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Predicting wheat head blight incidence using models based on meteorological factors in Pergamino, Argentina

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Abstract

A computer program using the language and statistical procedures available from SAS (Statistical Analysis System) was written in order to identify the most highly correlated meteorological factors with the incidence of wheat head blight (caused by *Fusarium graminearum* Schwabe) at Pergamino, in the humid pampeana region. Applying linear regression techniques, different models from simple up to a maximum of three independent variables were fitted to the data (1978–1990). The meteorological variables were processed in a time segment beginning eight days prior to the heading date (50% of emerged ears) and finishing when 530 degree days were accumulated (26–32 days). The number of two day periods with rainfall and relative humidity >81% in the first day and relative humidity ≥78% in the second (NPPRH) was the variable that showed the strongest association with disease incidence (FI) (R^2 = 0.81). After examining the models in several ways (R^2, Adjusted R^2, PRESS statistic), two equations were selected: FI% = 20.37 + 8.63 NPPRH – 0.49 DDXNT (R^2 = 0.86) and FI% = 16.39 + 5.43 NPPRH – 0.45 DDXNT + 2.95 DPRH (R^2 = 0.886), in which DDXNT represents the daily accumulation of the residuals resulting from subtracting 9 to the minimum temperature values (<9 °C) and the exceeding amounts of maximum temperatures from 26 °C and DPRH is the number of days with precipitation and relative humidity greater than 83%. Successful local predictions of incidence of scab for the years 1991–1993 (reserved for validation purposes) were achieved using both equations.

Introduction

Scab or head blight caused by *Fusarium* species is a common destructive disease of wheat in humid and semi-humid growing areas of the world [Wiese, 1988; Cook and Veseth, 1991; Bai and Shaner, 1994]. Besides producing loss of yield and shrivelled grain, the fungus can synthesize important mycotoxins affecting both man and animals.

In Canada, severe epidemics of wheat scab were associated with high rainfall in June, July and August [Sutton, 1982]. In the Netherlands, head blight incidence was positively correlated with the precipitation registered in June where wheat flowering is normally concentrated [Daamen *et al.*, 1991].

Fusarium head blight has been observed in all wheat regions of South America. The disease occurs frequently in southern states of Brazil especially when wheat heading takes place during rainy periods [Reis, 1988; Metha, 1993].

In Argentina, wheat scab is caused mainly by the facultative fungus *Fusarium graminearum* (Schwabe) (teleomorph = *Gibberella zeae* (Schw.) Petch). Besides damaging wheat, the disease can also affect oat, barley, rye and corn. Scab is especially common on wheat after corn, as the latter can serve as a major source of inoculum. In the spring ascospores are dispersed by wind and deposited on heads of wheat at flowering, infecting first the anthers and thereafter ovaries and developing kernels.

Epidemics are more severe in the humid pampeana region. In the southeastern area of the Buenos Aires province, the epidemics registered in 1963, 1976, 1977 and 1985 produced serious damage, especially in durum wheats. In the east central part of the pampeana region, moderate to severe outbreaks were observed in 1927, 1945, 1950, 1960, 1963, 1967, 1977, 1978, 1985 and 1993. During the last three attacks in the southeastern Córdoba province, yield losses ranged from 5 to 30%. Under several variety-seeding date situations and natural infections in Pergamino (northeastern Buenos Aires province), losses of weight of kernels per head fluctuated from 17% to 47% in 1986 and 1987. Grain production rather than grain development was mainly damaged by the deleterious effect of the pathogen [Annone and Frutos, 1988; Galich, 1987; Galich and Galich, 1994].

Very little local information is available concerning the influence of environmental factors on the presence of this fungal disease. Many references suggest that warm temperatures, frequent rainfalls and high humidity conditions around the wheat anthesis stage are associated with intense infections [INTA, 1981; Antonelli, 1983; Annone *et al.*, 1994].

The objectives of this study were to determine and quantify the influence of meteorological variables on the incidence of scab in wheat, assuming no constraints in inoculum availability. Resulting predicting statistical models could be used to assess the disease potential in the pampeana region and to help growers in selecting control strategies such as cultural control, resistant varieties and chemical treatments.

