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Responding to an Introduced Pathogen: *Podosphaera macularis* (Hop Powdery Mildew) in the Pacific Northwest

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Abstract

Powdery mildew of hop (*Humulus lupus* L.), which is caused by *Podosphaera macularis* (formerly *Sphaerotheca macularis*) was found in the Yakima Valley, WA in 1996 and subsequently spread to the growing regions in Oregon and northern and southern Idaho. To rapidly assist growers in reducing the cost associated with the preventive fungicide program, the Gubler/Thomas grape powdery mildew risk infection model was adapted for hops. In addition, field surveys were utilized to identify other management practices that impacted disease development. Weather networks were established and utilized to deliver daily regional maps indicating the risk index. These maps were posted to the web for daily access. Lessons learned from this experience will be useful in addressing future pathogen introductions.

In 1996, despite years of quarantine efforts, *Podosphaera macularis* [Braun] {formerly *Sphaerotheca macularis* [Wallr.:Fr] Lind. (synonym *S. humuli* [DC.] Burrill)} was reported on *Humulus lupulus* L. (hops) for the first time in the Pacific Northwest (3). Hop powdery mildew (HPM) was found first on greenhouse-grown plants in the lower Yakima Valley in June 1996 and in another greenhouse in April 1997 near Toppenish, WA (45 miles distant from first occurrence). The disease was not observed in the field until June 1997. By July the disease was found throughout the Washington hop-growing region and resulted in the complete loss of 810 hectares (US$10,000,000) of a highly susceptible variety. HPM was not observed in Oregon or Idaho until July 1998. Currently, hop powdery mildew epidemics occur annually in all production regions.

In the Pacific Northwest, annual losses attributed to HPM and its management are estimated to be 15% or US$988/ha (US Hop Industry Plant Protection Committee, 2001). In 2001, 50% of the aroma variety 'Willamette' grown in Oregon was rejected by the contracting brewery due to cone browning after drying (attributed to nonvisible infections of *P. macularis* [Mahaffee, *unpublished*]) resulting in an additional US$5 million in losses that year. These nonvisible infections have also been linked to early maturing in other varieties, resulting in reduced alpha-acid (Mahaffee, *unpublished*). Such losses have added to the effects of an economic depression in the hop market and have placed several growers into bank receivership.

In Europe, HPM is managed using an intensive fungicide program augmented with labor-intensive cultural practices. Although this program was initially adopted by Pacific Northwest growers, it is not considered an economically sustainable approach for disease management on the large scale of US hop farms due to its exorbitant cost. In order to economically manage HPM, growers needed to minimize fungicide applications and develop cultural practices that reduced inoculum and management costs. Growers must also be concerned about pesticide resistance management due to the number of pesticide applications used and the fecundity of the pathogen. Methods that reduce the number of pesticide applications or appropriately time their application would be useful in delaying resistance development.

In order to accomplish these goals, an increased understanding of the effects of environmental parameters on disease development in hop yards was needed. Extensive field surveys were conducted in 1999-2000 in conjunction with controlled environment studies to develop the data needed to adapt the Gubler/Thomas risk index of grape powdery mildew and identify or adapt cultural practices to facilitate HPM management.

The information presented below is a brief summary of the data and concepts that have been developed since the fall of 1998. Rapid solutions were made possible by extracting from practices and disease risk models used to control powdery mildew in other crops instead of starting everything anew for HPM.

Initial Inoculum and Spread

Flagshoots, early spring shoots colonized by *P. macularis*, serve as the initial source of inoculum in the Pacific Northwest (5) . Cleistothecia have not been observed (3; Mahaffee, *unpublished*). Field surveys of hop yards in Washington and Oregon conducted from 1999 to 2002 revealed that flagshoots are found on average in about 1.8% of the hills in Washington and 0.02% of the hills in Oregon (5; Mahaffee, *unpublished*). The practice of crowning (removal of buds in the upper 5 to 8 cm of soil in early spring) for downy mildew control in Oregon appears to be the main reason for the differences between Oregon and Washington.

Secondary spread (conidial infection that occurs after pruning but before training) appears to be strongly correlated to the quality of pruning (5). Pruning is a practice Washington growers use to coordinate harvest dates. Pruning involves the removal of early spring shoot growth, either by chemical or mechanical means, in order to favor later shoot growth. Field observations and preliminary studies suggest that if all green plant material is removed with pruning and a fungicide program is initiated when 15 to 30 cm of regrowth in 50% of the hills is present, then fall or early spring crowning in Washington was not needed. Demonstration plots in 2002 indicate that this practice results in reduced secondary spread with a potential savings of $148 to $296/ha depending on the method of pruning and irrigation.

