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Prospecting brown rust of sugarcane in São Paulo-Brazil under climate change scenarios

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ABSTRACT

Climate change can cause significant shifts in the occurrence and severity of agricultural diseases, altering the distribution of phytosanitary problems with severe economic, social, and environmental consequences. Despite their importance, these new geographic and temporal distributions of plant diseases still demand scrutiny. In the present study, we prospect the geographic distribution of sugarcane brown rust (*Puccinia melanocephala*) considering average temperature and relative humidity in the main producing region of the state of São Paulo. The geographic database was structured using GIS with projections of future climate change provided by IPCC. Mathematical logic equations were defined and applied to data of average temperature and relative humidity, resulting in monthly maps of climate favorability for the occurrence of the disease. Prospective maps for three future periods (2011-2040, 2041-2070, and 2071-2100) and two greenhouse gas emission scenarios were compared to the reference period (1961-1990). The analysis considered months from December to May. Our study shows a tendency of decrease in the favorability for the disease in a longer term (2071-2100), more noticeable in the scenario A2 than in B1. These results suggest; however, that this disease demands attention in the management of the producing region for future climate scenarios.

Introduction

Global atmospheric carbon dioxide concentrations are now higher than at any time in at least two million years, and concentrations of methane and nitrous oxide are higher than at any time in at least 800,000 years (IPCC, 2021). As a result of the continuous growth of greenhouse gas (GHG) concentrations, global surface temperature will continue to increase until at least the mid-century under all emission scenarios considered, unless deep reductions in carbon dioxide and other GHG emissions occur in the coming decades (IPCC, 2021). Regarding the possible scenarios, global surface temperature is very likely increase by 1.0 °C to 1.8 °C under a very low GHG emissions scenario (optimistic), and by 3.3 °C to 5.7 °C under a very high GHG emissions scenario (pessimistic), over the period of 2081–2100, when compared to 1850–1900 (IPCC, 2021). Additionally, to global warming, climate change also involves a wide range of events, including rising sea levels, melting glaciers, changes in rainfall regimes, and extreme weather events (heat waves, floods, droughts, tropical cyclones, etc.), that will intensify and become more frequent in most regions of the world.

Concerning crop productivity, climate change will be increasingly detrimental as levels of warming progress (Mbow et al., 2019). Sugarcane production in the world will be negatively affected by changes in climate conditions and the most significant challenges will rise as a consequence of the increases in the frequency and intensity of extreme weather events, especially drought (Zhao and Li, 2015).

Brazil is the world's largest producer of sugarcane and, the Southeast region stands for 63% of the country's production (CONAB, 2020), with the state of São Paulo being responsible for 51.8% (CANA, 2021).

In the sugarcane producing region of the state of São Paulo, future projections indicate increases in potential and actual evapotranspiration, resulting in higher water deficits due to the rise in air temperature and, in 2090, in the worst-case scenario, a significant deficit in water is predicted, which will have negative impact on yield of rainfed crops (Santos and Sentelhas, 2012). On the other hand, in a simulated study also carried out for São Paulo State, a positive yield response for 2050 was found, justified mainly by the higher carbon dioxide concentration which increased the efficiency in water use (Marin et al., 2013). However, considering sugarcane yield at levels of temperatures and carbon dioxide above current, Zullo et al. (2018) estimated an increase in areas of low water availability for the current sugarcane expansion areas (south of Goiás and northwest of São Paulo), while no change will be observed in the traditional production areas located in the eastern of São Paulo. This indicates the vulnerability of the crop on account of climatic risk areas due to the availability of water in a spatially heterogeneous way.

