A Method of Predicting Epidemic Development of Wheat Leaf Rust

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ABSTRACT

A stepwise multiple regression computer program was used to formulate equations to predict per cent disease severities of wheat leaf rust (*Puccinia recondita* f. sp. *tritici*). Equations were generated for winter and spring wheats by analysis of biological and meteorological data from 24 winter wheat and 16 spring wheat locations. Equations were in the form $Y_i = b_1X_{1i} + \dots + b_nX_{ni} + K$, where X_{ni} values (independent variables) were measures of disease severity, weekly urediospore numbers, cumulative urediospore numbers, average maximum temperature, average minimum temperature, hr of free moisture as dew or rain per day and days of precipitation, respectively, recorded during the seven days immediately preceding the date of prediction. The dependent variable (Y_i) was the $\log_{10}$ or $\log_e \frac{x}{1-x}$ transformation of per cent disease severity recorded 8 days after the date of prediction.

Analysis of data from individual locations was of little value in determining the independent variables to be used in prediction. When data from all winter wheat locations were combined, however, coefficients of determination (R^2) indicated that variation in disease severity, minimum temperature, and either hr of free moisture or days of precipitation explained over 70% of the variation in epidemic development. R^2 values indicated that in spring wheats, weekly or cumulative urediospore numbers could be substituted for disease severity in the prediction model.

Partial regression coefficients (b) from 1967 and 1968 combined data were used to predict leaf rust severities at successive wheat growth stages up to hard dough for several 1968 locations. Data from those locations were not used to calculate b values used in prediction. The average variation between actual and predicted severities was 5% when predictions were made between wheat growth stages, boot to milk. Phytopathology 60:805-811.

Wheat leaf rust, incited by *Puccinia recondita* Rob. ex Desm. f. sp. *tritici*, can reduce wheat yields by as much as 50% in the Great Plains area of the USA (13). Resistant cultivars are the primary means of control; however, changes in virulence of the parasite population reduce long term effectiveness of specific resistance.

Chemical control of leaf rust has been neither effective nor economical because the complex interrelationships between weather, amount of inoculum, rate of disease development, and reduction in yield have not been defined. The margin of profit to the wheat grower does not permit empirical use of fungicides; consequently, a reliable leaf rust forecasting system is essential if fungicides are to be effective and economical in reducing losses.

Extensive studies have been conducted on the epidemiology of leaf rust, but there were few attempts to forecast disease severities. Instead, emphasis was placed on following the seasonal development of leaf rust by the date of first appearance of urediospores on spore traps and of uredia in the field, the number and intensity of spore showers, and by meteorological observations (1, 2, 4, 5, 6, 7, 8, 11, 14, 16).

Chester (3) developed a leaf rust forecasting procedure for Oklahoma based on the severity of rust on 1 April. He found that seasonal temperature and moisture patterns after 1 April did not markedly affect the rate of disease development, as epidemic potential after that date was predetermined by amount of inoculum. Because a logarithmic increase in leaf and stem rust severity can occur in 4-5 days (12), extremely favorable or unfavorable environmental conditions could modify Chester's forecasts.

Infection by *P. recondita* depends on the presence of (i) viable inoculum on susceptible host tissue; (ii) temperatures favorable for urediospore germination and infection; (iii) free moisture for spore germination (3). Several factors affecting leaf rust development were studied under controlled environments (3), but development in the field is subject to environments that fluctuate according to diurnal and seasonal patterns, and are not easily programmed in environmental chambers. In addition, short irregular changes in those patterns affect subsequent disease development. In our study, several biological and meteorological variables that might be useful in leaf rust prediction are examined, several methods of transforming variables are tried, and prediction equations in the form $Y_i = b_1X_{1i} + \dots + b_nX_{ni} + K$ are tested.

