Potato Late Blight Forecasting Models for the Semiarid Environment of South-Central Washington

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ABSTRACT

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Relationships between weather and outbreaks of potato late blight in the semiarid environment of south-central Washington for a 25-year period were examined with linear discriminant and logistic regression analyses. The response variable was a year either with or without a late blight outbreak. A linear discriminant function with an indicator variable for the occurrence of an outbreak during the preceding year (Y_p), number of days of rain during April and May (R_{am}), and number of days of rain during July and August (R_{ja}) correctly classified the disease status for 92% of the years. The percentage of years with disease outbreaks correctly classified (sensitivity) and years without disease correctly classified (specificity) were each 92%. A second linear discriminant function with Y_p, R_{am}, and total precipitation during May when daily minimum temperature was ≥5°C (P_m) correctly classified the disease status for 88% of the years, with a sensitivity of 92% and a specificity of 85%. Logistic regression, which unlike discriminant analysis does not assume multivariate normality, led to similar results. These results suggest that the relative disease status of a given year can be predicted before the first of June, which is 4 to 10 weeks after planting and 14 days before late blight has been observed in this region in any year. With this system, growers can be alerted relatively early in the growing season of the likelihood of a late blight outbreak in the region, providing sufficient time to thoroughly monitor individual fields and initiate fungicide sprays.

Additional keywords: *Phytophthora infestans.*

In the semiarid environment of south-central Washington, late blight, caused by *Phytophthora infestans* (Mont.) de Bary, was first identified on potato, *Solanum tuberosum* L., during 1947 when weather was unusually cool, cloudy, and wet. It was reported next during 1974 and occurred in fields during 7 of 16 years between 1974 and 1989. More recent outbreaks have occurred during 1990 to 1994. Several factors may have contributed to the recent outbreaks of late blight in the region, including above average precipitation (19), an increased proportion of the *P. infestans* population that is insensitive to the fungicide metalaxyl (6,7,12), and expanded production of potato cultivars that are extremely susceptible to *P. infestans* (17,19).

The role of the environment in the development of late blight epidemics has been well documented (14,30,36). Cool, wet weather with rainfall and ambient relative humidity (RH) above 90% and temperatures of 7 to 21°C favor late blight development (2,22,30, 36,37). Sprinkler irrigation increases late blight in arid regions of Israel (29,31,32). Management of potato late blight has been augmented in several regions of North America and Europe by scheduling fungicide applications with environment-based disease-prediction models (2,11,16,21,23,37,38). However, little quantitative information is available on the role of weather in the development of late blight in the semiarid environment of south-central Washington, and thus, an adequate model has not been developed for irrigated potato production in this region (9).

Because late blight occurs irregularly in south-central Washington, many growers are unprepared to initiate early fungicide applications when the disease is present. Potatoes are irrigated mainly with center-pivot systems in this region. Once potato plants are infected after row closure microclimatic conditions generally are favorable for continued disease development whenever the field is irrigated (9,19). Row closure is when foliage between rows just touches and, for the main cultivar grown, Russet Burbank, generally extends from the second week of June in the southern section of the region to the end of June in the northern section. Fungicide control of late blight is protective, and to achieve the maximum effect, the first application must be made just before the fungus is introduced into the crop (15). Advance knowledge of the likelihood of a late blight outbreak in the region would be beneficial to growers to trigger disease-monitoring operations and initiate fungicide sprays.

Linear discriminant and logistic regression analyses were useful in quantifying the effect of weather on the development of hop downy mildew (18). The purposes of this study were to extend this modeling approach to better understand the role of weather on the development of late blight epidemics in a semiarid environment and to develop a forecasting model to aid in regional management of this disease.