Climate change can modify not only the geographic distribution of crops but also the disease distribution in a given growing region, altering potential crop yield losses (Porter et al., 2014). However, the effects of climate change on plant diseases will not be similar for all regions and crops; on the contrary, they shall differ for each pathosystem in specific regions of the world, which requires case-by-case studies of diseases responses on crop species or varieties (Ghini et al., 2012). This is due to the fact that areas previously free of certain pathogens may, in future climate scenarios, present potential risk for the occurrence of diseases (Bettiol et al., 2017), or even significantly affect the occurrence, prevalence, and intensity (severity and incidence) of the established diseases. Geographic and temporal distribution maps allow assessing the impact of favorability for the occurrence of the disease, showing differences among producing regions in Brazil in the future scenarios (Angelotti et al., 2017).

Found in Brazil in 1986 (Takeshi and Rago, 2016), brown rust, caused by *Puccinia melanocephala*, is an important disease of sugarcane and is present in practically all growing areas around the world (Barreto et al., 2017); however, Brazil still lacks studies on the favorability of this disease when future climatic scenarios are taking into account. The aim of this study was to prospect the geographic distribution of sugarcane brown rust (*Puccinia melanocephala*) considering average temperature and relative humidity in the main producing region of the state of São Paulo.

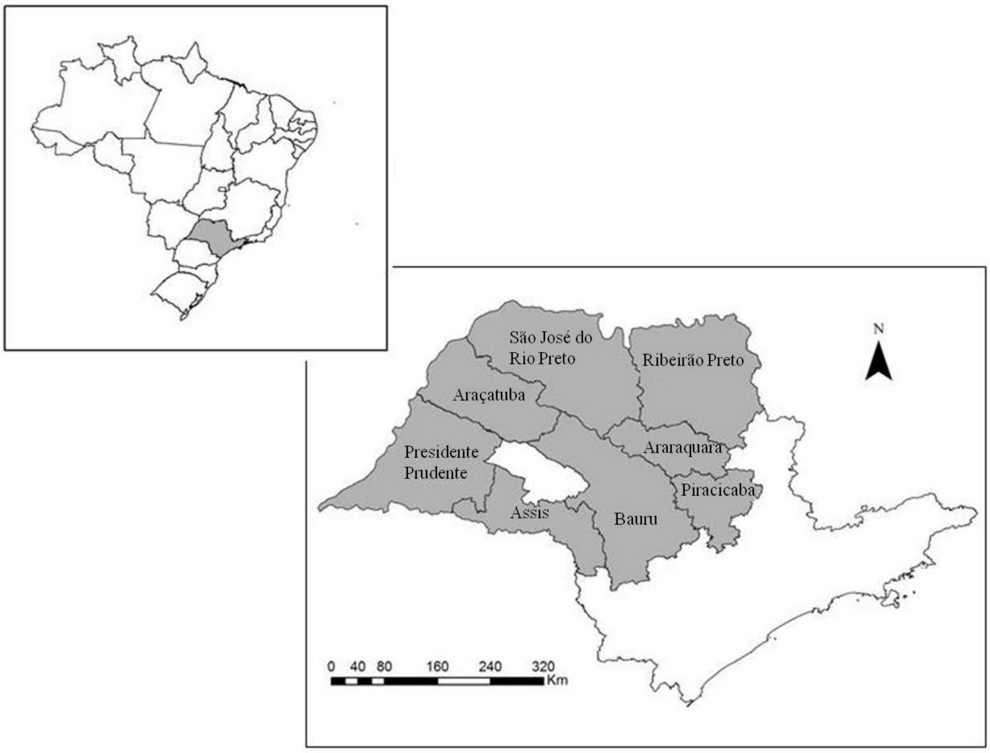
Materials and Methods

This study considered eight mesoregions located in the northwest and midwest of São Paulo: Araçatuba, Araraquara, Assis, Bauru, Piracicaba, Presidente Prudente, Ribeirão Preto, and São José do Rio Preto (Figure 1). Each of these mesoregions had more than 5% of its producing area dedicated to sugarcane in the 2016/17 harvest season (IBGE, 2019).

As reference period, climate information from 1961 to 1990 obtained from the Climate Research Unit (2021) and described by New et al. (1999) was considered.

