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# Risk Factors and Modeling of Powdery Mildew Occurrence on Hop Cones

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## ABSTRACT

Powdery mildew of hop (caused by *Podosphaera macularis*) can substantially reduce crop cone yield and quality. Risk factors associated with the incidence (proportion) of diseased cones were identified and formalized in a linear mixed model based on published data from 12 fungicide efficacy trials conducted during 2000 to 2008. Models that included risk factors of disease incidence on leaves, rain, temperature, and fungicide timing during critical cone developmental stages, explained 87 to 91% of the variability in observed incidence of diseased cones. Predictions of disease levels in 2009 with data sets collected independently of those used for model development (validation data sets) were imprecise ($R^2$ = 0.55), in part because fungicide effect were not represented accurately. When the fungicide effect variable was revised, the model explained 74% of the variability in the observed incidence of diseased cones in validation data sets. Sensitivity analyses indicated that the effect of fungicide application timing is substantial, and suggests appropriate timing of efficacious treatments is critical for minimizing levels of powdery mildew at harvest. Future research is planned to link the disease risk model to a crop damage function to inform and optimize late season management decisions for powdery mildew.

**Figure 1.** Hop cones with powdery mildew, resulting in malformation and discoloration.

## MATERIALS AND METHODS

Data on the incidence of diseased cones, leaves, and fungicide applications was obtained from 12 fungicide trials conducted by Washington State University during 2000 to 2008, a total of 114 treatment evaluations (data sets). Weather data near the field site were obtained from the nearest regional weather station, and used to calculate potential predictor variables for cone infection. Preliminary identification of factors associated with cone infection was conducted by creating scatter plots of the incidence of diseased cones and weather and inoculum variables, and calculation of Spearman's correlation coefficient.

A set of predictor variables highly correlated with the incidence of diseased cones were combined in a linear mixed model in SAS version 9.2 assuming that the effect of trial nested within year was a random effect. Disease incidence values were logit transformed to restrict model predictions between 0 and 1. Final models were selected based on Akaike Information Criterion, the number of predictor variables, and biological considerations of the interpretation of the variables. After inspection of predictions in the model development data set, the model was evaluated with data collected from commercial hop yards of cultivars Galena, Columbus, Tomahawk, and Zeus during 2000 to 2007. The model also was evaluated and updated with data from 32 treatments evaluated in two fungicide trials conducted in 2009. The incidence of diseased cones observed in 2009 was compared to model predictions of disease incidence to evaluate forecast skill and potential biases in the model. After this evaluation, the model parameters were estimated again with the full data set (including 2009 data) to improve parameter estimates.

## RESULTS

•Independent variables selected after inspection of numerous variables and preliminary models were maximum mean disease incidence on leaves between mid-July to mid-August (Fig. 2A), log-transformed millimeters of rain from 30 July to harvest, number of days when temperature was greater than or equal to 33.9ºC (93ºF) from 30 July to harvest, a binary indicator variable for application of a quinoline fungicide (Quintec) or boscalid + pyraclostrobin (Pristine) during 27 July to 10 Aug (referred to as 'fungicide program') (Fig. 2B), and an interaction variable for disease incidence on leaves and the fungicide program.

•Models developed with data from 2000 to 2008 and 2000 to 2009 explained 91% and 87%, respectively, of the variability in observed incidence of diseased cones (Fig. 3A). Parameter estimates for the preliminary model are given in Table 1, and can be used to estimate disease incidence on cones after back transformation by $y = 1/(1+\exp(-x))$.

•Some bias was evident, as the model overestimated disease incidence on some years (2007) and under estimated disease incidence during others (2006).

