Proposal of a weather-based prediction system for Yellow Sigatoka in Santa Catarina State, Brazil

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Abstract – Banana (*Musa* spp.) is one of the main fruits produced in Brazil, and its production is among the largest in the world. The Sigatoka disease complex is widely distributed across banana producing regions mainly comprising the fungi *Pseudocercospora fijiensis* and *P. musae*, causal agents of Black and Yellow Sigatoka, respectively. This study observed the epidemiological factors affecting the development of Yellow Sigatoka disease in a banana plantation not sprayed with fungicides in the subtropical climate of Santa Catarina, Brazil, to propose a prediction system for the disease. Yellow Sigatoka severity was assessed using Infection Index, Gross Sum and Youngest Leaf Spot. Air temperature (°C), relative air humidity (%) and leaf wetness (h) were monitored by an automatic meteorological station with data collected each 30s. Leaf wetness and average temperature are the main meteorological variables that explain Yellow Sigatoka increase. A prediction system model was developed to predict disease severity.

Index terms: Temperature; Leaf Wetness; Disease Progress Curve; *Musa* spp.

Proposição de um sistema de previsão da Sigatoka Amarela baseado em variáveis meteorológicas no Estado de Santa Catarina, Brasil

Resumo – A bananeira (*Musa* spp.) é uma das principais frutíferas cultivadas no Brasil. A produção brasileira de bananas está entre as maiores do mundo. O complexo de Sigatoka é uma doença amplamente distribuída nas regiões produtoras de banana do mundo, compreendendo principalmente os fungos *Pseudocercospora fijiensis* e *P. musae*, agentes causais da Sigatoka Negra e Amarela, respectivamente. Este trabalho teve como objetivo observar fatores epidemiológicos que afetam o desenvolvimento da Sigatoka Amarela em uma plantação de banana não pulverizada com fungicidas em clima subtropical de Santa Catarina, Brasil, a fim de propor um sistema de predição da doença. A Sigatoka Amarela foi avaliada por meio do Índice de Infecção, Soma Bruta e Primeira Folha Manchada. A temperatura do ar (°C), a umidade relativa do ar (%) e o molhamento foliar (h) foram monitorados por meio de estação meteorológica automática com coleta de dados a cada 30s. Concluímos que o molhamento foliar e a temperatura média são as principais variáveis meteorológicas que explicam a severidade da doença. Foi proposto um sistema de previsão para a Sigatoka Amarela e desenvolvido um modelo para prever a evolução da doença.

Termos para indexação: Temperatura; Molhamento Foliar; Curva de Progresso da Doença; *Musa* spp.

Introduction

Banana (*Musa* spp.) is one of the main fruit plants produced in Brazil, and its production is among the largest in the world (Datapandas, 2023). Santa Catarina is one of the main state producers of banana, accounting for around 10% of the national production and is an important source of income for rural families (Epagri/Cepa, 2022). The Sigatoka disease complex is widely distributed in banana producing regions comprising mainly the fungi *Pseudocercospora fijiensis* and *P. musae*, causal agents of Black and Yellow Sigatoka, respectively. This complex is important not only due to its wide distribution but also for the damage and losses it causes such as leaf necrosis, reduced plant growth, delayed development, loss of fruit quality, premature and uneven fruit maturation, reduced bunch weight and reduced number of commercial bunches, which lower the productivity between 35% and 80% (Mobambo *et al*., 1993; Castelan *et al*., 2012; Kimunye *et al*., 2020). *Pseudocercospora fijiensis* is considered the main constraint to banana production in Brazil but *P. musicola* is widespread, imposing substantial costs to affected growers and production losses of up to 50% (Matos and Cordeiro, 2011; Brito *et al*., 2015). Despite the existence of banana cultivars resistant to Black and Yellow Sigatoka, the area planted with susceptible cultivars in Brazil remains considerable due to agronomic and consumer market factors, making the Sigatoka disease complex a

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constant concern for many producers. Some climatic factors have been associated with ascospores and conidia germination and *P. fijiensis* infection. Both propagules need high relative humidity or near saturation (above 92% for conidia and 98% for ascospores) to germinate and penetrate stoma (Jacome *et al*., 1991), requiring a film of water in foliar surface for ascospore infection but not for conidia (Cabi, 2022). Optimum temperature for ascospore germination is 27ºC (Stover, 1983; Jacome *et al*., 1991; Porras and Pérez, 1997). For *P. musicola*, the optimum temperature for ascospore germination is 25°C (Cabi, 2022). However, knowledge about the influence of meteorological variables in severity increase (colonization) of Yellow Sigatoka is scarce.