Monthly mean air temperatures from 2011 to 2100, available in a yearly basis, were obtained from AR4 - Fourth Assessment Report of IPCC (2007) considering 15 GCMs - General Circulation Models: BCCR-BCM2.0 (Bjerknes Centre for Climate Research, Noway), CGCM3.1.T47 (Canadian Centre for Climate Modelling & Analysis, Canada), CNRM-CM3 (Météo-France, France), CSIRO-Mk3.0 (CSIRO Atmospheric Research, Australia), ECHO-G (Meteorological Institute of the University of Bonn, Germany/Korea), GFDL-CM2.0 (US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA), GISS-ER (Goddard Institute for Space Shuttles, USA), UKMO-HadCM3 (Hadley Centre for Climate Prediction and Research / Met Office, United Kingdom), UKMO-HadGEM1 (Hadley Centre for Climate Prediction and Research / Met Office, United Kingdom), INM-CM3.0 (Institute for Numerical Mathematics, Russia), MIROC3.2.medres (Center for Climate System Research, Japan), ECHAM5 (Max Planck Institute for Meteorology, Germany), MRI-CGCM2.3.2 (Meteorological Research Institute, Japan), CCSM3 (National Center for Atmospheric Research, USA), and PCM (National Center for Atmospheric Research, USA), for A2 (pessimistic) and B1 (optimistic) greenhouse emission scenarios (IPCC, 2000).

Figure 1. Main sugarcane producing region in the state of São Paulo - Brazil, showing the mesoregions considered in this study.



Relative humidity, on the other hand, was calculated through Tetens' formula (Tetens, 1930) using, as input, both atmospheric pressure at sea level and specific air humidity data of seven GCMs (BCCR-BCM2.0, CGCM3.1.T47, CNRM-CM3, GISS-ER, INM-CM3.0, MIROC3.2.medres, and MRI-CGCM2.3.2), as well as the altitude data from SRTM (Shuttle Radar Topography Mission).

A computer system for the management of climate data was developed using Firebird 2.0 database management system, Delphi Object Pascal language, and IBExpert tool for data manipulation (Hamada et al., 2017). For each model, averages of three periods (2011-2040, 2041-2070, and 2071-2100) and monthly values for the two future emission scenarios A2 and B1 were obtained. Since each GCM presented different and low spatial resolutions, the data were submitted to interpolation methods to obtain 0.5° × 0.5° of latitude and longitude, adopted in this study. After taking averages considering GCMs, a bias correction was processed, as described by Hamada et al. (2017), to minimize the divergence between the observed values and the corresponding retrospective projections of the models, resulting in the corrected projections. Ever since before any climate change impact studies, it is often necessary to adjust (*i.e.*, correct) the climate simulations (Ayar et al., 2021). This procedure is performed through bias correction and downscaling approaches, which have been adopted by many users of GCMs, mainly because they are generally biased, and their resolution is often lower than desired (Maraun, 2016).

Idrisi 32 GIS (Geographic Information System) was used to integrate and analyze the future climate and reference period databases of average temperature and relative humidity. These two climate variables are the most significant environmental factors in the development of brown rust (Raid and Comstock, 2006; Rott et al., 2018) and are considered by several studies (Barrera et al., 2013; Sanjel et al., 2019; Chaulagain et al., 2021).

Mild temperature and higher relative humidity are favorable conditions for the incidence of the disease (Ido et al., 2006) and, in which brown rust symptoms are more severe (Sord et al., 1988; Raid and Comstock, 2006). The optimal temperature ranges for spore germination of brown rust were found between 15 °C to 30 °C (Sotomayor et al., 1983), from 17 °C to 27 °C (Barrera et al., 2012), and from 20 °C to 25 °C (Tokeshi and Rago, 2016); however, when associated to favorable humidity, infection might occur within the temperature range of 5 °C to 34 °C (Raid and Comstock, 2006). High temperatures have been linked to lower severity and the decline of epidemics (Barrera et al., 2013), with a rapid decrease in spore germination at temperatures above 30 °C (Sotomayor et al., 1983). In another study, disease severity was low at 15 °C and 31 °C, regardless of leaf wetness (free moisture on leaf surface) duration (Barrera et al. 2012).