MATERIALS AND METHODS

Weather data collected at the Irrigated Research and Extension Center near Prosser, WA (Fig. 1), were used for analyses. This location was selected because late blight in south-central Washington generally occurs first near the Columbia River, either south or east of Prosser, and then progresses northward as the season develops. Variables used in these studies include: daily total rainfall, number of days with rain ≥0.25 mm, number of consecutive days with rain ≥0.25 mm, daily and mean monthly minimum and maxi-

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mum temperatures from April through September of each year, monthly mean temperature, mean minimum temperature, and minimum temperature, number of days each month with temperatures below –17.8°C, and monthly precipitation from November through February preceding each growing season. A threshold of 0.25 mm of rain was chosen because this was the least amount of measured rain during the study period, and –17.8°C is approximately equal to 0°F and is a relative measure of coldness to many growers in the region. Air temperatures were measured at a height of 1.5 m above the soil surface, and rainfall was measured from November 1969 through 1987 with a hygrothermograph and a rain gauge, respectively, and from 1988 through 1994 with a probe thermistor (model 107, Campbell Scientific, Logan, UT) and a tipping-bucket rain gauge (Qualimetrix, Oakland CA), respectively.

Meteorological data from 1970 through 1994 were used to evaluate the effects of weather on late blight development in south-central Washington and for model development. This period represents the length of time potatoes in this region have been grown primarily under center-pivot irrigation systems (3). Potato fields in the study area were monitored regularly by growers and field men, and any suspected observations of late blight were brought to the attention of G. E. Easton or D. A. Johnson. Years in which late blight was observed in any field located within the region and was confirmed by either Easton or Johnson were classified as outbreak years. Years in which no late blight was reported were classified as nonoutbreak years.

Discriminant analysis and logistic regression were used to develop a forecasting model for late blight outbreaks (26). Examination of the raw data indicated that the prior year's outbreak status was useful in predicting the current year's outbreaks. Therefore, the prior year's outbreak status was included in nearly all models examined. Stepwise discriminant analysis was used to identify weather variables that contributed to correctly predicting outbreak occurrence. To reduce the number of independent variables considered in any one stepwise discriminant analysis, weather variables containing redundant information were considered in separate discriminant analysis runs. However, all meaningful weather variables were considered for their ability to predict outbreaks in at least one discriminant analysis. In addition, an interactive graphics package (SAS INSIGHT [33]) allowed exploration of the relationships among several weather variables and the occurrence of outbreaks to reduce the chance that effective combinations of variables would be overlooked by the stepwise analysis. Variables that appeared promising for classification of years as outbreak and nonoutbreak by stepwise discriminant analysis, interactive graphics analysis, or biological considerations were included in stepwise logistic regression analyses.

One method of evaluating prediction models is to reclassify the years used to create the models. Because this method may overestimate model performance, the cross-validation method also was used for model evaluation in discriminant analysis (SAS PROC DISCRIM), and a one-step approximation was used in logistic regression (SAS PROC LOGISTIC). Final models were selected for their ability to correctly classify years as outbreak or nonoutbreak by resubstitution and cross-classification. Sensitivity and specificity also were considered, where the former term refers to correct classification of outbreak years and the latter refers to correct classification of nonoutbreak years (10). Furthermore, variables were selected on the basis of their predictive ability in combination with other independent variables not by the strength of their one-at-a-time measure of correlation. To avoid model overspecification, models containing few independent variables were desirable.

Linear discriminant analyses assume homogeneous covariance matrices for each classification group and multivariate normality of the independent variables. Equality of covariance matrices was tested with Bartlett's modification of the likelihood ratio test (1, 27). The assumption of multivariate normality is suspect because the binary variable, outbreak/nonoutbreak, is included among the independent variables. The assumption of multivariate normality required for parametric discriminant analysis is not necessary for logistic regression to be valid (28).