Materials and Methods.—In 1967 and 1968, two cultivars of *Triticum aestivum* L. em Thell. were planted in 12 × 18 m plots at 24 winter wheat locations in Texas, Oklahoma, Kansas, and Nebraska, and at 16 spring wheat locations in South Dakota, North Dakota, and Minnesota. Bison (C.I. 12518) or Baart (C.I. 1697) was used as a susceptible cultivar at all winter and spring wheat locations, respectively. The second cultivar planted was one predominantly grown in the area. That combination of cultivars enabled us to measure rate of disease development on a susceptible cultivar and on a commercial cultivar, which in most cases was resistant to portions of the parasite population.

Random samples of 40 culms of each cultivar were collected weekly until boot stage, and thereafter twice weekly. Samples were placed in padded envelopes or 3-inch mailing tubes and airmailed to the Rust Laboratory in Manhattan, Kansas, where leaf rust severity was recorded as number of uredia per culm. When leaf rust severity reached 1% (18 uredia/culm), subsequent severity estimates were made using the modified Cobb scale (9). Samples were collected daily from the Bison plot at Manhattan in 1968.

Glass rod impaction traps (10) mounted on weather vanes in or near the nurseries were used to provide a measure of urediospore numbers. Spore numbers were expressed as numbers deposited per cm^2 per day.

Weather data were recorded from instruments located at the plots. Hours of free moisture occurring as dew and rain were recorded by a Taylor dew meter (15) at 12 locations in 1967 and 16 locations in 1968.

Analyses of the relationships between disease severity and biological-meteorological variables were made using simple and multiple regression techniques. Disease severity was used as the dependent variable; two measures of temperature, two of moisture, and three of inoculum were used as independent variables. Since we wanted to develop an 8-day forecasting system, regression analyses were structured around measures of temperature, moisture, and inoculum recorded 8-14 days before each estimate of the dependent variable.

Logit and $\log_{10}$ transformations of uredial and urediospore numbers were used in several analyses. Van der Plank (17) showed that rate of epidemic development can be expressed by the logistic function, and that the logit, $\left(\log_e \frac{x}{1-x}\right)$, can be used to analyze epidemics caused by pathogens which multiply exponentially, such as the rust fungi.

Regression analysis, with disease severity (dependent variable) transformed as either the logit or the $\log_{10}$, was applied to our data using various combinations of the following as independent variables: (i) the logit or $\log_{10}$ of total cumulative spore numbers recorded 8 days prior to the dependent variable; (ii) the logit or $\log_{10}$ of the total weekly spore numbers recorded 8-14 days prior to the dependent variable; (iii) the logit or $\log_{10}$ of disease severity observed 8 days prior to the dependent variable; (iv) average maximum temperature recorded 8-14 days prior to the dependent variable; (v) average minimum temperature recorded 8-14 days prior to the dependent variable; (vi) average hr of free moisture per day occurring as dew and rain 8-14 days prior to the dependent variable; and (vii) the number of days of measurable precipitation recorded 8-14 days prior to the dependent variable.

Transformations were made by subroutines within simple and multiple regression computer programs. All tests of significance were calculated at the 0.05% level.

Epidemic development on each cultivar in 1967 was analyzed using a stepwise multiple regression computer program. The order that independent variables enter the regression equation is determined by an F test that ranks the variables in descending order, according to their value in explaining variation in the dependent variable.

Statistical analysis of 1967 data was hindered by lack of degrees of freedom for individual locations. Therefore, data from winter wheat locations where free moisture records were available were combined according to cultivar (Bison or second cultivar) and analyzed. Also, data from all 1967 winter wheat cultivars were combined and analyzed as one test. The same procedure was followed for data from 1967 spring wheat and 1968 winter and spring wheats. Finally, data from 1967 and 1968 were combined and analyzed by cultivar; then data from all cultivars were combined and analyzed.

Partial regression coefficients obtained in the analysis of combined data were used to predict leaf rust severities on cultivars not included in the regression analysis.

RESULTS.—In the simple regression analysis of 1967 data, variation in minimum temperature effectively explained variation observed in disease severity at all winter wheat locations and three of four spring wheat locations. Variation in hr of free moisture explained a significant amount of variation at two winter wheat and three spring wheat locations. However, 50 to 90% of the variation in a simple regression model remained unexplained when only meteorological variables were used.