Table 1. Mean percent *Fusarium* incidence (AFI) for each group of varieties joined by their heading date (mean date ± 2 days). The initial and final Julian day (IJD, FJD) of the time period analyzed in each case is pointed out. The origin of the wheat head blight incidence data from Pergamino is specified: ROET (Red Oficial de Ensayos Territoriales) or RIT (Regional Internal Trials)

Year	Heading date (Julian day)	IJD	FJD	AFI (%)	Data origin
1978	278	270	301	71	ROET
1978	284	276	306	53	ROET
1978	299	291	319	57	ROET
1979	288	280	309	4	RIT
1979	296	288	317	6	RIT
1980	279	271	303	61	ROET
1980	293	285	315	50	ROET
1980	302	294	323	14	ROET
1982	295	287	318	7	RIT
1982	301	293	323	4	RIT
1983	283	275	302	14	ROET
1983	292	284	312	27	ROET
1984	287	279	307	21	ROET
1984	293	285	313	30	ROET
1984	296	288	317	34	ROET
1985	297	289	317	50	RIT
1986	278	270	300	18	ROET
1986	298	290	319	19	ROET
1987	293	285	314	47	ROET
1987	301	293	320	54	ROET
1987	306	298	324	40	ROET
1990	299	291	318	23	ROET

Materials and methods

Disease data

Fusarium incidence (AFI) observations (percentage of diseased heads within a plot) were obtained from the national wheat nursery (Red Nacional de Ensayos Territoriales (ROET)) and regional internal trials (RIT) conducted at Pergamino Experiment Station (latitude, 33°56′ S; longitude, 60°33′ W). Many commercial wheat varieties are sown on up to six different dates every year. In each experiment phenological data such as dates of crop emergence, heading and maturity are registered; grain yield determined; records of incidences of pests, diseases and other adversities are kept. The *Fusarium* incidence data set for the period 1978–1990 (missing data for 1981, 1988 and 1989) was defined after a prior grouping of varieties (more than eight varieties per group) according to their heading dates (departure from mean heading date: ± 2 days). Heading was recorded for each plot when 50% of the heads were fully emerged, equivalent to GS 55 [Zadoks *et al.*, 1974]. A mean percent disease incidence was calculated from the values recorded for the varieties of each selected group.

The final disease data set including 22 observations is shown in Table 1. The number of observations per year is governed by the number of varieties annually available and the possibility of grouping more than eight varieties dispersed ± 2 days around mean group heading date. The 1991, 1992 and 1993 observations were reserved for validation purposes.

Meteorological data

Daily maximum (MaxT) and minimum (MinT) temperature, relative humidity (RH) and precipitation (P) data recorded by standard instruments were obtained from the weather station located at the Pergamino experiment center in which the wheat trials including disease assessments were made. Daily average temperature (Tav) was calculated by adding the daily minimum and maximum temperatures and dividing by two. Based on these meteorological data, the following weather variables were processed and evaluated for various time periods around wheat heading: precipitation frequency (PF), total accumulated precipitation in millimeters (TP), total days with air shelter relative humidity (average of the 0800, 1400 and 2000 h observations) greater than different values such as 81% (DRH81) and 80% (DRH80). Combining both precipitation and humidity the following variables were defined: total days with simultaneous occurrence of precipitation (>0.2 millimeters) and air RH greater than 83% (DPRH), number of two day periods on which the first registered precipitation $\geq$0.2 millimeters and air RH >81% and the second day observed air RH $\geq$78% (NPPRH).

From daily maximum and minimum temperature observations their corresponding mean values were calculated (MMAXT, MMINT). The sum of the exceeding amounts of daily maximum temperature from 26 °C along the sensible period defined a new degree day variable (DDMAXT):

$$\text{If MaxT} > 26\ ^\circ\text{C then DDMAXT} = \Sigma^d(\text{MaxT} - 26\ ^\circ\text{C}) \quad (1)$$

being d=days of the period.

When daily minimum temperatures were lower than 9 °C, the accumulated differences between 9 and minimum temperature values established the degree day variable called DDMINT:

$$\text{If MinT} < 9\ ^\circ\text{C then DDMINT} = \Sigma^d(9\ ^\circ\text{C} - \text{MinT}) \quad (2)$$

being d = days of the period.

