CLIMATIC VARIABLES THAT CONTROL DEVELOPMENT OF STRIPE RUST DISEASE ON WINTER WHEAT

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Abstract. The frequency and severity of the stripe rust disease (caused by *Puccinia striiformis*) on winter wheat in the Pacific Northwest of the U.S.A. has increased since 1958 in association with climatic variation. From 1968-1979, rust intensities on 'Gaines' wheat were most highly correlated with accumulated negative degree days (NDD) between 1 December and 31 January and positive degree days (PDD) between 1 April and 30 June. NDD and PDD were calculated from a 7 °C base. Linear regression equations using NDD alone accounted for 76% of the variation in stripe rust. When NDD and PDD were combined, 88% of the variation in stripe rust was explained. When a growth index (GI), and NDD plus PDD were used as independent variables in a multiple regression analysis, 91% of the variation in disease was explained. Frequency of precipitation in June was correlated with stripe rust intensity, but when it was added to the multiple regression analysis, it explained less than an additional 1% of the variation. The relationships between NDD, PDD, and disease index help to explain why stripe rust was not severe from 1941 to 1957. Methods used in this research should be applicable to similar studies of the effect of climatic variation on other pests.

1. Introduction

Stripe rust is a disease of wheat (*Triticum aestivum* L. em Thell) caused by the fungus *Puccinia striiformis* West. The fungus infects primarily the foliage, but may also infect the heads. The disease reduces the wheat yield and in severely infected fields, the loss may be total. In the U.S.A., stripe rust is most important in the Pacific Northwest (PNW). The history of its occurrence in this region was reviewed by Coakley (1978, 1979). Analysis of meteorological data for the PNW indicated that since 1961, above-normal winter and below-normal spring temperatures were associated with the increased frequency and severity of stripe rust epidemics (Coakley, 1979).

Subsequent research by Coakley and Line (1981) quantified climatic conditions that influence the development of stripe rust on winter wheat. They tested for correlation between numerous meteorological factors and the intensities of rust that occurred at

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Pullman, Washington, from 1963 to 1979 on the winter wheat cultivars 'Omar' (very susceptible) and 'Gaines' (susceptible in the seedling stage but resistant at later growth stages at high temperatures). Rust intensity was found to be most highly correlated with negative degree days (NDD) accumulated between 1 December and 31 January and positive degree days (PDD) accumulated between 1 April and 30 June (NDD and PDD are, respectively, the negative and positive departures of the daily average temperature from a 7°C base). NDD was the best parameter for predicting rust intensity. In Gaines, 73% of the variation in the disease index was explained by NDD. Temperature variation affected disease intensity in Gaines more than in Omar; this was related to the different susceptibilities of the cultivars to stripe rust (Line *et al.*, 1976).

The objective of the research reported here was to improve this quantification of the relationship between climatic variables and stripe rust.

2. Data Source

2.1. *Meteorological Data*

For Pullman, WA (latitude 46°46'N, longitude 117°12'W, elevation 775 m), daily meteorological data for December 1940 to August 1979 were obtained from the National Climatic Center, Asheville, NC. The data consisted of minimum and maximum temperatures, total precipitation, snowfall, and depth of snow on the ground. No data were available for April 1950 to September 1951 or July 1974 and these periods were omitted from calculations of monthly averages. Monthly averages for all years were inserted for the missing values when moving-average lines were calculated to show long-term trends. Temperature data were missing for 8 days in 1956 and 1957. Monthly average temperatures were calculated by averaging the data for the last day preceding and first day succeeding the missing data and by using that value to replace the missing data.

2.2. *Disease Intensity Data*

Stripe rust intensity (estimated percentage of the total leaf and glume surface covered by rust) was recorded periodically at various stages of plant growth for several hundred cultivars and breeding lines of wheat. The wheat trials were planted at numerous locations in the PNW with each cultivar or line in single rows 1.5-3.0 m long. The frequency and time of observations varied from year to year and from location to location, but were usually made between stage 3 (jointing) and stage 8 (dough) using the growth scale described by Zadoks and Konzak (1974). Stripe rust intensity was usually low at stage 3 and was seldom recorded beyond stage 8 because a disease increase after that stage had little additional effect on wheat yields. The rate of rust and plant development varied from year to year.

