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A Model-based Assessment of the Impacts of Climate Variability on Fusarium Head Blight Seasonal Risk in Southern Brazil

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Abstract

The frequency of Fusarium head blight (FHB) outbreaks increased considerably in many countries in the last two decades. We used a crop-disease model to assess the impacts of climate variability over a 50-year period at Passo Fundo, Rio Grande do Sul, Brazil. Thirty individual simulation runs of a wheat model were performed for each year by varying planting dates from 1 June to 30 June. For each simulation, an FHB risk index was estimated with the disease model using the heading date simulated by the crop model. A seasonal FHB risk index was estimated by averaging the 30 indices each year. Our simulation results showed that climate at Passo Fundo became favourable to FHB after the 1980s following a period of less favourable conditions for epidemics in the 1960s and 1970s. The risk for FHB was higher for the later planting dates in the most recent decades. Consideration of sea surface temperature (SST) anomalies (deviations from long-term mean values) in the Tropical Pacific Ocean allowed the separation of groups of years with frequently low FHB risk (negative SST anomalies, La Niña like years) and years with frequently high FHB risks (positive SST anomalies – El Niño like years, and near-normal SST – neutral years). Southern Atlantic SST anomalies were then included to separate years with different FHB risks in El Niño-like years and Neutral years. However, the consideration of these anomalies did not result in an improvement. Our results suggest that increased spring rainfall linked to warm sea surface temperature in the Pacific after the 1980s was associated with higher frequency of FHB epidemics in southern Brazil.

Introduction

Wheat (*Triticum aestivum* L.) is an important crop in Brazil especially in the south: 90% of the growing area is established in the states of Rio Grande do Sul and Paraná. In this sub-tropical environment, wet conditions during spring favor the occurrence of several crop diseases such as rusts, leaf spots and flowering diseases (Fernandes, 1997). Usually, two to three fungicide applications may be needed for controlling these diseases, and this practice significantly increases production costs (Picinini et al., 1996).

Fusarium head blight (FHB) is a disease of increasing concern to wheat production. The wider adoption of minimum and no tillage, short rotations with maize and global climate variability and change are central in the debate on the causes for the re-emergence and expansion of the disease worldwide (McMullen et al., 1997). Similarly to other parts of the world, an increasing frequency of severe FHB outbreaks has been reported in Brazil in the last two decades (especially after 1990) resulting in severe yield losses (Fernandes, 1997; Panisson et al., 2003). The main causal agent of the disease in Brazil is *Gibberella zeae* (Schwein.) Petch. (anamorph *Fusarium graminearum* Schwabe) (Angelotti et al., 2006), a homothallic fungus that survives in host debris on the soil. Inoculum is ascospores and macroconidia that are dispersed by rain splash and wind, landing on wheat heads and infecting the plant during flowering and grain-filling stages. Economic losses result from decreased grain yield and quality because of contamination by toxins produced by the fungus, mainly deoxynivalenol (DON) (McMullen et al., 1997). Wheat varieties that are highly resistant to the disease or tolerant to the toxin are not available and chemical control is limited by cost, efficacy and an incomplete understanding of factors that influence disease development (Goswami and Kistler, 2004).

Agriculture is one of the most vulnerable sectors of the society to climate variability and change (Parry and Carter, 1989). Current variability and potential changes in both global and regional climate are expected to greatly affect farmers and consumers and the sector needs to be both aware of and prepared for these changes (Rosenzweig et al., 2001). Information from historical and projected climate-change scenarios is critical for decision makers to implement the most appropriate policies and short- to long-term management recommendations using disease risk assessment methods (Yang, 2006). In the case of FHB, variability and changes in climate that cause an increase in spring temperature and rainfall are likely to influence disease risk, since FHB is favoured by a wet and warm environment. A change of *Fusarium* species in European regions has been associated with changes in both climate and agronomic factors. A recent study showed that *F. graminearum* frequency has increased progressively in parts of north-western Europe (Jennings et al., 2004).