Effects of Temperature on Infection Frequency

Because information on the temperatures conducive for HPM development was needed to adapt the Gubler/Thomas model, controlled environment experiments were conducted to determine the effect of temperature on infection of leaf tissue by conidia. Three sets of experiments were conducted.

In the first set, plants were inoculated with powdery mildew conidia and exposed to constant temperatures of 12, 15, 18, 21, 24, 27, and 30°C. Disease developed at all temperatures except 30°C. However, the infection frequency and lesion size were reduced significantly at temperatures above 24°C (5). The latent periods were observed to be approximately 10 days at 12 and 15°C and 5 days at 18 to 27°C.

In the second set, plants were inoculated and exposed to temperatures of 30°C or greater for 3, 6, and 9 h and then placed at 18°C to allow disease development. This experiment was designed to determine the minimum exposure time needed at these higher temperatures to inhibit disease development. Results indicated that exposure of conidia to temperatures > 30°C for 6 h or more reduced the infection frequency by at least half with no infection occurring when conidia were exposed to temperatures greater than 36°C for as little as 3 h.

In the third set, plants were inoculated then incubated at 18°C for a period of 8, 24, or 48 hours prior to exposure to temperatures > 30°C. Exposure to 30°C and above after 8 h incubation at 18°C resulted in 50% or greater reduction in infection. Only exposure to 36, 39, or 42°C resulted in significant reduction after 24 or 48 h exposure. Young colonies (i.e., 2 days old or less) exposed to temperatures greater than 39°C for 6 h were killed.

Two additional experiments were conducted to test the effects of brief exposures to supra-conducive temperature on host susceptibility and infection potential of conidia. To examine host susceptibility, plants were grown at 18 (control), 24, 26, 28, 30, or 32°C for 10 days, then inoculated and placed back in their respective chambers for an additional 0, 24, or 240 h. The 0 and 24 h treatments were placed at 18°C for 10 and 9 days, respectively, after exposure to supra-conducive temperatures. Plants grown at 32°C with 0 h additional exposure to supra-conducive temperatures had 80% less disease than those grown at 18°C with 0 h exposure to supra-conducive temperatures.

To examine the infection potential of conidia, 10-day-old colonies on plants grown at 18°C were exposed to temperatures of 30°C or greater for 6 h then incubated at 18°C for 15 h. Conidia were harvested from each plant and inoculated onto another set of plants, incubated at 18°C for 7 days and then rated for the development of disease. Plants which were inoculated with conidia exposed to temperatures of 30°C and greater had at least 70% fewer lesions than plants inoculated with conidia exposed to constant 18°C.

Field Surveys

Intensive surveys were conducted in Oregon and Washington in 1999-2001 to determine the effect of various factors on epidemic development. Two important observations were made. First, a strong relationship ($r^2 = 0.68$) between cone and leaf disease incidence (averaged over the season or as an area under the disease progress curve) was found, indicating that managing disease development on leaves would reduce cone infections. Second, disease incidence was much greater in Washington than in Oregon and Idaho (5). This regional difference facilitated the elucidation of parameters and control measures that impacted disease development.

Analysis of disease data from field surveys corroborates growth chamber studies in that disease development is observed to be most rapid in spring and late summer, when temperatures are most favorable for disease development and there is an abundance of young, susceptible tissue present. Furthermore, there is a strong correlation between disease development and the date at which the first fungicide was applied, but not between disease development and the number of applications or amount of active ingredient applied. Thus, it appears that managing powdery mildew in all regions is largely dependent on early season control measures.

Rainfall appears to negatively impact disease development. Both Oregon and Washington have highly favorable temperatures from March through June for infection of hop by *P. macularis*. However, disease development is limited in Oregon during this period. Hop production in Washington is in a very arid region receiving only 25 cm of annual rainfall, while the Willamette Valley in Oregon receives an average of 121 cm of rainfall per year with 30 cm occurring March to May and 9.7 cm from June to August. In Oregon, the most rapid development of the epidemic occurs once the rainy season has ended, late June through August. The Oregon spring rains result in extended periods of leaf wetness (often 48 to 72 hours), which appears to be unfavorable to *P. macularis* conidia dispersal and germination.

Results from field surveys also indicate that disease development is reduced greatly during summer, when ambient temperatures reach well above 30°C for the majority of the day in Washington and southern Idaho and periodically in Oregon. Consequently, later-season control measures do not need to be applied at the same intensity as in the early to mid-season. So far, results from growers' fields have validated these observations. In Washington, some growers stop fungicide applications in mid-July even though harvest will not occur until mid-September with only slight increases in field disease levels.

