Equations for Predicting Wheat Stem Rust Development

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ABSTRACT

Stepwise multiple regression techniques were used to identify those meteorological and biological variables useful in explaining variation in stem rust (*Puccinia graminis* f. sp. *tritici*) severities 7, 14, 21, and 30 days after severity estimates were made. Variables which were most significant in the successful prediction of stem rust development were: disease severity estimates; weekly and cumulative number of urediospores deposited per cm^2; cultivar; wheat growth stage; maximum temperature; minimum temperature; a fungal-temperature growth function; and a fungal infection function.

Coefficients of determination (R^2) for the most efficient combinations of these variables were .745, .664, .509, and .362 for the 7-, 14-, 21-, and 30-day forecast periods, respectively. Stem rust development was more accurately explained by use of disease severity estimates as the inoculum variable than by the use of urediospore numbers. We were unable to accurately predict stem rust development using only meteorological variables. Equations were in the form $Y_i = K_i + b_1X_{1i} + \dots + b_nX_{ni}$.

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Wheat leaf and stem rust incited by *Puccinia recondita* Rob. ex Desm. f. sp. *tritici* and *P. graminis* Pers. f. sp. *tritici*, respectively, are major causes of loss of wheat productivity around the world (7). In the past, cereal rust studies dealing with sources of resistance, race surveys, and the ecology of the pathogen have resulted in the development of the wheat varieties resistant to the prevailing races of rust, and have led to increased wheat yields. The objectives of this study were to identify biological and meteorological variables that relate to disease development, and ultimately to develop mathematical equations to predict stem rust severity and crop loss. We have previously identified those meteorological and biological variables useful in explaining and predicting epidemic development of wheat leaf rust (1, 4) and were able to predict the resulting reduction in wheat yields (2). Because the same environmental factors, but with different cardinal points, that affect leaf rust development also affect stem rust development, we have used the meteorological and biological data and statistical techniques reported earlier (1, 4) to delineate the major factors contributing to stem rust epidemics and formulate equations, in the form $Y_i = K_i + b_1X_{1i} + \ldots + b_nX_{ni}$, to predict stem rust development in the Great Plains.

MATERIALS AND METHODS.—Location of nurseries in the Great Plains of the USA and the meteorological and biological data recording procedures were reported previously (1, 2). When stem rust severity reached 1% (10 uredia/culm), subsequent severity estimates were made using the modified Cobb Scale (5).

Stepwise multiple regression analysis, with percent stem rust severity recorded 7, 14, 21, and 30 days after date of prediction (DP) as the dependent variable, was applied to our data using the following independent variables: (i) $\log_{10}$ of percent stem rust severity (DS) on DP; (ii) $\log_{10}$ of cumulative number of *P. graminis* urediospores/cm^2 trapped to DP (CSN); (iii) $\log_{10}$ of number of *P. graminis* urediospores/cm^2 trapped during the 7 days prior to DP (WSN); (iv) average minimum temperature (MIN) during the 7 days prior to DP; (v) average maximum temperature (MAX) during the 7 days prior to DP; (vi) a temperature-fungal growth function (SIN^2) (3, 6); (vii) wheat growth stage (GS) on date predicted; (viii) average hours of free moisture (FM) as dew or rain per day during the 7 days prior to DP; (ix) number of days with rainfall $\geqslant$0.25 mm (PREC) during the 7 days prior to DP; (x) logistic (8) rate of stem rust increase from date stem rust first observed to DP (R-DS); (xi) logistic increase of cumulative number of *P. graminis* urediospores/cm^2 from date first spore trapped to DP (R-CSN); (xii) the sum of an infection function (IF) prior to DP, where each day is given either a value of 1, when minimum temperature is $\geqslant$10 C, with $\geqslant$4 hr of free moisture and at least one *P. graminis* urediospore/cm^2 is trapped, or a value of 0, when one or more of those three measurements is not met; (xiii) the infection function (WIF) summed for the 7 days prior to DP; (xiv) a numeric code (1-99) for each cultivar (VAR); and (xv) a numeric code for each nursery (LOC).

Transformations were made by subroutines within the stepwise multiple regression computer program, and all tests of significance were calculated at the 0.05 percent level.

RESULTS.—Data from all winter and spring wheat nurseries were combined and analyzed as one test. Data from all nurseries with dew records were also combined and analyzed. There were only 11 observations of stem rust severity 30 days prior to the date predicted. Therefore, to be able to use the entire set of observations, we gave zero DS data a value of 0.0001 and zero WSN and CSN data a value of 0.1. Our biological rationale for adding a value to zero data was our belief that an extensive examination of the nursery would reveal stem rust present as either urediospores or uredia indistinguishable from leaf rust without microscopic examination.

Of the 15 variables used in the analysis, only DS, WSN, CSN, GS, IF, and WIF were significantly correlated with stem rust development. Coefficients of determination (r^2) for variables used in the analysis of data obtained 7, 14, 21, and 30 days prior to the dependent variable are shown in Table 1. DS had the highest r^2 value of any of the independent variables for the 7-, 14-, and 21-day forecast periods. However, the r^2 value for CSN was slightly higher for the 30-day forecast period. This is not surprising because there were only 11 observations of stem rust severity 30 days prior to the date predicted; however, 91 observations of urediospore deposition occurred in the same period.