In analyzing epidemics on individual cultivars, an inoculum variable entered the stepwise multiple regression equation first at most locations. A weather variable entered next and explained a significant amount of variation in disease severity at 50% of the locations. All succeeding variables were nonsignificant (Table 1).

In the stepwise multiple regression program, the symbol used to express the amount of variation in the dependent variable explained by multiple regression is R^2. In the same program, the symbol for the amount of variation in the dependent variable explained by simple regression is r^2.

Coefficients of determination (r^2) for simple regression indicated that r^2 values for inoculum were not significantly greater than those for minimum temperature at most locations (Table 2). Also, r^2 values for disease severity, weekly urediospore numbers, and cumulative urediospore numbers at individual locations were not significantly different, indicating that any of the inoculum variables could be substituted in the prediction model. A larger number of observations may show that significant differences exist between inoculum variables and between inoculum and minimum temperature, as analysis of 1967, 1968, and 1967 and 1968 combined data indicated that differences do exist in amount of variation explained by inoculum variables.

Coefficients of determination (R^2) for transformed and nontransformed estimates of disease severity always were greater than those for weekly urediospore numbers and cumulative urediospore numbers in 1967, 1968, and 1967 and 1968 combined Bison data (Table 3). With combined Baart data, however, R^2 values for transformed estimates of disease severity were greater than those for weekly urediospore numbers and cumulative urediospore numbers only in 1967, while nontransformed values were greater in 1967, 1968, and 1967-68. R^2 values for weekly urediospore numbers and cumulative urediospore numbers were higher than R^2 values for disease severity when transformations were used on Baart data in 1968 and 1967 and 1968 combined data.

TABLE 1. Coefficients of determination (R^2) obtained in the logit and $\log_{10}$ analyses of 1967 data and the order variables entered the stepwise multiple regression program

Cv. and location	Transformation	R^2 value and order[a]						
Bison winter wheat								
Denton, Texas	Logit	DS	MIN	PREC	CSN	FM	WSN	MAX
		.745	.819	.897	.912	.931	.939	.941
	Log_{10}	DS	MIN	PREC	CSN	FM	WSN	MAX
		.731	.805	.893	.904	.927	.933	.935
Goodwell, Okla.	Logit	DS	PREC[b]	MIN	MAX	WSN	PREC	CSN
		.814	.906	.922	.933	.935	.935	.937
	Log_{10}	DS	PREC[b]	MIN	WSN	FM	CSN	MAX
		.835	.906	.933	.941	.947	.949	.951
Stillwater, Okla.	Logit	WSN	MAX[b]	FM	PREC	CSN	MIN	DS
		.872	.912	.922	.949	.955	.956	.956
	Log_{10}	WSN	MAX[b]	FM	PREC	CSN	MIN	DS
		.876	.916	.925	.962	.968	.972	.974
Manhattan, Kans.	Logit	CSN	FM	PREC	WSN	DS	MAX	MIN
		.769	.835	.850	.882	.893	.893	.895
	Log_{10}	CSN	FM	PREC	WSN	DS	MAX	MIN
		.771	.821	.835	.874	.885	.885	.885
Colby, Kans.	Logit	CSN	MAX	WSN	DS	PREC	MIN	FM
		.702	.821	.880	.891	.901	.933	.937
	Log_{10}	CSN	PREC	DS	FM	MIN	MAX	WSN
		.702	.814	.863	.895	.903	.918	.924
Baart spring wheat								
Eureka, S. Dak.	Logit	DS	PREC	MIN	CSN	MAX	FM	WSN
		.867	.956	.958	.960	.964	.966	.966
	Log_{10}	DS	PREC	MIN	FM	CSN	MAX	WSN
		.835	.925	.941	.949	.958	.970	.982
Langdon, N. Dak.	Logit	CSN	PREC[b]	WSN	DS	MIN	MAX	FM
		.863	.935	.962	.972	.972	.972	.972
	Log_{10}	CSN	PREC[b]	WSN	DS	MIN	MAX	FM
		.865	.935	.962	.972	.972	.972	.972

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = number of days of precipitation; FM = average hr of free moisture per day.

