Models of Early Spring Survival of Wheat Leaf Rust in the Central Great Plains

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ABSTRACT

Eversmeyer, M. G., and Kramer, C. L. 1998. Models of early spring survival of wheat leaf rust in the central Great Plains. *Plant Dis.* 82:987-991.

Severe leaf rust epidemics, which result in economic yield reductions in the Great Plains wheat-producing region of the United States, are usually initiated by *Puccinia recondita* f. sp. *tritici* inoculum that has survived in the local field from the previous wheat crop until early spring. Models were developed for an epidemic year beginning at physiological maturity of one wheat crop to maturity of the following wheat crop. Meteorological variables for periods prior to final tiller development of the wheat crop during 1980 to 1992 at several sites in the central Great Plains winter-wheat-production area were used to model inoculum survival from one wheat crop until early spring of the next crop. Stepwise multiple regression was used to identify weather variables that explained the most variation in inoculum survival at the final tiller development wheat growth stage. Inoculum survival was recorded on a 0 to 9 scale with 0 indicating no survival and 9 indicating inoculum on all wheat plants in the field. Independent variables used in development of models were daily deviations from the 10-year average of maximum and minimum temperature, fungal temperature equivalence function, cumulative fungal temperature function, precipitation, cumulative precipitation, and snow cover averaged for 10-day periods prior to dates inoculum forecasts were desired. Models were constructed to forecast inoculum survival from data collected prior to fall wheat planting, the beginning of winter dormancy of the wheat, and the final tiller development wheat growth stage. Of the observed occurrences of leaf rust overwintering, 70% were forecast by models constructed using weather data prior to wheat planting decision time. Overwintering could be forecast by models constructed with data prior to the wheat entering winter dormancy 80% of the time. Models constructed with data collected prior to final tiller development in the spring forecast overwintering of leaf rust inoculum 95% of the time. Results from these models will be used to develop forecasts of leaf rust epidemics and resulting yield reductions.

Additional keywords: modeling, *Triticum aestivum*, wheat leaf rust

Survival of *Puccinia recondita* Rob. ex Desm. f. sp. *tritici* between Great Plains wheat (*Triticum aestivum* L.) crops depends on the amount of moisture and maximum and minimum temperatures occurring between harvest and emergence of the new wheat crop in the fall. Inadequate rain or abnormally high temperatures may prevent establishment of volunteer wheat after harvest, which reduces or prevents survival of *P. recondita* inoculum from the previous crop (4). Winter survival of inoculum on volunteer wheat or on the

fall-planted crop depends largely on sufficient moisture for infection and protection of infected leaves by snow cover from sudden changes to sub-freezing temperature.

Urediniospores from *P. recondita* infections that have survived in local fields provide the inoculum for wheat leaf rust epidemics in 8 out of 10 years in the central winter-wheat-producing region of northern Texas to southern Nebraska. In those years that endogenous inoculum does not survive in the local field, the inoculum originates as airborne urediniospores deposited from air masses that have traversed areas of infected wheat farther south (1,3-5,8,10,14-16). Our previous studies of wheat leaf rust epidemics in Kansas found that statewide yield reductions were always greater than 2% when *P. recondita* survived winter and early spring within local fields (13,19).

For development of our models, we used an epidemic year defined as the period from physiological maturity (i.e., 23 June at Manhattan, Kansas or 22 May at Denton, Texas) of one wheat crop to physiological maturity of the next crop (11). Earlier studies (3) indicated that leaf

rust would survive most years in the area from Dallas, Texas to Lincoln, Nebraska until completion of final tillering, which is Feeke's growth stage 4 (GS 4; 17). GS 4 of the winter wheat crop occurs by day 270 of the epidemic year in the central Great Plains area (Fig. 1).

The primary objective of this study was to determine meteorological variables occurring during the epidemic year that could be used to model survival of *P. recondita* inoculum assessed at or prior to GS 4. In studies reported here, we have used regression techniques to identify and quantify meteorological variables useful in constructing a series of models to forecast overwintering of *P. recondita* inoculum in the central Great Plains winter-wheat-production area (Fig. 2). Separate models were constructed to forecast overwintering of *P. recondita* at planting in September, during winter dormancy in November, and as a result of crop conditions at GS 4 in the spring.

