Two Degree-Day Models for Predicting Initial Emergence of Hop Shoots Systemically Infected with *Pseudoperonospora humuli*

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ABSTRACT

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Two degree-day models were developed to predict the appearance in the spring of the first hop (*Humulus lupulus*) shoots systemically infected with *Pseudoperonospora humuli* in commercial hopyards of the cluster cultivars in the Yakima Valley of Washington. One model was based on total degree-days above air temperatures of 6.5 C accumulated from the time when temperatures reached a threshold after 1 February until the day before the emergence of the first systemically infected shoot from perennial hop crowns. A mean of 111.3 (range 30.5) accumulated degree-days was derived from 11 yr of field data, and the model effectively predicted the first appearance of systemically infected hop shoots in the Yakima Valley. A second model developed from 5 yr of data on soil temperatures calculated degree-days by summing soil temperatures above 6.5 C and was also an effective predictor of the emergence of the first systemically infected hop shoot. The soil temperature model had a mean of 88.7 (range 12.6) accumulated degree-days. These models can be used as part of a disease forecasting system to determine when monitoring of hopyards for downy mildew should begin in order to manage the disease in Washington hopyards.

Downy mildew of hop (*Humulus lupulus* L.), caused by *Pseudoperonospora humuli* (Miyabe & Takah.) G. W. Wils., is a serious threat to profitable hop production in the Yakima Valley of Washington. Severe epidemics of the disease have occurred in the Yakima Valley on average in one of every 3 yr (9). Cluster-type cultivars, which are susceptible to downy mildew, accounted for nearly 80% of hop production in Washington in the early and mid 1980s and still account for about 26% of the crop. Sanitation practices and timely applications of fungicides before the onset of warm, wet weather are needed to manage the disease in the cluster cultivars (13).

P. humuli overwinters as mycelium in infected crowns and buds of the perennial hop plant (2,12). Mycelium may invade shoots growing from infected crowns or buds in the spring. These systemically infected shoots, known as "primary basal spikes," are typically stunted and chlorotic and have brittle leaves that curl down. Sporangia borne on the abaxial leaf surfaces of the primary basal spikes serve as primary inoculum for epidemic development (10). In Washington State, disease assessments in hopyards for primary basal spikes and a disease forecasting model that estimates sporangium production from a multiple regression equation (8) are used to schedule fungicide applications and sanitation practices to manage downy mildew of hop (7,13).

Hop shoots in the Yakima Valley usually begin growing between mid-February and late March, and the first primary basal spikes are evident a few days to 6 wk later. Because of the long period during which spikes may appear, considerable time is required to assess hopyards for primary basal spikes. Because temperature over a period of time in the spring appeared to affect the emergence of primary basal spikes (D. Johnson, *unpublished observation*), this study was undertaken to develop a degree-day model to predict initial spike emergence in commercial hopyards of Cluster cultivars in the Yakima Valley. Degree-day models have been used to predict development of other plant diseases (1,3,11).

MATERIALS AND METHODS

Six to 14 commercial hopyards (5–10 ha each) of the cluster cultivars L-1, E-2, and L-8 throughout the Yakima Valley were monitored for the first emergence of primary basal spikes each year from 1980 to 1990. The yards monitored were not necessarily the same each year because some yards were removed by growers. An observer walked straight-line transects or large letter *W*s in each yard three to five times per week after shoots began growing in the spring until a spike was observed. Hop is grown in hills, and 500–2,000 hills per yard were examined each sample day for the presence of primary basal spikes.

Air and soil temperatures were recorded at the Irrigated Agriculture Research and Extension Center near Prosser, WA. The air temperature 2 m above the ground was measured with a hygrothermograph in a weather station from 1980 to 1987 and with a Fenwal Electronics UUT51J1 thermistor (model XN217 probe, Campbell Scientific, Logan, UT) from 1988 to 1990. The soil temperature at a depth of 20 cm was measured from 1986 to 1990 with a model 105T thermocouple from Campbell Scientific.