The winter wheat cultivar 'Gaines' was selected for the research reported here because it has been a major cultivar in the PNW since 1962 and because the development of stripe rust on it is closely related to climatic conditions (Coakley and Line, 1981). Disease data for Gaines were collected at four locations near Pullman for 1968-1979 and averaged for each year. The source of disease was from naturally-occurring stripe rust except at one location where some stripe came from adjacent plots artificially inoculated with rust in the spring. This additional source influenced results only in 1979 when little or no naturally-occurring rust survived the winter. Average percent intensities were grouped and converted to a 0-9 disease index to simplify comparison of disease intensity with climatic variations (Figure 1). An interpretation of the disease index resulted in categories of light, moderate, and severe disease (see Figure 1, right vertical axis).

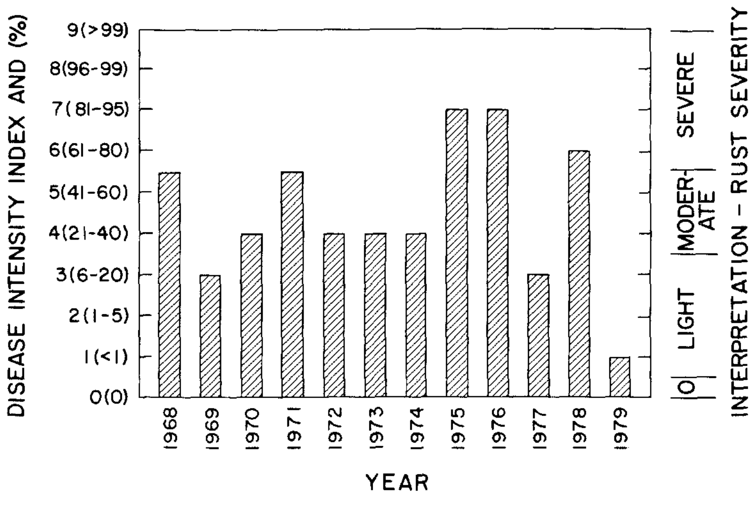


Fig. 1. Stripe rust disease on 'Gaines' winter wheat at Pullman, WA, 1968-1979. The disease intensity index (0-9) represents a range in intensity from 0-100% infection (shown in parentheses).

2.3. *Degree days*

To study the cumulative effect of temperature on disease, degree days were calculated using a 7 °C base. The 7 °C base was selected because Sharp (1965) reported that 7 °C was the optimum temperature for germination of the stripe rust spores and infection of the wheat plant. Daily maximum and minimum temperatures were averaged to give the daily average temperature ($\bar{T}$). Departures of the daily average temperature from a 7 °C base were calculated daily to determine positive degree days (PDD) or negative degree days (NDD) for that day.

$$\text{If } \bar{T} > 7\ ^\circ\text{C}, \quad \text{PDD} = \Sigma\,(\bar{T} - 7\ ^\circ\text{C}).$$
$$\text{If } \bar{T} < 7\ ^\circ\text{C}, \quad \text{NDD} = \Sigma\,|\,\bar{T} - 7^\circ\text{C}\,|$$

The number of PDD and NDD were calculated for each month, starting in September, and for each successive month in combination with all succeeding months in the growing season (through August).

3. Results

3.1. Relation of Disease Intensity to Climatic Variables

The correlation between disease index (see Figure 1) and the monthly and seasonal maximum, minimum, and average temperatures, total precipitation, frequency of precipitation, and cumulative PDDs and NDDs were calculated. The most significant correlation coefficients (r) are presented in Table I.

TABLE I. Correlations between climatic parameters and stripe rust intensity index on 'Gaines' winter wheat and statistical significance (P) of the correlation coefficient (r). Data collected at Pullman, WA 1968-1979 at anthesis, milk, or dough stage of plant growth.

Parameter			Gaines	
			r	P
Precipitation Frequency	Month	June	0.64	0.05
Minimum Temperature	Season	Winter	0.71	0.01
Minimum Temperature	Season	Spring	−0.62	0.05
Minimum Temperature	Month	April	−0.52	0.05
Average Temperature	Month	January	0.85	0.001
Average Temperature	Month	June	−0.69	0.01
Negative Degree Days	Cumulative	1 Dec. to 31 Jan.	−0.87	0.001
Positive Degree Days	Cumulative	1 Apr. to 30 June	−0.82	0.001
Negative Degree Days + Positive Degree Days	Cumulative	1 Dec. to 31 Jan. + 1 Apr. to 30 June	−0.94	0.001

Frequency of precipitation during June was the only precipitation parameter significantly correlated with disease index (Table I). The correlation between precipitation frequency and disease index is not independent of the inverse correlation ($r = -0.69$, $P \leqslant 0.01$) between June precipitation frequency and June average temperature.