MATERIALS AND METHODS

Survival of *P. recondita* during the fall and early spring phases of epidemics was assessed by wheat disease monitoring surveys or nursery observations throughout the wheat-growing region of Texas, Oklahoma, and Kansas during the crop years 1965 to 1996. Surveys were conducted in major wheat-production areas of the region by examination of fields at 30- to 40-km intervals. Experimental nurseries or cultivar trials in the areas surveyed were used to obtain data on cultivars with known degrees of resistance to leaf rust. Percentage of leaf area infected by *P. recondita* (20) or amount of inoculum survival was recorded prior to GS 4 each year. Amount of survival of *P. recondita* during the winter and early spring development of the rust epidemic was recorded on a 0 to 9 scale (Table 1). Cooperators used Optical Mark Sense cards from 1971 to 1988 to record observations (12).

During periods in the winter or early spring when no signs of leaf rust were visible in the field in Kansas or northern Oklahoma, wheat plants from each survey stop were transplanted into 10-cm-diameter pots and transferred to a 20°C greenhouse to allow development of latent infections. Rust development was recorded either on the 0 to 9 scale or as percent leaf area infected after 10 to 14 days.

We used stepwise multiple regression to identify weather variables that explained

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Joint contribution of the USDA-ARS, the Department of Plant Pathology, and Division of Biology, Kansas State University. Contribution no. 97-78-J of the Kansas Agricultural Experiment Station.

Accepted for publication 18 May 1998.

Publication no. D-1998-0629-01R

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most variation in survival of wheat leaf rust inoculum at GS 4. Daily maximum and minimum temperatures, precipitation, and snow cover for a weather station representative of an overwintering area were obtained from records of the National Weather Service. Initially, weather stations were selected based on proximity to sites in every county surveyed. After initial analysis of data for individual locations, weather stations were selected because of similar wheat cultural practices, wheat growth stages, temperature, or annual precipitation.

Moving 10-year averages were determined for each daily weather variable or variable calculated from daily observations. For example, the 10-year average maximum temperature for 1980 was determined using data for 1970 to 1979 and the 1981 10-year average maximum temperature used data for 1971 to 1980.

In our models, the dependent variable was the amount (0 to 9) of wheat leaf rust inoculum observed at or prior to GS 4 for each overwintering area. Independent variables were the daily observations of average maximum temperature (MX) during the prior 10 days, average minimum temperature (MN) during the prior 10 days, average precipitation (P) during the prior 10 days, average snow cover (SC) during the prior 10 days, cumulative precipitation

(TP) since the start of the epidemic year, average fungal temperature equivalence function (SIN; 2,6) during the prior 10 days, cumulative fungal temperature equivalence function (CSIN) since the start of the epidemic year, and average daily or cumulative deviations (MXD, MND, PD, SCD, TPD, SIND, CSIND) from the 10-year average for each of the preceding variables (MX, MN, P, SC, TP, SIN, CSIN, respectively) during the prior 10 days. Preliminary models were constructed for every day from harvest (the beginning of the new epidemic year) to GS 4 using the independent weather variables averaged during the previous 10 days. Models constructed to forecast *P. recondita* overwintering at 10-day intervals throughout the fall and winter included all daily variables recorded from harvest to date of prediction.

Hourly temperatures used in the SIN were calculated on the basis of a 10-h linear rise from a minimum temperature at 6:00 A.M. to a maximum temperature at 4:00 P.M. and a linear 14-h drop to the next day's minimum temperature (9,18). Updated 10-year averages for each variable were used to develop and verify new models for each year.

Stepwise regression identified combinations of variables that explained a significant amount of variation in inoculum survival at GS 4. Constant values and partial

regression coefficients for those variable combinations with highest R^2 values and that significantly affected survival of inoculum were used to predict *P. recondita* f. sp. *tritici* inoculum survival at GS 4 for years not included in the formulation of the model. We tested the precision of the models by calculating average variation between survival observed in the field and predicted survival (9). Models with the highest R^2 , lowest average variation, and fewest independent variables were selected as working models for areas within the region with similar weather patterns, cultural practices, or both.