Degree-days were calculated from daily air temperatures by adding the maximum and minimum temperatures, dividing by two, and subtracting the base temperature from the result. For soil temperature, a daily mean was calculated from 24 hourly readings, and degree-days were calculated by subtracting the base temperature from the daily mean temperature.

Several base temperatures and starting times for the summation of degree-days were tried to find the model that best predicted the initial emergence of spikes. Base temperatures tried were 5, 6, 6.5, 7, 8, and 9 C. Degree-day values calculated from air temperatures were summed beginning either 1 February or after the last cold period since 1 February, where a "cold period" was defined as five or more consecutive days each with a degree-day value less than or equal to zero and such that if the cold period contained only 5 days, the mean of the degree-day values was also less than or equal to −2. Degree-day values calculated from soil temperatures were summed beginning with the first positive degree-day value after 1 February. Models both including and excluding negative daily values in the summations were tried. Values were summed until the day before the first spike was observed.

Air temperature data from 1980 through 1986 and soil temperature data from 1986 through 1988 were used to develop preliminary degree-day models to predict first emergence of spikes in 1987–1990 from air temperature and in 1989 and 1990 from soil temperature. All years of data were included in the final models. The sample range, variance, and coefficient of variation, calculated over the years of the study, were used to select the most appropriate models. To deter-

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mine whether crop phenology was associated with the first emergence of primary basal spikes, the date when healthy shoots of cluster cultivars in the Yakima Valley were first 5–11 cm long was noted from 1984 through 1990.

RESULTS

The first primary basal spikes appeared over a 29-day period, from 4 April (in 1983, 1986, and 1990) to 3 May (in 1982), during the 11 yr of the study (Table 1). The first spikes were observed 2–21 days after hop shoots were 5–11 cm long in 1984–1990.

Degree-days accumulated from air temperatures with a base of 6.5 C had a smaller coefficient of variation than calculations using bases of 5, 6, 7, 8, or 9 C. Models that summed only positive degree-day values were superior to those that included negative values. Summations initiated after the last 5-day cold period following 1 February had a lower range, variance, and coefficient of variation than summations beginning on 1 February, beginning on other arbitrary dates, or based on cold periods shorter than five consecutive days.

Similarly, degree-days accumulated from soil temperatures with a base of 6.5 C had a smaller coefficient of variation than accumulations calculated with the other bases, and summing only positive degree-day values gave better results than summing positive and negative values. The soil-temperature model had a smaller coefficient of variation than the air-temperature model (Table 1).

The mean from the air-temperature model based on data from the first 7 yr of the study (1980–1986) was 114.1 degree-days, and the mean from the soil-temperature model based on data from 1986–1988 was 91.2 degree-days. Both means were good predictors of initial spike emergence, in 1987–1990 in the case of the model using air temperatures and in 1989 and 1990 in the case of the model using soil temperatures. The 114.1 degree-day mean of the first 7 yr for the air-temperature model occurred 3 days after the actual date of the first emergence of spikes in 1987 and 1990, 1 day after the actual date in 1988, and 1 day before the actual date in 1989. The 91.2 degree-day mean of the first 3 yr for the soil-temperature model occurred 1 day after the actual date of first spike emergence in 1989 and 1990.

The mean degree-day accumulation based on air-temperature data for all 11 yr of the study was 111.3 (Table 1). This value occurred within 5 days of the actual date of the first emergence of spikes from 1980 through 1990 (Table 1). The day that the mean degree-day accumulation based on soil-temperature data for 1986–1990 (88.7) occurred was within 1 day of the actual date of first spike emergence for these years (Table 1).