RESULTS

Late blight was observed during 12 of 25 years in commercial fields, from 1970 through 1994 (Table 1). Years in which outbreaks occurred were 1974 to 1977, 1982 to 1984, and 1990 to 1994. Total areas affected by late blight during years with outbreaks varied from 40 to more than 20,000 ha. Areas cropped to potato

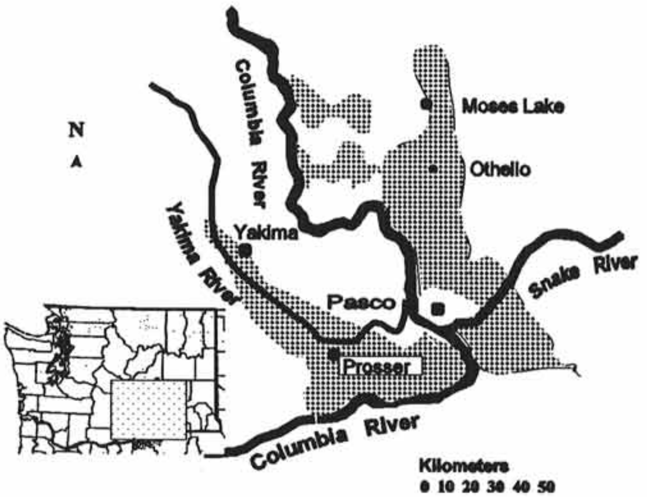

Fig. 1. Map of south-central Washington (insert) showing area of potato production studied (shaded).

TABLE 1. Area of potato production in south-central Washington affected by *Phytophthora infestans*, number of days with rain during April and May (R_{am}), number of days with rain during July and August (R_{la}), and precipitation during May when the daily minimum temperature was ≥5°C (P_m) at Prosser from 1970 through 1994

Year	Area affected[a] (ha)	R_{am} (days)	R_{la} (days)	P_m (mm)
1970	0	8	1	5.84
1971	0	9	4	6.86
1972	0	9	6	47.29
1973	0	6	1	8.89
1974	50	16	6	7.37
1975	810	10	7	5.08
1976	120	12	12	3.30
1977	40	10	4	11.44
1978	0	11	10	14.99
1979	0	8	9	4.06
1980	0	13	1	37.84
1981	0	8	3	18.54
1982	10,100	15	6	7.87
1983	14,150	9	12	11.68
1984	150	17	1	9.15
1985	0	5	4	11.43
1986	0	8	3	8.13
1987	0	5	5	4.83
1988	0	15	3	11.93
1989	0	12	8	13.70
1990	250	12	10	19.04
1991	>15,000	11	4	13.71
1992	>20,000	12	6	0.51
1993	>15,000	20	9	18.29
1994	530	16	2	25.15
Mean ± SE[b]	6,350[c]	11.1 ± 0.8	5.5 ± 0.7	13.08 ± 2.08

[a] Values are estimates. Area cropped to potatoes varied between 30,400 and 50,200 ha.

[b] Mean ± standard error of the mean.

[c] Mean when late blight was reported.

in south-central Washington varied from 30,400 to 41,300 ha in the 1970s, from 35,200 to 50,200 ha in the 1980s, and from 45,300 to 53,400 ha in 1990 through 1994.

Two models were selected to describe the occurrence of late blight outbreaks by a combination of stepwise discriminant analysis (SAS STEPDISC), stepwise logistic regression (SAS LOGISTIC), and graphic analysis (SAS INSIGHT). Models that correctly classified most years with discriminant functions, logistic regressions, and cross-validation were identified. For the first model (model 1), an indicator variable for the presence of a late blight outbreak during the preceding year (Y_p), number of days of rain during April and May (R_{am}), and number of days of rain during July and August (R_{ja}) were selected as predictors. For the second model (model 2), Y_p, R_{am}, and total precipitation during May when the daily minimum temperature was $\geq 5°C$ (P_m) were selected as predictors.