[b] Addition of the independent variable significantly reduced unexplained variation in disease severity.

TABLE 2. Coefficients of determination (r^2) for logit and $\log_{10}$ analyses of 1967 weather and inoculum data

		Inoculum[a]			Temp.[a]		Moisture[a]		
Cv. and location		DS	WSN	CSN	MAX	MIN	FM	PREC	N[a]
Bison winter wheat									
Denton, Texas	Logit	.745	.666	.698	.073	.624	.733	.160	11
	Log_{10}	.731	.640	.671	.065	.624	.142	.728	
Goodwell, Okla.	Logit	.813	.759	.980	.476	.602	.486	.401	12
	Log_{10}	.814	.757	.778	.426	.345	.487	.401	
Stillwater, Okla.	Logit	.731	.872	.840[b]	.104	.376	.001	.011	17
	Log_{10}	.734	.876	.841[b]	.100	.387	.000	.008	
Manhattan, Kans.	Logit	.758	.691	.769	.067	.500	.006	.005	18
	Log_{10}	.755	.686	.771	.065	.486	.013	.007	
Colby, Kans.	Logit	.594	.544	.702	.202	.504	.050	.098	11
	Log_{10}	.593	.543	.702	.208	.493	.050	.098	
Baart spring wheat									
Eureka, S. Dak.	Logit	.867	.465	.408	.415	.298	.678	.750	12
	Log_{10}	.835	.629	.830	.461	.513	.483	.814	
Langdon, N. Dak.	Logit	.667	.663	.863	.625	.501	.028	.085	11
	Log_{10}	.667	.666	.865	.604	.494	.027	.085	

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = days of precipitation; FM = average hr of free moisture per day; N = number of observations.

[b] r^2 for CSN at Stillwater, Okla., was significantly greater than r^2 for minimum temp.

TABLE 3. Coefficients of determination (R^2) obtained from combined data using several combinations of independent variables

Cv. and year	Independent variables in equation[a]	Transformation: None	Log$_{10}$	Logit	N[a]
Bison winter wheat					
1967	DS, MIN, PREC	.486	.805	.802	165
	WSN, MIN, PREC	.384	.667	.669	165
	CSN, MIN, PREC	.367	.684	.685	165
1968	DS, MIN, PREC	.610	.823	.820	220
	WSN, MIN, PREC	.348	.714	.714	220
	CSN, MIN, PREC	.312	.712	.719	220
1967 and 1968	DS, MIN, PREC	.573	.814	.811	385
	WSN, MIN, PREC	.319	.674	.677	385
	CSN, MIN, PREC	.281	.669	.675	385
Baart spring wheat					
1967	DS, MIN, PREC	.264	.677	.678	36
	WSN, MIN, PREC	.256	.507	.508	36
	CSN, MIN, PREC	.259	.554	.556	36
1968	DS, MIN, PREC	.667	.555	.599	41
	WSN, MIN, PREC	.419	.801	.811	41
	CSN, MIN, PREC	.408	.782	.795	41
1967 and 1968	DS, MIN, PREC	.677	.607	.633	77
	WSN, MIN, PREC	.434	.632	.707	77
	CSN, MIN, PREC	.423	.689	.715	77

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = days of precipitation; FM = average hr of free moisture per day; N = number of observations.