The influence of El Nino/Southern Oscillation (ENSO) on the spring rainfall in southern South America and Brazil has been widely known and reported by several researchers in the last 20 years (Ropelewski and Halpert, 1987; Díaz et al., 1998; Baethgen and Magrin, 2000; Grimm et al., 2000). Research indicates that rainfall in the austral spring months (October, November and December) is usually higher (lower) than normal in El Nino (La Nina) years. Some authors have reported that the sea surface temperature (SST) in the Atlantic Ocean also affects the precipitation in the spring and summer of the south-eastern South American region (Díaz et al., 1998; Barros et al., 2000). For example, Magrin et al. (2007) found that the consideration of the Atlantic Ocean SSTs in a window south of the Equator (0–20°S, 30°W–10°E) improved the predictability of soybean yields in Argentina when compared with considering only the SSTs in the El Nino region. Rainfall in spring (that includes the wheat flowering stage in southern Brazil) affects the incidence of FHB and consequently the SSTs in the ENSO region and potentially in the southern Atlantic Ocean could also be related to FHB outbreaks.

Several empirical and process-driven FHB models have been developed for predicting disease incidence, infection risk, disease severity or DON levels (Moschini and Fortugno, 1996; Hooker et al., 2002; De Wolf et al., 2003; Rossi et al., 2003; Del Ponte et al., 2005b). Such models are useful for either seasonal disease forecasting or risk assessment studies often linked to long-term climate scenarios and directed at exotic, new or emerging diseases (Yang, 2006). In this study, we used a climate-driven crop-disease model with historical long-term climate dataset from Passo Fundo, Rio Grande do Sul, with the objectives of: (i) identifying climate patterns in a 50-year period that relate to inter- and intra-annual variability and trends in FHB risk and (ii) exploring the effect of the ENSO and South Atlantic Ocean sea surface temperature anomalies on the estimated seasonal FHB risk.

Material and Methods

Study area and climate datasets

Passo Fundo is located at the Planalto Médio Region, northern Rio Grande do Sul State, Brazil (latitude 28°15′00′S and longitude 52°25′12′W). The region is one of the major wheat production areas in Brazil. The criteria for choosing Passo Fundo were that FHB research has been conducted at Embrapa Trigo (the National wheat research center) for over 25 years and there were records for FHB epidemics and epidemiological parameters that could be used for model construction and validation. A long-term daily weather dataset for Passo Fundo was available from 1957 to 2006 and included records for minimum and maximum air temperature, solar radiation and rainfall measured at a standard weather station.

Crop and disease model description

An FHB infection-risk simulation model (Del Ponte et al., 2005b) was linked to a wheat simulation model included in Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003). The crop models contained in DSSAT are detailed biological simulation models of crop growth and development that operate on a daily time step. The inputs required to run the models are daily weather variables, crop management information (planting date, fertilizer use, irrigation, etc.), cultivar characteristics and soil profile data. Output from the models includes dates for phenological events, grain yield, total biomass and biomass partitioning between the different plant components at harvest. Model inputs used in our study included initial water and nitrogen content in the soil profile, and date of planting (1 June to 30 June). Planting density, sowing depth, date and rate of fertilization were specified according to standard local commercial practices. Cultivar was set to BR 23, which is susceptible to FHB. Climatic inputs for the crop simulation models were observed daily maximum and minimum temperatures, precipitation and solar radiation corresponding to the period 1957–2006.

The link between the wheat and the disease model is the heading date estimated by the wheat model for each simulation run. In brief, the host component of the disease model (Del Ponte et al., 2005b) estimates the daily progression of flowering from the heading date simulated by the wheat model. The proportion of anthers extruded during the flowering period is estimated based on temperature-derived non-linear functions set to BR 23. Another temperature-derived function calculates the daily frequency of infection whenever an infection period occurs. An infection period is defined based on threshold values that combine daily precipitation and observed mean daily relative humidity in a 2-day window. Daily infection risks are then estimated as the product of the daily proportion of susceptible tissue, infection frequency and airborne inoculum density. The latter component is a function of mean daily relative humidity and rainfall occurrence. The seasonal risk index (sum of daily infection risks) explained the variation in disease severity ($r^2 = 0.93$) in an independent dataset used for model evaluation (Del Ponte et al., 2005b).