The favorable environmental conditions that lead to a greater predisposition to the incidence of the disease vary according to the sugarcane growing regions worldwide. Thus, for our study region, criteria sets were established considering slightly different ranges of temperature and relative humidity, which were then applied to the reference period database producing maps. The set of criteria chosen by the authors was the one that produced the most fitted maps. Therefore, the criteria of climatic favorability for the occurrence of brown rust were defined using the following classes: favorable (relative humidity above 70% and mean temperature between 18 °C and 25 °C), less favorable (relative humidity above 70% and mean temperatures below 18 °C or above 25 °C, or with relative humidity below 70% and mean temperatures between 18 °C and 25 °C) and unfavorable (relative humidity below 70% and mean temperatures below 18 °C or above 25 °C). The criteria were translated into mathematical logic functions using GIS, resulting in prospective maps of climate favorability for the occurrence of the disease for the future periods and scenarios studied.

The area corresponding to the main sugarcane producing mesoregions of São Paulo State was overlaid onto the maps.

The analysis considered the months from December to May, which are the most susceptible to brown rust infestation in sugarcane in the studied region (Rago et al., 2012), especially in newly planted sugarcane, *i.e.* from 2 to 6 months (Tokeshi and Rago, 2016).

Results and Discussion

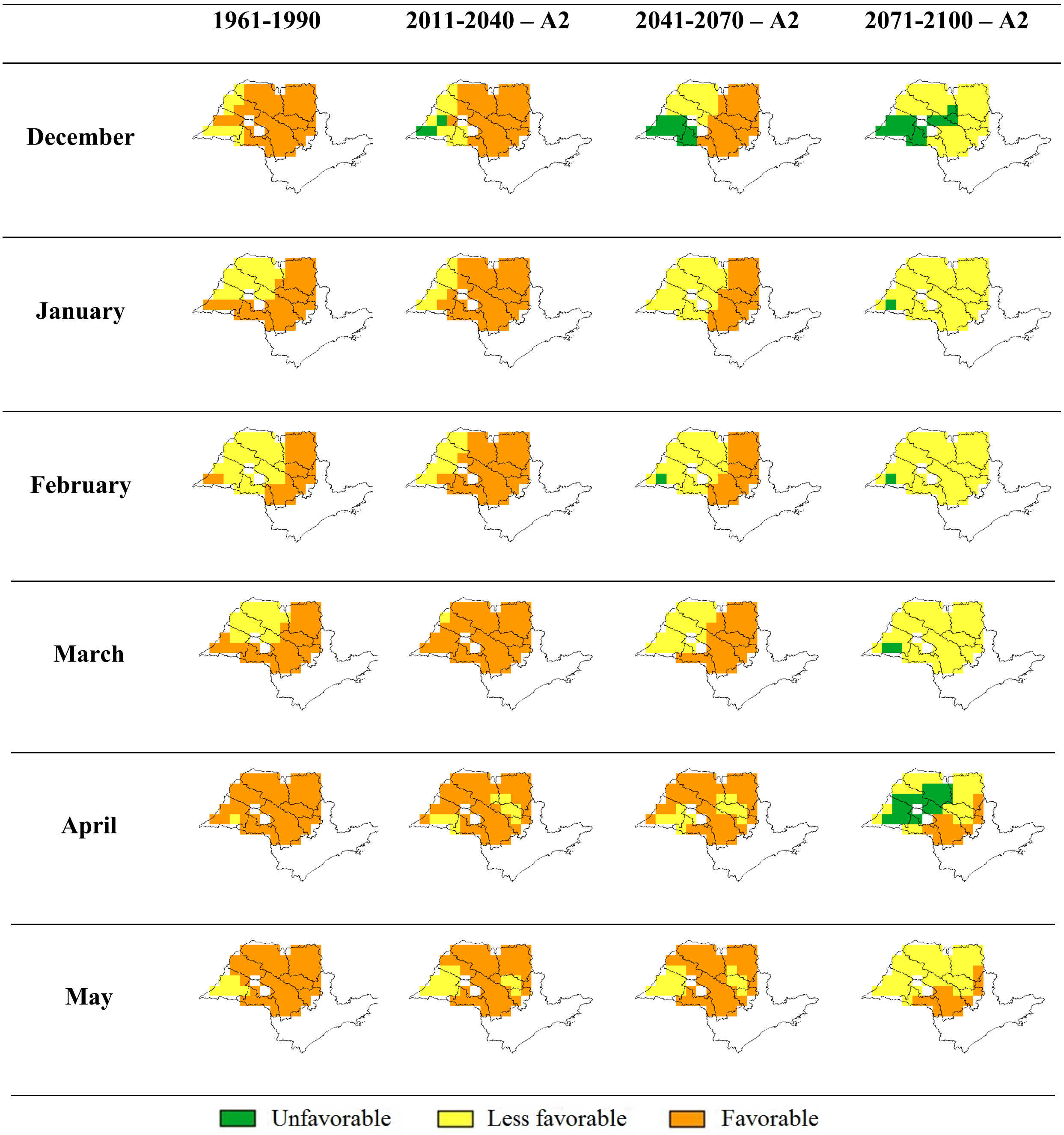
The maps of geographic distribution of *Puccinia melanocephala* (Figures 2 and 3) in the main sugarcane producing region of São Paulo State for future scenarios demonstrated a clear trend of decrease in the favorability considering the most favorable period for the disease development (from December to May), when compared to the reference period of 1961-1990. Areas regarded as less favorable will increase along the future periods; that is, this trend can be either due to the increase of average temperature (above 25 °C) with high relative humidity (above 70%), or due to the reduction of monthly relative humidity (below 70%) within the optimal temperature range (from 18°C to 25 °C). Then, by observing the spatial distribution of each climatic variable, it was verified that the predominant factor for the decrease in favorability in the future will be the decrease in relative humidity. For successful spore germination and infection, and hence, spread of the disease, several hours of free moisture on the leaf surface at a favorable temperature is necessary (Raid and Comstock, 2006). Thus, according to Sanguino (2008), in order to complete its cycle in the host plant, brown rust needs high relative humidity, whose availability plays an important role in the disease severity during the epidemic (Barrera et al., 2013).

The tendency of reduction in disease favorability will be more noticeable in the scenario A2 than in B1 (Figure 4) when considering a further period (2071-2100). In the reference period (1961-1990), on average from December to May, the favorable area for the development of the disease corresponds to 71% of the region. In 2011-2040, it corresponds to 83% and 50%, respectively in the scenarios A2 and B1; in 2041-2070, it corresponds to 51% (A2) and 34% (B1); and in 2071-2100, to 5% (A2) and 22% (B1). Therefore, the favorable area will be reduced as the future periods elapse, for both scenarios, except for the scenario A2 during 2011-2040, whose growth varied from 71% to 83% compared to the reference period. This was favored by an increase in temperature. For the two first future periods, 2011-2040 and 2041-2070, favorable area in A2 will be higher than in B1, benefited by a higher mean temperature; however, in 2071-2100, climate conditions in A2 will greatly reduce the favorability when compared to B1, reaching both boundaries of lower relative humidity and higher temperature. Nevertheless, although the trend is towards a reduction in the area regarded as favorable, it will still play an important role as a disease that will still require attention in this producing region.

