Weather Factors Affecting Downy Mildew Epidemics of Hops in the Yakima Valley of Washington

Dennis A. Johnson, C. B. Skotland, and J. R. Alldredge

Extension plant pathologist and plant pathologist, Washington State University, Irrigated Agriculture Research and Extension Center, Prosser 99350; and assistant professor, Statistical Services and Biometry, Washington State University, Pullman 99164, respectively.
Scientific Paper 6164, Project 0056, of the College of Agriculture Research Center. Supported in part by the Washington Hop Commission.
Accepted for publication 12 October 1982.

ABSTRACT

Johnson, D. A., Skotland, C. B., and Alldredge, J. R. 1983. Weather factors affecting downy mildew epidemics of hops in the Yakima Valley of Washington. Phytopathology 73:490-493.

Weather records were compared with the occurrence of downy mildew epidemics of hops over a 28-yr period in the Yakima Valley in Washington. Above-normal temperatures in April and wet weather in April and May favored development of downy mildew, but wet weather with low minimum temperatures did not. The amount of initial inoculum influenced the occurrence of epidemics. Potential incidence of hop downy mildew in the Yakima Valley could be determined in early May based on above-normal temperatures and rainfall in April, the incidence of systemically infected shoots in hop yards, and the likelihood for wet weather in May.

Additional key words: compensation, disease forecasting, epidemiology, *Humulus lupulus, Pseudoperonospora humuli.*

Downy mildew of hops (*Humulus lupulus* L.) (caused by *Pseudoperonospora humuli* (Miy. et Tak.) Wils.) is a serious disease in many areas of the world where hops are grown (3,6). Because this disease is more severe in areas of higher rainfall, most hop production in North America has shifted from moist areas to more arid areas (14,16). For example, the Yakima Valley in Washington ranks number one in North America and number two in the world for hop production. However, downy mildew has been a serious threat to hop production in the Yakima Valley in 9 of 28 yr since 1954. The cluster cultivars, which are extremely susceptible to infection and account for over 80% of the crop, are an important component of downy mildew epidemics of hops in Washington.

Forecasting models for hop downy mildew have been developed for the hop-growing areas in England, Germany, Yugoslavia, and Czechoslovakia (11,12). These models are empirical, include environmental variables, and some also include an inoculum concentration variable to predict disease symptoms. Royle (11) accurately predicted downy mildew symptoms with a multiple regression equation that included the independent variables of rain-wetness duration, amount of rainfall, and airborne spore concentration, and also with a second equation that involved only relative humidity and rainfall.

Hop downy mildew is associated with moist weather (10,17). Temperature also influences disease development, possibly through its effect on sporulation (15,18) and infection (10). This study was initiated to relate the effects of moisture and temperature variables and the development of hop downy mildew epidemics during a 28-yr period in the Yakima Valley of Washington relative to eventually developing a forecasting system for the disease.

MATERIALS AND METHODS

Years with severe downy mildew epidemics from 1954 to 1981 were identified from Washington Hop Commission newsletters, which described crop conditions each year. Years with no mention of downy mildew epidemics were classified as having either no or only mild epidemics, and those for which epidemics were mentioned were classified as having had severe epidemics.

The severity of epidemics was quantified in 1980 and 1981. Disease incidence was monitored from mid-April to mid-August in six hop yards both years by determining the percentage of hop hills with systemically infected shoots (1,14,16) along four transects in each yard. Transects ran the length of rectangular, 4- to 10-ha yards. Different yards were monitored each year.

Hop production extends for 80 km from Yakima and Moxee, southeast to Prosser (Fig. 1). Weather data from the National Oceanic and Atmospheric Administration (5) for Sunnyside, WA, were analyzed because downy mildew epidemics are usually most severe in an area along the Yakima River 10 to 15 km northwest of Prosser, near Sunnyside (Fig. 1). Weather data from 1954 to 1981 were analyzed from April through August, because vegetative growth of hops occurs from mid-April to mid-August or mid-September when the crop is harvested. Stepwise discriminant analyses were used to identify parameters for predicting the occurrence of epidemics.