Other thresholds for maximum and minimum temperatures were assessed. The influence of both extreme temperatures disease incidence was considered by adding the last two variable values (DDXNT = DDMAXT + DDMINT). The cumulative effect of daily average temperature (Tav) on pathogen infection was evaluated by calculating the accumulation of positive degree days with base temperatures of 7, 10, 15, 20 and between 10 and 20 °C (DD7, DD10, DD15, DD20, and DD1020 respectively).

Data analyses

A program was written using the SAS language [Statistical Analysis System, 1988] to process the environmental variables and to examine their association with disease incidence. As the first step of the analysis, the Rsquare procedure from SAS was utilized to identify the time interval around wheat heading that showed the strongest association between meteorological variables and head blight incidence. The different starting points previous to the heading dates and lengths for the time intervals were taken into consideration. The lengths were expressed as accumulated degree days at the end of the period, with a base daily average temperature of 0 °C.

The model selection was based on two statistical procedure of SAS: Rsquare and Stepwise, and biological criteria. The first procedure involved the comparison of the coefficients of determination (R^2) for all possible linear regression models, in this case up to a maximum of three explanatory variables. The SAS Stepwise procedure calculates, for each of the independent variables, F statistics that reflect the variable's contribution to the model if it is included. Variables are added one by one to the model. At each step, the variable added is the one that maximizes the fit of the model. Each time a new factor is included, all previously entered variables are re-evaluated on the basis of their partial F-statistics. Options allow specification of criteria for entry into the model (SLE) and for staying in the model (SLS). After examining the biological sense and stability of regression coefficient signs, many models were excluded.

A final evaluation of the models was based on the following three criteria [Berenson *et al.*, 1983; Coakley *et al.*, 1985; Coakley *et al.*, 1988]:

a) Determination coefficient (R^2): the proportion of variance of the response that is predictable from the regressor variable is calculated as:

$$R^2 = 1 - (\text{SSE}/\text{SST}) \quad (3)$$

in which SSE is the error sums of squares and SST is total sums of squares.

b) Adjusted determination coefficient (R^2adj): the corresponding value, adjusted for the number of parameters in the model, is an alternative to R^2 (SAS REG procedure). It is calculated as:

$$R^2adj = [(1 - (n - i)(1 - R^2))/(n - p)] \quad (4)$$

in which n is the number of observations used to fit the model, p the number of parameters in the model, i is 1 if the model includes an intercept term and is 0 otherwise.

c) Root mean square error (RMSE): a lower error value indicates a better fitting model. It is calculated for each predicted equation by the square root of the mean value of the PRESS statistic (predicted error sum of squares, SAS Reg procedure). After deleting the first observation from the available data set (n = 22), a linear regression model is fitted to the remaining n − 1 data points and used for predicting the dropped observation. The prediction error for this point is given by the difference between the observed and predicted value. Once the first observation is returned, the process is repeated for all the other data points. The sum of squares of these n deleted residuals is called the PRESS statistic.

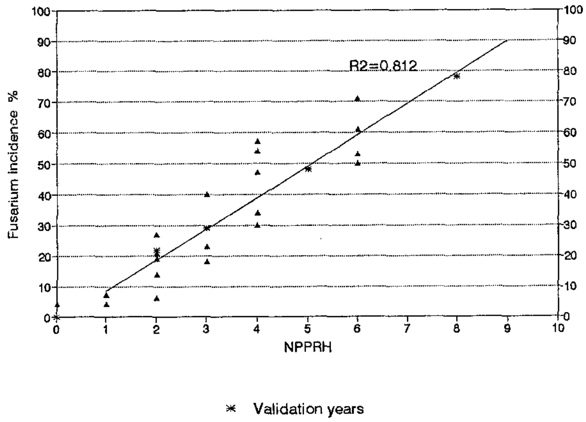

Fig. 1. Regression of *Fusarium* incidence (%) on number of two day periods with occurrence of rainfall (>0.2 mm) and shelter air relative humidity >81% during the first day and relative humidity ≥78% in the second day (NPPRH). Regression equation: PFI% = −1.66 + 10.15 NPPRH R^2 = 0.81.

