Predicting Wheat Leaf Rust Severity Using Planting Date, Genetic Resistance, and Weather Variables

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ABSTRACT

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Leaf rust epidemics of wheat, caused by *Puccinia recondita* f. sp. *tritici*, were analyzed for the 1972 to 1990 growing seasons. The disease severity values recorded for leaf rust in early and late bread-wheat planting dates at Pergamino were used to identify the best genetic and environmental predictors of disease severity. Leaf rust severity (early planting date) could be predicted (R^2 = 0.88) as a function of heat accumulation (base daily mean temperature >12°C), days with relative humidity >70% without precipitation, and a cultivar resistance index. For late planting date, the predictive value of meteorological variables decreased, while the importance of the resistance index increased over that found for the early seeded trials. In general, predicted and observed leaf rust severity levels agreed during 1994 to 1996 at Pergamino, and for trials (1991) that were grown at some distance from the area where the original data for model development were recorded.

Additional keywords: forecasting, *Triticum aestivum*

Leaf rust, caused by *Puccinia recondita* f. sp. *tritici*, is present every year in the bread-wheat area of Argentina. The appearance of new races and conditions favorable for diffusion of the pathogen enhance the likelihood of epidemics that may significantly reduce wheat yield. Although plant resistance is the main method to avoid epidemics and minimize yield losses, changes in pathogen virulence and the lack of effective durable resistance support the need for forecasting models. These models are needed if fungicides are to be effective and economical in reducing crop losses that may be attributed to new races of the pathogen (11,23). Within the Pampeana wheat-growing area, leaf rust develops from year to year on volunteer wheat plants, on other grass hosts, and from infections produced by airborne spores originating in diseased wheat crops grown earlier in northern areas of Argentina and border countries (15).

Wheat yields associated with leaf rust were reported to be reduced by (i) 5 to 15% in susceptible cultivars in Canada, (ii) 10% (mild epidemic year) to 21.9% (severe epidemic year) for 1976 to 1990 in the United States, and (iii) up to 40% in Mexico in 1976 and 1977 (21,22,24). In Argentina, over 2,800,000 tons of wheat were estimated to have been lost due to leaf rust during the period 1948 to 1958 (20), and the yields were reduced by approximately 80 kg/ha for each 10% of leaf rust severity when yield exceeded 1,100 kg/ha (26). Wheat yield losses were between 38.6 to 50.5% and 8.7% for early and late epidemics, respectively (13).

Crop models, meteorological data, and remote sensing may be the most useful tools for forecasting the occurrence of a particular disease (14). Wheat rust epidemics have been successfully predicted using mechanistic (1) and empirical approaches (2,6,7,10). The empirical models were based on either meteorological factors alone (6,7,25) or both biological and meteorological factors (2,10,11). While most previous studies analyzed a few selected cultivars, a leaf rust-prediction model was developed in Europe that considered mean disease severities observed on several cultivars (8). Leaf rust curves on three cultivars were explained by cumulative degree days (>20°C) following inoculation (25).

A forecast based on the severity of leaf rust on 1 April was developed in Oklahoma (3,4), where winter temperature and precipitation are extremely important for predicting leaf rust severity. In Argentina, hours of dew and accumulated degree days over 10°C in August (end of winter) explained 90% of disease severity variation for many commercial cultivars (17).

Accordingly, the objective of this study was to consider the effect of cultivar resistance when identifying and quantifying the association between meteorological variables and maximum leaf rust severity at early phenological wheat growth stages.

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MATERIALS AND METHODS

Disease data. The national nursery ROET (Red Oficial de Ensayos Territoriales) included several commercial bread-wheat cultivars that were established annually within the main wheat-growing area of Argentina on up to six planting dates. Throughout the period 1972 to 1990, mean percent observed severities (MOS%) were annually calculated from maximum leaf rust assessments made on the cultivars included in the ROET trials at Pergamino Experiment Center (latitude 33°56′S, longitude 60°33′W). The whole-plant severity assessments were for June to July (early) and August (late) planting dates.