If DS, WSN, and CSN were allowed to enter the stepwise multiple regression program, DS entered first, and either WSN or CSN entered the regression equation next, except for the 30-day analysis when CSN entered first and DS was the second variable to enter the regression equation (Table 2). Wheat growth stage and the cultivar being sampled were usually the next variables to enter the regression model and explained a significant amount of the remaining variation in stem rust development.

When DS was the only inoculum variable permitted to enter the equation, IF was the second variable to enter the equation and the amount of variation in the dependent variable that was explained by the independent variables decreased by 3% (R^2 values decreased .03). Wheat growth stage on the date predicted was the third variable, and the cultivar being sampled was the fourth variable that explained a significant amount of the remaining unexplained variation in stem rust development when included with DS and IF in a regression equation. Number of hours of free moisture (FM) explained a significant amount of variation in stem rust development in the 7-, 14-, and 30-day analysis, and was near significance in the 21-day analysis. Maximum (MAX) and minimum (MIN) temperature or the temperature-fungal growth function (SIN^2) were seldom effective in explaining stem rust development. However, the temperature-fungal growth function

TABLE 1. Coefficients of determination (r^2) for independent variables used in the regression analyses of wheat stem rust severities on biological and metorological data

Predictive period (days)	DS	CSN	WSN	GS	IF	WIF	VAR	LOC	SIN^2	MAX	MIN	FM	PREC	R-CSN	R-DS	N
							Data from stations with dew records[a]									
7	.675	.494	.501	.085	.0367	.234	.059	.001	.073	.061	.023	.011	.009	.067	.216	579
14	.569	.440	.447	.115	.318	.287	.057	.001	.085	.053	.039	.010	.001	.066	.176	575
21	.346	.324	.213	.100	.233	.230	.240	.000	.056	.022	.048	.002	.004	.096	.054	545
30	.163	.199	.170	.089	.119	.145	.062	.003	.047	.038	.065	.061	.034	.072	.018	535
							Data from all stations[b]									
7	.659	.495	.493	.076	*	*	.060	.001	.068	.054	.026	*	.010	.072	.227	774
14	.536	.403	.403	.080	*	*	.067	.001	.079	.047	.041	*	.001	.072	.180	770
21	.381	.314	.302	.078	*	*	.064	.001	.067	.024	.061	*	.008	.099	.065	765
30	.151	.207	.173	.074	*	*	.068	.002	.067	.038	.072	*	.033	.019	.015	760

[a] DS = Log_{10} percent disease severity on date of prediction (DP). CSN = Log_{10} cumulative number of *Puccinia graminis* urediospores trapped to DP. WSN = Log_{10} number of urediospores trapped during the 7 days prior to DP. GS = Wheat growth stage on date predicted. IF = Cumulative infection function. WIF = Weekly infection function. VAR = Numeric code for cultivar. LOC = Numeric code for nursery. SIN^2 = Temperature-fungal growth function. MAX = Average maximum temperature during the 7 days prior to DP. MIN = Average minimum temperature during the 7 days prior to DP. FM = Average number of hours of free moisture during the 7 days prior to DP. PREC = Number of days with $\geq$0.25 mm of rain during the 7 days prior to DP. R–CSN = Logistic rate of increase of CSN to DP. R-DS = Logistic rate of increase of DS to DP. N = Number of observations used in the analyses.

[b] IF, WIF, and FM were not included in the analysis of data from all stations.

TABLE 2. Constant values and partial regression coefficients (b) for those variables used to predict stem rust severities where dew records are available

Predictive period[a]	K[b]	DS	IF	GS	WSN	CSN	VAR	R-CSN	FM	SIN^2	R^2
7	–0.3179	0.4135		0.0455	0.4310	–0.1809	0.0046	–0.5628			.745
7	–0.1367	0.4696	0.1358	0.0654			0.0047		–0.0431		.730
14	–0.4571	0.3835		0.1181	0.2233		0.0060				.664
14	–0.1729	0.4282	0.1368				0.0048		–0.0415		.654
21	–0.3990	0.4036	0.1087	0.1476		0.2770	0.0066				.509
21	–0.2817	0.4806	0.2216	0.1774			0.0055				.479
30	–0.7229	0.3334		0.1442	0.2158	0.1410	0.0103		0.0508	0.0049	.362
30	–0.7914	0.4045	0.2439	0.1664			0.0095		0.0455	0.0058	.338

[a] All inoculum variables were allowed to enter the first equation in a predictive period. Only DS or CSN was allowed to enter the second equation as an inoculum variable.

[b] K = Constant term. DS = Log_{10} percent disease severity on DP. IF = Cumulative infection function. GS = Wheat growth stage. WSN = Log_{10} weekly spore numbers. CSN = Log_{10} cumulative spore numbers. VAR = Cultivar code. R-CSN = Logistic rate of increase of CSN to DP. FM = Hours of free moisture for the 7 days prior to DP. SIN^2 = Fungal-temperature growth function. R^2 = Coefficient of determination for the equation.