Classification functions obtained from the discriminant analysis for model 1 were nonoutbreak: $-5.636 + 1.774(Y_p, 1 = \text{yes}, 0 = \text{no}) + 0.974(R_{am}) + 0.500(R_{ja})$; and outbreak: $-14.546 + 5.776(Y_p, 1 = \text{yes}, 0 = \text{no}) + 1.506(R_{am}) + 0.711(R_{ja})$. Classification functions for model 2 were nonoutbreak: $-4.426 + 2.052(Y_p) + 0.863(R_{am}) + 0.052(P_m)$; and outbreak: $-11.886 + 6.191(Y_p) + 1.462(R_{am}) - 0.033(P_m)$. Years were classified as outbreak or nonoutbreak based on which function had the largest calculated value. Values of the independent variables for each year are listed in Table 1.

Classification functions obtained from the discriminant analysis correctly classified 23 of 25 years (92%) for model 1 and 22 of 25 years (88%) for model 2. Sensitivity and specificity were high for both models (Table 2). Misclassified years were 1978 and 1990 (one nonoutbreak year and one outbreak year) for model 1 and 1978, 1988, and 1990 (two nonoutbreak years and one outbreak year) for model 2. Homogeneity of within-group covariance matrices, a necessary assumption for discriminant analysis, was not rejected for either model ($P = 0.7485$ and $P = 0.6593$, respectively).

The cross-validation analysis correctly classified 84 and 88% of the years with respect to an outbreak or nonoutbreak for models 1 and 2, respectively. Sensitivity and specificity were high for both models (Table 2). Misclassified years were 1978, 1982, 1988, and 1990 for model 1 and the same for model 2, except for 1982, which model 2 correctly classified.

Logistic regression was used for classification in the following manner: for model 1, the likelihood function was computed: $lf = 11.470 - 3.880(Y_p, 1 = \text{yes}, 0 = \text{no}) - 0.716(R_{am}) - 0.259(R_{ja})$; for model 2, the likelihood function was computed: $lf = 7.548 - 3.553(Y_p) - 0.629(R_{am}) + 0.090(P_m)$. Next PROB was determined: $\text{PROB} = 1/[1 + \exp(lf)]$. If PROB was <0.5, then the year was classified as nonoutbreak; if PROB was ≥ 0.5, then the year was classified as outbreak. The likelihood ratio chi-square, with 3 df for testing the significance of the models, was 20.914 for model 1 and 20.539 for model 2.

TABLE 2. Accuracy, sensitivity, and specificity of two sets of variables used to predict potato late blight when analyzed by linear discriminant and logistic regression analyses

	Independent variables[a]	
Analysis	Y_p, R_{am}, R_{ja}	Y_p, R_{am}, P_m
Discriminant[b]	92	88
Sensitivity[c]	92	92
Specificity[d]	92	85
Cross-validation[b]	84	88
Sensitivity	83	92
Specificity	85	85
Logistic regression[b]	88	88
Sensitivity	92	92
Specificity	85	85

[a] Y_p (no = 0, yes = 1) = indicator variable for the presence of a late blight outbreak during the preceding year; R_{am} = number of rainy days during April and May; R_{ja} = number of rainy days during July and August; and P_m = total precipitation (in millimeters) during May when the daily minimum temperature was $\geq 5°C$.

[b] Accuracy = percentage of years with or without late blight outbreak classified correctly.

[c] Sensitivity = percentage of years with late blight outbreaks classified correctly.

[d] Specificity = percentage of years without outbreaks classified correctly.

The logistic regression function correctly classified 88% of the years as outbreak or nonoutbreak for both models. Sensitivity and specificity were high for both models (Table 2). Misclassified years were 1978, 1988, and 1990 for both models.

DISCUSSION

Meteorological factors apparently have a major influence on late blight development in south-central Washington. The number of rainy days during April and May, number of rainy days during July and August, and total precipitation during May when the daily minimum temperature was $\geq 5°C$ were good indicators of late blight outbreaks.