Cultivar resistance to leaf rust was derived from ETRE (Ensayo Territorial de Resistencia a Enfermedades) multilocation field studies carried out under high inoculum levels (19). The annually planted cultivars were grouped in two categories according to the disease severity ratings obtained by averaging the ETRE records for each cultivar and all locations. The mean ETRE disease severity values defined the resistance grade (RG) for resistant (RG = 0, mean severity <40%) and susceptible (RG = 1, mean severity ≥40%) cultivars. Based on the RG, a resistance index (RI) was computed for each year by dividing the number of sowed resistant cultivars (RG = 0) by the total number of cultivars. Finally, for each year, mean severities per resistance grade (MOS%RG) were calculated by adding the severities of the resistant (RG = 0) or susceptible (RG = 1) cultivars and dividing by the respective number of resistant or susceptible entries.

The proposed models for predicting leaf rust severities were validated using 1994, 1995, and 1996 ROET data from Pergamino and 1991 disease information (16) from Balcarce (latitude 37°45′S, longitude 58°18′W), M. Juárez (32°41′S, 62°07′W), Paraná (31°50′S, 60°31′W), and Sáenz Peña (26°52′S, 60°27′W).

Meteorological data. Daily meteorological data recorded at the Pergamino weather station were analyzed using SAS procedures (release 6.03, SAS Institute Inc., Cary, NC). In several monitoring periods, the following environmental variables were calculated and then evaluated for their utility in predicting leaf rust severity: (i) precipitation frequency; (ii) total accumulated precipitation in millimeters; (iii) number of dry days (precipitation <0.2 mm) and average relative humidity (RH) >70% (DRH70), as calculated from the

0800-, 1400-, and 2000-h observations (iv) mean minimum temperature; (v) mean maximum temperature; (vi) total degree-day accumulation of base daily mean temperature (MT) >11°C and RH >50%, if MT >18°C then MT = 18°C (DD11); (vii) total degree-day accumulation of base daily MT >12°C and RH >49%, if MT >18°C then MT = 18°C (DD12); and (viii) other thermal values not shown.

Development of predicted equations. Several starting dates and lengths expressed as accumulated degree days (base daily average temperature, 0°C), were tested from late July to early October using the R^2 SAS procedure to identify the most appropriate monitoring period. Linear regression models (dependent variable MOS%) were used to examine the association between genetic (RI) and meteorological factors with MOS%. Equations with up to three independent variables were developed using the REG, R^2, and stepwise SAS procedures. Some alternative models were eliminated by applying biological criteria or because of unrealistic positive or negative relationships. The final selection of the best regression equations was based on the determination coefficients (R^2), and stepwise procedures (6,7,18). The general linear model (GLM) SAS procedure was used to develop the best GLMs to predict MOS%RG based on meteorological factors and their interactions with RG.

RESULTS

The monitoring periods starting on 16 and 28 August and ending when 475 and 460 degree days were accumulated for early and late planting dates, respectively, showed the closest climate-disease relationships.

Linear regression models. The best simple and multiple equations for predicting mean maximum leaf rust severity, including meteorological and genetic (RI) factors as linear independent components, are presented in Table 1. For early planting date, the model involving DD12 (Table 1, equation A) explained 72% of the disease severity variation while the best bivariate (R^2 = 0.86) and trivariate (R^2 = 0.88) linear models included the variables DD12, RI (Table 1, equation B), and DRH70 (Table 1, equation C), respectively. For late planting date, the RI was the single genetic variable most highly associated (Table 1, equation D) with leaf rust maximum severity (R^2 = 0.50). The importance of meteorological factors in predicting rust severity was not as great as it had shown to be for early planting date (i.e., the best variable, DD11, had a determination coefficient of only 0.39; Table 1, equation E). Among the equations, the model (Table 1, equation F), including variables DD11 and RI, accounted for a relatively high proportion of the variability of leaf rust severity levels (R^2 = 0.75). For both planting dates, the relationship between RI and disease severity was negative, as expected.

The equations C (early) and F (late) were adjusted to the data when the stepwise procedure was used with variables to enter and variables to remain fixed at 0.114 (Table 1). This result, combined with criteria related to R^2, biological sense, and simplicity, were taken into consideration to select the C and F models for validation purposes (1994 to 1996 Pergamino ROET data). The C model was also used to validate the 1991 disease data at Balcarce, M. Juárez, Paraná, and Sáenz Peña.