For monthly variables, January and June average temperatures had the highest correlations with disease index (Table I). The average temperatures for those months in years with severe, moderate, and light stripe rust (see Figure 1) are shown in Figure 2. The average January temperature in years with severe rust was 6.3 °C above the average temperature in years with light rust. For June, the average temperature for years with severe disease was 2.7 °C lower than in years with light disease.

Total negative degree days (NDD) from 1 December to 31 January and total positive degree days (PDD) from 1 April to 30 June were most highly correlated with disease index. When NDD and PDD were added together, the correlation with disease index was even greater ($r = -0.94$). To quantify the relationship of disease index to NDD and PDD, linear regression analysis was used and the regression equations are shown in Figure 3a-c. Disease intensity (index) decreased as both NDD increased (which corresponded to lower winter temperatures) and PDD increased. NDD explained 76% of the variation in disease

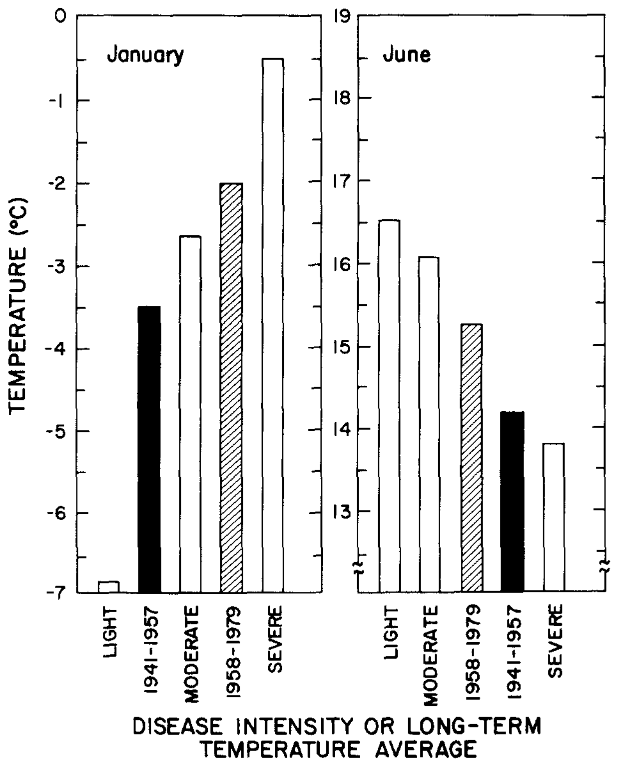


Fig. 2. Average temperatures for January and June at Pullman, WA, for years during 1968-1979 when stripe rust was light, moderate, or severe on 'Gaines' winter Wheat and for 1941-1957 and 1958-1979.

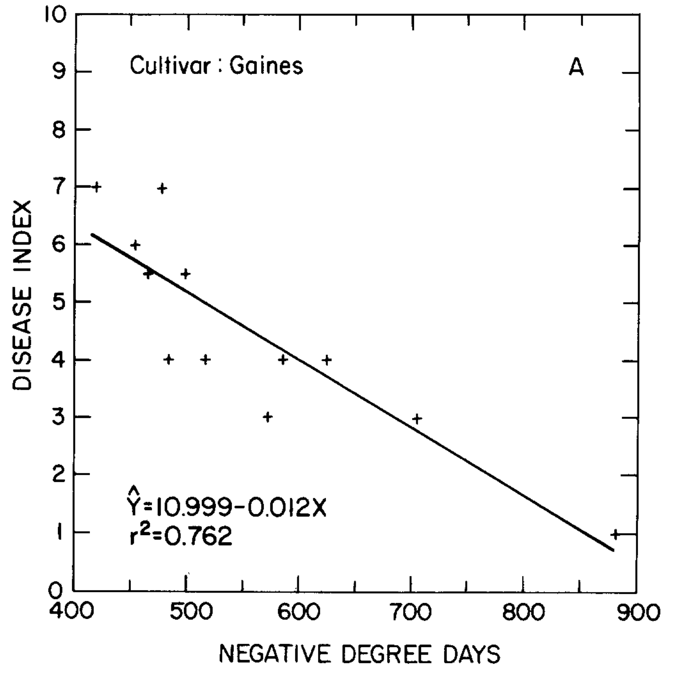
index and was the best single parameter for predicting disease development. When NDD and PDD were combined, 88% of the variation in index was explained.