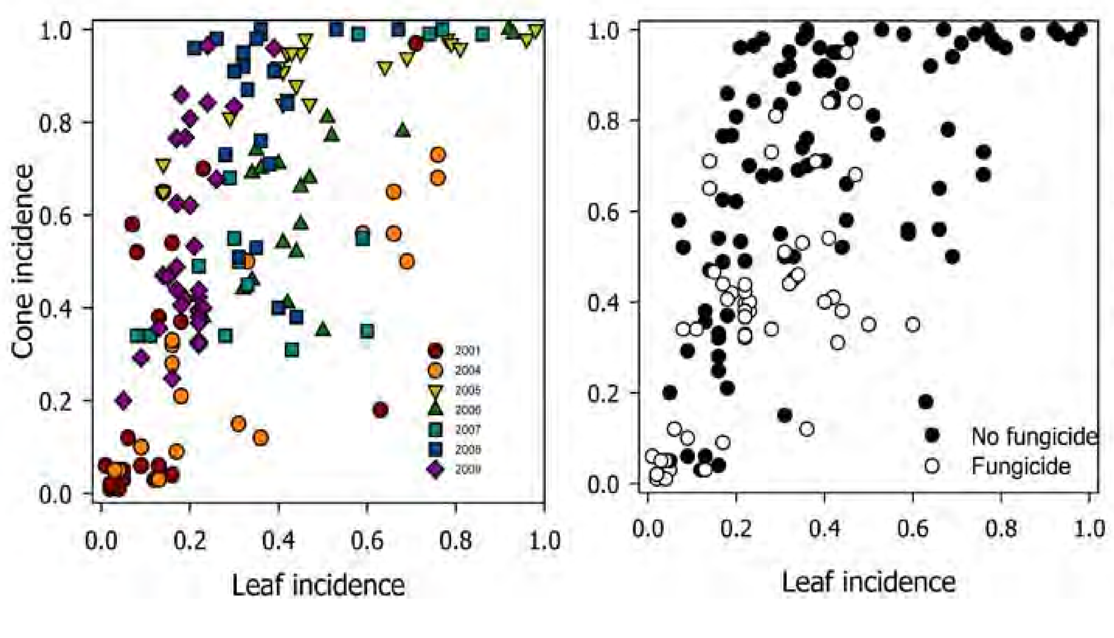


**Figure 2. A,** Association of the incidence of leaves with powdery mildew and the incidence of cones with powdery mildew in trials conducted during 2000 to 2009. The same data is presented in **B** with the open circles indicating plots that received an application of a quinoline fungicide (e.g., Quintec) or boscalid + pyraclostrobin (Pristine) during 27 July to 10 Aug. This time period appears to be a critical developmental stage for cone infection.

**Table 1.** Fixed effect variables and parameter estimates for cone infection model

| Effect[ab] | Estimate | Standard error | *P* |
|---|---|---|---|
| Intercept | 0.2244 | 0.614 | 0.7211 |
| Leaf incidence | 0.8385 | 0.086 | <.0001 |
| Leaf incidence*Fungicide | -0.3547 | 0.133 | 0.0088 |
| Fungicide-0 | 1.7381 | 0.228 | <00001 |
| Fungicide-1 | 0 | . | . |
| Log-rain | 1.5950 | 0.525 | 0.0029 |
| Days temperature ≥33.8ºC | -0.1905 | 0.053 | 0.0004 |

[a] Variables were calculated from 30 July to harvest. Fungicide is an indicator variable for the fungicide program defined in the text, where 0 = the fungicide program was not applied and 1 = the fungicide program was applied.

[b] Leaf incidence was calculated as the maximum mean incidence of diseased leaves between 15 July and 15 August for Moxee and Yakima Indian Reservation, or between 1 July and 1 August for yards in the lower Yakima Valley. Leaf incidence*fungicide is a variable for the product of leaf incidence and application (1 or 0) of quinoline fungicide or boscalid + pyraclostrobin between 27 July and 10 August.