Model adjustments

We modified two components of the original disease model: the infection period and the inoculum estimation as follows. (i) *Infection period* – we used only rainfall as a moisture-related variable to define the occurrence of an infection period because there was no information for relative humidity in the 50-year climate dataset. Therefore, a rule was created so that an infection period was calculated whenever a window of two consecutive rainy days was recorded in the climate dataset (precipitation >0.5 mm each day). (ii) *Airborne inoculum* – the function for predicting inoculum index (that typically ranges from 0.8 to 1.2) was not used because of the needed daily mean relative humidity as predictor variable of inoculum density in the original model. We preliminarily tested the correlation of the infection risks estimated by the modified version using a 20-year dataset containing daily relative humidity (1981 to 2000) for comparison with the original model. The Pearson's correlation coefficient was 0.92 (data not shown).

Simulation runs

For each year in the 50-year period (1957 to 2006), 30 runs of the crop-disease model were performed from sowing dates ranging from 1 June to 30 June, the recommended sowing period for Passo Fundo. For each model run, both the heading date and the respective FHB risk index were estimated. The FHB risk index was the accumulation of daily risk values from a period of time of approximately 20 days (from the 5th to 25th day after heading), i.e. during the flowering and postflowering period. A seasonal FHB risk index was obtained from averaging disease risk indices from the 30 model runs in a single year.

Inter- and intra-annual variability and trend of FHB risk index

To test for significant long-term trends in FHB seasonal risk in the time series, non-parametric Mann–Kendall tests were performed (Gilbert, 1987) with trend (slope) judged significant when $P < 0.05$. This trend analysis technique is useful to detect a monotonic trend, which is a gradual change that is either increasing or decreasing with no reversal direction in a time series. LOWESS, which stands for locally weighted regression smoother (Cleveland, 1979) was fitted to the FHB seasonal risk for visualizing the trend. The technique is a data smoothing algorithm that uses a moving window superimposed over a graph of data that produces a smoothed relationship of two variables.

Influence of ENSO phases and SAO anomalies on FHB seasonal index

An oceanic index for the Tropical Pacific (El Niño region 3.4) in October–December of the current year was used to define ENSO phases. Years were classified in quartiles and three categories were defined: 'Warm' (upper quartile), 'Neutral' (central 50%, i.e. between 25 and 75%) and 'Cold' (lower quartile). The SST anomalies (i.e. deviations from long-term mean values) were obtained from NOAA's CPC – Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

South Atlantic Ocean (SAO) temperature anomalies (20°–60°W, 20°–50°S) were classified in terciles and three categories were used: 'Warm' (wSAO = upper tercile), 'Neutral' (between 33 and 66%) and 'Cold' (cSAO = lower tercile). The data used for SAO analyses came from NOAA NCDC (ERSST dataset, 2 × 2 resolution) and was obtained from IRI's Data Library (http://iridl.ldeo.columbia.edu/index.html). The Climate Predictability Tool (CPC, developed in the IRI, available at: http://portal.iri.columbia.edu/portal/server.pt) was used to perform principal component analysis using the SSTs from all oceans of the world (global NOAA NCDC ERSST dataset) as independent variable and the FHB seasonal risk index as the dependent variable. The principal component analysis was performed to detect which were the regions of the oceans worldwide where variation in the SST was more closely related to the observed variability of the FHB risk index.

Results

Intra and inter-annual FHB risk variability

Heading dates from the 1500 total model runs occurred from day 244 (1 September) to 280 (7 October). Most of heading dates occurred between 10 September and 30 September. Therefore, weather information from mid-September to mid-October, the time of flowering, was most critical to estimate the seasonal FHB risk at Passo Fundo. FHB risk index ranged from 0.52 to 12.86 with a median value of 4.34 in the 50-year period. A fluctuating pattern of the seasonal risk was observed with a downward trend during the 1960s and 1970s and upward trend after the 1980s, although neither trend was significant according to the Mann–Kendall test ($P > 0.05$). Fig. 1 depicts the median, trend and intra-annual variability of FHB risk indices in the time series. The largest magnitude of variability in the FHB risk index was found at the intra-annual scale. When all years were combined, no trend could be detected in the relationship between planting date and risk index (Fig. 2). However, when splitting the time series in two halves (1957–1979 and 1980–2006), FHB risk indices tended to increase sharply in the later sowing dates for the most recent years (1980–2006) (Fig. 2). No statistical test was used to verify significance in the difference of the trends.