Multiple regression analysis was used in order to determine if the remaining variation in disease index could be explained by available variables. Because disease index was determined from disease intensity at different growth stages, a growth index (GI) variable was added. June precipitation frequency (JPF) was also added as a variable. Variables, constant values, regression coefficients, and R^2 are given in Table II.

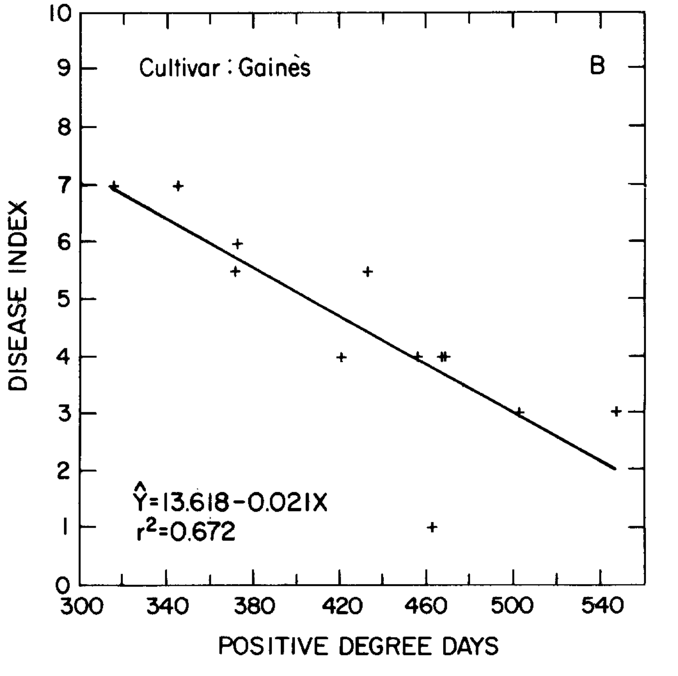
Equation 8, (Table II) which used the variables NDD + PDD and GI, was selected as the best equation for predicting disease index in Gaines winter wheat. Together the climatic variables and growth stage accounted for 91% of the variation in disease index. Equation 8 which used NDD + PDD was selected over Equation 7 which used NDD and PDD as independent variables because NDD and PDD were correlated with each other (r = 0.629). The addition of JPF (Equation 12) accounted for only an additional 0.12% of the variation in disease index.

3.2. Long-term Climatic Trends

Stripe rust was not an important disease on winter wheat between the mid-1930's and 1957. Beginning in 1958, stripe rust increased in occurrence and severity in the PNW