Analysis of nursery data (11) indicated that data summed or averaged over 10 days gave the best fit to a model, but summing or averaging data over shorter or longer time periods did not significantly affect the precision of the model. However, data for periods longer than 20 days tended to reduce R^2 values and precision of the model. Preliminary models were developed from data for the 1973 to 1982 crop years and verified using data from the 1983 to 1986 crop years at selected weather stations. Subsequently, data for all crop years from 1965 to 1995 were added to update the models, which were verified using the next crop year's observations.

RESULTS

During the period 1965 to 1996, incidence of wheat leaf rust infection observed

Fig. 1. Epidemic year, dates, and Feeke's wheat growth stages used for Manhattan, Kansas.

Fig. 2. Central Great Plains area surveyed for survival of wheat leaf rust. Dots indicate approximate location of National Weather Service data collection points. Data combined for all points in each area to construct survival models. WB = Western Nebraska; WK = Western Kansas; NK = Southern Nebraska and Northern Kansas; KO = Southern Kansas and Northern Oklahoma; PH = Panhandle of Oklahoma and Texas; OT = Southern Oklahoma and North Texas.

on plants in the fall survey area ranged from trace to 100% incidence. Snow cover during winter dormancy influenced inoculum survival in northern and western Kansas in most years. Warmer temperatures or high winds removed snow cover, which resulted in death of infected leaves when they were exposed to temperatures of -10 to -15°C after several days with above-normal daytime temperatures.

Models constructed by combining data from all locations explained less than 50% of the variation in inoculum survival at GS 4. The 18 to 50 variables entered into these models made them less desirable for use in forecasting inoculum survival. Therefore, models were constructed using survey data collected within 80 km of selected weather stations for 1965 to 93. These models explained 70 to 93% of the variation in inoculum survival using 3 to 11 variables.

Models for inoculum survival observed at GS 4, constructed for each area from data for 1980 to 1993, are presented in Table 2. Models derived from data for 3 to 5 days on either side of those reported resulted in similar precision in modeling inoculum survival (*data not shown*).

Models constructed to forecast inoculum survival at GS 4 from all daily weather observations at a specific site included daily variables and deviations from the 30-year average for epidemic day 10, 40, 70, 100, 150, 170, 190, 210, 230, 240, and 270. Because of the association of average daily variables (MX, MN, P, SIN, SC, TP) with cumulative variables, the average daily variables were dropped from the analysis and only deviations of each variable from the 10-year average were included in the models. Dropping the daily variables from the model did not significantly reduce the amount of variation in inoculum survival that could be explained by the remaining variables. Although some of the same variables (MXD1, MND1, or MXD10) entered into models for different sites, a single set of variables (MXD1, MND4, ACC10, CSIN10, and so on) could not be identified that would adequately model inoculum survival at every site for each date of prediction. Models listed in Table 2 were the least affected by the addition of another year's data and were more precise (9) in forecasting leaf rust survival at GS 4.

Models constructed to forecast overwintering of inoculum at GS 4 from data

obtained prior to the time planting decisions would be made included at least one temperature variable (MXD1, MND1, or CSN1) from the first 10 days of the epidemic year (i.e., 10 days after the previous crop reached physiological maturity; Table 2). Precipitation (ACC1) measured during those 10 days also entered into the model for most of the locations associated with lower yearly precipitation totals. Of the observed occurrences of inoculum overwintering, 70% would be forecast by these models at planting decision time. Amount of inoculum survival was usually underestimated, especially in those years when substantial overwintering occurred.

Models constructed to forecast overwintering of inoculum at GS 4 from data collected prior to the time winter wheat started into winter dormancy included most of the same variables that were used in the models for planting time. Models for sites in northwest and western Kansas and western Nebraska included a variable for snow cover as the winter wheat crop entered dormancy. Of the occurrences of inoculum overwintering, 80% would be forecast by these models at the beginning of winter dormancy.