Years with above-normal rainfall in either April or May were analyzed further to compare daily minimum and maximum temperatures during wet periods of years with and without severe epidemics. A wet period was identified as a day with rainfall >0.3 mm in years that exceeded the 28-yr mean for precipitation or days of precipitation in either month. These periods were chosen as a means to indicate temperature when sporulation and infection might occur. The maximum and minimum temperatures of each

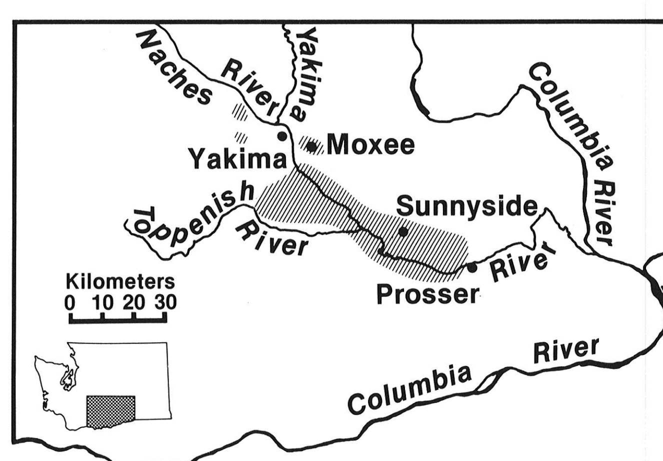

Fig. 1. Map of an area in south-central Washington (see inset) showing areas (shaded) of hop production.

wet period were determined. Total precipitation and number of wet periods were determined when the minimum temperature of the wet period was above 7 C. This temperature was chosen because the quantity of sporulation in the field increases rapidly when minimum night temperatures are above 7 C (D. A. Johnson and C. B. Skotland, *unpublished*).

RESULTS

Severe hop downy mildew epidemics occurred in 9 yr during the period 1954 to 1981, and 19 yr had little or no disease (Table 1). Total precipitation, days of precipitation >0.3 mm, and minimum daily temperatures were generally greater in April and May of years with severe epidemics than in years with mild or no epidemics (Table 2). There were essentially no differences in these observations in June, July, and August of epidemic and nonepidemic years. There was also no significant difference in maximum daily temperatures in any month from April through August between epidemic and nonepidemic years during the 28-yr period. Daily mean temperatures (not shown) followed the same pattern as minimum daily temperatures, but differences in daily mean temperatures in April and May between epidemic and nonepidemic years were less than those with minimum temperatures.

A stepwise discriminant analysis program (2) selected April precipitation and the number of days with precipitation >0.3 mm in May as predictors of downy mildew epidemics. Classification functions obtained were:

TABLE 1. Weather parameters at Sunnyside, WA, related to the severity of downy mildew of hops during 28 yrs in the Yakima Valley