Cultivar : Gaines
A
DISEASE INDEX
NEGATIVE DEGREE DAYS
Ŷ=10.999-0.012X
r²=0.762



Cultivar : Gaines
B
DISEASE INDEX
POSITIVE DEGREE DAYS
Ŷ=13.618-0.021X
r²=0.672

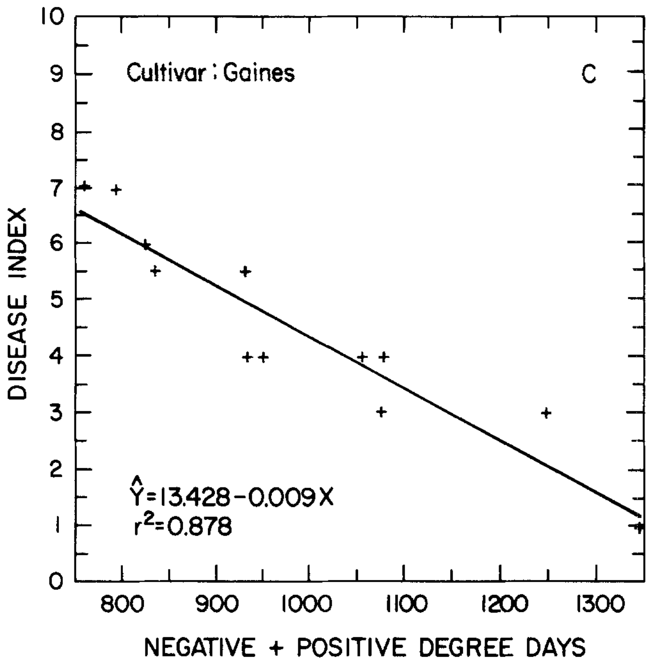
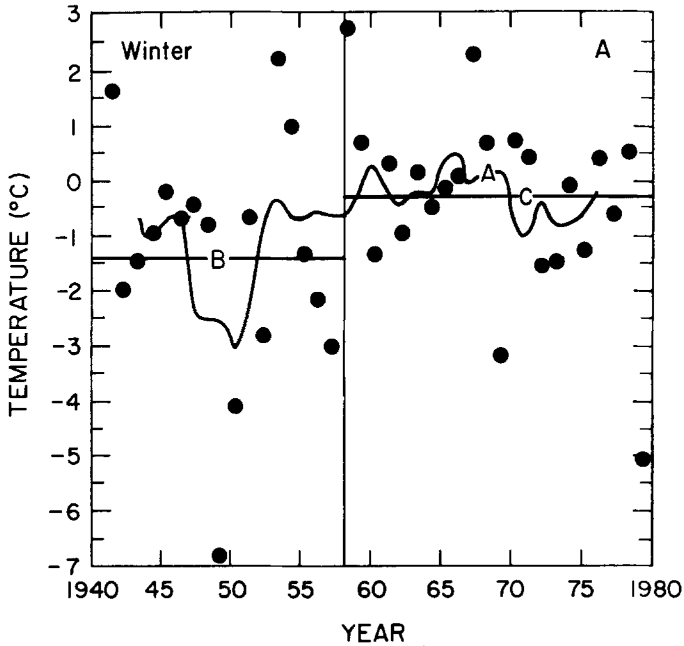


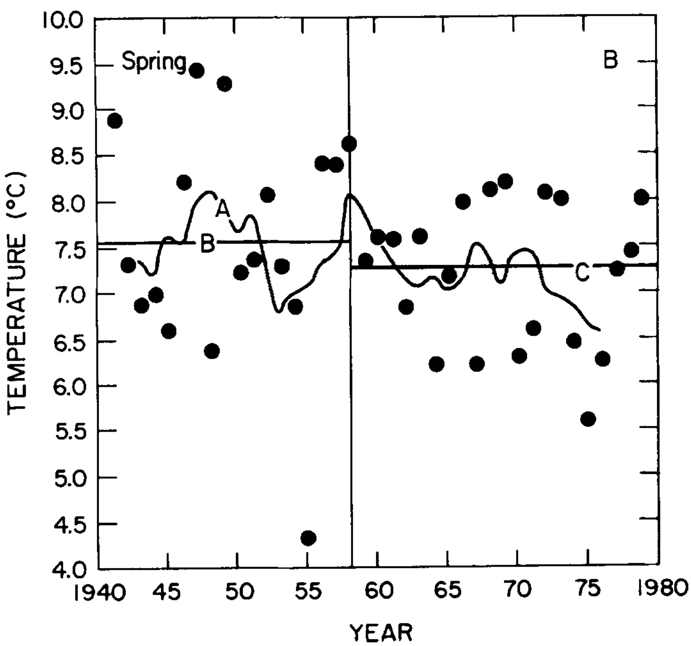
Fig. 3. Stripe rust index on 'Gaines' winter wheat expressed as a function of (A) negative degree days (NDD), (B) positive degree days (PDD), and (C) NDD + PDD. Disease and meteorological data were collected at Pullman, WA, for 12 yrs between 1968 and 1979. NDD were the total accumulated from 1 December to 31 January and PDD were the total accumulated from 1 April to 30 June, each with a base of 7°C. $\hat{Y}$ = predicted disease intensity index, X = NDD, PDD, or NDD + PDD.