Table 1. Simple and multiple leaf rust severity prediction (PS%) models for early and late planting date based on Red Oficial de Ensayos Territoriales bread-wheat trials at Pergamino for the period 1972 to 1990[a]

Date, equation	Model	R^2
Early planting date[b]		
A	PS% = –10.36 + 0.68 DD12	0.7183
B	PS% = 6.50 + 0.65 DD12 – 25.90 RI	0.8585
C	PS% = 4.42 + 0.61 DD12 + 0.57 DRH70 – 30.01 RI	0.8828
Late planting date[c]		
D	PS% = 55.88 – 46.77 RI	0.5020
E	PS% = –13.76 + 0.57 DD11	0.3918
F	PS% = 16.64 + 0.46 DD11 – 40.38 RI	0.7527

[a] RI = resistance index; DD11 and DD12 (degree days) are thermal independent variables, where DD11 = total degree-day accumulation of base daily mean temperature (MT) >11°C and relative humidity (RH) >50%, if MT >18°C then MT = 18°C, and DD12 = total degree-day accumulation of base daily MT >12°C and RH >49%, if MT >18°C then MT = 18°C; and DRH70 (days) is a hydric independent variable, number of dry days (precipitation <0.2 mm) and average RH >70%.
[b] Monitoring period from 16 August (Julian day 228) to accumulated 475 degree days.
[c] Monitoring period from 28 August (Julian day 240) to accumulated 460 degree days.

Table 2. General linear models to predict wheat leaf rust severities (PS%) according to genetic and meteorological variables and interactions with resistance grade (RG) based on early and late Red Oficial de Ensayos Territoriales planting dates at Pergamino for the period 1972 to 1990[a]

Date, source[b]	SS[c]	*F*	*P* > *F*
Early planting date[d]			
RG	13,735.8	230.39	0.0001
DD12	3,042.9	51.04	0.0001
DRH70	461.0	7.73	0.0091
DRH70 × RG	382.23	6.41	0.0166
Late planting date[e]			
RG	9,525.73	64.93	0.0001
DD11	3,300.41	22.50	0.0001

[a] RG = 0, resistant and RG = 1, susceptible.
[b] DD11 = total degree-day accumulation of base daily mean temperature (MT) > 11°C and relative humidity (RH) > 50%, if MT > 18°C then MT = 18°C; DD12 = total degree-day accumulation of base daily MT > 12°C and RH > 49%, if MT >18°C then MT = 18°C; and DRH70 = number of dry days, precipitation <0.2 mm and average RH > 70%.
[c] SS = sum of squares.
[d] Monitoring period from 16 August (Julian day 228) to accumulated 475 degree days. Equation A1: RG = 0, PS% = –20.2068 + 0.5603 DD12 + 1.944 DRH70 – 1.8214 DRH70 × RG; equation A2: RG = 1, PS% = –2.1875 + 0.5603 DD12 + 1.944 DRH70; R^2 = 0.91; number of cultivars (*N*) = 36.
[e] Monitoring period from 28 August (Julian day 240) to accumulated 460 degree days. Equation B1: RG = 0, PS% = –31.4842 + 0.59 DD11; equation B2: RG = 1, PS% = 1.99 + 0.59 DD11; R^2 = 0.74; *N* = 34.

General linear models. The SAS GLM procedure fit two models for both resistant (equation A1) and susceptible (equation A2) cultivars by which over 90% of disease variability was explained (Table 2). For early planting dates, significant effects (P < 0.05) were observed by RG, DD12, and DRH70 meteorological factors, and the interaction component between DRH70 and RG (Table 2).

For late planting dates, the GLM with RG as a classification factor and DD11 as a linear trend component accounted for 74% of the total variance (equations B1 and B2). In this case, the interaction term was not significant (Table 2).

Validation. As a first step, predicted leaf rust severity levels using the C, A1, and A2 models for early planting dates and F, B1, and B2 models for late planting date were contrasted with those observed from 1994 to 1996 at Pergamino. Three levels of disease severity (S = severe, M = moderate, and L = light) were recognized with thresholds (80 and 25% probability points) derived from the empirical distribution of observed disease severity values. A group of 13 contrasts out of 18 showed agreement between predicted and observed disease levels, and the remaining did not show a great discrepancy (Table 3).

