Regional Models for Predicting Stripe Rust on Winter Wheat in the Pacific Northwest

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ABSTRACT

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Statistical models were developed for predicting stripe rust (caused by *Puccinia striiformis*) on winter wheat cultivars Gaines, Nugaines, and Omar at Lind, Pullman, and Walla Walla, WA, and Pendleton, OR, in the Pacific Northwest. Two regional models were developed for each cultivar based on the relationship of disease intensity index to standardized negative degree days (NDDZ) accumulated during December and January, the Julian day of spring (JDS) (defined as the date when 40 or more positive degree days [PDD] had accumulated during the following 14 days) and PDD for the 80-day period after the JDS. The first model, which used NDDZ and JDS as independent variables, can be used in early spring to make disease intensity index predictions. Such predictions are needed to enable timely spring management decisions. The second model, which adds PDD as an independent variable, increases the accuracy of the prediction, but allows less time for managerial decisions. The accuracy of the models was verified in two tests by randomly removing the equivalent of two years' data, reformulating the models from the remaining data, and using the new model to compare actual recorded disease and predicted disease. The predicted disease intensity index was within one standard error of the actual recorded disease index 70% of the time when NDDZ and JDS were used as independent variables. Incorrect predictions often occurred during years when spring conditions were unusually favorable or unfavorable for disease development. These predictions could be corrected by adding the PDD variable. With background knowledge of a region, predictions of disease intensity index in that region could be made with only meteorological data. The regional model was also used to predict stripe rust at a fifth site (Mt. Vernon, WA) which is in the far northwest corner of the Pacific Northwest and was not included in the development of the models.

Additional key words: linear regression, quantitative epidemiology.

Since 1961, stripe rust caused by *Puccinia striiformis* West. has frequently reduced yield of susceptible cultivars of wheat (*Triticum aestivum* L. em Thell) in the Pacific Northwest region of the USA. The frequency and severity of stripe rust epidemics was associated with above-average winter temperatures and below-average spring temperatures (1,2). Coakley and Line (1) proposed a local model for predicting stripe rust on the winter wheat cultivars Gaines and Omar based on either accumulated winter temperatures (negative degree days [NDD]) or accumulated spring temperatures (positive degree days [PDD]) at Pullman, WA. When the sum of NDD and PDD together with a factor for growth stage were used as independent variables in a multiple regression analysis, 91% of the variation in disease intensity index was explained (2). These local models predicted stripe rust at Pullman, but did not adequately predict stripe rust at other locations in the Pacific Northwest (3).

To improve prediction of stripe rust in the Pacific Northwest, the NDD data were standardized (NDDZ) by using the method described by Davis (4) before formulation of the local Pullman regression model. By using the NDDZ value for the time period at each site that was most highly correlated with accumulated NDD at Pullman during December and January, the resulting local NDDZ model could be used to predict disease at four other sites in the Pacific Northwest. When the NDDZ model was used, there were no significant differences between the actual mean disease index and predicted mean disease index at any of the sites. Accumulated PDD partially explained the model's small (but consistent) underprediction at one site and overprediction at the three other sites, but PDD could not be incorporated directly into the local NDDZ model to improve predictions because the accumulated PDD at Pullman was significantly less than the accumulated PDD at three of the four other sites (3).

The objective of this research was to improve the local model and to develop a regional model for each of the winter wheat cultivars Gaines, Nugaines, and Omar which would be based on all the available disease intensity data for four sites in the Pacific Northwest and would include a factor for the different spring conditions at each site. The regional model could then be used to make a specific prediction of disease intensity on a cultivar using just the meteorological data at that site.

MATERIALS AND METHODS

Data on rust intensity and infection type, stage of plant growth, and maximum and minimum temperature at four sites in the Pacific Northwest (Lind, Pullman, and Walla Walla, WA, and Pendleton, OR) were used (Fig. 1). All four sites have different local meteorological conditions (3).

Data on disease intensity and infection type for wheat cultivars Gaines, Nugaines, and Omar at the four sites were collected (Table 1) at growth stages 7 (milk) or 8 (dough) (7). Infection type was indicated by the basic and expanded scales of Line et al (5) to describe the host-parasite interaction as shown by symptoms and signs of stripe rust. The basic scale classifies the host-parasite interaction in three categories, 2, 5, and 8, in which the host develops resistant, intermediate, and susceptible reactions, respectively.