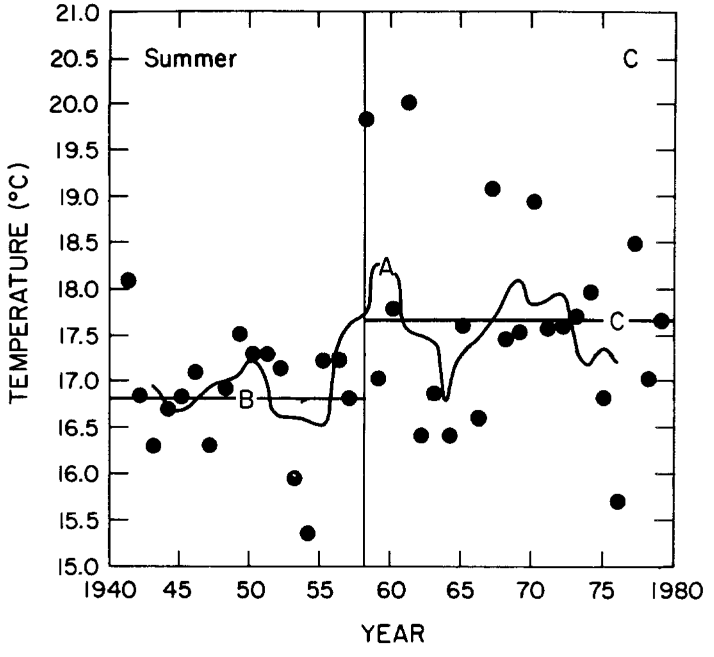
TABLE II. Variables, constants, regression coefficients, and R^2 for predicting stripe rust disease index on winter wheat.

	Variables[a]						
Equation	K	NDD	PDD	NDD + PDD	GI	JPF	R^2
1	1.8929					0.3815	0.4037
2	0.6441				0.5085		0.0368
3	13.6176		−0.0212				0.6722
4	10.9992	−0.0117					0.7624
5	13.4280			−0.0091			0.8774
6	13.8853	−0.0079	−0.0116				0.8838
7	10.2442	−0.0088	−0.0096		0.4283		0.9061
8	10.0024			−0.0090	0.4464		0.9059
9	13.6919	−0.0079	−0.0114			0.0104	0.8839
10	13.0514			−0.0088		0.0218	0.8782
11	10.5241	−0.0091	−0.0100		0.4620	−0.0304	0.9074
12	10.2434			−0.0093	0.4813	−0.0295	0.9071

[a] K = constant; NDD = negative degree days; PDD = positive degree days; GI = growth index; JPF = June precipitation frequency; R^2 = percent of variability fit by the model.
Equations based on 12 yr disease data for 1968-1979 at Pullman, WA.


Winter
A
TEMPERATURE (°C)
YEAR
B
C
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
1940
45
50
55
60
65
70
75
1980


Spring
B
TEMPERATURE (°C)
YEAR
A
C
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
1940
45
50
55
60
65
70
75
1980



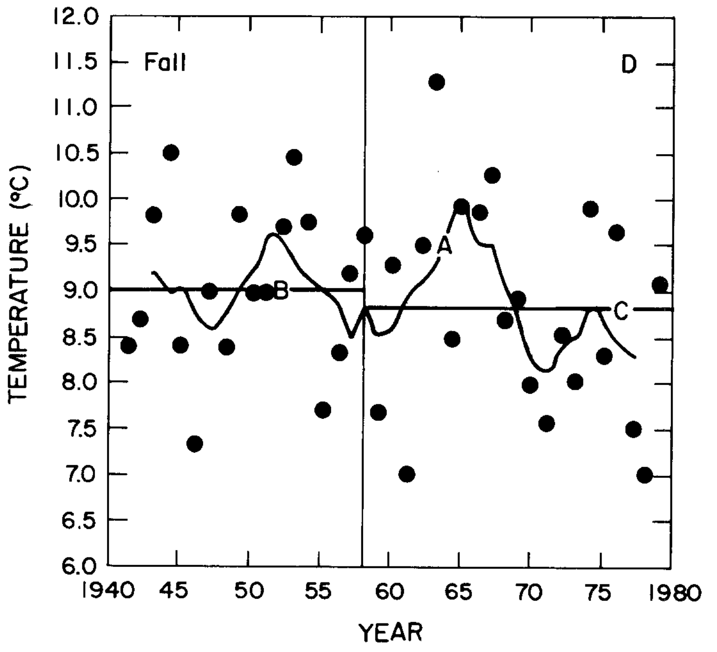


Fig. 4. Seasonal temperatures at Pullman, WA, 1941-1979 for (A) winter (December, January, and February); (B) spring (March, April, and May); (C) summer (June, July, and August), and (D) fall (September, October, and November). The five-year moving average (Line A) indicates temperature trends. Average temperatures for 1941-1957 (Line B) and 1958-1979 (Line C) are shown.