Results

The closest associations between environmental variables and wheat head blight incidence data were obtained using a period beginning eight days prior to heading date (average of the date values recorded for the varieties including each group) and ending when 530 degree days of daily average temperature were accumulated (base temperature: 0 °C). The duration of this time intervals lasted from 26 to 32 days for the 22 observations analyzed.

The linear regression analysis used to determine the relationship between meteorological factors and *Fusarium* incidence enabled the identification of the variables with the highest significant correlations ($P < 0.05$, Table 2). From the preceding, several interesting relationships are worth mentioning. The one-variable regression model including NPPRH explained more than 81% of the variation of disease incidence (Equation A, Table 2). Severe disease levels (predicted *Fusarium* incidence (PFI) greater than 45%) are expected to occur when more than four two day infection periods (NPPRH) at the time segment around heading stage are registered (Fig. 1). Simple linear equations that included the meteorological variables DRH80, DRH81 and DPRH were slightly less efficient for predicting disease incidence than equation A (R^2 = 0.7799, 0.7784 and 0.7686 respectively). The temperature parameter that correlated best with Fusarium incidence was DDXNT (R^2 = 0.4344). In contrast, association between head blight incidence and number of days with precipitation (PF) was among the weakest (R^2 = 0.1736).

The Stepwise procedure was used to determine the best set of meteorological data to predict disease incidence. All the variables left in the model were significant at the 0.05 level (SLS). The same significance level (SLE = 0.05) was especified for entry into the model. The regression equation that best fit the data was the one which included NPPRH and DDXNT (Prob >F = 0.0001 and 0.0193 respectively) as independent variables (Equation E). This equation and the others previously identified by Rsquare (Table 2), were analyzed according to their R^2, R^2adj and RMSE values. By these criteria, the model involving NPPRH, DDXNT and DPRH (Equation G) showed the most appropriate result (greatest R^2 and R^2adj, lowest RMSE). The best two variable equations including NPPRH and DDXNT (Equation E) observed the second lower value of RMSE. Because of its simplicity (parsimony criterion), the last equation with only two explanatory variables permits a more adequate and easier interpretation of the responses comparing to higher degree models.

Other interesting models are those adding the effect of DRH81 or DRH80 to that expressed by NPPRH and DDXNT (Equations H and I, Table 2).

Validation

Disease incidence (ROET experiments) and meteorological data from Pergamino for the years 1991, 1992

Table 2. Simple and multiple predicted models of *Fusarium* Incidence (PFI%) in wheat (site: Pergamino), with the regression coefficients and meteorological variables. The corresponding determination coefficients (R^2), adjusted determination coefficients (R^2adj) and values of RMSE (square root of the mean of PRESS statistic) are specified

Model	R^2	R^2adj	RMSE
A. PFI% = − 1.66 + 10.15 NPPRH	0.8124	0.8030	9.51
B. PFI% = − 9.34 + 5.68 DRH80	0.7799	0.7689	10.28
C. PFI% = − 6.91 + 5.49 DRH81	0.7784	0.7674	10.35
D. PFI% = − 3.12 + 7.73 DPRH	0.7686	0.7571	10.65
E. PFI% = 20.37 + 8.63 NPPRH − 0.49 DDXNT	0.8604	0.8457	8.89
F. PFI% = 22.36 + 6.43 DPRH − 0.56 DDXNT	0.8347	0.8173	9.73
G. PFI% = 16.39 + 5.43 NPPRH − 0.45 DDXNT + 2.95 DPRH	0.8863	0.8674	8.35
H. PFI% = 13.56 + 6.11 NPPRH − 0.41 DDXNT + 1.73 DRH81	0.8758	0.8551	8.96
I. PFI% = 12.17 + 6.32 NPPRH − 0.39 DDXNT + 1.70 DRH80	0.8739	0.8529	9.06