Models constructed to forecast overwintering of inoculum at GS 4 using data collected anytime prior to GS 4 usually included one or two variables from the 10-day period after physiological maturity of the prior crop. Most of the sites where snow was common included at least one measure of snow cover in the final model. Minimum temperature deviations observed during the winter months were included in models for most sites. These models forecast inoculum overwintering 95% of the time. Forecasts of expected amounts of overwintering of leaf rust were rounded to the nearest whole positive number (Table 2). The observed value in Table 2 is the maximum survival observed within the model area.

DISCUSSION

Survival of *P. recondita* inoculum, either as urediniospores from sporulating lesions or as latent infections within wheat leaves, from physiological maturity of one winter wheat crop to spring green-up of the next, is critical to development of leaf rust epidemics that will cause economic losses in wheat production. We have been unable to

show a cause and effect of severity of fall leaf rust infections with final disease severities observed the next spring. Previous studies have shown that overwintering of *P. recondita* in Kansas always resulted in a greater than 2% statewide reduction in wheat production (12).

Epidemics in individual fields or areas may result in severe reductions in yields of greater than 50% when rust has overwintered locally (7). Economic losses also will occur in individual fields or areas when no overwintering of inoculum is observed. However, these losses are usually less than 10%. One of the recommendations for control of wheat leaf rust in the central Great Plains has been elimination of volunteer wheat during the summer and fall months prior to fall wheat planting. We have observed scattered volunteer wheat plants, including single plants, infected with leaf rust that have survived and served as foci for inoculation of a field. Final leaf rust severities were 80 to 100% in these fields, compared to adjacent fields of the same cultivar, where no volunteer plants were observed, with 10 to 30% severities.

Presence of mycelium in the living tissues of the host is the most important factor determining overwintering of *P. recondita* in the winter-wheat-growing region of the central Great Plains. Survival of the host tissue harboring the mycelium is dependent on not having severe freezing of wheat after abnormally warm temperatures, especially as the wheat breaks dormancy. When leaf rust does not overwinter in a field or nursery within an area, then long-distance airborne dispersal (>80 km) becomes the mechanism of introduction of primary leaf rust inoculum. Airborne introduction of primary inoculum in years not favorable for leaf rust survival usually occurs 30 days after GS 4 at Manhattan, Kansas (3). This reduces the number of potential generations of fungal development by four, which allows cultivars with moderate levels of resistance to escape severe infection.

The inclusion of precipitation or precipitation deviation in models indicates the importance of moisture in the establishment of volunteer wheat in the area and infection of those volunteer plants by *P. recondita* early in the summer. We believe the inclusion of temperature or moisture deviation variables in models for planting date is reflective of the effect of measurement of deviations during the normally hot, dry conditions during mid- to late July. Leaf rust is prevalent on volunteer wheat which has been established immediately following harvest in years with cooler daytime temperatures and above normal moisture. In addition, cooler maximum temperatures allow infected leaves to remain on the plants longer than in hot, dry conditions. A wider differential between maximum and minimum temperatures

Table 1. Codes used in determining levels of survival of *Puccinia recondita* during winter and early spring development of an epidemic

Code	Explanation
0	No uredinia found in the field or on transplanted plants ^a
1	One or two uredinia found in the field or on transplants
2	Uredinia can be found in the field by close examination (1 uredium/1,000 plants)
5	Uredinia can be found in the field easily (1 uredium/10 plants)
8	Uredinia can be found on most plants in the field
9	Uredinia on all plants

^a Plants transplanted from the field into pots in a 20°C greenhouse and inspected 10 to 14 days later for presence of uredinia from latent infections.

results in more frequent and longer periods of dew formation, which increases the infection of volunteer or early seeded wheat by leaf rust inoculum.