(Coakley and Line, 1981). Since the climatic record for Pullman began in 1941, we compared the long-term climatic means for 1941-1957 (when stripe rust was not considered important) with those for 1958-1979 (when stripe rust was important) to determine if there were any climatic trends which could have influenced stripe rust occurrence.

Daily precipitation and temperature data for December 1940 to August 1979 were summarized on a monthly and seasonal basis. Average temperature and total precipitation for each season were calculated; December 1940 to November 1957 means were compared with those for December 1957 to August 1979.

The mean average winter (December, January, and February) temperature was –1.4 °C for 1941-1957 and –0.3 °C for 1958-1979 (Figure 4a). From 1958 to 1979, 18 of 22 winter average temperatures were above the mean temperature for 1941-1957 and rust disease was frequently severe during that period of higher temperatures.

The mean spring (March, April, May) temperature (Figure 4b) was higher for 1941-1957 (7.6 °C) than for 1958-1979 (7.2 °C). There was a decrease in variability of spring temperatures which coincided with the increase in stripe rust. Before 1958, 6 of 15 springs had average temperatures $\geqslant$ 8.2 °C – 9.4 °C. Since 1959, the highest average temperature was 8.2 °C.

Although average summer (June, July, August) temperatures increased since 1958 (Figure 4c), the most severe stripe rust occurred in years with below average summer temperatures.

Mean fall (September, October, November) temperatures decreased from 9.0 °C during the 1941-1957 period to 8.8 °C during 1958-1979 (Figure 4d); however, no temperature trend was evident.

Total precipitation for each season differed $\leqslant$ 6.5 mm between the two time periods. For winter, spring, summer, and fall, respectively, that was less than 3, 5, 10 and 4% of the total precipitation that occurred in those seasons during 1941-1957.

NDD and PDD values were calculated for 1941-1979 and used in Equation 5 (Table II) to determine whether the frequency of years with predicted severe, moderate, and light rust had changed since 1958. The percentage of years with disease indices falling in each disease intensity category was calculated for 1941-1957 and 1958-1979 (Figure 5). The percentage of years when severe rust was predicted increased from 20% during the pre-1957 period to 32% during the post-1958 period. In actuality, 42% of the years from 1968-1979 developed severe rust (Figure 5). For 1941-1957, light disease was predicted for 27% of the years, whereas in 1958-1979, it was predicted for only 9% of the years. Therefore, based on NDD and PDD accumulations, the 1941-1957 period was not as favorable for the development of stripe rust disease as was the 1958-1979 period.

4. Discussion and Conclusions

The accumulation of NDD between 1 December and 31 January and PDD between 1 April and 30 June accounted for most of the variability in stripe rust index on Gaines winter wheat. Disease data for 1968-1979 were recorded more accurately than for previous years. Using this time period reduced the number of degrees of freedom by 5 when

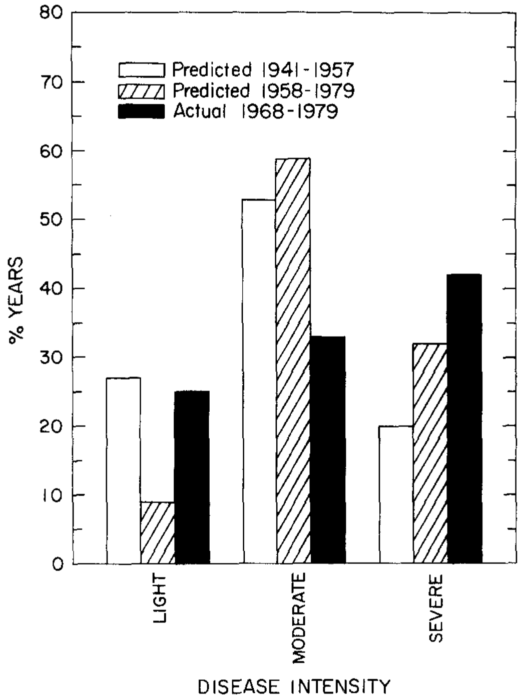


Fig. 5. Percentage of years in 1941-1957 and 1958-1979 that were predicted to have light, moderate, and severe stripe rust on 'Gaines' wheat based on the regression equation $\hat{Y} = 13.4280 - 0.0091X$ where $\hat{Y}$ = predicted disease index and X = NDD + PDD. (NDD = negative degree days between 1 December and 31 January, and PDD = positive degree days between 1 April and 30 June.) And percentage of years between 1968 and 1979 that actually had light, moderate, and severe stripe rust intensity on Gaines.

compared with the earlier analysis (Coakley and Line, 1981) but increased the linear relationship between disease intensity and climatic variables.