When data were combined, minimum temperature was always equal to or better than maximum temperature in explaining variation observed in disease severity, although differences were nonsignificant. Differences between r^2 values for precipitation and hr of free moisture were nonsignificant, and neither variable consistently gave a higher r^2 than the other. When data from individual locations were analyzed, small changes in those relationships between maximum and minimum temperatures and between precipitation and hr of free

TABLE 4. Average variation (% severity) between observed and predicted leaf rust severities at Manhattan, 1968

		Prediction equations[a]						
Wheat growth stages and transformation	Cv.	DS MIN FM	DS MIN PREC	WSN MIN FM	WSN MIN PREC	CSN MIN FM	CSN MIN PREC	All variables
Boot to milk								
None	Bison	5.4	5.4	5.8	6.0	7.4	7.0	5.1
	Ottawa	4.8	4.8	6.2	7.0	8.1	8.6	4.6
	Bsn/Ott[b]	5.1	5.1	6.0	6.5	7.8	7.8	4.8
Log$_{10}$	Bison	6.6	9.8	5.4	6.1	6.1	6.8	[c]
	Ottawa	5.5	8.2	5.7	6.1	6.7	7.4	[c]
	Bsn/Ott	6.1	9.0	5.6	6.1	6.4	7.1	[c]
Logit	Bison	6.4	8.4	4.8	5.7	5.6	6.4	9.0
	Ottawa	5.3	7.0	5.3	5.7	6.2	7.0	8.8
	Bsn/Ott	5.9	7.7	5.1	5.7	5.9	6.7	[c]
Tillering to boot								
None	Bison	3.6	3.2	8.4	5.1	8.5	4.8	3.4
	Ottawa	3.8	3.2	8.5	5.2	8.7	5.0	3.6
	Bsn/Ott	3.7	3.2	8.4	5.1	8.6	4.9	3.5
Log$_{10}$	Bison	.7	.5	.3	.5	.3	.4	4.4
	Ottawa	.6	.3	.3	.3	.3	.4	5.7
	Bsn/Ott	.6	.4	.3	.4	.3	.4	5.0
Logit	Bison	.8	.5	.2	.3	.2	.4	.5
	Ottawa	.7	.2	.2	.2	.4	.5	.2
	Bsn/Ott	.8	.3	.2	.2	.3	.4	.3

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = days of precipitation; FM = average hr of free moisture per day.

[b] Average variation in severities on Bison and Ottawa.

[c] No predictions made using all seven variables.

moisture were noted between years and between cultivars within years, but no definite pattern was detected.

Statistical tools to evaluate differences between equations are not available. Therefore, b values obtained from regression equations for all combinations of inoculum, moisture, and temperature were used to predict leaf rust severities at several locations during 1968. Data used for prediction were not from the cultivars involved in formulating prediction equations.

Average variation ($\sqrt{(y-\hat{y})^2/n}$) between observed and predicted severities was calculated and used to determine which equation was the most precise. Variation was always least with equations from combined data.

Variation between observed and predicted rust severities at Manhattan was between 4.8 and 9.8%. Leaf rust severities during the wheat growth stages, boot to milk, generally were predicted within 5% using an 8-day forecast (Table 4). Predictions made with equations using no transformation of disease severity always were more precise than those using both transformation of disease severity and cumulative spore numbers, and $\log_{10}$ transformation of weekly spore numbers. Predictions made using the logit transformation of weekly spore numbers were equally as accurate as those using no transformation of disease severity when hr of free moisture were included in the prediction equation, but not as accurate if days of precipitation were used as the moisture variable.

Logit or $\log_{10}$ transformation of data between tillering and boot growth stages greatly increased the accuracy of predictions over those made with no transformation of data (Table 4). Predictions made using either $\log_{10}$ or logit transformation of spore numbers were more accurate than those using transformations of disease severity. Inclusion of three instead of all seven independent variables in the prediction model resulted in less than a 0.3% increase in the average variation between predicted and observed severities.

Hours of free moisture were not available for locations used to test the spring wheat equations. In contrast to winter wheats, logit and $\log_{10}$ transformations of disease severities on spring wheats increased the accuracy of predictions over those obtained with no transformations between successive wheat growth stages, tillering to boot and boot to milk. However, with weekly and cumulative spore numbers, the use of transformations decreased the accuracy of predictions made for successive wheat growth stages between boot and milk (Table 5).