Risk Assessment Model

A disease forecasting model for hop powdery mildew was developed by modifying and adding rules to the Gubler/Thomas model for grape powdery mildew (1,4) using the results from controlled environment studies (5) and field surveys discussed above. The model calculates an infection risk index using temperature (15-min intervals) and daily rainfall from 6:15 a.m. to 6:00 a.m. the next day as model inputs. The value of the infection risk index is used to determine the spray interval (number of days) between applications (Table 1).

Table 1. Examples of treatment timing guidelines based on hop powdery mildew risk index and application material.

Infection Risk Value	Active Ingredient	Application Interval
0 to 30	Biologicals	see label**
	Copper, Sulfur	14 days**
	Bicarbonates	10 days**
	DMI fungicides*	18 days**
	Oils	14 days**
	Strobilurins	14 days**
40 to 60	Biologicals	see label
	Copper, Sulfur	10 days
	Bicarbonates	8 days
	DMI fungicides*	10 days
	Oils	10 days
	Strobilurins	14 days
70 to 100	Biologicals	see label***
	Copper, Sulfur	7 days***
	Bicarbonates	7 days***
	DMI fungicides*	10 days***
	Oils	7 days***
	Strobilurins	7 days***

* Demethylation inhibitors such as tebuconazole or myclobutanil
** or labeled maximum
*** or labeled minimum
Legal uses of pesticides are constantly changing, therefore always obtain and review a label prior to any using any product.

The model starts for the season either when 15 to 30 cm of growth from 50% of the hills is observed at bud break or when 15 to 30 cm of regrowth is observed after spring pruning. In 2001, the infection index increases by 20 points on days where: (a) a minimum of six continuous hours of temperatures (T) occurred such that 16°C $\leq$ T $\leq$ 27°C; (b) there were less than 6 hours with temperatures above 30°C; and (c) less than 2.5 mm of rainfall occurred on that day. On days when these three conditions are not met, 10 points are subtracted from the index with a minimum and maximum index of 0 and 100, respectively.

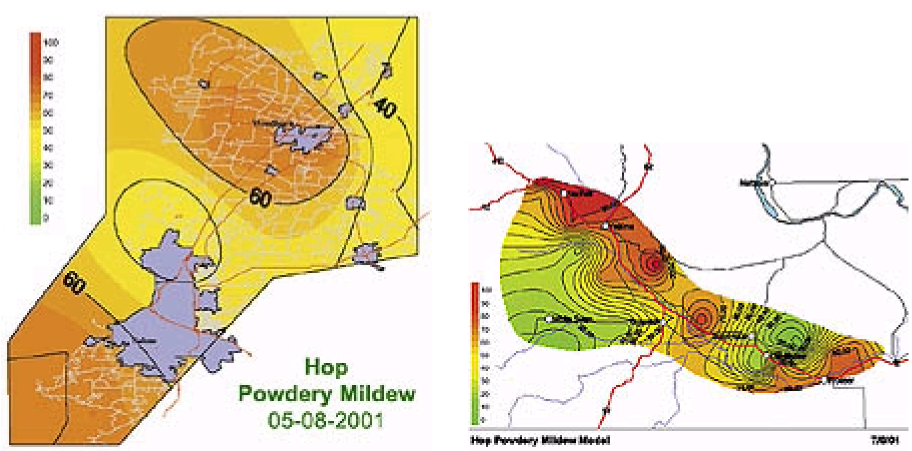
Fifteen and 27 fields were regularly monitored for disease development in Oregon and Washington, respectively. Each grower was asked to split the field such that half was managed according to the model and the other half using their "standard" methods. However, no grower maintained the split fields for the duration of the season. Growers reported either that they followed the model or that they did not. Instead of following the specific guidelines on spray intervals, growers integrated their scouting reports and the risk index rules to shorten and extend application intervals based upon the logistics of their ranch. On average, growers reporting using the model made 9.1 fungicide applications resulting in 9.33% cone incidence of mildew infection while growers indicating they did not use the model made 10.3 fungicide applications and had 23.9% cones infected. The model did appear to overestimate infection risk in July and August. This overestimation was likely due to the effects of temperature on plant susceptibility and conidia production as indicated by the controlled environment experiments (described above).

The model was validated, in part, by programming growth chambers with hourly temperature data from specific days and placing inoculated plants in these conditions for 24 h before incubating at 18°C for 9 days. Assessment of 6 individual days, representing 2 marginally conducive days (i.e., only 6 hours with temperatures between 16 to 27°C) and 4 nonconducive days, indicated that there was little or no infection on nonconducive days, with abundant infection on marginally conducive days.