More of the total variability is explained by the regression when NDD and PDD are combined. A relationship exists between NDD and PDD. Winters with low temperatures (high NDD) were usually associated with springs with high temperatures (high PDD), and this combination was least favorable for stripe rust development. Adding NDD and PDD together helped to adjust for years with extremely low or high winter temperatures which were not followed by comparable extremely high or low spring temperatures. For example, when these variables were used separately the following occurred: In 1979, which had the lowest winter temperatures during the 1968-1979 period, 882 NDD accumulated and the predicted index had a residual of 0.3417; however, spring conditions were average and 462 PDD resulted in a predicted index with a residual of –2.8114. When NDD + PDD was used, the residual for the predicted index was only –0.2316.

NDD and PDD were combined because of the problem that arises in multiple regression when the independent variables contain related information (Mosteller and Tukey, 1977). One way to avoid this problem is to replace significantly correlated variables with a linear combination of them.

Adding the growth index (GI) to NDD + PDD improved the predictive ability of the regression equation by adjusting for the differences in plant development at the time that disease intensities were recorded.

Frequent precipitation in the spring has been reported to be important for development of stripe rust epidemics in the Pacific Northwest (Hendrix, 1964); however, our results indicate that no precipitation parameter had a sufficiently high correlation with disease intensity as to be useful for predicting the disease index. June precipitation frequency (JPF) was significantly correlated with disease index (Table I), but JPF was more highly correlated with average June temperature. It appears that differences in stripe rust from year to year are directly related to temperature and are less influenced by precipitation frequency. This was supported by the results of multiple regression analysis (Table II) which showed that the addition of JPF did not explain any additional variation in the disease index.

The models can be applied to predicting stripe rust severity. Since NDD occur early in the growing season, they are more useful for making early estimates of subsequent disease development. When there is less than 500 NDD, severe rust develops on Gaines. Under those conditions a grower might consider spring application of chemicals or replanting with an alternate crop, especially if the cultivar does not have temperature-sensitive resistance (Line *et al.*, 1976). The prediction could be greatly strengthened if an accurate long-term forecast were available for spring temperatures. For winter wheats, PDD are less useful for management decisions to minimize disease severity, because total PDD are not known until 1 July when the most important disease increase has already occurred. However, PDD may be useful for predicting stripe rust on spring wheat. Using NDD + PDD and GI in Equation 8 (Table II) on July 1 would allow a good estimate of final disease index. Work is underway by Line to determine the relationship of yield losses to rust intensity (and therefore rust index). When this is completed, it should be possible to predict yield losses based directly on NDD + PDD and GI on July 1. This information could be used to make decisions that are normally made post-harvest.

The results of this research support the earlier conclusion that climatic variation has increased the frequency and severity of stripe rust in the PNW (Coakley, 1979). Since 1958, the trend toward higher winter temperatures and lower spring temperatures has been associated with the increase in disease intensity. High winter temperatures (low NDD) favored survival of overwintering stripe rust inoculum and may have allowed some fungal growth. The stripe rust fungus survives in the wheat plant unless infected leaves are killed by low temperature (Lloyd, 1968; White, 1970). Although snow cover may modify survival of the wheat foliage, when temperatures are very low for several weeks such as in 1969 and 1979, it is not always adequate for protection, and most of the infected wheat foliage is eliminated. This greatly reduces the chances of an epidemic in the spring. Low spring temperatures (low PDD) had a greater effect on disease index in temperature-sensitive cultivars such as Gaines than on fully susceptible cultivars (Coakley) and Line, 1981). Low temperatures reduce adult-plant resistance and delay maturation of the wheat plant, thus providing a longer period for disease to develop to high intensities.

Our results also provide a description of the linear relationships between stripe rust and the temperature at Pullman, WA. Research is underway to test these relationships at other locations in the PNW.

The methods described in this paper should be applicable to studies of other diseases and other pests that have adequate data bases. Without such studies, it is difficult to assess how climatic variation may affect agricultural production.

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