

## Climate risk scenarios of orange rust for the sugarcane-producing regions of Argentina and Brazil

Cenários de risco climático da ferrugem alaranjada para as regiões produtoras de cana-de-açúcar da Argentina e do Brasil

Escenarios de riesgo climático de la roya naranja para las regiones productoras de caña de azúcar de Argentina y Brasil

Received: 10/18/2022 | Revised: 11/04/2022 | Accepted: 11/15/2022 | Published: 11/22/2022

**Francislene Angelotti**

ORCID: <https://orcid.org/0000-0001-7869-7264>

Embrapa Semi-arid, Brazil

E-mail: [francislene.angelotti@embrapa.br](mailto:francislene.angelotti@embrapa.br)

**Cristina Del Carmem Morales**

ORCID: <https://orcid.org/0000-0001-7930-328X>

Instituto Nacional de Tecnología Agropecuaria, Argentina

E-mail: [morales.cristina@inta.gob.ar](mailto:morales.cristina@inta.gob.ar)

**Emília Hamada**

ORCID: <https://orcid.org/0000-0002-6214-884X>

Embrapa Environment, Brazil

E-mail: [emilia.hamada@embrapa.br](mailto:emilia.hamada@embrapa.br)

**Eduardo Matias Bisonard**

ORCID: <https://orcid.org/0000-0002-5479-9300>

Instituto Nacional de Tecnología Agropecuaria, Argentina

Email: [bisonard.matias@inta.gob.ar](mailto:bisonard.matias@inta.gob.ar)

**Renata Ribeiro do Valle Gonçalves**

ORCID: <https://orcid.org/0000-0002-0981-3062>

State University of Campinas, Brazil

E-mail: [renata@cpa.unicamp.br](mailto:renata@cpa.unicamp.br)

**Alejandro Mario Rago**

ORCID: <https://orcid.org/0000-0003-0900-0317>

Instituto Nacional de Tecnología Agropecuaria, Argentina

E-mail: [rago.alejandro@inta.gob.ar](mailto:rago.alejandro@inta.gob.ar)

### Abstract

Risk analysis of climate change on the spatial distribution of sugarcane orange rust (*Puccinia kuehnii*) is a strategic study for plant protection to minimize future damages. The objective of this work was to evaluate the potential risk of the occurrence of orange rust in Argentina and Brazil under the climate change scenarios. A mapping methodology integrated the data of climate projections and the phytosanitary problem supported by Geographic Information System (GIS). Normal climate (1961-1990) and future climate (2011-2040, 2041-2070, and 2071-2100) from Intergovernmental Panel on Climate Change were considered. The conditions of climatic favorability for the occurrence of the disease were established by means mathematical logic criteria of GIS, based on knowledge of the authors, who incorporated the implicit effects of the interaction of the virulent pathogen, susceptible host, and predisposing environmental characteristics. The favorability for the occurrence of sugarcane orange rust in the main sugarcane producing regions of Argentina and Brazil varied over the months considered of the cultivation cycle. For Argentina, the future climate scenarios predicted a reduction in favorability for the occurrence of sugarcane orange rust from December to February and an increase in April. In Brazil, the climatic favorability decreased from December to March and increased in May.

**Keywords:** Climatic favorability; *Puccinia kuehnii*; Temperature.

### Resumo

A análise de risco de mudanças climáticas na distribuição espacial da ferrugem alaranjada da cana-de-açúcar (*Puccinia kuehnii*) é um estudo estratégico para a proteção de plantas a fim de minimizar danos futuros. O objetivo deste trabalho foi avaliar o risco potencial da ocorrência de ferrugem alaranjada na Argentina e no Brasil, sob cenários de mudanças climáticas. A metodologia de mapeamento integrou os dados das projeções climáticas e do problema fitossanitário por meio do Sistema de Informações Geográficas (SIG). Foi considerado o clima normal (1961-1990) e o clima futuro (2011-2040, 2041-2070 e 2071-2100) do Painel Intergovernamental sobre Mudanças Climáticas. As condições de favorabilidade climática para a ocorrência da doença foram estabelecidas por meio de critérios lógicos

matemáticos do SIG, baseados no conhecimento dos autores, que incorporaram os efeitos implícitos da interação do patógeno virulento, hospedeiro suscetível e características ambientais predisponentes. A favorabilidade para a ocorrência da ferrugem alaranjada da cana-de-açúcar nas principais regiões produtoras de cana-de-açúcar da Argentina e do Brasil variou ao longo dos meses considerados do ciclo de cultivo. Para a Argentina, os cenários climáticos futuros previram uma redução na favorabilidade para a ocorrência da ferrugem alaranjada da cana-de-açúcar de dezembro a fevereiro e um aumento em abril. No Brasil, a favorabilidade climática diminuiu de dezembro a março e aumentou em maio.