Disease intensity was converted to a 0–9 scale of disease intensity index (DI) with DI = 0 (0% disease), 1 (<1%), 2 (1–5%), 3 (6–20%), 4 (21–40%), 5 (41–60%), 6 (61–80%), 7 (81–95%), 8 (96–99%), and 9 (>99%). When the last recorded DI was at stage 7, the DI for growth stage 8 was estimated by extrapolation of the DI at growth stage 7, taking into account infection type at stage 7 (Table 2). The rules for extrapolation were developed from data on disease

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TABLE 1. Stripe rust intensity index[a] on plants of cultivars Omar, Gaines, and Nugaines for Pullman (PW), Lind (LW), Walla Walla, WA (WWW), and Pendleton (PO), OR, in 1968 to 1981.

	Gaines				Nugaines				Omar			
Year	PW	LW	WWW	PO	PW	LW	WWW	PO	PW	LW	WWW	PO
1968	5.5a	···	···	···	5.0a	···	···	···	···	···	···	···
1969	2.0	···	···	···	2.0	···	···	···	3.5	···	···	···
1970	3.0	···	···	3.0a	2.0	···	···	4.0a	7.0	···	···	8.0a
1971	5.5	···	3.0	3.5	5.0	···	2.0	2.5	8.5	···	5.0	7.5
1972	3.0a	···	···	···	2.5a	···	···	···	6.0a	···	···	···
1973	3.0	···	···	1.0a	3.0	···	···	···	7.5	···	···	1.5a
1974	···	···	4.0a	···	···	···	3.0a	···	···	···	7.0a	···
1975	6.5	7.0	4.0	···	6.5	5.0	4.0	···	7.5	7.0	7.5	···
1976	6.5	3.0	6.0a	5.0a	7.0	3.5	6.0a	3.0a	8.0	7.0	···	7.0a
1977	···	···	···	···	···	···	···	···	···	···	···	···
1978	6.0a	4.0	···	···	3.5a	3.0	···	···	9.0a	4.0	···	···
1979	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0
1980	6.5	···	5.0	···	4.5	3.0a	5.0	···	8.5	6.0	7.0	···
1981	7.5a	···	6.5	5.5	7.0	···	6.5	4.5	9.0a	8.5a	8.0	8.5
$\bar{x}$	4.7	3.8	4.2	3.2	4.1	3.1	3.9	3.0	7.0	5.6	5.9	5.6

[a] The disease intensity data collected at growth stages 7 and 8 were converted to a 0–9 scale disease index (DI) with DI = 0 (0% disease), 1 (<1% disease), 2 (1–5%), 3 (6–20%), 4 (21–40%), 5 (41–60%), 6 (61–80%), 7 (81–95%), 8 (96–99%), and 9 (>99%). Missing data are indicated by three dots. Data collected at growth stage 7 (indicated by the letter a following the DI) are given as an extrapolated DI for stage 8 based on disease index and infection type at stage 7 as described in Table 2.