(SIN^2) explained a significant amount of variation in the 30-day analysis.

A temperature measurement explained a significant amount of the variation in stem rust development when hours of free moisture were not available for inclusion in the analysis (Table 3). The R^2 values for those equations, developed without hours of free moisture as an independent variable, were .02 to .06 lower than equations with hours of free moisture included.

If DS was omitted from the analyses and CSN or WSN was used as the inoculum variable, the R^2 values obtained in the analysis were from .20 to .40 lower than when DS was used as the inoculum variable.

Separate analysis of winter and spring wheat nurseries produced r^2 and R^2 values which were lower than those reported in Tables 1-3. Meteorological variables alone could not be used successfully to predict stem rust development as evidenced by the R^2 values for those equations, which were much lower and ranged from .163 to .250. Constant values (K) and partial regression coefficients (b) for equations used to predict stem rust development are shown in Tables 2 and 3.

DISCUSSION.—*P. graminis* rarely overwinters north of Denton, Texas. Thus, the primary inoculum was exogenous to the nurseries included in the analyses. This was in contrast to *P. recondita*, which overwinters to some extent in most of the winter wheat area but seldom overwinters in the spring wheat area. Unlike the leaf rust studies (1,4) where a

TABLE 3. Constant values and partial regression coefficients (b) for those variables used to predict stem rust severities where dew records are unavailable

Predictive period[a]	K[b]	DS	GS	VAR	WSN	CSN	SIN^2	MAX	MIN	R-CSN	PREC	R^2
7	−0.5207	0.4191	0.0661	0.0050	0.2495					−0.5531		.722
7	0.2748		0.1019	0.0051			0.0082	0.5152				.692
14	−0.0090	0.3940	0.0929	0.0059	0.2290		0.0047	−0.0179	0.0156			.630
14	0.2654	0.4953	0.1329	0.0056			0.0087	−0.0117				.592
21	−0.3183	0.4074	0.1247	0.0079	0.1701	0.1356		−0.0198	0.0327			.532
21	0.2545	0.5428	0.1518	0.0072			0.0062	−0.0270	0.0325			.475
30	−0.6978	0.3316	0.1451	0.0103		0.3691	0.0057				0.0582	.353
30	−0.4384	0.5131	0.1722	0.0103			0.0047	−0.0201	0.0383			.301

[a] All inoculum variables were allowed to enter the first equation in a predictive period. Only DS or CSN was allowed to enter the second equation as an inoculum variable.

[b] K = Constant term. DS = Log_{10} percent disease severity on DP. GS = Wheat growth stage. VAR = Cultivar code. WSN = Log_{10} weekly spore numbers. CSN = Log_{10} cumulative spore numbers. SIN^2 = Fungal-temperature growth function. MAX = average maximum temperature. MIN = Average minimum temperature. R-CSN = Logistic rate of increase of CSN to DP. PREC = Days of precipitation $\geqslant 0.25$ mm. R^2 = Coefficient of determination for the equation.

separate set of equations was necessary to predict leaf rust development in the winter and spring wheat areas, one set of equations could predict stem rust development in the Great Plains.

We have not identified all those meteorological and biological variables or interactions between variables that affect stem rust development. These are temporary equations, and as yet are untested on data not included in their development. Standard errors of the estimate obtained in the regression analysis indicate that we should be able to predict stem rust development within 9 and 18% at 7 and 30 days, respectively. Final severities can be predicted more accurately than severities at earlier dates.

Analyses of stem rust data reported here and the leaf rust data reported earlier (1, 4) show that an inoculum variable is necessary for maximum accuracy in any rust prediction system. The entry of a numerical code for cultivar into the prediction equation recognizes the importance of specific resistance or differences in horizontal resistance in attempts to predict stem rust development.

The rate of rust development and the final rust severity can be accurately estimated when leaf or stem rust is present in the field on the date of prediction. However, if leaf or stem rust is not present on the date of prediction, our equations usually underestimate the rate of development and the final severity. We believe that other variables or combinations of existing variables can be used to improve the accuracy of prediction of stem rust development. Accuracy may be increased by including, as independent variables in the analyses, disease severity estimates and/or urediospore numbers observed in an area believed to provide inoculum for the area in which rust development is being predicted. This would allow us not only to overcome the problem of measuring the inoculum potential but also to increase the length of the forecast period from 30 to 45 days or longer.

We anticipate that those cultivars with similar resistance to the prevailing parasite population will be grouped together and given a numerical value according to patterns of rust development. The more resistant cultivars will be given a lower numerical value than the more susceptible cultivars or cultivars on which the rate of rust development is faster.

Success in our effort to accurately estimate epidemic development of leaf and stem rust and the resulting crop loss would provide a vast amount of information useful for making decisions on which wheat varieties to grow, whether alternative rust control measures, such as chemicals, are necessary and/or economical, and the marketing of the wheat crop for the greatest economic return to the producer. It would also improve national planning by providing more accurate and advanced assessment of national and international wheat production.

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