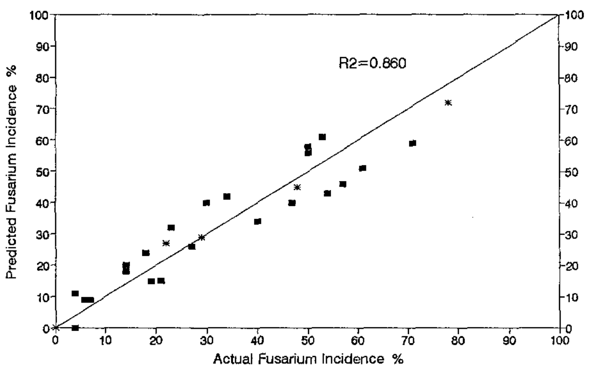

Fig. 2. Distribution of the points relating actual *Fusarium* incidence (AFI%) and predicted *Fusarium* incidence (PFI%) around the line with slope equal to 1 (perfect relationship). PFI values are estimated by the regression equation E (two independent variables): PFI% = 20.37 + 8.63 NPPRH − 0.49 DDXNT $R^2 = 0.86$.

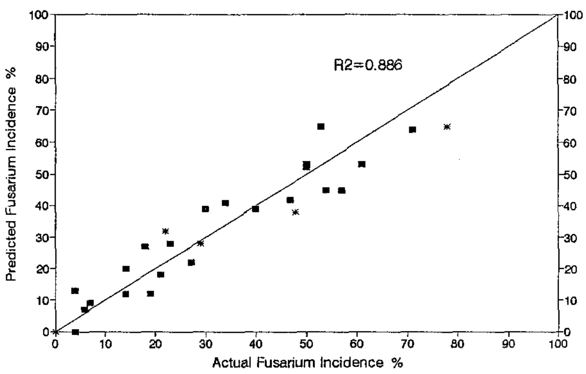

Fig. 3. Distribution of the points relating actual *Fusarium* incidence (AFI%) and predicted *Fusarium* incidence (PFI%) around the line with slope equal to 1 (perfect relationship). PFI values are estimated by the regression equation G (three independent variables): PFI% = 16.39 + 5.43 NPPRH − 0.45 DDXNT + 2.95 DPRH $R^2 = 0.886$.

and 1993, were used to validate the models E and G (Table 3). Both two and three variable models made accurate predictions of wheat scab incidence if these values are compared to those actually registered.

For determining the accuracy of Fusarium incidence predictions by the equations E and G relative to actual disease incidences, the predicted values were plotted against the observed ones for the years utilized in the development of the models and for those used to validate (Fig. 2 and 3). The closeness of the points to the line with a slope equal to 1 (perfect relationship) indicated the suitability of both two and three variable models for making predictions of disease incidence.

Discussion

Even though primary inoculum source for wheat scab varies with cropping systems around the world, the grass residue, cornstalks and wheat stubble can be the principal reservoir of the fungus [Ayers *et al.*, 1975; Wiese, 1988; Bai and Shaner, 1994]. From these sources ascospores and conidia are dispersed by air currents to wheat heads [Sutton, 1982]. In southern Brazil,

Table 3. Comparison of predicted *Fusarium* incidence by the equations E (two variables – PFI E) and G (three variables – PFI G) and actual incidence (AFI) registered at Pergamino (ROET experiments) for the years 1991, 1992 and 1993. Mean wheat heading date (from more than 8 commercial varieties), initial and final Julian day of the time period around heading date (IJD and FJD), and meteorological variable values, are showed

Year	Heading Julian day	IJD	FJD	Meteorological variables					AFI %	PFI E %	PFI G %
		Julian day		DRH80 days	DRH81 days	DPRH days	NPPRH periods	DDXNT °C			
1991	289	281	310	12	10	4	3	36.2	29	29	28
1991	297	289	318	12	9	5	2	22.0	22	27	32
1992	291	283	312	3	3	2	0	73.2	0	0	0
1993	298	290	318	11	10	7	8	35.4	78	72	65
1993	304	296	323	8	7	4	5	38.2	48	45	38

ascospores formed in perithecia on dead or damaged host tissue, or saprophitically on a wide range of native grasses are the main inoculum [Reis, 1987]. Monthly airborne ascospore measurements made in southern Brazil [Reis *et al.*, 1988] determined that ascospore inoculum exists in the air throughout the entire year. In the humid pampeana region, where the double cropping wheat/soybean system and wheat planted after corn are the principal crop rotations, many of those weed species observed in Brazil are also present. In the 1993 wheat growing season perithecia of *Gibberella zeae* were found on weed debris, near Pergamino [Annone *et al.*, 1994]. These considerations have confirmed the ubiquitous nature of *F. graminearum* which has resulted in a lack of efficacy of crop rotation as an effective means of disease control. Also based on these same arguments, the assumption of no inoculum constraints has been accepted in this research.