	April			May			June		
	Precipitation			Precipitation			Precipitation		
Years	Total (mm)	Days> 0.3 mm (no.)	Min. daily temp. (C)	Total (mm)	Days> 0.3 mm (no.)	Min. daily temp. (C)	Total (mm)	Days> 0.3 mm (no.)	Min. daily temp. (C)
Severe downy mildew									
1981	0	0	4.0	8	4	7.3	11	4	9.8
1980	17	4	5.2	31	7	8.1	33	9	10.6
1978	24	8	4.4	11	4	6.4	10	4	11.4
1974	32	6	4.2	7	5	6.1	6	2	11.3
1963	40	11	3.4	14	3	6.7	3	3	10.8
1962	16	5	4.6	39	11	6.4	0	0	9.3
1958	38	9	3.3	9	5	10.8	4	4	13.8
1957	11	4	3.9	31	8	10.2	9	1	11.2
1956	0	0	3.3	9	7	9.6	20	8	9.6
Mild or no downy mildew									
1979	9	3	3.8	3	2	7.9	0	0	10.8
1977	0	0	4.7	20	7	5.8	5	2	12.3
1976	15	7	3.7	1	2	7.0	0	0	8.7
1975	19	5	1.4	5	2	6.6	2	2	10.3
1973	3	1	3.3	4	1	7.1	0	0	10.7
1972	1	1	1.9	61	6	8.8	28	5	12.0
1971	4	1	2.6	11	4	7.9	17	7	9.7
1970	5	1	1.8	3	2	6.4	1	1	12.6
1969	18	4	3.6	14	4	8.7	9	3	14.3
1968	0	0	2.4	3	3	7.7	7	4	12.1
1967	22	7	1.9	5	2	7.6	15	2	12.7
1966	0	0	3.6	0	0	7.4	16	3	10.8
1965	8	7	4.5	4	1	6.5	12	5	11.1
1964	3	1	1.8	0	0	5.9	17	5	10.8
1961	30	5	3.8	29	6	7.6	13	4	12.3
1960	19	6	4.0	18	7	6.4	3	1	10.3
1959	3	3	3.2	6	3	5.7	6	5	10.7
1955	18	5	1.3	9	3	6.2	7	5	11.0
1954	5	2	2.8	10	5	7.6	18	7	9.6
Mean	12.9	3.8	3.3	13.0	4.1	7.4	9.7	3.4	11.1
$\sigma/\sqrt{n}$	2.3	0.6	0.2	2.6	0.5	0.2	1.6	0.5	0.2

TABLE 2. Comparison of weather parameters at Sunnyside, WA, for years of severe versus mild hop downy mildew

	Precipitation (mm)		Days with precipitation >0.3 mm		Minimum daily temperature (C)		Maximum daily temperature (C)	
Month	Severe[a]	Mild[b]	Severe	Mild	Severe	Mild	Severe	Mild
April	19.8 ± 5.0[c]	9.6 ± 2.1	5.2 ± 1.3	3.1 ± 0.6	4.0 ± 0.2	3.0 ± 0.2	19.0 ± 0.6	18.1 ± 0.4
May	17.7 ± 4.1	10.8 ± 3.3	6.0 ± 0.8	3.2 ± 0.5	8.0 ± 0.6	7.1 ± 0.2	23.5 ± 0.8	23.4 ± 0.3
June	10.7 ± 3.4	9.3 ± 1.8	3.9 ± 1.0	3.2 ± 0.5	10.9 ± 0.4	11.2 ± 0.3	27.7 ± 0.6	27.8 ± 0.4
July	5.4 ± 1.5	5.6 ± 1.7	1.7 ± 0.6	1.9 ± 0.5	12.7 ± 0.5	12.9 ± 0.2	31.6 ± 0.5	31.9 ± 0.3
August	5.7 ± 2.4	7.8 ± 2.2	2.6 ± 0.7	2.3 ± 0.6	11.9 ± 0.4	11.8 ± 0.4	31.1 ± 0.6	31.0 ± 0.5

[a] Data for 9 yr of severe downy mildew epidemics.
[b] Data for 19 yr with either mild or no downy mildew.
[c] Mean ± standard error of mean.

Severe: 0.18 (April precipitation) + 1.20 (May days > 0.3 mm) − 6.04
Mild: 0.09 (April precipitation) + 0.63 (May days > 0.3 mm) − 2.10

Both classification functions were evaluated for each year. A year was then assigned to the group with the largest classification function. These classification functions correctly classified 79% of the years with respect to downy mildew occurrence.

The epidemic years of 1956 and 1981 were incorrectly classified. In these years, there was no rain in April and the amount of rainfall was below the 28-yr mean in May, but above the 28-yr mean in June (Table 1). However, the days in which precipitation occurred in 1956 and 1981 equalled or exceeded the 28-yr mean in May and June.