**Palavras-chave:** Favorabilidade climática; *Puccinia kuehnii*; Temperatura.

## Resumen

El análisis de riesgo del cambio climático sobre la distribución espacial de la roya naranja de la caña de azúcar (*Puccinia kuehnii*) es un estudio estratégico para la protección vegetal con el fin de minimizar daños futuros. El objetivo de este trabajo fue evaluar el riesgo potencial de ocurrencia de roya naranja en Argentina y Brasil bajo los escenarios de cambio climático. Una metodología de mapeo integró los datos de las proyecciones climáticas y la problemática fitosanitaria apoyada en el Sistema de Información Geográfica (SIG). Se consideró el clima normal (1961-1990) y el clima futuro (2011-2040, 2041-2070 y 2071-2100) del Panel Intergubernamental sobre Cambio Climático. Las condiciones de favorabilidad climática para la ocurrencia de la enfermedad se establecieron mediante criterios lógicos matemáticos de SIG, basados en el conocimiento de los autores, quienes incorporaron los efectos implícitos de la interacción del patógeno virulento, huésped susceptible y características ambientales predisponentes. La favorabilidad para la ocurrencia de la roya naranja de la caña de azúcar en las principales regiones productoras de caña de azúcar de Argentina y Brasil varió a lo largo de los meses considerados del ciclo de cultivo. Para Argentina, los escenarios climáticos futuros pronosticaron una reducción en la favorabilidad para la ocurrencia de la roya naranja de la caña de azúcar de diciembre a febrero y un aumento en abril. En Brasil, la favorabilidad climática disminuyó de diciembre a marzo y aumentó en mayo.

**Palabras clave:** Favorabilidad climática; *Puccinia kuehnii*; Temperatura.

## 1. Introduction

Orange rust caused by the fungus *Puccinia kuehnii* E. J. Butler is the most recent disease in sugarcane cultivation in the Americas. It was restricted in Australia and Southeast Asia as a secondary disease, but it has become a major disease since detection in Florida - USA in 2007 (Comstock et al., 2008). From there on the pathogen was identified in different countries of the Americas, including Brazil (Barbasso et al., 2010) and Argentina (Funes et al., 2016). In Argentina, the first record of the disease was in a small sugarcane area in the province of Misiones, near the Brazilian border, and so far, this pathogen has not been verified in the main sugarcane-producing area, as the provinces of Tucumán, Salta, and Jujuy (Funes et al., 2016). On the other hand, in Brazil, this pathogen gained economic importance due to the damage caused in the main producing regions of the State of São Paulo (Klosowski et al., 2015; Sentelhas et al., 2016).

The occurrence of this disease is closely related to the favorable environmental conditions at a critical stages of the pathogen's biological cycle and the adoption of susceptible sugarcane cultivars. The climatic conditions are very important in the occurrence of the infection cycle, for example, changes in rainfall pattern and increases in air temperature may alter the geographical and temporal distribution of diseases (Nazir et al., 2018). With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers (IPCC, 2021). Thus, understanding how these changes impact the plant disease epidemics is a challenge for agronomic research, since yield losses directly affect the food security (IPCC, 2019).

Sugarcane orange rust development is favored by prolonged periods with night temperatures between 20 °C and 22.2 °C. However, maximum air temperatures above 32.2 °C negatively affect the development of the disease (Sangel et al., 2019). Epidemiological data of the disease associated with the use of geographic information system allow the analysis of the spatial distribution of plant diseases (Sumida et al., 2019; Sentelhas et al., 2016).