Based upon 2001 field observations and additional controlled environment experiments, new rules were developed. In 2002, the model consisted of the following rules applied in the specified order: (i) If there were greater than six continuous hours above 30°C, then subtract 20 points, else; (ii) If there were greater than 2.5 mm rainfall, then subtract 10 points, else; (iii) If there were greater than six continuous hours above 30°C on the previous day, then no change in the index, else; (iv) If there were at least six continuous hours of temperatures between 16 and 27°C, then add 20 points, else; (v) If none of the above rules apply, then subtract 10 points. If a rule is true, then none of the subsequent rules take effect. This model is currently being validated in grower fields and small plots.

Delivery of the Forecasts

The risk index was delivered to growers daily using three web sites (Fig. 1). To increase the utility of the risk index, a five-day forecast was developed in partnership with FieldWise and Fox Weather (Fig. 2). National and regional weather forecasts were adapted for each weather station using proprietary algorithms and historical site-specific weather data. The forecast was posted to a web page every evening (Fig. 2) and contained predicted high and low temperature, humidity, wind, and predicted rainfall in addition to the predicted risk index. Growers utilize this information to better judge whether to shorten or extend spray intervals. The utility of the weather disease forecast is being validated in 2002, with current accuracies of 84, 71, 65, 55, and 48% for 1, 2, 3, 4, and 5 days in advance, respectively. The forecast looks like a very promising addition to the risk infection index, since it helps the grower better plan applications. Currently, approximately 60% of hop acreage in Oregon, Washington, and Idaho is managed using the infection risk model. Increased use is expected once the 5-day forecast is available to all growers.



A B

Fig. 1. Examples of regional maps generated from weather networks. Model values are determined for each weather station and values between sites are interpolated using geostatistics. Color coding is provided for the map index values. (A) Regional map of the Willamette Valley, Oregon; (B) Regional map of the Yakima Valley, Washington.

Fig. 2. Example weather and infection risk index forecast for an individual station.

Lessons Learned

The urgency of having to control an introduced pathogen with the potential to cause complete crop loss with little or no first-hand knowledge brings numerous challenges while creating a unique synergy between growers, researchers, private industry, processors, and information service providers that facilitate rapid acceptance and implementation of control measures. In both 2001 and 2002, most of the growers cooperating on the validation of the model ended up using the model on all their fields based on the early-season success. Due to the perceived early success of the research and its impact on reducing costs, it has been difficult to observe fields that were not being managed according to our research proposals.

In addressing this crisis, numerous lessons have been learned that could facilitate the response to future introductions of other plant pathogens. Representatives from the Environmental Protection Agency (individuals involved in granting FIFRA Section 18 or 24c exemptions for pesticides), the state's department of agriculture, research institutions, private industry, information service providers, processors/dealers, and grower commissions for the affected regions as well as neighboring states or growing regions should be involved in all decisions regarding research direction, possible eradication efforts, and assessment and monitoring efforts. Involve any potential industry partners as soon as you can identify them in order to develop systems around their expertise and ensure rapid deployment of research results. They often have the knowledge you are trying to create and have cost-effective systems for information retrieval and delivery. Remember, it is more important to figure out how to contain, control, or eradicate the pathogen than to figure out how it got there. Consider modifying an existing model instead of starting anew. Involve experience that covers a broad range of crops, but the same type of pathogen, to find the commonalities. Do not assume spread will be slow or geographically limited and that quarantines will work. Immediately establish a rapid method of communication and protocol for posting and disseminating information. Postings should be sent to all members instead of only individuals thought to need the information. Set strict timelines for when all decisions must be made, even if they have to be made with incomplete information, and establish methods for monitoring progress. Constantly reassess the direction of all activities and do not be afraid to change midstream. Establish clear responsibilities for all individuals but do not set strict limits. All data should be shared with other researchers, even failures. Opinions or interpretations of the data will differ with the group. Thus, do not be afraid to present all sides to the growers. They need to understand the risk but they still have to act.

While there is still a lot to be learned about HPM and its management, an integrated control system is in place that has returned viable economics to hop production. Initial control costs of $1,400/ha in 1998 have been reduced to $740/ha on average and disease levels have been greatly reduced. It does not appear that the introduction of HPM into the Pacific Northwest will have the same impact as past introductions (2). Unlike New York and California, hop production in the Pacific Northwest is likely to continue. We are no longer in crisis management mode, and are instead beginning to take advantage of the synergy among the group to develop novel management approaches to all aspects of hop production and extend this knowledge into management of other crops.

In the future, as in this case, the ability to rapidly respond and develop economical management options for an introduced pathogen will be dependent on blending the resources and expertise of the private industry, public research, the growers, and other interested parties. The rapid delivery and implementation, and thus the economic savings, of this effort would not have been possible without the extensive knowledge and developed technology from FieldWise and Fox Weather, complemented by the research capacity and grower connections of the public researchers and by the input of growers and processors.

Disclaimer and Acknowledgments

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