In the nonepidemic years, four years were misclassified. The 3 yr with either mild or no epidemics (1960, 1961, and 1969) had high total precipitation and many days of precipitation during April and May. The remaining misclassified year, 1977, had total precipitation and days of precipitation in May greater than the 28-yr means (Table 1). However, in 1977 there was no precipitation in April and low minimum daily temperatures occurred in May (Table 1). Also, low minimum daily temperatures occurred during wet periods in 1960 and 1977 (Table 3). Precipitation and minimum daily temperatures appeared to have been favorable for downy mildew development in 1961 and 1969.

When the minimum daily temperatures for April and the number of days of precipitation in May were used in the classification functions, 82% of the years were correctly classified. Misclassified years were the epidemic years 1958 and 1963 and the nonepidemic years 1960, 1961, and 1977. The first set of predictors were selected over these because of higher *F* values during the stepwise analysis.

The misclassified epidemic years in the second discriminant analysis, 1958 and 1963, had minimum temperatures in April above or equal to the 28-yr mean, and both had high total precipitation in April and a high number of days of precipitation or total precipitation in May (Table 1). The year 1958 had a high number of wet periods with warm minimum daily temperatures in April and May (Table 3). The misclassified nonepidemic years were also misclassified in the first analysis.

When minimum daily temperatures in April and May and the number of days of precipitation in May were used in the classification functions, 71% of the years were correctly classified.

In years with severe epidemics, the average minimum temperature was generally higher in April and May during wet periods than in years of high rainfall and mild or no epidemics (Table 3). Years with severe epidemics generally had more precipitation, and temperatures above 7 C during wet periods than years with high rainfall and mild or no epidemics.

The percentage of hills with systemically infected shoots on 1 May in six yards ranged from 0.1 to 0.4%, with a mean of 0.17% in 1980; it ranged from 0.4 to 2.5%, with a mean of 1.1% in 1981. Disease incidence on 2 July ranged from 36 to 60%, with a mean of 46% in three yards not treated with fungicides in 1980; it ranged from 33 to 95%, with a mean of 56% in three yards not treated with fungicides in 1981.

DISCUSSION

Above-normal rainfall in April, May, and June and above-normal minimum temperatures in April and May favored downy mildew epidemics. Precipitation in April, days of precipitation in May, and minimum daily temperatures in April were good indicators of disease development. Precipitation in May contributed more to disease development than did precipitation during the other months. Precipitation in April did not always occur in years with severe epidemics. However, years with severe epidemics but little precipitation in April (1956 and 1981) had abundant precipitation in May and June, which extended the time for epidemics to develop into June. For example, in 1981 high

TABLE 3. Weather parameters related to the severity of downy mildew of hops during years with high rainfall in April or May in Sunnyside, WA

	April				May			
	Mean temperature during wet periods		Precipitation and no. of wet periods when min. temperature was >7C		Mean temperature during wet periods		Precipitation and no. of wet periods when min. temperature was >7C	
Years	Min. (C)	Max. (C)	Precip. (mm)	Wet periods (no.)	Min. (C)	Max. (C)	Precip. (mm)	Wet periods (no.)
Severe downy mildew								
1981	...	...	0	0	8.6	21.8	8	3
1980	8.1	18.1	16	3	8.9	20.3	30	6
1978	4.6	16.7	3	1	8.8	19.3	11	3
1974	5.8	16.0	28	3	7.7	18.9	6	3
1963	3.4	13.5	0	0	7.6	14.3	13	2
1962	5.3	19.4	11	2	7.0	17.8	34	7
1958	3.6	16.0	3	2	12.0	25.9	5	4
1957	6.7	18.2	5	3	11.3	24.8	31	8
1956	...	...	0	0	10.0	21.2	9	7
Mean	5.4	16.8	7.3	1.6	9.1	20.5	16.3	4.8
$\sigma/\sqrt{n}$	0.6	1.7	3.2	0.4	0.6	1.2	3.9	0.7
Little or no downy mildew								
1977	...	...	0	0	5.5	20.2	8	2
1976	4.8	17.0	2	2	3.9	20.3	0	0
1975	2.9	13.1	1	2	8.6	21.1	5	2
1972	7.2	21.1	1	1	7.2	19.4	57	3
1969	4.3	17.5	4	1	8.8	21.1	13	3
1967	1.1	12.1	0	0	7.8	19.2	2	1
1961	4.7	15.7	5	1	8.1	20.2	12	3
1960	4.9	16.0	3	2	5.6	19.3	13	3
1955	3.6	14.1	0	0	8.0	14.1	9	3
Mean	4.2	15.8	1.8	1.0	7.1	19.4	13.2	2.2
$\sigma/\sqrt{n}$	0.6	1.0	0.6	0.3	0.6	0.7	5.7	0.4