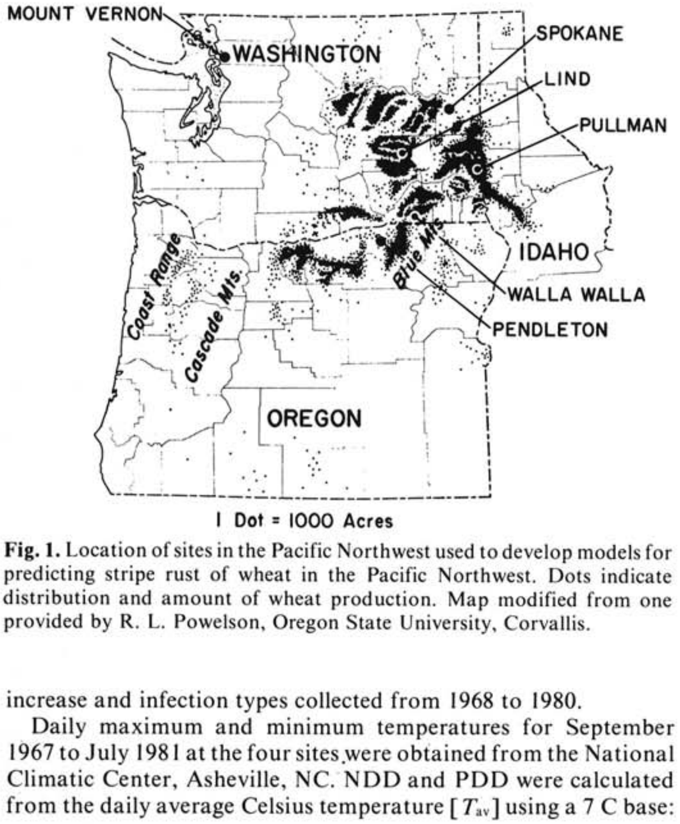

Fig. 1. Location of sites in the Pacific Northwest used to develop models for predicting stripe rust of wheat in the Pacific Northwest. Dots indicate distribution and amount of wheat production. Map modified from one provided by R. L. Powelson, Oregon State University, Corvallis.

TABLE 2. Constants for extrapolating disease intensity index taken at growth stage 7 to growth stage 8 based on infection type[a] and disease index at growth stage 7

Disease index (DI) at stage 7	Infection type (IT) at stage 7	Constants to add to DI at stage 7 to estimate DI at stage 8
DI⩾8	IT⩾5	+1/2
	IT<5	+0
5 ⩽ DI < 8	IT⩾5	+1
	IT<5	+0
DI<5	IT⩾5	+1/2
	IT<5	+0

[a] Infection types 2, 5, and 8, indicate in the host a resistant, intermediate or susceptible reaction, respectively, to stripe rust (5).

TABLE 3. Means of negative degree days (NDD), Julian day of spring (JDS) and positive degree days (PDD) for sites in the Pacific Northwest based on data from 1968 to 1979

Site	NDD[a]	JDS[b]	PDD[c]
Lind, WA	542	94 (4 April)	515
Pullman, WA	554	111 (21 April)	508
Walla Walla, WA	375	74 (15 March)	455
Pendleton, OR	409	84 (25 March)	493

[a] Accumulated from 1 December to 31 January.

[b] Day from which ⩾40 PDD accumulated over the following 14 days; actual date given in parentheses.

[c] Accumulated for 80 days beginning on JDS.

increase and infection types collected from 1968 to 1980.

Daily maximum and minimum temperatures for September 1967 to July 1981 at the four sites were obtained from the National Climatic Center, Asheville, NC. NDD and PDD were calculated from the daily average Celsius temperature [T_{av}] using a 7 C base:

$$\text{If } T_{av} < 7\text{ C then NDD} = \Sigma|T_{av} - 7\text{ C}|$$

$$\text{If } T_{av} > 7\text{ C then PDD} = \Sigma(T_{av} - 7\text{ C}).$$

Total NDD from 1 December to 31 January were calculated for each year at each site. This time period, which is approximately the coldest 62 days at each site, was most highly correlated with final DI in previous studies (1,2). Because the magnitude of NDD for each site was different (Table 3), it was necessary to standardize the NDD data for each site and each year. Standardized values (NDDZ) for each site were calculated by subtracting the 1968–1979 mean NDD ($[\text{NDD}]_{av}$) from the yearly NDD value (NDD_i) and dividing by the standard deviation of the mean (s) as described by Davis (4):

$$\text{NDDZ} = (\text{NDD}_i - [\text{NDD}]_{av})/s.$$

An example of this calculation was given (3).

Spring warming and consequently resumption of plant growth and rapid rust development start at a different time at each site. The following method was used to identify the beginning of the warming period at each site. PDD values were calculated for a 14-day period beginning 1 March. Then the calculation period was moved ahead by 1 day (eg, 1–14 March, 2–15 March, 3–16 March...) until the first period with a PDD value of at least 40 was identified. The beginning date of calculation was then designated as the Julian day of spring (JDS). For example, in 1969 at Pullman, 42 PDD accumulated from April 24 (Julian day 114) to May 3, hence the JDS was 114. The mean JDS for the period 1968 to 1979 was calculated for each site (Table 3). The accumulation of 40 PDD