The area regarded as favorable also varies along the months from December to May (Figure 4). Within the reference period, February presented the lowest favorable area (44%), due to higher temperatures (above 25 °C) which occur in great area of the northwest of the state of São Paulo (Figure 2 and 3), while April presented the highest favorable area (98%) both because of optimal temperature and relative humidity ranges. In 2011-2040, for the scenario A2, all months presented more than 70% of favorable area, with the highest observed in March (98%), due to an increase in temperature reaching the optimal range. On the other hand, for the scenario B1, the lowest favorable area was observed in February, with peak in April (91%). In 2041-2070, for the scenarios A2 and B1, favorable area decreased when compared to the previous period. Lastly, in 2071-2100, for the scenario A2, only April and May presented favorable area (around 25%); and for the scenario B1, from December to May, the favorable area ranged from 6% to 31%.

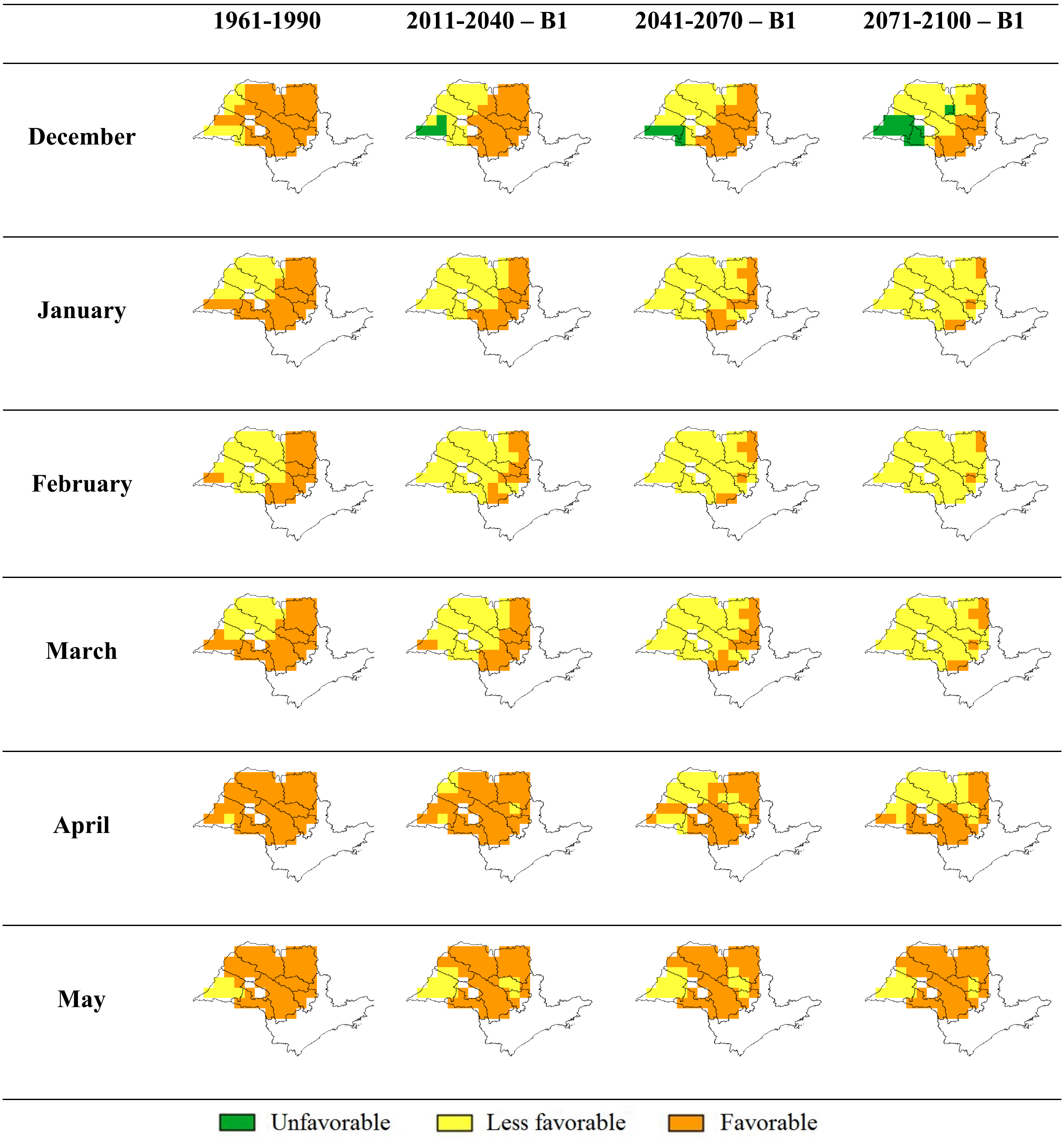
The mesoregions (Figures 2 and 3) located in the midwest of the state of São Paulo (Araraquara, Assis, Bauru, Piracicaba, and Ribeirão Preto) were generally more favorable than those in the northwest (Araçatuba, Presidente Prudente, and São José do Rio Preto), varying along the months and future periods. Thus, the results allow prospecting a gradual reduction in the favorable area for sugarcane brown rust not only by quantifying the area considering the variation in time of both the months of the year and the future time periods for A2 and B1 scenarios, but also by verifying the spatial variation in the main producing region of São Paulo State.