precipitation in June contributed to disease development when preceded by wet weather in May.

Severe epidemics occurred when above-normal minimum temperatures in April were followed by warm, wet weather in May. Warm weather in April promotes vegetative growth, early emergence of systemically infected shoots, and earlier infection. Warm minimum temperatures were needed during wet periods in April and May for epidemic development, whereas cool minimum temperatures during wet periods were not favorable for disease development (Table 3). The nonepidemic years, 1960 and 1977, were misclassified in the discriminant analyses because cool temperatures during wet periods checked disease development.

Royle (10) reported that downy mildew infections in England were not correlated with temperatures, whereas we found that warm minimum daily temperatures in April and May favored disease development. An explanation is that temperature was not sufficiently low in England to restrict disease development (10), whereas in Washington, low temperatures frequently restrict sporulation and infection, especially in the spring when rain usually occurs. We have observed that night temperatures <5 C inhibit sporangial formation on systemically infected shoots. Royle (9) reported that the threshold for local infection is 5 C, and for systemic shoot infection it is 8 C.

Average minimum temperatures were superior to average daily temperatures as indicators of downy mildew development, because spring night temperatures frequently are low even though daily maximum temperatures may be relatively high.

Shaner and Finney (13) found that frequency of rainfall was more closely related to severity of Septoria leaf blotch of wheat in Indiana than was total rainfall. Frequency of rainfall reflected duration of leaf wetness better than total rainfall (13). Total rainfall was not highly correlated with frequency of rainfall in Indiana ($r =$ 0.41), whereas they were highly correlated in Washington ($r = 0.89$, 0.73, and 0.80 in April, May, and June, respectively). Frequency of rainy days was a better predictor of hop downy mildew epidemics than total rainfall in May, the month when moisture appeared to be most important for disease development.

A severe epidemic did not occur in 1969 when weather apparently favored disease development. An explanation may be a low level of initial inoculum. Because of a federal marketing order, hop acreage in the Yakima Valley was gradually reduced from 8,540 ha in 1965 to a low of 7,312 ha in 1969. Hop yards with a high incidence of downy mildew infection will have many missing and unthrifty plants and such yards would be the first to be removed from production. *P. humuli* overwinters as mycelium in infected crowns in Washington State (14), and removal of these crowns would reduce primary inoculum.

Many more systemically infected shoots were found on 1 May in 1981 than in 1980. Severe epidemics occurred both years, and the more abundant inoculum in 1981 probably was due to a high number of crowns that were infected in 1980. The 1981 season was drier than other years having severe downy mildew epidemics, but the high level of initial inoculum was sufficient for high disease incidence when accompanied by moderate moisture and very susceptible cultivars. The same combination may have occurred in 1962–1963 and 1957–1958. Further, a buildup of initial inoculum of *P. humuli* in years with mild epidemics may contribute to epidemics in years with moderate moisture. For example, infections probably occurred in May 1955 (Table 3), which increased the initial inoculum from infected perennial crowns for 1956. Rotem et al (8) reported a similar phenomenon for infection of potato with *Phytophthora infestans*. They demonstrated that a favorable level of either temperature, inoculum concentration, or wetting duration (or a favorable combination of two of these factors) may compensate for a certain deficiency in the third factor. Hypotheses of compensation were proposed by Rotem (7) to explain such phenomena.