Chemical spraying is the main method to control the Sigatoka disease complex, with a wide range of chemical products registered with the Brazilian Ministry of Agriculture (MAPA). Cultural control (e.g., phytosanitary defoliation), weed control and balanced fertilization greatly influence disease management (Beltrame *et al*., 2023). However, intensive fungicide spraying in commercial banana orchards can exceed 30% of production costs (Churchill, 2011). Disease management with reduced costs requires knowledge of some aspects of the pathogen biology and epidemiology. Several works reported a relation between the climate and Sigatoka disease complex infection (Strobl and Mohan, 2020; Hernandéz *et al*., 2005; Fouré, 1994; Gauhl, 1990; Stover, 1980). This association can explain the difference in prevalence of Black and Yellow Sigatoka in Santa Catarina: Black Sigatoka is prevalent in the north and Yellow Sigatoka in the southern coast, which is an important production region (Peruch *et al*., 2022).

Thus, this study observed the dynamics of Yellow Sigatoka and its relation with meteorological variables to propose a weather-based prediction system to manage the disease efficiently.

Materials and Methods

The experiment was conducted in an 8-year-old 'Prata Catarina' banana orchard (*Musa* AAB, Pomme subgroup) measuring 0.25 ha at Epagri/Estação Experimental de Urussanga, Santa Catarina state, Brazil (28° 31' 21.911" S 49° 19' 16.039" W; altitude 49 m). Climatic classification according to Köppen is humid subtropical, with precipitation well distributed along the year and hot summer (Cfa). Average annual rainfall is approximately 1600mm. Soil type is Red Yellow Argisol (Santos *et al*., 2018) with 22 to 25% clay and rock of granite origin. The orchard was planted in a single row with spacing of 3,0 m x 2,5 m (1333 plants/ha) without irrigation system. Plants were fertilized each 4 months with 100 g NPK (12-06-24)/plant, representing a total annual of 63 kg N, 32 kg P and 128 kg K/ha.

As Yellow Sigatoka disease is endemic to the region, the orchard was not sprayed with fungicides for all the experimental period. The sole management measure employed was a sanitary defoliation of leaves with more than 1/3 foliar area diseased each 3-4 months. Eight plants were randomly chosen for evaluation each 14 days for 2 years. Three methods of disease severity assessment were used: Gross Sum (GS) (Bureau *et al.*, 1992), Infection Index (II) and Youngest Leaf Spotted (YLS) (Carlier *et al*., 2003). To estimate the epidemiological infection process, Yellow Sigatoka was assessed considering only stage 2 lesions (Meredith, 1970). This variable was named Gross Sum New Lesions (GSNL). Air temperature (°C) and relative air humidity (%) were monitored by a meteorological station (HOBO WARE ®) throughout the experimental period using two sensors located at 4.10m (Sensor 1) and 1.25m (Sensor 2) height inside the banana orchard. Leaf wetness (h) was measured only at 4.10m. Data were collected and registered each 30s. Variables were abbreviated as follows: average air temperature (TM), average of minimum air temperature (TN), relative air humidity (RH) followed by the number 1 and 2 for sensors 1 and 2, respectively, and leaf wetness (LW). The variable relative air humidity was expressed in hours of relative air humidity above 80% (RH80) and above 90% (RH90) for the two sensors. Leaf wetness was expressed in hours of leaf wetness above 90% (LW90) and above 95% (LW95) for all the sensor surface. Values of the meteorological variables refer to the average from 14 days prior to disease evaluation except for leaf wetness and precipitation, the values of which refer to the daily sum in those days.