Reinfection periods during the winter and early spring are extremely important in

winter survival of *P. recondita* when snow cover is not present. Positive average deviations of the SIN for leaf rust and of TP indicate that warmer- and wetter-than-average conditions during the overwintering phase of the epidemic can increase the

probability of reinfection and survival. Snow cover, which protects the infected wheat tissue from drastic temperature fluctuations during the winter and early spring, is apparently more important than the actual minimum temperature in sur-

Table 2. Weather variables, their partial regression coefficients, and coefficients of determination (R^2) for estimating amount of *Puccinia recondita* overwintering at final tiller development in various areas in the central Great Plains winter-wheat-producing region. Observed overwintering (obs) versus predicted (pred) amount for each model and area are presented for 1993 to 1996 data

Area ^b , wheat stage	Models ^a	R ²	1993		1994		1995		1996	
	Beta coefficient meteorological variables ^c		obs ^d	pred	obs	pred	obs	pred	obs	pred
Western Nebraska										
Planting date	$-0.234 \times \text{ACC1} - 0.085 \times \text{MXD1} - 0.022 \times \text{CSN1}$ $- 0.198 \times \text{ACC4} + 0.002 \times \text{CSN4} - 0.061 \times \text{MND7}$ $+ 0.213 \times \text{ACC10} + 0.025 \times \text{MND10}$	0.720	1	1	0	1	1	0	0	0
	$-0.059 \times \text{MND4} + 0.008 \times \text{CSN4} - 0.075 \times \text{MND7}$ $- 0.004 \times \text{CSN10} - 0.620 \times \text{SCD16}$	0.698	1	1	0	0	1	0	0	0
Wheat dormancy	$-0.044 \times \text{MXD4} + 0.088 \times \text{CSN4} - 0.087 \times \text{MND7}$ $- 0.004 \times \text{CSN10} - 0.0659 \times \text{SCD17} - 0.010 \times \text{MXD19}$ $- 1.428 \times \text{SCD19} + 0.021 \times \text{MXD21} - 0.217 \times \text{SCD26}$	0.769	1	1	0	0	1	1	0	0
Final tiller										
Northern Kansas – Southern Nebraska										
Planting date	$0.200 \times \text{ACC1} + 0.112 \times \text{MXD1} - 0.108 \times \text{MND1}$ $+ 0.009 \times \text{CSN1} - 0.089 \times \text{ACC4} - 0.107 \times \text{MND4} + 0.001 \times$ $\text{CSN7} + 0.050 \times \text{ACC10} + 0.033 \times \text{MXD10} - 0.053 \times \text{MND10}$	0.829	5	1	0	0	5	8	0	0
	$-0.134 \times \text{MND4} - 0.036 \times \text{MXD7} - 0.001 \times \text{CSN7}$ $- 0.049 \times \text{MND15} - 0.135 \times \text{ACC16} - 0.011 \times \text{MND16}$	0.809	5	3	0	0	5	1	0	0
Wheat dormancy	$0.040 \times \text{MXD1} - 0.074 \times \text{MND1} - 0.048 \times \text{MND4} - 0.001$ $\times \text{SN4} - 0.621 \times \text{SCD17} + 0.011 \times \text{MND23} + 0.275 \times \text{SCD23}$ $+ 0.026 \times \text{ACC26} + 0.019 \times \text{MXD26} + 0.994 \times \text{SCD26}$	0.840	5	5	0	0	5	3	0	0
Final tiller										
Western Kansas										