Airborne ascospores discharged from hydrated perithecia are deposited on spikelets infecting firstly the extruded anthers and thereafter ovaries and developing caryopsis. The role of exposed anthers as a pathogen food base is fundamental for a successful infection [Strange *et al.*, 1974; Strange and Smith, 1978]. The duration of the period with externally retained anthers lasted 30 days in a commercial wheat crop (southern Brazil), from the beginning of heading to early grain development stage [Reis, 1988]. This susceptible time segment defined in the wheat cycle was coincident with that assessed by the present study (26–32 days).

Using an empirical approach, some meteorological variables have a close correlation with the incidence of wheat scab. The biological meaning of these high risk weather factors was evaluated examining their agreement with fungus environmental requirements. Warm temperatures and persistent surface wetness (48–60 h) favor the infection of wheat head blight [Andersen, 1948]. Fungus humidity requirements for producing the infection are met by the wetting originating in rainfall events. Rainfall promotes conditions favorable for spore germination and penetration by providing the moisture necessary for wheat head wetness. The length of the head wetness period following rain is dependent upon the evaporative power of the air. Lower air relative humidity levels lead to higher water vapor atmospheric demands producing shorter wetness periods. Not having rainfall duration measurements, the potential lengths of head wetness periods are better considered by combining the occurrence of precipitation with high air relative humidity records in two day segments. The low correlation between precipitation frequency (PF) and incidence of the disease found in this study ($R^2 = 0.1736$), confirms the necessity of evaluating meteorological variables which combine the effects of those two weather elements (precipitation and relative humidity). For this reason the variable NPPRH exhibited the strongest association with the disease.

In the pampeana region during October when anthesis predominantly takes place, both low and high temperatures may influence the infection processes. This effect was evaluated by developing factors which take into account mean and extreme daily temperatures. Finally, daily minimum temperatures below 9 °C and maximum temperatures greater than 26 °C registered around anthesis stage were found to inhibit the fungus. The DDXNT variable produced a significant contribution for explaining the variability of wheat scab incidence.

After running the SAS Stepwise procedure with a level of significance of 5% for both SLE and SLS, a linear regression model including NPPRH and DDXNT as independent meteorological variables was fitted. Besides explaining more than 86% of the variation in disease incidence, this equation was satisfactory because of its simplicity and ease of interpretation in relation to more complex models.

In the decision making processes concerning the control of the disease non-chemical and chemical measures can be considered. The sowing of break crops not vulnerable to the disease, the diversification of sowing dates, and the growing of wheat varieties which have observed some resistance to the disease, are some of the proper cultural practices which mitigate the effects of *Fusarium graminearum*. Regarding chemical control, the decision to spray during anthesis has to be taken after analyzing the disease climatic potential of the local growing area, the expected wheat yields and the recent weather conditions. In this last regard, the evaluation of both the number of two day periods with the characteristics indicated by the NPPRH variable and the temperature conditions, registered from the beginning of heading to the point of maximum presence of exposed anthers (seventh-eighth day), might be useful to decide rationally whether to spray a fungicide or not. If there were doubts about the decision of chemical protection, a short range meteorological forecast could extend the time period under evaluation. Thus, nearly half of the susceptible period for the infection would be assessed by this procedure, helping in making the decision of whether to spray.

The agreement between the observed and estimated incidence values for the years reserved for validation purposes, confirms the worth of the fitted models for local disease predictions. As with every empirical relationship, its aptness for being employed in other geographic areas should be carefully analyzed. Confident models for predicting wheat head blight incidence might be used to assess the climatic potential regarding the disease in the pampeana region. Also, the probability of occurrence of severe disease incidences, changing wheat sowing dates, could be evaluated for several sites from the models.

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