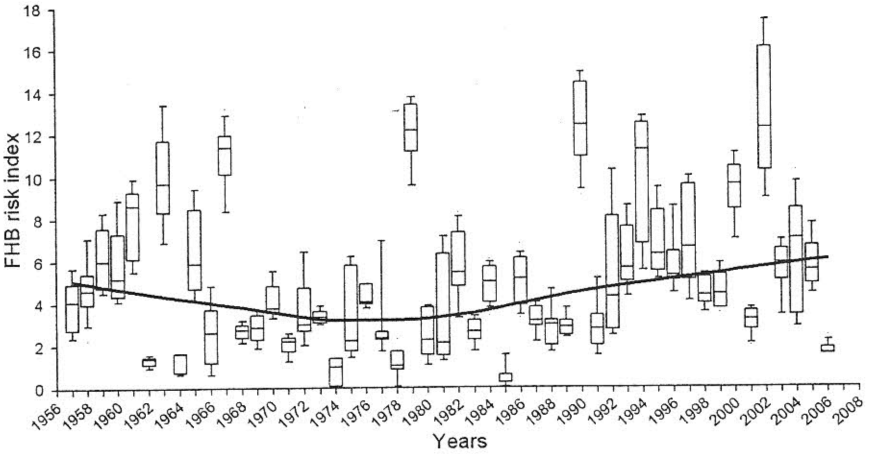

Fig. 1 Inter- and intra-annual Fusarium head blight risk indices estimated by a crop-disease simulation model for 30 yearly runs (for 30 sequential sowing dates) in a 50-year period (1957–2006). Box-plots represent the variability of the disease risk indices within a year, where a black line is the median value for the year. The thicker line is the LOWESS smoothed trend of the time series

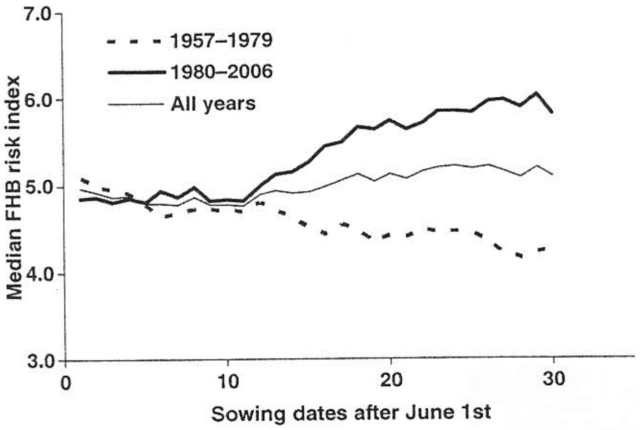

Fig. 2 Median FHB risk index for all years and two periods in the 50-year time series of Fusarium head blight risk indices. The 30 yearly simulations runs were performed by a crop-disease model starting at 1 June for the location of Passo Fundo, RS, Brazil

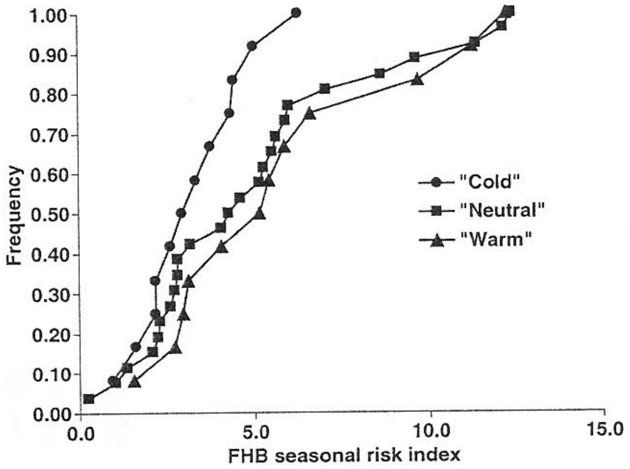

Fig. 3 Cumulative frequency distribution of FHB seasonal risk index for different classes of ENSO years. 'Cold' – lower quartile of SST anomalies (El Niño 3.4 region), 'Warm' – lower quartile of SST anomalies, 'Neutral' – SST anomalies in the central 50%