TABLE 4. Regional equations for prediction of stripe rust intensity index on three winter wheat cultivars at Lind, Pullman, and Walla Walla, WA and Pendleton, OR

Cultivar	Equation[a]	R^2
Gaines	1: $\hat{y} = 1.5752 - 1.4174\text{NDDZ} + 0.0253\text{JDS}$	0.67
	2: $\hat{y} = 3.9390 - 1.2115\text{NDDZ} + 0.0328\text{JDS} - 0.0065\text{PDD}$	0.69
Nugaines	1: $\hat{y} = 1.9970 - 1.1500\text{NDDZ} + 0.0162\text{JDS}$	0.52
	2: $\hat{y} = 4.6292 - 0.9241\text{NDDZ} + 0.0251\text{JDS} - 0.0073\text{PDD}$	0.55
Omar	1: $\hat{y} = 2.3400 - 1.8970\text{NDDZ} + 0.0377\text{JDS}$	0.77
	2: $\hat{y} = 4.5272 - 1.7235\text{NDDZ} + 0.0420\text{JDS} - 0.0054\text{PDD}$	0.78

[a] Equations and R^2 from multiple regression analyses of stripe rust intensity index ($\hat{y}$ = DI, see Table 1, footnote a) as a function of standardized negative degree days (NDDZ), Julian day of spring (JDS) and positive degree days (PDD) at each site for the years 1968 to 1981.

TABLE 5. Wheat stripe rust actual disease intensity index (ADI) and predicted disease intensity index (PDI) for three wheat cultivars in 1973, 1975, 1978, and 1981 using regression models developed on 1) all 1968–1981 ADI except 1973 and 1975 and then on 2) all ADI data except 1978 and 1981 for Lind, Pullman, and Walla Walla, WA, and Pendleton, OR

		Gaines		Nugaines		Omar	
Site	Year	ADI	PDI	ADI	PDI	ADI	PDI
Lind	1975	7.0	4.8 a[x]	5.0	4.2	7.0	7.1
	1978	4.0	4.6	3.0	4.1	4.0	7.0 b
	1981	···	···	···	···	8.5	9.1
Pullman	1973	3.0	3.6	3.0	3.0	7.5	5.4 a
	1975	6.5	5.0 a	6.5	4.3 a	7.5	7.5
	1978	6.0	5.4	3.5	4.7	9.0	8.2
	1981	7.5	6.6	7.0	5.7	9.0	10.0
Walla Walla	1975	4.0	5.0	4.0	4.4	7.5	7.3
	1981	6.5	4.6 a	6.5	4.0 a	8.0	7.0
Pendleton	1973	1.0	2.5 b	···	···	1.5	3.8 b
	1981	5.5	4.6	4.5	4.1	8.5	7.0

[x] PDIs followed by the letter a were more than one standard error below the ADI; PDIs followed by the letter b were more than one standard error above the ADI.

during 14 days was selected instead of other criteria because it avoided identification of short periods of warm temperatures in late winter.

The PDD values for the years 1968–1979 were calculated for an 80-day period beginning on the mean JDS at each site. Average PDD values for each site are given in Table 3.

The variables NDDZ, JDS, and PDD were used in linear and multiple linear regression analysis to determine their relationship to the disease intensity indices for the three cultivars at the four sites.

RESULTS AND DISCUSSION

Development of regional models. Regression equations were formulated for each of the three cultivars using the DI data (Table 1) as the dependent variable. The independent variables NDDZ, JDS, and PDD were used alone and in combination. Equations for prediction of the disease intensity index by using NDDZ and JDS and then NDDZ, JDS, and PDD as independent variables, and the percent variability for these predictions explained by R^2 for each cultivar are given in Table 4. The majority of the variability in DI on Omar and Gaines was due to NDDZ and JDS. The lower R^2 values for Nugaines indicated that these variables do not adequately explain variation in DI on this cultivar. These results are consistent with previous ones (1), which showed that disease development on Omar and Gaines was more dependent on temperature than disease development on Nugaines.

For all cultivars, adding PDD as a variable increased the accuracy of the model only 1–3%. When the relative contributions of the independent variables to the R^2 were considered, the most important variable was NDDZ; for example, NDDZ explained about 63% of the variability in the disease index on Gaines.