Pearson's correlation (R) analysis at 5% probability of error was performed between meteorological variables and disease assessment methods (SPSS Statistics). Disease progress curves were plotted for GS, II and YLS throughout the experimental period. A disease progress curve, considering only young leaf spots (stage 2 lesions), was plotted to observe its influence on Yellow Sigatoka disease development (Meredith, 1970). The disease progress curve for II was plotted and fitted to classic plant disease models with statistical software R (R Core Team, 2023), using the epifitter package (Alves and Del Ponte, 2021). Multiple regression analysis was performed and a model was developed to correlate the essential meteorological variables with Yellow Sigatoka disease severity development (SPSS Statistics). Limits of the variables used in the prediction system were empirically defined and based on data from the first year of evaluation. Frequency of occurrence of the meteorological variables influencing Yellow Sigatoka disease development was graphically observed.

Results and Discussion

Pearson's correlation analysis showed that leaf wetness variables LW95 and LW90 had moderate positive correlation with GS ($R=0.4394$; $p<0.01$ and $R=0.3915$; $p<0.05$, respectively) (Figure 1). Average of minimum air

temperature (TN1 and TN2) had negative correlation with GS (R=-0.6686; p<0.01 for TN1 and R=-0.6808; p<0.01 for TN2) and with II (R=-0.4717; p<0.01 for TN1 and R=-0.5198; p<0.01 for TN2). Average air temperature (TM1 and TM2) had strong negative correlation with GS (R=-0.7137; p<0.01 for TM1 and R=-0.7190; p<0.01 for TM2) and moderate negative correlation with II (R=-0.4856; p<0.01 for TM1 and R=-0.5267; p<0.01 for TM2). These same temperature variables, however, had strong correlation with YLS (R=0.7047; p<0.01 for TN1 and R=0.7105; p<0.01 for TN2; R=0.7603; p<0.01 for TM1 and R=0.7611; p<0.01 for TM2). YLS had weak positive correlation with GSNL (R=0.3452; p<0.05). Meteorological variables related to air relative humidity showed no significant correlation with the Sigatoka assessment methods, except for RH902 with GSNL (R=0.3617; p<0.05). However, these variables had a strong positive correlation with LW variables. Average air temperature and LW95 had negative correlation (R=-0.3316; p<0.05 for TM1 and R=-0.3730; p<0.05 for TM2). Temperature variables TN2 and TM2 had positive correlation with GSNL (R=0.3618; p<0.05 and R=0.3433; p<0.05, respectively). Although this association occurred only for sensor 2, the two sensors located at different height showed strong correlation with each other for the same variables evaluated.

LW95 was environmental variable that most influenced disease severity, as measured by GS. However, linear regression analysis also considered TM1 as described below:

$$GS = 8951{,}173 + 15{,}786LW95 - 401{,}541TM1$$

In which GS is Gross Sum, *LW*95 represents leaf wetness hours in the 14 days before assessment and *TM*1 is the average air temperature in the period. Importantly, GSNL, which is a portion of GS, had positive correlation with LW90 (Figure 1). In a preliminary study of forecast and warning for Black Sigatoka