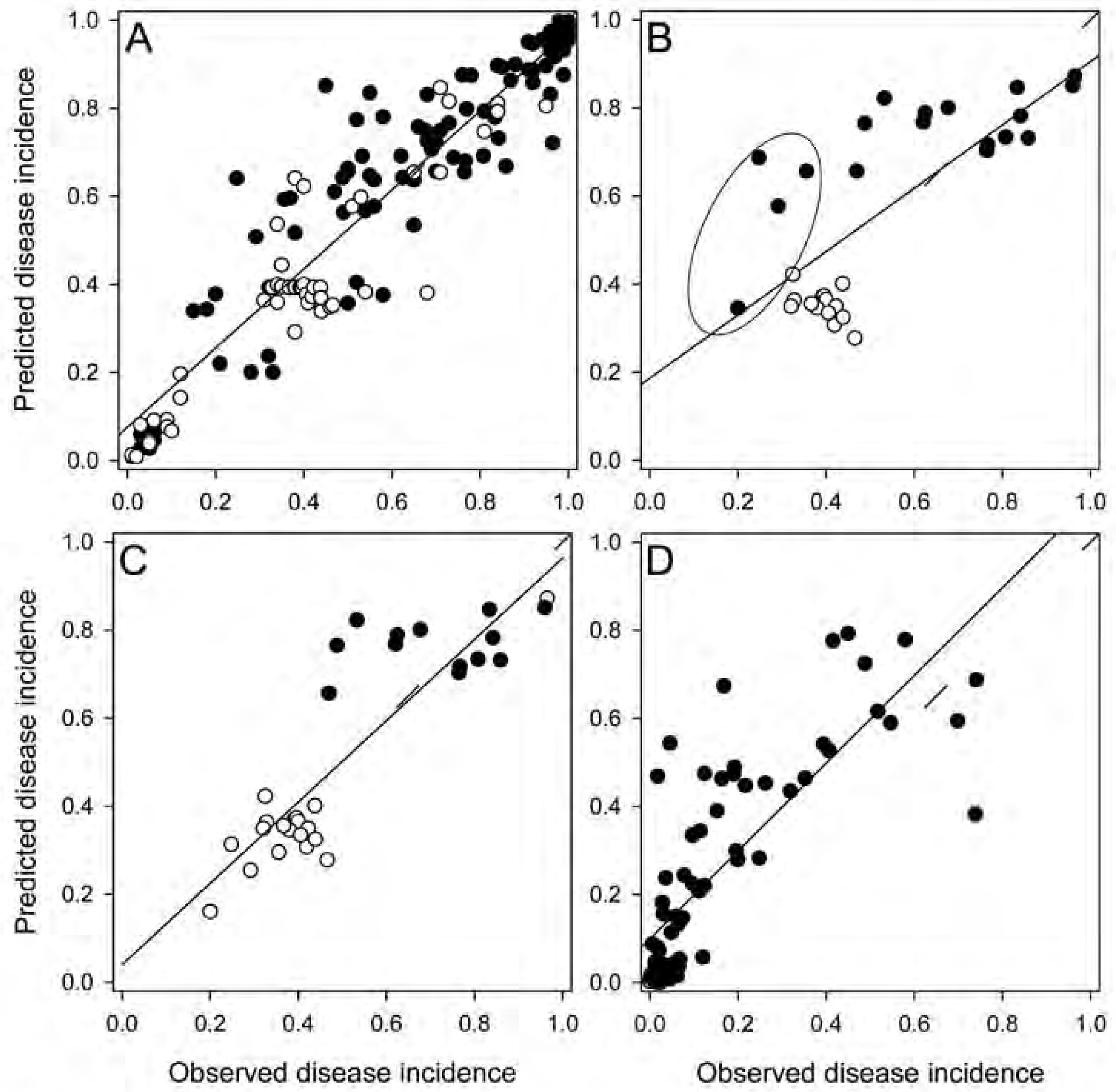


**Figure 3. A,** Model estimates of the incidence of cones with powdery mildew in Washington based on data in experimental plots from 2000 to 2009. **B,** Prediction of observed disease incidence in 2009 with the model developed with data from 2000 to 2008. The circled data points indicates plots where the fungicide effect was revised in **C** to better reflect fungicide effects on cone infection. **D,** Predictions of disease incidence in commercial yards during 2000 to 2007. Open circles in **A to C** indicate plots that received an application of a quinoline fungicide or boscalid + pyraclostrobin between 27 July and 10 August **(A and B),** or 22 July to 10 August **(C).**

•Prediction of 2009 disease levels with the model developed with data from 2000 to 2008 was imprecise ($R^2$ = 0.55; Fig. 3B), which was related in part to accounting for fungicide effects. When the fungicide effect for these observations were revised to consider the critical period from 22 July to 10 August, the model explained 74% of the variability in disease incidence in the 2009 data sets (Fig. 3C).

•Estimates of cone infection in commercial yards with the model were $R^2$ = 0.30 when the model was applied directly. Inspection of data sets where the model did not estimate disease incidence accurately indicated that early termination of fungicide applications by the grower before 10 August was associated with underestimation of disease.

•A correction factor for early termination of fungicide applications was developed by an iterative procedure. Rules were developed that if: (i) the last application of a synthetic fungicide was made before 10 Aug; or (ii) the interval between the last two fungicide applications was greater than 27 days, then add 1.43 to the model prediction, i.e., $y = 1/(1+\exp(-(x+1.43)))$. When this correction factor was applied, the model explained 63% of the variability in measured cone incidence (Fig. 3D).

•Sensitivity analysis indicated that the timing of highly efficacious fungicide treatments during the critical period of cone susceptibility is very important in estimating the final incidence of powdery mildew on cones.

## DISCUSSION

Development and early evaluation of these models has helped to identify several risk factors for cone infection, namely disease incidence on leaves, rain and temperature during cone development, fungicide application timing, and the date of the last fungicide application. The effect of the fungicide application timing is particularly substantial, and suggests appropriate timing of efficacious treatments is critical for minimizing levels of powdery mildew at harvest. Based on the 2009 predictions, the critical time period for defining the fungicide effect and leaf incidence x fungicide interaction is not precisely defined yet and may occur before 27 July in some years or situations, perhaps in response to crop phenology. A final year of validation is planned for 2010. The cone infection model will then be linked to a damage function and evaluated for its ability to improve late-season disease management decisions.

## LITERATURE CONSULTED

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