Figure 2. Climatic favorability for the occurrence of sugarcane brown rust (*Puccinia melanocephala*) in the main producing region of the state of São Paulo - Brazil, from December to May, for the reference period (1961-1990) and for the scenario A2, considering 2011-2040, 2041-2070, and 2071–2100.



A point to consider in the study of crop disease risk is how detailed the data about the specific plant–pathogen relationship should be considered when talking about potential effects of climate change on plant pathogens and the related crop disease risks. Data can be collected in field and lab conditions, such as in a study of brown rust carried out in Florida – USA, which observed that maximum disease severity was correlated with the number of nightly hours with an average temperature of 20 °C to 22.2 °C (Sanjel et al., 2019). This author also observed a slightly higher correlation when relative humidity above 90% was included in the number of nightly hours with an average temperature of 20 °C to 22.2 °C. In another study considering Australia, Chakraborty et al. (1998) cite that brown rust relies on periods of dry weather with dew at night; furthermore, other weather-biophysical interactions can occur affecting the disease, such as higher night temperatures that may reduce the number of nights with dew or even shift the period when heavy dews occur to earlier in the spring. Because of these detailed data of climate variables, it can be concluded that predicting the effect of climate change on *Puccinia melanocephala* is not

Figure 3. Climatic favorability for the occurrence of sugarcane brown rust (*Puccinia melanocephala*) in the main producing region of the state of São Paulo - Brazil, from December to May, for the reference period (1961-1990) and for the scenario B1, considering 2011-2040, 2041-2070, and 2071–2100.



an easy task. Future scenarios of disease, in general, are simulated using projections of future climate variables generated by GCMs operating on larger scales of temporal and spatial resolutions, which restricts the use of all detailed data on the specific plant–pathogen relationship and contrasts long-term climate and short-term weather conditions. However, despite the limitations of the results obtained, this methodology provides a useful instrument to study the impacts of climate change on the disease (Ghini et al., 2008; Ghini et al., 2011a).

The favorable area for the occurrence of brown rust as a parameter to represent disease risk was adopted in this study. This parameter was obtained through a model (criteria of climatic favorability) based on expert knowledge, to predict how projected changes in climate will alter the disease spatial and temporal distributions. Although associating the future risk to yield losses or gains was not the aim of this article, it is advisable to estimate potential losses in quality and yield due to crop diseases in future climate scenarios. Nevertheless, just a few researchers in the world have attempted to link plant disease simulation models to crop models, both driven

Figure 4. Area occupied by classes of favorability for the occurrence of sugarcane brown rust (*Puccinia melanocephala*) in the main producing region of the state of São Paulo - Brazil, from December to May, for the reference period (1961–1990) and for the scenarios A2 and B1, considering 2011–2040, 2041–2070, and 2071–2100.

by regional climatic scenarios (Juroszek et al., 2020). Regarding sugarcane in Brazil, there are no studies linking the future brown rust disease risk to crop yield, nor other studies considering the effect of the disease on crop yield simulation under climate change scenarios.