Using the models developed in this study, forecasts for the occurrence of late blight could be made each year on 1 June. This is 4 to 10 weeks after planting and 14 days before late blight was observed in any year studied. The values of the three variables, Y_p, R_{am}, and P_m, from model 2 would be available on 1 June, and both discriminant and logistic functions could be used. If model criteria for the occurrence of a late blight outbreak were fulfilled before 1 June, a forecast for the potential occurrence of an outbreak could be made earlier.

Model 1 could be used through July and August if late blight had not been observed earlier. The value of one of three variables of model 1, R_{ja}, would not be available until 31 August, but the model could be used by solving for the value of R_{ja} needed for an outbreak to occur and comparing it to the normal (mean for 25-year period = 5.5 days; Table 1) and expected occurrences of rainy days during July and August based on weather forecasts. The calculations could be made repeatedly, and the forecast could be updated as weather and crop conditions changed during July and August.

These empirically based forecasts for the presence or absence of late blight would be general in nature, advising growers near the beginning of the growing season of the likelihood of an outbreak. Such warning is important in Washington, where late blight is sporadic in occurrence and growers are not accustomed to applying fungicides early in the season. When a late blight outbreak is likely, growers can monitor individual fields more thoroughly and initiate fungicide sprays in areas with a history of early occurrence of late blight before row closure.

Several late blight forecasting systems have used weather variables to successfully forecast the initial occurrence of late blight in a region (2,16,24,35,37). Two of these are systems developed in Holland by Van Everdingen (35) and in England by Beaumont (2). The "Dutch rules" developed by Van Everdingen (35) consist of (i) dew during at least 4 h at night, (ii) a minimum temperature of 10°C or higher, (iii) mean cloudiness of 0.8 or more on the next day, and (iv) measurable rainfall during the next 24 h. Control measures are recommended when all four conditions are obtained (35). Beaumont (2) developed the "temperature-humidity rule" in England, which consists of two or more consecutive days with (i) minimum temperature not less than 10°C, and (ii) relative humidity not below 75%. In these cases late blight is expected 15 to 21 days later.

Model 2 in this study is more useful than model 1 because it can be used directly in making late blight forecasts early in the season. It also correctly classified more years and had a higher sensitivity with the cross-validation for the discriminant analyses. A high sensitivity would be more desirable than a high specificity in models used in Washington because it is probably better to be expecting an outbreak and not to experience one than not to expect an outbreak and have one occur.

The importance of initial inoculum for the development of late blight epidemics has long been recognized, and many weather-based forecasting models make the assumption that initial inoculum is constantly present (23). In this study, initial inoculum was identified as an important factor for the development of late blight outbreaks by including an indicator variable for the presence of an outbreak during the preceding year. If an outbreak occurred during the preceding year, there was a greater likelihood that inoculum would survive the winter in infected tubers buried in soil, in cull piles, or held in storage. Easton (9) concluded that cold winters eliminated overwintering inoculum. However, we did not find an effect of low winter temperatures on late blight development during the following year. This may be due to infected tubers being buried below the frost line in fields or infected tubers being removed from storage and placed in refuse piles in late winter. Infected seed tubers brought into Washington from seed-production areas with late blight during the previous year also may have been sources of initial inoculum.

The relative importance of infected seed in the production of initial inoculum is unknown. MacKenzie (23) thought that the likelihood of initial inoculum coming from seed was high when one considered that tubers can be infected and that 2 tons of seed are needed to plant 1 ha of potatoes. The actual proportion of blighted tubers in seed stocks is unknown and is often assumed to be at a low level (15,23). *P. infestans* and other organisms usually rot late blight-infected tubers, preventing sprouting and, thus, infection of sprouts (22,34). Hirst and Stedman (15) found that of 3,260 infected tubers planted as seed in five successive years, 0.64% produced stems invaded from below ground by *P. infestans*. Infected tubers at or near the soil surface are considered the main source of inoculum in central Washington (3). Infected tubers in refuse dumps are frequently considered the most important and effective sources of primary *P. infestans* inoculum quantitatively (4,5). Certainly, the three sources of tuber-borne inoculum, infected tubers as culls, volunteer potatoes, and seed, must be considered in managing late blight. A low level of initial inoculum is assumed by BLITECAST, and high-quality seed and good sanitation practices are important requirements for the successful operation of BLITECAST (23) and the models in this study.