TABLE 5. Average variation (% severity) between observed and predicted leaf rust severities at Carrington, Park River, and Minot, North Dakota, 1968

Wheat growth stages and transformation	Cv.	Prediction equations[a]		
		DS MIN PREC	WSN MIN PREC	CSN MIN PREC
Boot to milk				
None	Baart	10.9	15.6	15.4
	Selkirk	3.7	4.5	4.8
	Baart/ Selkirk[b]	7.3	10.1	10.1
$\log_{10}$	Baart	10.3	18.3	19.4
	Selkirk	2.8	8.6	9.5
	Baart/ Selkirk	6.6	13.5	14.5
Logit	Baart	10.1	17.8	18.4
	Selkirk	2.6	7.9	8.0
	Baart/ Selkirk	6.4	12.9	13.2
Tillering to boot				
None	Baart	1.9	2.6	2.6
	Selkirk	1.9	2.6	2.7
	Baart/ Selkirk	1.9	2.6	2.6
$\log_{10}$	Baart	.2	.3	.2
	Selkirk	.1	.3	.3
	Baart/ Selkirk	.1	.3	.2
Logit	Baart	.2	.3	.2
	Selkirk	.0	.3	.3
	Baart/ Selkirk	.1	.3	.2

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = days of precipitation.

[b] Average variation in severities on Baart and Selkirk.

Predictions of rust severity, between tillering and boot growth stages, usually were higher than the actual severities observed in both winter and spring wheat regions. Prediction equations using logit or $\log_{10}$ transformations of spore numbers predicted rust severities on wheat most accurately when severities were below 1% or when wheat was in the joint growth stage at both Manhattan and Carrington (Table 6). At both locations, rust severities at anthesis were predicted most accurately by equations using disease severity as the inoculum variable. Equations including either the logit or $\log_{10}$ transformation of weekly spore numbers or disease severity as the inoculum variable with hr of free moisture and minimum temperature as the weather variables predicted rust severities most accurately on wheat at the milk growth stage at Manhattan. In contrast, only disease severity, minimum temperature, and days of precipitation predicted severities with any accuracy at Carrington (Table 7).

DISCUSSION.—Environment is a complex term that includes many factors which must be beyond a minimum threshold for disease development to occur. To study the interrelationships of the independent variables (biological and meteorological) with disease development, the independent variables must be limiting or fluctuating between minimum and maximum conditions necessary for disease development. A change in one environmental factor may alter the effect of other environmental factors on disease development. For example, precipitation washes inoculum from the air, reduces light intensity, lowers temperatures, and increases the probability of dew formation for several succeeding days. Dew usually occurs more frequently than rain in the Great Plains, and hr of free moisture proved to be the most accurate measure of moisture available for leaf rust development, as shown by the increased precision in predicting leaf rust severities with hr of free moisture rather than days of precipita-

TABLE 6. Actual and predicted leaf rust severities (%) for various wheat growth stages at Manhattan, Kansas, and Carrington, North Dakota during the 1968 crop year

				Prediction equations[a]						
Cv. and location	Trans-formation	Growth stage	Actual sever-ity	DS MIN FM	DS MIN PREC	WSN MIN FM	WSN MIN PREC	CSN MIN FM	CSN MIN PREC	All vari-ables
Bison winter wheat										
Manhattan, Kans.	None	Joint	0.5	4.1	3.5	9.3	5.6	9.3	5.2	4.0
	Log_{10}	Joint	0.5	0.0	0.0	0.4	0.4	0.6	0.6	0.5
	Logit	Joint	0.5	0.0	0.0	0.4	0.4	0.6	0.6	0.0
	None	Anthesis	11.0	10.0	10.0	7.2	6.3	7.5	7.0	10.0
	Log_{10}	Anthesis	11.0	9.8	9.2	4.7	4.2	5.5	5.0	[b]
	Logit	Anthesis	11.0	10.0	9.8	5.3	4.7	6.3	5.7	9.8
	None	Milk	29.5	22.1	21.3	18.7	14.7	12.9	10.8	22.0
	Log_{10}	Milk	29.5	26.7	20.5	28.7	19.0	16.9	12.7	[b]
	Logit	Milk	29.5	26.3	21.2	27.4	19.5	17.9	13.7	26.3
Baart spring wheat										
Carrington, N. Dak.	None	Joint	0.2		0.0		0.5		0.6	
	Log_{10}	Joint	0.2		0.0		0.3		0.2	
	Logit	Joint	0.2		0.0		0.3		0.2	
	None	Anthesis	18.0		5.8		5.2		5.4	
	Log_{10}	Anthesis	18.0		5.6		3.4		3.7	
	Logit	Anthesis	18.0		6.3		4.1		4.3	
	None	Milk	59.0		46.3		9.9		9.9	
	Log_{10}	Milk	59.0		48.2		14.0		11.3	
	Logit	Milk	59.0		45.4		15.5		12.8	