ENSO and SAO influences

The classification of years using El Niño SST anomalies, separated three classes of years: 'Cold' years ('La Niña' like), 'Warm' (El Niño like) or 'Neutral' years. FHB risk was clearly lower in the 'Cold' years. However, 'Warm' and 'Neutral' years behaved similarly with respect to FHB risk. Fig. 3 shows the cumulative frequency distribution of the FHB index for the three classes of years used in our study ('Cold', 'Warm' and 'Neutral'). For example, the figure indicates that the median value (frequency = 0.5) of the FHB index in the 'Cold' years was about half of the median values in the: 'Warm' or 'Neutral' years. Also, the maximum values of the FHB risk index in 'Warm' and 'Neutral' years was approximately 2.5 times greater than the maximum FHB index values for the 'Cold' years. The figure also shows that the frequency of observed FHB risk index values of 5.0 or higher was 50–60% in 'Warm' and 'Neutral' years, while the corresponding frequency for 'Cold' years was less than 10%.

The principal component analysis revealed two oceanic regions of the world where SSTs showed the strongest relationship with the FHB index risk: the Tropical Pacific (El Niño region) and a region in the southern Atlantic located between 20°W and 60°W longitude, and 20°–50°S latitude (data not shown). The SST anomalies in this region of the Atlantic were then considered in our analysis as an attempt to improve the separation of FHB risk between the 'Neutral' and the 'Warm' ENSO years (i.e. considering only the Tropical Pacific). However, the addition of the Atlantic SST anomalies did not improve the classification of FHB risk as compared with using the Pacific SST only (data not shown).

Discussion

Our simulations show distinct inter-annual and inter-decadal variations of the FHB risk related to climate variability at Passo Fundo. A few high risk years were detected in the 50-year study period and more frequent above-median risk years were observed after 1990. Although our model is a simplification of a complex system that estimates only risk of infection and not disease development, model predictions of extremely low and extremely high risk years matched quite well with reported field data. The first documented studies on FHB in the region date from the mid 1960s when efforts were made to improve disease control with fungicides (benzimidazole) and breeding programmes for FHB resistance (Luzzardi et al., 1972; Osório et al., 1973). In the 1990s, Reis et al. (1996a,b) estimated wheat losses averaging 5.4% because of FHB based on data collected in experimental plots established in a 10-year period (1984–1994) at Passo Fundo and concluded that FHB was less important in the 1980s. In their report, disease incidence (not severity) estimated in experimental plots in 1990 and 1994 was 30% and 80%, respectively. It is noteworthy that these two observed severe epidemic years were also detected as high FHB seasonal risk in our study. Highest yield losses (around 10%) were estimated for the years 1990 and 1994 (Reis et al., 1996a,b). During the mid- to late 1990s FHB was considered a re-emerging disease in Brazilian wheat because more frequent severe epidemics started to be observed (Fernandes, 1997).

Recent observations in experimental plots carried out at Embrapa Trigo in the last decade using a large set of wheat varieties show distinct variations both, between and within seasons and among the studied varieties (Lima et al., 2005, 2006, 2007). For most years, starting in 1998, moderate epidemic levels have usually been observed with near-median severity (6–12%) for all varieties and planting dates. However, a few years presented either low or high epidemic levels. For instance, median severity was 18.8% for the year 2000 (Del Ponte et al., 2005b) and below 3.5% for years 2003 and 2006 (Lima et al., 2005). Observations were not available for the year 2002 because of hail damage in the plots. In conclusion, in the last 10 years, about half of the seasons reached an either light or severe epidemic level which is consistent with our simulations. Panisson et al. (2003) estimated mean yield losses of 17.4% because of FHB in seven experimental plots at Passo Fundo with disease incidence ranging from 84 to 90% in 2000. Such losses were three times higher than mean losses estimated in the 10-year period from 1984 to 1994 and the authors strongly recommended the use of fungicides to minimize potential losses by FHB. The re-emergence of the disease in Brazil in the last decade has led to increasing investments in identification of FHB resistance sources (Lima et al., 2000) and improvement of disease control with fungicides (Reis et al., 1996b). In Argentina, a series of more severe FHB epidemics was also recorded in the early to mid-1990s (Moschini and Fortugno, 1996) and resulted in yield reduction but also in worse grain quality, especially because of grain contamination by *Fusarium* mycotoxins (Dalcero et al., 1997).