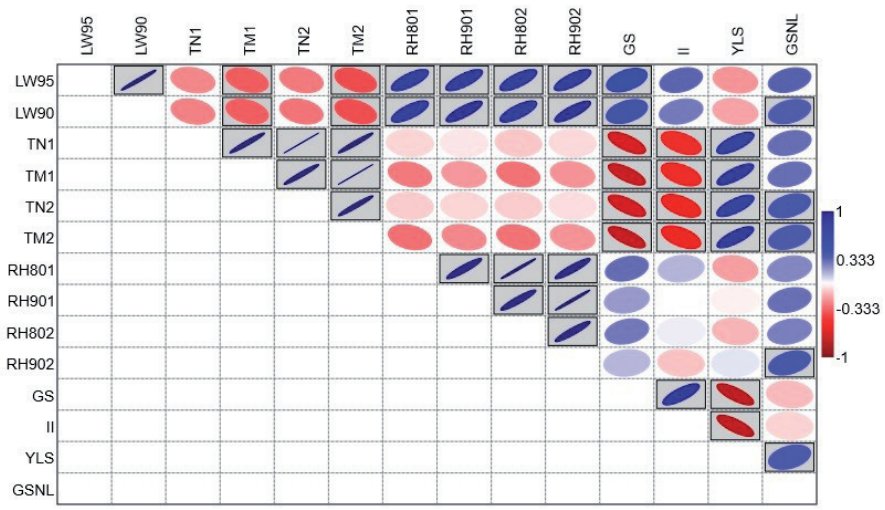

Figure 1. Correlation matrix of Yellow Sigatoka assessment methods and meteorological variables. Gray boxes mean significant correlation. Blue ellipses mean positive correlation. Red ellipses mean negative correlation. The lighter the shade, the closer to zero
Figura 1. Matriz de correlação de métodos de avaliação da Sigatoka Amarela e variáveis meteorológicas. Quadrados cinzas indicam correlação significativa. Elipses azuis indicam correlação positiva. Elipses vermelhas indicam correlação negativa. Quanto mais próximo ao azul claro ou ao vermelho claro mais próximo de zero

disease, Hernández *et al*. (2005) proposed linear regression models equations for II in function of some meteorological variables. According to the authors, none of the equations had determination coefficient (R^2) above 0.33 and the better equation referred to accumulated data of six consecutive weeks before evaluation. In the present study, the linear regression model equation was significant (p<0.01) and had a moderate determination coefficient (R^2=0.55), indicating that 55% of the disease behavior is explained by accumulated values of *LW95* and *TM1* 14 days before evaluation.

Figure 2 (A) shows the dynamics of LW95 and TM1 from March 2022 to January 2024. Higher growth of the disease corresponds to TM1 between 13°C and 25°C and LW95 above 160 hours.

Figure 2 (B) considers only new lesions (type 2) throughout the period evaluated. The year period most favorable to infection process were warmer months (November to May). Generally, the infection process is impaired in the cooler months (June, July and August), increasing occasionally. However, the peak of the disease occurs in cooler months. We hypothesized that optimal leaf wetness hours for colonization occur in cooler months; however, even with lower temperatures they are still favorable to *P. musae* colonization, but not to infection.

Leaf wetness also influenced the infection process. When these values lowered, even with optimal temperatures, the occurrence of new lesions decreased. Conversely, highly elevated temperatures impair the disease. Based on these observations, we empirically defined some temperature limits and leaf wetness hours considered favorable or not to Yellow Sigatoka development as follows:

13°C ≤ Tm ≤ 21°C and LW > 160
Or
21°C < Tm ≤ 25°C and LW > 130.

These limits and combinations were favorable to Yellow Sigatoka severity increase. The following limits were considered unfavorable:

13°C < Tm ≤ 21°C and LW < 160
Or
Tm > 25°C

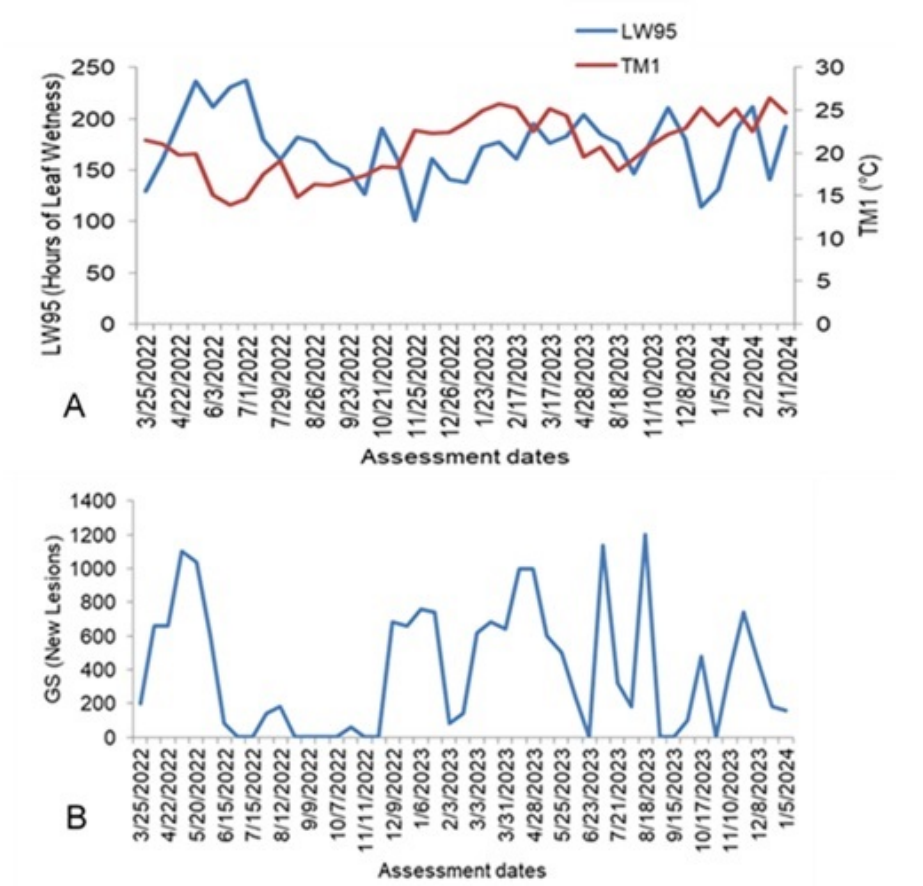

Figure 2. Dynamics of leaf wetness hours (LW95) and average air temperature of sensor 1 (TM1) in the 14 days prior to disease assessment (A). Disease severity using Gross Sum (GS) method considering only new lesions (stage 2) throughout the experimental period (B)
Figura 2. Dinâmica das horas de molhamento foliar (LW95) e da média da temperatura do ar do sensor 1 (TM1) nos 14 dias anteriores à avaliação da doença (A). Severidade da doença usando o método da Soma Bruta (GS), considerando somente lesões novas (estágio 2) durante o período experimental (B)

Our prediction system for Yellow Sigatoka was based on the considerations above. Previous results have showed that germination rates and germinative tube growth decrease between 23% and 26% after 24h under 30°C and 32°C, respectively, in relation to maximum observed under optimal temperature (25°C) conditions for *P. musicola* (Stover, 1983; Coelho Filho *et al*. 2021). Despite this reduction, germ tube is still able to grow at these temperatures. Limiting temperatures for germinative tube growth was reported to be 10°C to 35°C (Coelho Filho; Cordeiro, 2011; Coelho Filho *et al*., 2021); however, this limiting temperatures cannot be extrapolated in practice due to variations in temperature and when working with temperature averages. Moreover, the optimal temperatures for tube growth and germination rates cannot equal the disease development. Thus, we observed and considered that the average limit temperatures for disease development are 13°C and 25°C in the 14 days before evaluation, because disease generally increased in this range.

Yellow Sigatoka shows higher adaptability to temperatures under 15°C compared with Black Sigatoka. This fact can explain the prevalence of Yellow Sigatoka over Black Sigatoka in southern Santa Catarina, where that temperature is common in cooler months. We observed that, in general, at lower temperatures, the main factor for disease increase is leaf wetness hours. These results are consistent with Coelho Filho e Cordeiro (2011) e Coelho Filho *et al*. 2021, who stated that temperature effect is directly dependent of optimum humidity conditions. Without them, growth is impaired.

Figure 3 shows the disease progress curve using GS and II method with the occurrences of favorable climatic conditions defined by the prediction system for Yellow Sigatoka disease. Arrows indicate the time in which climatic conditions for severity increased or decreased in banana 'Catarina' and the corresponding increase or decrease in disease severity. Four pointed stars indicate days in which it was not possible to collect complete meteorological data in the defined intervals. Epidemiological year was defined by the period between the lesser II register and the maximum peak of this variable. Points without arrows or stars, in the epidemiological year, indicate days in which the system failed.

Differently from the other evaluation methods, higher YLS values indicate low disease severity. However, to better compare the methods, YLS underwent a log transformation (11 - x) to look graphically similar to those methods (Figure S1).

YLS shows the same behavior trend seen for the other disease severity assessment methods. Lower values occurred between the months of December and February, and higher values between the months of June and August.

Disease progress curve was plotted for the two epidemic years based on II (Figure S2AB). Both disease progress curves were adjusted for different classical models of disease evolution in 2022 (Figure S2C) and in 2023 (Figure S2D).