Planting date	$0.109 \times \text{ACC1} - 0.018 \times \text{CSN1} - 0.047 \times \text{ACC4} - 0.021$ $\times \text{MND4} + 0.004 \times \text{CSN4} - 0.021 \times \text{MXD7} + 0.051$ $\times \text{ACC10} + 0.001 \times \text{CSN10}$	0.629	2	1	0	0	5	2	0	0
	$0.022 \times \text{MND4} - 0.014 \times \text{MXD7} + 0.021 \times \text{MXD10}$ $+ 0.002 \times \text{CSN10} - 0.021 \times \text{MND16} + 1.822 \times \text{SCD16}$	0.651	2	5	0	1	5	2	0	0
Wheat dormancy	$0.002 \times \text{CSN10} + 1.284 \times \text{SCD17} - 0.534 \times \text{SCD21}$ $+ 0.033 \times \text{ACC26} - 0.015 \times \text{MXD26}$	0.661	2	5	0	0	5	4	0	0
Final tiller										
Southern Kansas–Northern Oklahoma										
Planting date	$0.331 \times \text{ACC1} + 0.013 \times \text{CSN1} - 0.028 \times \text{MND4} - 0.005 \times \text{CSN4}$ $- 0.047 \times \text{ACC7} - 0.003 \times \text{CSN7} + 0.039 \times \text{ACC10}$ $+ 0.034 \times \text{MXD10} + 0.004 \times \text{CSN10}$	0.818	5	1	1	1	5	5	1	1
	$0.306 \times \text{ACC1} + 0.031 \times \text{MXD1} + 0.075 \times \text{ACC4} - 0.005 \times \text{CSN4}$ $- 0.063 \times \text{MND7} + 0.061 \times \text{ACC10} - 0.248 \times \text{ACC15}$ $- 0.047 \times \text{MND16} + 0.190 \times \text{ACC16}$	0.810	5	3	1	1	5	4	1	1
Wheat dormancy	$0.034 \times \text{MXD1} - 0.044 \times \text{MND7} + 0.013 \times \text{MXD15}$ $+ 9.860 \times \text{SCD17} - 0.084 \times \text{MND19} + 2.381 \times \text{SCD19} - 0.888$ $\times \text{SCD23} + 0.050 \times \text{ACC26} + 0.080 \times \text{MND26} + 1.28 \times \text{SCD26}$	0.875	5	5	1	1	5	4	1	1
Final tiller										
Panhandle Texas, Oklahoma										
Planting date	$0.013 \times \text{CSN1} - 0.209 \times \text{ACC4} - 0.077 \times \text{MND7}$ $+ 0.172 \times \text{ACC10} - 0.001 \times \text{CSN10}$	0.721	1	2	0	1	2	3	0	0
	$-0.266 \times \text{ACC1} + 0.010 \times \text{CSN1} - 0.094 \times \text{MND7}$ $- 0.024 \times \text{MND15} + 0.084 \times \text{ACC16}$	0.756	1	1	0	1	2	1	0	0
Wheat dormancy	$-0.068 \times \text{MND7} - 0.067 \times \text{ACC10} - 0.017 \times \text{MXD15}$ $+ 0.319 \times \text{SCD19} - 0.030 \times \text{MND24} - 4.561 \times \text{SCD24}$ $+ 0.104 \times \text{ACC26} - 0.030 \times \text{MND26}$	0.868	1	1	0	1	2	3	0	0
Final tiller										
Northern Texas–Southern Oklahoma										
Planting date	$-0.107 \times \text{ACC1} - 0.060 \times \text{ACC7} + 0.146 \times \text{ACC10}$ $- 0.110 \times \text{ACC1} + 0.113 \times \text{MND1} + 0.129 \times \text{ACC10} - 0.103$ $\times \text{MND10} - 0.073 \times \text{MXD15} - 0.023 \times \text{ACC16} - 0.019 \times \text{MXD16}$	0.787	3	2	1	1	3	1	1	1
	$-0.115 \times \text{ACC4} + 0.085 \times \text{ACC10} - 0.101 \times \text{MXD15}$ $- 0.038 \times \text{MXD19} - 0.078 \times \text{ACC21} + 0.057 \times \text{MXD21}$ $- 0.062 \times \text{MND21} + 0.082 \times \text{ACC26} + 0.034 \times \text{MND26}$	0.859	3	2	1	1	3	1	1	1
Wheat dormancy										
Final tiller										