Use of only NDD and JDS data enabled prediction early in the spring, whereas it is not possible to use PDD data until the end of spring. Adding PDD improved the accuracy of predictions the most in years with very favorable or unfavorable spring conditions for disease development. We use equation 1 (Table 4) in early February to make preliminary predictions, consider spring conditions as they develop, and then use equation 2 when the PDD data become available at each site to make final predictions of DI.

PDD values were also standardized using the same method as described for NDDZ, but standardization added no significant accuracy to the predictions.

Validation of regional models. To test the validity of the models, two years were randomly removed from the data base in two separate tests (1973 and 1975 in the first test, and 1978 and 1981 in the second). The remaining data were then used to develop new regression equations, and these equations were then used to predict disease intensity indices for the years that had been removed from the data base. No significant differences (based on *t*-test) were found between the average actual recorded disease index (ADI) and average predicted disease index (PDI) for any cultivar in any test year (Table 5).

A standard error of prediction also was calculated for each year (6). Of the 30 predictions made for the three cultivars during the four test years, 21 were within the standard error of prediction, six were greater than one standard error below the ADI and three were greater than one standard error above the ADI (Table 5). In short, 70% of the ADI were within the standard error of the PDI.

Why were the predictions off by more than one standard deviation 30% of the time? The models tested did not include accumulated PDD. When the PDI was more than one standard error from the ADI, the PDDZ and the departure of spring precipitation from normal for April, May, June were examined. In 1973 at Pendleton, where predicted disease on Gaines and Omar was greater than the recorded disease, PDD accumulation was much greater than normal and spring precipitation was below normal. These conditions would limit expected disease development (1). In 1975, the disease index for Gaines at Pullman and Lind, and for Nugaines at Pullman were underpredicted but PDD values at both locations were below normal which would provide more favorable conditions for rust development. In 1981, at Walla Walla, where disease index also was underpredicted, precipitation was above normal during April and June and probably contributed to disease being higher than that predicted. Also, conditions for fall establishment and increase of rust were unusually favorable at Walla Walla in 1981, thus increasing the amount of rust in early spring when plants were least resistant.

In summary, seven out of nine inconsistencies in prediction were due to unusually favorable (or unfavorable) spring conditions which are not accounted for by the variables included in the models. Finally, there may be unusual error associated with some of the recorded data. For example, at Lind in 1975 the ADI for Gaines is higher than expected, based on the normal ranking of the relative susceptibility of the cultivars which leads us to believe the data may be erroneous.

For 1982, DI data were available for the three cultivars only at Pullman and Walla Walla. The regional model equations 1 and 2 correctly predicted DI in four out of six predictions. At Pullman, the ADI on Gaines and Omar were more than one standard error below predicted disease index, but the plant stand at these sites was reduced by unknown factors during the winter, which probably further reduced survival of *P. striiformis*.

A Mt. Vernon site was included in previous research (3) but excluded from the development of the regional model because DI data were not available for growth stages 7 and 8 except in 1976 and 1979. Equations 1 and 2 of the regional model were used to predict the disease indices for the three cultivars for 1976 and 1979 at Mt. Vernon. Four out of six predictions were correct and the other two were below ADI by more than one standard error. These results indicate that the regional model can be used at a site not included in its development.

The technique we have described for validation of the regional model's accuracy would also be applicable for testing other statistical models which are developed using all available data.

Advantages of regional models. These regional models have several advantages over the local models which were developed for Pullman and modified for application to the other sites (3). First, predictions can be made for each site using only the meteorological data at that site. Second, a variable that helps account for different spring conditions at the various sites has been included. Third, predictions using NDDZ and JDS can be improved by the addition of PDD but the time available for managerial decisions is shorter. Predictions using NDDZ and JDS allow decisions to be made early enough to permit use of a fungicide. The predictions were used in 1981 to justify an emergency registration of a fungicide that when used resulted in yield increases of more than 27×10^3 metric tons in the Pacific Northwest. The regional model also has potential for use in assessing the impact of stripe rust in regions where disease data are not available, but data on the historical importance of the disease, susceptibility of the cultivars, and weather in the region are available.

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