauvignon flowers, found that infection of the flowers by *B. cinerea* required only 2 h of wetness duration at the optimum temperature of 24 C.

Other pathogen- and host-related parameters could be included to enhance the effectiveness of the model. Bulit's model (3) for *B. cinerea* included pathogen inoculum density; however, for a facultative saprophyte such as *B. cinerea* inoculum in vineyards is almost always present and may not be as important a parameter as presence or absence of a conducive environment. Strizyk's model (14) included effects of host susceptibility due to phenology and variety as well as temperature and humidity effects on infection, germination, and sporulation. However, Strizyk's model is not yet readily available. The role of host susceptibility, spatial heterogeneity of environmental conditions within a vineyard, vine canopy, and grape cluster could be incorporated into the Botrytis model. More specifically, cluster architecture will greatly affect localized wetness duration (16). In addition, the model will need to be tested in high humidity climates.

Botrytis bunch rot is one of the most important diseases of grapes worldwide. This simple, empirically derived disease model is based on the interaction of the environmental parameters of wetness duration and temperature on grape berry infection. When incorporated into a weather station it provides useful, on-site, and timely information on the occurrence of these infection periods. Chemical intervention occurs only when needed, reducing the potential of resistance development and making possible a more efficient and rational use of fungicides in the vineyard.

LITERATURE CITED

1. Biggs, A. R., and Northover, J. 1988. Influence of temperature and wetness duration on infection of peach and sweet cherry fruits by *Monilinia fructicola*. Phytopathology 78:1352-1356.
2. Bulger, M. A., Ellis, M. A., and Madden, L. V. 1987. Influence of temperature and wetness duration on infection of strawberry flowers by *Botrytis cinerea* and disease incidence of fruit originating from infected flowers. Phytopathology 77:1225-1230.
3. Bulit, J., and Lafon, R. 1970. Quelques aspects de la biologie du *Botrytis cinerea* Pers., agent de la pourriture grise des raisins. Connaiss. Vigne Vin 4:159-174.
4. Campbell, C. L., and Madden, L. V. 1990. Introduction to Plant Disease Epidemiology. John Wiley & Sons, New York.
5. Carreno, I., and Alvarez, M. 1990. Determinacion de razas resistentes de *Botrytis cinerea* de vides e fungicidas dicarboximidas. Agricultura Tecnica (Santiago) 50(3):298-303.
6. English, J. T., Bledsoe, A. M., Marois, J. J., and Kliewer, 1990. Influence of grapevine canopy management on evaporative potential in the fruit zone. Am. J. Enol. Vitic. 41:137-141.
7. English, J. T., Thomas, C. S., Marois, J. J., and Gubler, W. D. 1989. Microclimates of grapevine canopies associated with leaf removal and control of Botrytis bunch rot. Phytopathology 79:395-401.
8. Gubler, W. D., Bettiga, L. J., and Heil, D. 1991. Comparisons of hand and machine leaf removal for the control of Botrytis bunch rot. Am. J. Enol. Vitic. 42:233-236.
9. Gubler, W. D., Marois, J. J., Bledsoe, A. M., and Bettiga, L. J. 1987. Control of Botrytis bunch rot of grape with canopy management. Plant Dis. 71:599-601.
10. Kosuge, T., and Hewitt, W. B. 1964. Exudates of grape berries and their effect on germination of conidia of *Botrytis cinerea*. Phytopathology 54:167-172.
11. Nair, N. G., and Allen, R. N., 1993. Infection of grape flowers and berries by *Botrytis cinerea* as a function of time and temperature. Mycol. Res. 97(8):1012-1014.
12. Nelson, K. E. 1951. Factors influencing the infection of table grapes by *Botrytis cinerea* (Pers.) Phytopathology 41:319-326.
13. Nelson, K. E. 1951. Effect of humidity on infection of table grapes by *Botrytis cinerea*. Phytopathology 41:859-864.
14. Strizyk, S. 1983. Modele d'etat potentiel d'infection application au *Botrytis cinerea*. Version 1983. Association de coordination technique agricole. France.
15. Thomas, C. S., Marois, J. J., and English, J. T. 1988. The effects of wind speed, temperature, and relative humidity on development of aerial mycelium and conidia of *Botrytis cinerea* on grape. Phytopathology 78:260-265.
16. Vail, M. E., Marois, J. J. 1991. Grape cluster architecture and the susceptibility of berries to *Botrytis cinerea*. Phytopathology 81:188-191.
17. Vincelli, P. C., and Lorbeer, J. W. 1989. BLIGHT-ALERT: A weather-based predicative system for timing fungicide applications on onion before infection periods of *Botrytis squamosa*. Phytopathology 79:493-498.
18. Zhang, P. G., and Sutton, J. C. 1994. Effects of wetness duration, temperature, and light on infection of black spruce seedlings by *Botrytis cinerea*. Can. J. For. Res. 24:707-713.