[a] CSN = cumulative urediospore numbers; WSN = weekly urediospore numbers; DS = disease severity; MAX = average maximum temperature; MIN = average minimum temperature; PREC = days of precipitation; FM = average hr of free moisture per day.

[b] No prediction made using all seven variables.

tion (Table 4). However, inclusion of a precipitation variable increased the accuracy of prediction over that with no moisture variable.

Since dew usually occurs when daily temperatures are at or near the minimum, minimum temperature may provide the most accurate measure of temperature affecting disease development. In the early part of the growing season (tillering to boot), minimum temperatures are often below or fluctuating across the temperature threshold for leaf rust development, but maximum temperatures are at or near the developmental optimum and therefore do not limit disease development.

The critical period for rust control occurs early in the growing season, therefore leaf rust prediction equations should be refined to increase the forecast time from 8 to 30 days before heading. The ability to use 5 or 30-day weather forecasts to predict disease development may enhance the value of any prediction used as the basis for a fungicide control program. Prediction equations based on data from geographical areas having similar temperatures, moisture, and crop maturity patterns may be more accurate than those based on data from the entire winter or spring wheat region.

The final test of a prediction equation is how accurately it forecasts leaf rust development. Prediction equations, developed from these studies of biological-meteorological factors, predict leaf rust severities between boot and milk growth stages of wheat within 5%.

TABLE 7. Beta coefficients (b) used in testing prediction equations obtained from analysis of 1967 and 1968 combined data

	Prediction equations[a]					
Transformation	K	DS	WSN	MIN	FM	PREC
Winter wheat						
Logit	−0.29	0.8345		−0.0020	0.0746	
	−1.31		0.8057	−0.0041	0.1084	
Log_{10}	0.17	0.8167		−0.0007	0.0305	
	−2.23		0.7742	−0.0014	0.0438	
None	1.63	1.2444		−0.0063	0.1974	
Spring wheat						
Logit	−1.30	0.8312		0.0453		−0.2076
Log_{10}	0.19	0.7968		0.0102		−0.0309
None	−4.95	1.4097		0.1899		−0.3109

[a] K = constant term; DS = disease severity; WSN = weekly urediospore numbers; MIN = minimum temperature; FM = hr of free moisture; and PREC = days of precipitation.

Equations generated from 1967 and 1968 data would not accurately predict leaf rust severity in either year. However, when data from all cultivars in 1967, a year of light leaf rust, and 1968, a year of heavy leaf rust, were combined, the resulting equations accurately predicted leaf rust severities. We believe this resulted from the inclusion of data from a year in which weather and inoculum variables were marginal for leaf rust development with one in which the environmental conditions were optimal at many locations. The environmental conditions at the locations being predicted were within the extremes of those 2 years.

Prediction equations have been defined in precise terms, but their actual application must be modified in some situations. For instance, a severe spring freeze that kills infected host tissue and reduces inoculum negates the effect of endogenous inoculum as a variable. A change in the resistance of cultivars or in pathogenicity of the parasite population affects any disease forecast. With increased experience in disease forecasting, it should be possible to overcome such obstacles to accurate forecasts.

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