Although our model does not take into account other factors that affect epidemics, such as host resistance, agronomic factors and inoculum levels, our approach allowed to detect patterns of climate variability in the time series that were consistent with the observed FHB variation in this region.

Increasing FHB regional inoculum levels as a result of wider adoption of minimal or no-till practices and shorter crop rotations with maize are thought to be important causes of the re-emergence and/or expansion of FHB into several regions worldwide (McMullen et al., 1997). Our modelling study suggests that a recent highly variable and changing climate could have contributed strongly to the re-emergence of severe FHB epidemics in southern Brazil, together with other factors such as no-till, which is used in virtually all wheat-growing areas of the region. However, there is evidence that airborne *G. zeae* inoculum was present in the region before the wide adoption of minimum tillage. For example, Reis (1988) counted *F. graminearum* colonies on selective media placed daily in spore traps at different sites during the period 1983–1985, and showed that inoculum was present year-round and usually peaked during the spring season and decreased in the summer. The inoculum levels observed by Reis were similar to those observed in 2003 by Del Ponte et al. (2005a) using the same methodology. Recent studies have demonstrated the capability for long-distance dispersal of *G. zeae* inoculum, suggesting that regional inoculum levels may play an important role in local FHB epidemics (Maldonado-Ramirez et al., 2005). If this is true, climate variability might play a more important role in local epidemic frequency than the increased levels of residues on the soil surface due to no-till practices.

A previous study in China revealed an association between El Niño-dependent advance of the summer monsoon through East Asia resulting in increased precipitation and FHB outbreaks in eastern China. Those results showed that outbreaks could be predicted successfully 4 months in advance by measuring sea surface temperatures in the central Pacific (Zhao and Yao, 1989). Similarly our model-based study showed that the FHB risk index was lower during the 'Cold' phase of ENSO ('La Nina' like) and behaved similarly during 'warm' (El Nino-like) and 'neutral' phases. These results coincide with previous work conducted with maize in Southeast South America (Baethgen and Magrin, 2000) where La Niña-type years had stronger effects on spring rainfall than El Niño or Neutral years. ENSO is not the only large-scale source of climatic variability in Southeastern South America and the influence of the SAO on precipitation was demonstrated for Uruguay and southern Brazil by Díaz et al. (1998). However, the inclusion of South Atlantic SST anomalies in our study did not improve the classification of FHB risk years. One possible explanation is that the variability between years of the SST anomalies observed in the selected window of the Atlantic Ocean was quite small. Research conducted in central Argentina revealed that consideration of Atlantic anomalies in combination with ENSO anomalies improved prediction of crop yields (Magrin et al., 2007). Therefore, further research is needed to identify possible windows in the Atlantic Ocean that can improve prediction of FHB in southern Brazil, and perhaps explain why FHB seasonal risk can be very high in some years when the SST in the Tropical Pacific are cold (i.e. La Niña-like years).

It would also be instructive to model FHB risks under plausible climate scenarios for years into the future that may be influenced by decadal climate variability and longer-term climate changes. In our work, the trend line in Fig. 2 suggests a possible decadal variability of FHB seasonal risk, which is mainly influenced by increased rainfall during the spring months. If periods of several years with frequent below-average rainfall occur (similar to what happened during the 1970s), FHB risks could decrease considerably, although the effects of temperature variability also need to be taken into account.

The information we generated is useful for disease management because manipulation of sowing dates and use of early maturing varieties could help to escape from the period that is most favourable for initiation of epidemics, especially for growing seasons when surface temperatures in the Pacific are normal or above normal. In situations of non-limiting inoculum as frequently observed in Brazil, strategies and efforts for disease control should continue to be directed at continuing breeding for FHB resistance and improving crop protection with fungicides. In addition to the direct impact on crop losses, warmer and wetter environments that favour the disease might increase the risk of *Fusarium* toxins in wheat that pose a threat to humans and livestock, an issue that has received relatively little attention in Brazil, despite the increasing occurrence of FHB outbreaks.

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