Epidemics adjusted better to the monomolecular model in 2022 (R^2=0.9505; r=0.0039). In the following year, the epidemics adjusted better to the exponential model (R^2=0.9618; r=0.0050). Different infection rates for both years occurred, with the highest value occurring in 2023. This can be explained by the higher number

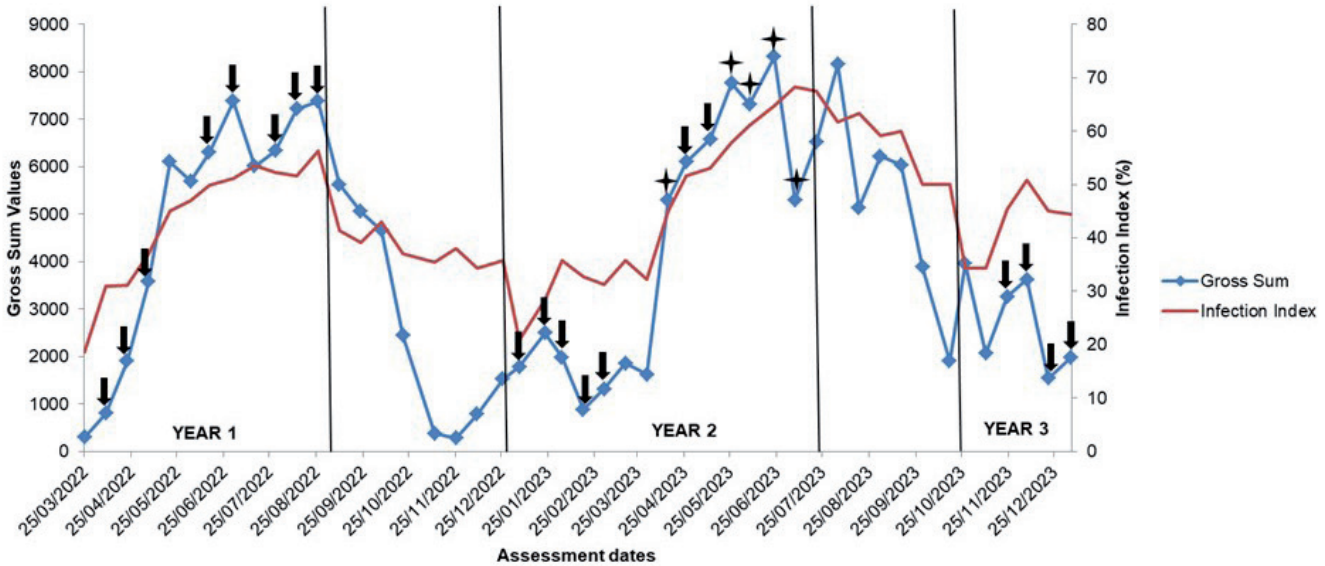

Figure 3. Disease progress curve for Gross Sum (GS) and Infection Index (II) methods throughout the experimental period. Arrows indicate assessment days in which meteorological conditions occurred in agreement to the prediction system for Yellow Sigatoka proposed. Four pointed stars indicate days in which it was not possible to collect meteorological data. Points without arrows or stars, in the epidemiological year, indicate days in which the system failed

Figura 3. Curva de progresso da doença para Soma Bruta (GS) e Índice de Infecção (II) durante o período experimental. As setas indicam os dias de avaliação nos quais ocorreram condições meteorológicas em concordância com o sistema de previsão da Sigatoka Amarela proposto neste trabalho. Pontos sem setas ou estrelas, no ano epidemiológico, indicam os dias nos quais o sistema falhou

of leaf wetness hours and optimal temperatures to disease development at the beginning of epidemics, remarkably in March 2023, when the disease had an explosive increase.

In Santa Catarina, Bioclimatic Pre-Warning is the standard disease evaluation system for controlling Sigatoka disease (Peruch *et al.*, 2022; Beltrame *et al.*, 2023). This system has been used successfully for more than 20 years, helping producers time fungicide sprays. However, developing new systems is important for the evolution of Sigatoka evaluation without field evaluations and higher spatial cover.

Conclusions

Leaf wetness and average air temperature are the main meteorological variables to explain the Yellow Sigatoka increase in the subtropical conditions of southern Santa Catarina.

We proposed a prediction system model to predict disease severity.

A 14-day period of average temperature ranging from 13°C to 21°C together with leaf wetness above 160 hours, or an average temperature above 21°C to 25°C together with leaf wetness above 130 hours determine disease increase.

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