Considering the 1991 disease and meteorological data from four locations, the portability of the predictions of the C linear model developed for Pergamino was tested. The moderate leaf rust epidemics observed at northern (Sáenz Peña) and southern (Balcarce) locations were well simulated by the model as well as the severe levels at central locations (M. Juárez and Paraná; Table 4).

DISCUSSION

The predictive models developed here are empirical and based on the analysis of historical series of disease severity, weather data, and cultivar leaf rust resistance. Similar approaches with modifications were carried out by Coakley et al. (6,7), Daamen et al. (8), and Moschini and Fortugno (17). In this study, besides analyzing environmental variables, a factor that accounts for the variation between years in the grade of resistance of wheat cultivars annually grown in ROET trials, was correlated with disease severity. Therefore, the RI was calculated as the proportion of cultivars which observed <40% of severity. In order to minimize the actual environmental component involving RI, the performance of each cultivar regarding the disease was evaluated by averaging the observed leaf rust severity values from multilocation ETRE trials affected by quite different weather conditions.

Several environmental variables may affect the production, dispersal, and survival of urediniospores (12). Temperature, humidity, and light may have pronounced effects on spore longevity. Winter temperatures and precipitation incremented the urediniospore amount while lower relationship occurred when spring weather was considered in Oklahoma (3–5). A strong association between severity and thermal variables was reported in Holland, but only a slight relationship was observed for hydric variables (8). Previous studies in Argentina indicated an association between dew and degree-day accumulation during August and leaf rust severity (17). The results of the present study, especially for wheat planted in June to July, corroborate the findings of Chester (4,5) regarding the importance of thermal variables on inoculum production throughout the period from first leaves to end of tillering. For early planting dates, the thermal variable DD12 combined with the RI and the hydric variable DRH70 (Table 1, equation C) described the maximum leaf rust severity expected (R^2 = 0.88). Disease severity especially increased with increasing degree-day accumulations of daily mean temperatures in the range of 12 to 18°C when the RH is greater than 49%, coinciding with the end of the winter. Due to the lack of dew data, days without precipitation and RH over 70% marginally explained the severity variation. The identified meteorological variables were consistent with controlled environment findings that indicated that the minimal continuous dew period necessary for infection increased from 4 to 6 h at optimal temperature (15°C for *P. recondita* f. sp. *tritici*) to at least 16 h at suboptimal temperature (9).

The results suggested that leaf rust severity may be predicted for early planting dates from data characterizing thermal variables (DD12) and in a low degree hydric conditions (DRH70) from mid-August to September. Throughout the end of the winter (August to September) in the Argentine Pampeana region, short wetness periods within the range required for leaf rust infection occur frequently, explaining the low correlation observed by indirect measurements of dew occurrence (e.g., DRH70). Attempts to include precipitation factors in the model were not successful and confirm the fact that short-term wetness duration requirements for rust infections may be established by dew.

There was low correlation (R^2 = 0.39) between meteorological factors and observed terminal disease data for August planting dates, suggesting that thermal variables alone may be of little predictive value for late plantings. RI explained half of variance of disease severity, pointing out the importance of resistant cultivars in determining leaf rust severity levels for late planting dates. Increasing levels of resistance reduced maximum leaf rust due to the slower disease development on resistant cultivars. Planting late (August), would prevent multiplication of rust inoculum throughout the period in which thermal environmental factors are near the lower threshold required by the pathogen. Later in the season, the meteorological requirements were always met, sharply reducing the predictive value of environ-

Table 4. Comparisons between leaf rust severity levels predicted from C model (PS-C) and those calculated from disease data (OS) registered on 67 cultivars at four locations of the Argentine bread-wheat area in 1991[a]

Location	DD12	DRH70	RI	Julian days	OS[b]	PS-C
Balcarce	44.8	27	0.70	228–266	M	M
M. Juárez	99.1	22	0.42	228–256	S	S
Paraná	116.2	17	0.39	228–253	S	S
S. Peña	66.4	7	0.75	228–247	M	M

[a] Equation C: PS% = 4.42 + 0.61 DD12 + 0.57 DRH70 – 30.01 RI, where PS% is predicted severity in percent; DD12 = total degree-day accumulation of base daily MT > 12°C and RH > 49%, if MT > 18°C then MT = 18°C; DRH70 = number of dry days, precipitation <0.2 mm and average RH > 70%; and RI: resistance index

[b] S = severe, when % severity values (predicted by equation C or mean observed severity) > = 40%; and M = moderate, when % severity values <40% and ≥15.7%. Light = % severity values <15.7%.