Forecasts for the potential incidence of hop downy mildew epidemics in the Yakima Valley could be made each year on 1 May. Moisture and minimum temperatures in April, the number of systemically infected shoots in yards at the end of April, and the weather forecast for May would need to be considered. Systemically infected shoots would be monitored in hop yards throughout the Yakima Valley to determine the initial inoculum. This empirical forecast would be general in nature, advising growers near the beginning of the growing season of the likelihood of an epidemic. Such an advanced warning is important when fungicides are to be applied over large areas and coordinated with irrigations. Use of a systemic fungicide, like metalaxyl, which provides protection for 4–6 wk, would have utility in this system. Further, in Washington we use the empirical forecast with a system to predict infection periods (4). The two systems provide a long-term outlook and specific forecasts for infection.

LITERATURE CITED

1. Coley-Smith, J. R. 1962. Overwintering of hop downy mildew *Pseudoperonospora humuli* (Miy. et Tak.) Wilson. Ann. Appl. Biol. 50:235-243.
2. Dixon, W. J., and Braun, M. B. 1977. BMDP-77. University of California Press, Berkeley.
3. Hoerner, G. R. 1932. Downy mildew of hops. Oregon Agric. Exp. Stn. Ext. Bull. 440. 11 pp.
4. Johnson, D. A., and Skotland, C. B. 1981. Forecasting downy mildew epidemics of hops. (Abstr.) Phytopathology 71:1005.
5. National Oceanic and Atmospheric Administration. 1954–1981. U.S. Department of Commerce. Environmental data and information service. Climatological data—Washington. Vols. 58–85, Nos. 4–8 (April–August). National Climatic Center. Asheville, NC.
6. Romanko, R. R. 1964. The history of hop downy mildew. Hop downy mildew—A symposium. Mod. Brewery Age 66:45-46.
7. Rotem, J. 1978. Climatic and weather influences on epidemics. Pages 317–338 in: Plant Disease, An Advanced Treatise. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York.
8. Rotem, J., Cohen, Y., and Putter, J. 1971. Relativity of limiting and optimum inoculum loads, wetting durations, and temperatures for infection by *Phytophthora infestans*. Phytopathology 61:275-278.
9. Royle, D. J. 1970. Infection periods in relation to the natural development of hop downy mildew (*Pseudoperonospora humuli*). Ann. Appl. Biol. 66:281-291.
10. Royle, D. J. 1973. Quantitative relationships between infection by the hop downy mildew pathogen *Pseudoperonospora humuli* and weather and inoculum factors. Ann. Appl. Biol. 73:19-30.
11. Royle, D. J. 1979. Prediction of hop downy mildew to rationalize fungicide use. Pages 49–56 in: Rep. Dep. Hop Res., Wye Coll., England. 1978.
12. Royle, D. J., and Kremheller, H. T. H. 1981. Downy mildew of the hop. Pages 395–419 in: The Downy Mildews. D. M. Spencer, ed. Academic Press, New York.
13. Shaner, G., and Finney, R. E. 1976. Weather and epidemics of Septoria leaf blotch of wheat. Phytopathology 66:781-785.
14. Skotland, C. B. 1961. Infection of hop crowns and roots by *Pseudoperonospora humuli* and its relation to crown and root rot and overwintering of the pathogen. Phytopathology 51:241-244.
15. Skotland, C. B. 1962. Factors affecting sporulation and infections by the hop downy mildew fungus, *Pseudoperonospora humuli*. (Abstr.) Phytopathology 52:753.
16. Skotland, C. B., and Romanko, R. R. 1964. Life history of the hop downy mildew fungus. Wash. Agric. Exp. Stn. Circ. 433. 6 pp.
17. Waggoner, P. E., Norvell, W. A., and Royle, D. J. 1980. The law of the minimum and the relation between pathogen, weather, and disease. Phytopathology 70:59-64.
18. Yarwood, C. E. 1937. The relation of light to the diurnal cycle of sporulation of certain downy mildews. J. Agric. Res. 54:365-373.