Concerning measures for disease control, brown rust has been managed by breeding and selecting for host plant resistance through genetic improvement programs (Hoy and Hollier, 2009). Due to climate change, environmental shifts can provide favorable conditions for diseases, either through pathogen variations, increasing inoculum potential, or through changes in the host physiological reactions, intensifying crop growth in certain periods and causing changes in genetic resistance (Sanguino, 2008). The adaptability of the pathogen affects resistance durability and makes the disease a continual threat and an ongoing challenge for breeding programs (Hoy and Hollier, 2009).

Overviewing more than 100 review articles related to the potential climate change effects on plant pathogens and crop disease risks during the past 30 years, Juroszek et al. (2020) cite that most of the first authors of review articles either work or worked in Australia, Europe, and the USA, where temperate and subtropical climatic conditions are mainly prevalent; and few first authors worked in countries where tropical and subtropical climatic conditions are mainly prevalent, such as Ghini et al. (2011b) in Brazil. Therefore, it is essential to carry out research to prospect new geographic and temporal distributions of plant diseases in Brazil, bearing in mind the promotion of suitable plant protection measures to help in the adoption of adaptation strategies in the face of future climate change scenarios.

Conclusion

The climate favorability for *Puccinia melanocephala* infestation on sugarcane in the main producing region of the state of São Paulo under climate change scenarios will decrease compared to the reference period of 1961-1990.

The trend in future scenarios is a decrease in favorability for the occurrence of the disease in a further period (2071-2100), more noticeable in the scenario A2 than in B1.

Despite the tendency observed in favorability, it is worth mentioning the importance that this disease demands attention in the management of the producing region for future climate scenarios.

Author’s contributions

E. HAMADA, F. ANGELOTTI and A. M. RAGO: conceptualization, work design, and data analysis. E. HAMADA and R. R. V. GONÇALVES: data processing and elaboration of graphics and figures. E. HAMADA and F. ANGELOTTI: writing, text review and English review.

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Previsão da ferrugem marrom da cana-de-açúcar em São Paulo-Brasil nos cenários de mudanças climáticas

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RESUMO

As mudanças climáticas podem causar significativas modificações na ocorrência e severidade de doenças agrícolas, alterando a distribuição dos problemas fitossanitários, com graves consequências econômicas, sociais e ambientais. Apesar de sua importância, essas novas distribuições geográficas e temporais das doenças de plantas ainda necessitam análise mais cuidadosa. No presente estudo, nós prospectamos a distribuição geográfica da ferrugem marrom (*Puccinia melanocephala*) da cana-de-açúcar considerando a temperatura média e a umidade relativa na principal região produtora do estado de São Paulo. O banco de dados geográfico foi estruturado em SIG com projeções das mudanças climáticas do IPCC. Equações de lógica matemática foram definidas e aplicadas aos dados de temperatura média e umidade relativa, resultando em mapas mensais da favorabilidade climática à ocorrência da doença. Os mapas prospectivos para três períodos (2011-2040, 2041-2070 e 2071-2100) e dois cenários de emissão de gases foram comparados com o período de referência (1961-1990). A análise considerou os meses de dezembro a maio. Nosso estudo mostra tendência de diminuição da favorabilidade da doença no prazo mais longo (2071-2100), mais pronunciado no cenário A2 do que no B1. Esses resultados sugerem, no entanto, que esta doença necessita atenção ao manejo da região produtora para os cenários climáticos futuros.

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