Table 3. Comparisons between leaf rust severity levels predicted (PS) from the models C, A1, and A2 for early planting dates and F, B1, and B2 for late planting dates with those observed (OS) at Pergamino (Red Oficial de Ensayos Territoriales trials) from 1994 to 1996[a]

								RG = 0[b]				RG = 1			
Date, year	DD12[c]	DD11	DRH70	RI	OS	PS-C	PS-F	OS	PS-A1	PS-B1	*N*	OS	PS-A2	PS-B2	*N*
Early planting date[d]															
1994	56.0	…	9	0.45	M	M	…	M	M	…	27	M	M	…	33
1995	64.5	…	8	0.73	M	M	…	M	M	…	19	M	M	…	7
1996	61.8	…	2	0.80	L	M	…	L	M	…	12	S	M	…	3
Late planting date[e]															
1994	…	96.0	…	0.50	M	…	S	M	…	S	8	M	…	M	8
1995	…	62.7	…	0.71	M	…	M	M	…	M	10	M	…	M	4
1996	…	69.1	…	0.92	L	…	L	M	…	M	24	M	…	M	2

[a] Three levels of disease severity (S = severe, M = moderate, and L = light) were recognized with thresholds (80 and 25% probability points) derived from the empirical distribution of observed disease severity values. S: severity values ≥40% (PS-C and PS-F or OS); ≥18.5% (PS-A1 and PS-B1 or OS); and ≥65% (PS-A2 and PS-B2 or OS). M: severity values <40 and ≥15.7%; <18.5 and ≥4.6%; and <65 and ≥36.3%. L: severity values <15.7%; <4.6%; and <36.3%.

[b] RG = resistance grade; RG = 0, resistant; RG = 1, susceptible.

[c] DD11 = total degree-day accumulation of base daily mean temperature (MT) > 11°C and relative humidity (RH) > 50%, if MT > 18°C then MT = 18°C; DD12 = total degree-day accumulation of base daily MT > 12°C and RH > 49%, if MT > 18°C then MT = 18°C; DRH70 = number of dry days, precipitation <0.2 mm and average RH >70%; RI = resistance index; and *N* = number of cultivars considered.

[d] Monitoring period from 16 August (Julian day 228) to accumulated 475 degree days.

[e] Monitoring period from 28 August (Julian day 240) to accumulated 460 degree days.

mental factors for wheat planted in August. Nevertheless, RI in combination with DD11 explained over 75% of the variation of leaf rust severity.

The validation of the prediction models for early planting dates using 1994 to 1996 Pergamino data indicated high agreement between observed and model-predicted severity levels. In some cases, the small number of disease observations available could distort the validation. Conditions during the end of the winter growing seasons in 1995 and 1996 were abnormally dry and the temperatures were above normal. In those uncommon years, moisture requirements may have been a limiting factor, which was considered in the model by not including in the degree-day summation those days when the air RH was below 49%. As expected, there was an inverse relationship between RI and the observed or predicted severities with a RI doubling its value from 1994 to 1996.

For testing the behavior of the Pergamino prediction model (Table 1, equation C) in other locations of the bread-wheat growing area, close agreement (Table 4) was recorded between observed and predicted disease severity levels at Balcarce (south of the wheat area), Sáenz Peña (far north of the wheat area), and central locations (M. Juárez and Paraná). The models predicted years with light, moderate, or severe leaf rust severity levels for locations far away from Pergamino. Early leaf rust epidemic development responsible for the greatest wheat yield losses (13) could be associated and predicted with the environmental factors identified in this study, especially for wheat cultivars planted in June to July.

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