DISCUSSION

The amount of initial inoculum influences the severity of epidemics of hop downy mildew in the Yakima Valley of Washington (9) because the cluster-type cultivars are very susceptible to infection (13) and because the epidemics are usually relatively short because of the onset of dry weather in late May or early June (9). Relatively large amounts of initial inoculum occur in some yards in the Yakima Valley (6). In general, lowering high initial inoculum levels effectively limits the severity of diseases caused by polycyclic pathogens, such as *P. humuli,* when the epidemic is relatively short (4,14).

Primary inoculum of *P. humuli* consists of sporangia borne on the abaxial leaf surface of primary spikes (10,15). The inoculum can be quantified by estimating both the number of spikes in a yard (by a visual sampling technique) and the number of sporangia per spike. After spike emergence, the number of sporangia per square centimeter of leaf area can be estimated from a multiple regression equation with minimum nightly temperature times number of hours with relative humidity greater than or equal to 80% and nightly mean relative humidity as independent variables (8).

In Washington, hopyards are monitored in the spring for primary spikes. Disease management decisions (13) can then be based on the quantity of inoculum as determined above and the likelihood of future warm (temperatures at or above 8 C), wet weather favorable for infection (7,10,13). Because the time of initial spike emergence varies widely among years, determining when to begin monitoring can reduce the considerable time required to quantify the incidence of spikes in yards.

The length of hop shoots did not appear to be a dependable indicator of when spikes would first emerge. However, the degree-day models developed in this study should be useful in predicting when spikes will begin to appear in the cluster-type cultivars and thus in indicating when monitoring should commence.

The air-temperature and soil-temperature models had ranges of 5 days and 1 day, respectively, for spike emergence. The 10th percentile of the distribution (5) for the soil-temperature model was 81 degree-days. This accumulation would be a satisfactory threshold for beginning monitoring, in that monitoring would begin before the emergence of the first spikes 90% of the time. (In using a percentile, I am assuming that the time of first spike emergence is normally distributed with respect to degree-days and that the sample mean and standard deviation are good estimates of the population mean and standard deviation [5]). Other hop cultivars may differ from the cluster types in the timing of the initial emergence of spikes.

Temperature affects sporulation, germination, infection, and colonization by *P. humuli* (8,10). The 6.5 C temperature base used in the degree-day models is near the temperature thresholds for these activities. For instance, sporulation begins at 5 C (8), and the lowest temperatures at which leaves and shoots are infected are 5 and 8 C, respectively (10). Temperature also influences the emergence of systemically infected hop shoots from infected crowns, as shown in this study.

That soil temperature gave a better model than air temperature was not surprising. Soil temperatures 20 cm deep varied less during a day and affected the

Table 1. Degree-day accumulation based on air or soil temperatures for the date during 1980–1990 and 1986–1990, respectively, when hop shoots systemically infected with *Pseudoperonospora humuli* (spikes) first appeared in commercial yards of the cluster cultivars in the Yakima Valley of Washington

Year	Date of emergence of first spike	Degree-day accumulation[a]	
		Air	Soil
1980	21 April	111.3 (0)	
1981	23 April	121.9 (1)	
1982	3 May	114.6 (0)	
1983	4 April	98.3 (5)	
1984	19 April	119.7 (1)	
1985	15 April	108.4 (1)	
1986	4 April	124.3 (5)	95.9 (1)
1987	7 April	102.1 (2)	83.3 (1)
1988	13 April	107.8 (1)	94.4 (0)
1989	14 April	122.4 (1)	84.4 (1)
1990	4 April	93.8 (3)	85.7 (1)
Mean	15 April	111.3	88.7
Range	29 days	30.5	12.6
Variance		106.7	35.2
Coefficient of variance (%)		9.3	6.7

[a] Base value used was 6.5 C. Values in parentheses indicate the number of days (absolute value) from the day that the yearly value occurred to the day that the mean for all years occurred.

hop crown more directly than did air temperatures. Beginning the summations after reaching a temperature threshold subsequent to a calendar date was more effective than simply beginning on the date itself.

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