^a A model for each date of prediction was constructed to forecast inoculum survival at final tillering growth stage using data observed before day 100 (planting date), 160 (wheat dormancy), or 270 (final tiller) of the epidemic year.

^b Data for leaf rust survival was combined for points in each area as indicated in Figure 2.

^c Variables used in the models are 10-day averages at the date of prediction. Numbers in each variable indicate the epidemic day used (1 = day 10, 24 = day 240); MND = minimum temperature deviation from the 10-year average; MXD = maximum temperature deviation from the 10-year average; CSN = deviation of temperature equivalence function from the 10-year average; SCD = deviation from the 10-year average; ACC = deviation in precipitation received to date from the 10-year average.

^d Survival on a 0 to 9 scale. See Table 1.

vival of *P. recondita* from fall infection to spring initiation of the epidemic.

Early warning of potential overwintering of wheat leaf rust inoculum will allow extension personnel to assist producers in production decisions to be made or control measures to be employed prior to and at planting and as the wheat crop breaks dormancy in the spring. Production decisions or control measures could include planting of resistant versus moderately susceptible cultivars which may have greater yield potential under no disease pressure, or the economic benefit or loss of using alternative control strategies such as fungicides. Results from these models will be included in models being developed to forecast both final leaf rust severity and yield reduction estimates.

LITERATURE CITED

1. Arthur, J. C. 1929. The Plant Rusts (Uredinales). John Wiley & Sons, New York.
2. Burleigh, J. R., Eversmeyer, M. G., and Roelfs, A. P. 1972. Development of linear equations for predicting wheat leaf rust. *Phytopathology* 62:947-953.
3. Burleigh, J. R., Schulze, A. A., and Eversmeyer, M. G. 1969. Some aspects of the summer and winter ecology of wheat rust fungi. *Plant Dis. Rep.* 53:648-651.
4. Chester, K. S. 1946. The Cereal Rusts. Chronica Botanica Co., Waltham, MA.
5. Christman, A. H. 1904. Observations on the wintering of grain rust. *Trans. Wis. Acad. Sci. Arts Lett.* 15:98-107.
6. Dirks, V. A., and Romig, R. W. 1970. Linear models applied to variation in numbers of cereal rust urediospores. *Phytopathology* 60:246-251.
7. Eversmeyer, M. G., and Browder, L. E. 1974. Effect of leaf and stem rust on 1973 Kansas wheat yields. *Plant Dis. Rep.* 58:469-473.
8. Eversmeyer, M. G., and Burleigh, J. R. 1968. Effect of temperature on the longevity of *Puccinia recondita* f. sp. *tritici* urediospores on dry wheat foliage. *Plant Dis. Rep.* 52:186-188.
9. Eversmeyer, M. G., and Burleigh, J. R. 1970. A method of predicting epidemic development of wheat leaf rust. *Phytopathology* 60:805-811.
10. Eversmeyer, M. G., and Kramer, C. L. 1994. Survival of *Puccinia recondita* and *P. graminis* urediospores as affected by exposure to weather conditions at one meter. *Phytopathology* 84:332-335.
11. Eversmeyer, M. G., and Kramer, C. L. 1996. Modeling winter and early spring survival of *Puccinia recondita* in wheat nurseries during 1980 to 1993. *Plant Dis.* 80:490-493.
12. Eversmeyer, M. G., Kramer, C. L., and Browder, L. E. 1976. A Wheat disease monitoring and forecasting system. *Proc. Am. Phytopathol. Soc.* 3:193.
13. Eversmeyer, M. G., Kramer, C. L., and Browder, L. E. 1988. Winter and early spring survival of *Puccinia recondita* on Kansas wheat during 1980-1986. *Plant Dis.* 72:1074-1076.
14. Freeman, E. M., and Johnson, E. C. 1911. The rusts of grains in the United States. U. S. Dep. Agric. Bur. Plant Ind. Bull. 216:1-87.
15. Hassan, Z. M., Kramer, C. L., and Eversmeyer, M. G. 1986. Summer and winter survival of *Puccinia recondita* and infection by soilborne urediospores. *Trans. Br. Mycol. Soc.* 86:365-372.
16. Hitchcock, A. S., and Carlton, M. A. 1893. Preliminary report on rust of grain. *Kans. Agric. Exp. Stn. Bull.* 38:1-14.
17. Large, E. C. 1954. Growth stages in cereals: illustration of the Feekes scale. *Plant Pathol.* 3:128-9.
18. Schrödter, H. 1965. Methodisches zur bearbeitung Phytometeropathologischer Untersuchungen, dargestellt am beispiel der Temperaturrelation. *Phytopathol. Z.* 53:154-166.
19. Sim, T. IV, Willis, W. G., and Eversmeyer, M. G. 1988. Kansas plant disease survey. *Plant Dis.* 72:832-836.
20. Tomerlin, J. R., and Howell, T. A. 1988. DISTRIN: A computer program for training people to estimate disease severity on cereal leaves. *Plant Dis.* 72:455-459.