In addition to initial inoculum, early season rain was an important indicator of late blight outbreaks. Favorable weather conditions were needed for inoculum to multiply in fields containing volunteer potatoes, in cull piles, in fields with infected seed, and for dissemination of sporangia to additional fields. Sporangia are sensitive to drying (25,39) and are disseminated most effectively from field to field during rainy periods (15). Once potato plants in a commercial irrigated field are infected after row closure, microclimate conditions generally are favorable for continued late blight development (9,19).

Mean monthly maximum temperatures of up to 30°C during June, 32°C during July, and 33°C during August and daily maximum temperatures of up to 41°C did not appear to deter late blight development, as indicated by the absence of a high temperature variable in our models. Wallin (36) reported that dehisced sporangia of *P. infestans* survived through the afternoon and into the evening on potato leaves when afternoon temperatures were 27 to 31°C but did not survive when temperatures were above 32°C. In growth chambers, dehisced sporangia at 30°C lost their infectivity after 8 h of exposure to 50% RH or after 24 h of exposure to 80% RH (29). However, even under the extremely unfavorable conditions of temperatures at 30, 35, or 40°C that usually prevail only temporarily, mycelium of *P. infestans* survived in leaf and stem tissue and was able to produce sporangia when conditions again became favorable (20,29).

The nonoutbreak year 1978 and the outbreak year 1990 were incorrectly classified with both linear discriminant and logistic regression analyses. The nonoutbreak year 1988 was incorrectly classified by all selected models and methods of analysis, except in model 1 by discriminant analysis. Either a relatively small outbreak or a lack of initial inoculum during wet years led to the incorrect classifications. The nonoutbreak year 1978 was preceded by a year that was classified as an outbreak year; however, the outbreak in 1977 was limited to about 40 ha on one farm. Apparently, because of the small area affected in 1977, inoculum did not survive to the 1978 season when moisture conditions were favorable for late blight development. Sufficient rainfall occurred for late blight development in 1988, but inoculum was not present from the preceding year. The outbreak in 1990 was relatively small with only 250 ha affected by late August.

Wet, warm weather and initial inoculum were identified as important factors influencing development of the recent late blight epidemics in Washington. Other factors, such as an increased proportion of the *P. infestans* population that is insensitive to metalaxyl (6,7,12,13) and the subsequent ineffectiveness of this fungicide, have increased the difficulty of managing late blight. A recent increase in the production of early-season potato cultivars that are more susceptible to late blight development than Russet Burbank (17) also is an important factor.

The A2 mating type of *P. infestans* has been introduced into North America (8) and was collected from south-central Washington in 1993 (13). Long-term effects on epidemic development from this migration are largely unknown (12). Models developed in this study may be useful in comparison with models developed for future epidemics to serve as a base in determining the effect of the introduction of the A2 mating type on epidemic development.

Discriminant and logistic regression analyses were useful in quantifying the effects of weather on the development of hop downy mildew (18) and potato late blight. Sensitivity and specificity were 100 and 86%, respectively, for a 10-year hop downy mildew data set, which was not used to develop the model. Logistic regression analysis had very similar results. Both the 28 years of hop training and the test data were collected at Prosser. However, one set of hop downy mildew predictors collected from Sunnyside, WA, about 27-km northwest of Prosser correctly classified only 60% of the Prosser test data (18). This illustrates the importance of using training and test data from the same location and meteorological data representative of the production area for model development and validation. The accuracy of the late blight models developed in this study might improve if meteorological data from additional locations were incorporated into the models. However, data from the Prosser station are advantageous because late blight generally occurs first near the Columbia River, either south or east of Prosser, and progresses northward as the season develops.

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