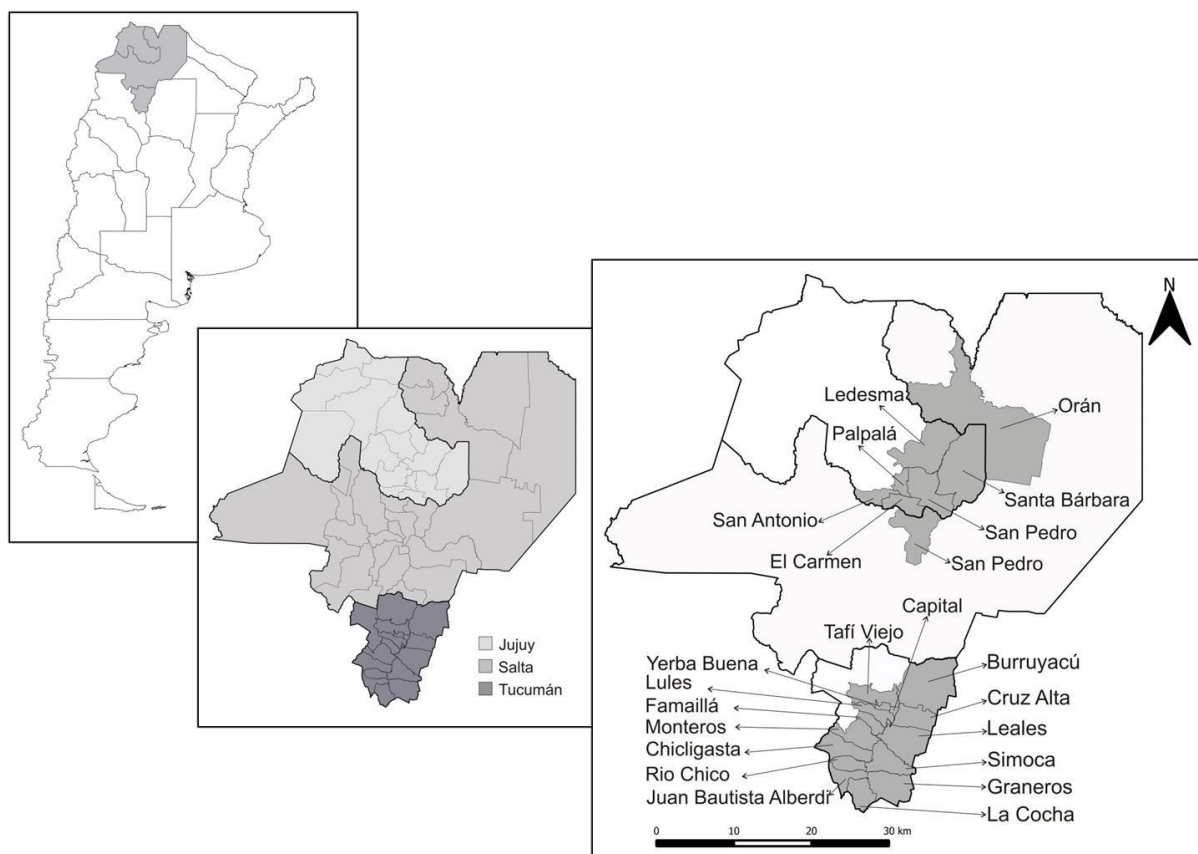
The influence of climate change has direct bearing to crop protection and it is important to consider its effects on a crop such as sugarcane, which is an important agricultural commodity for both Argentina and Brazil. The crop disease risk modelling study was carried out simulating the future geographic distribution based on climate change scenarios. This mapping

methodological approach can be strategic, as it shall assist in the preventive control of pathogens facing to climate change, avoiding/controlling the spread of disease, such as in areas with no occurrence (Alberto et al., 2019) and in neighboring countries for plant protection at the international level (Bisonard et al., 2020). Thus, the objective was to evaluate the potential risk of occurrence of orange rust in Argentina and Brazil under the climate change scenarios.

## 2. Methodology

Sugarcane constitutes an important commodity for Argentina and Brazil. Argentina has a total production of 17,652,814 ton (FAO, 2019) and the study area for Argentina comprises the provinces of Jujuy, Salta, and Tucumán, which represent 73%, 16.8%, and 9.3%, respectively, of the planted area of sugarcane (376,223 ha) (Benedetti, 2018). These provinces comprise the following departments: Ledesma, Santa Barbara, San Pedro, El Carmen, Palpalá, and San Antonio for Jujuy; Orán and General Güemes for the province of Salta; and Burruyacú, Cruz Alta, Leales, Simoca, Graneros, La Cocha, Juan Bautista Alberdi, Río Chico, Chicligasta, Monteros, Famaillá, Lules, Yerba Buena, Tafí Viejo, and San Miguel for Tucumán (Figure 1).

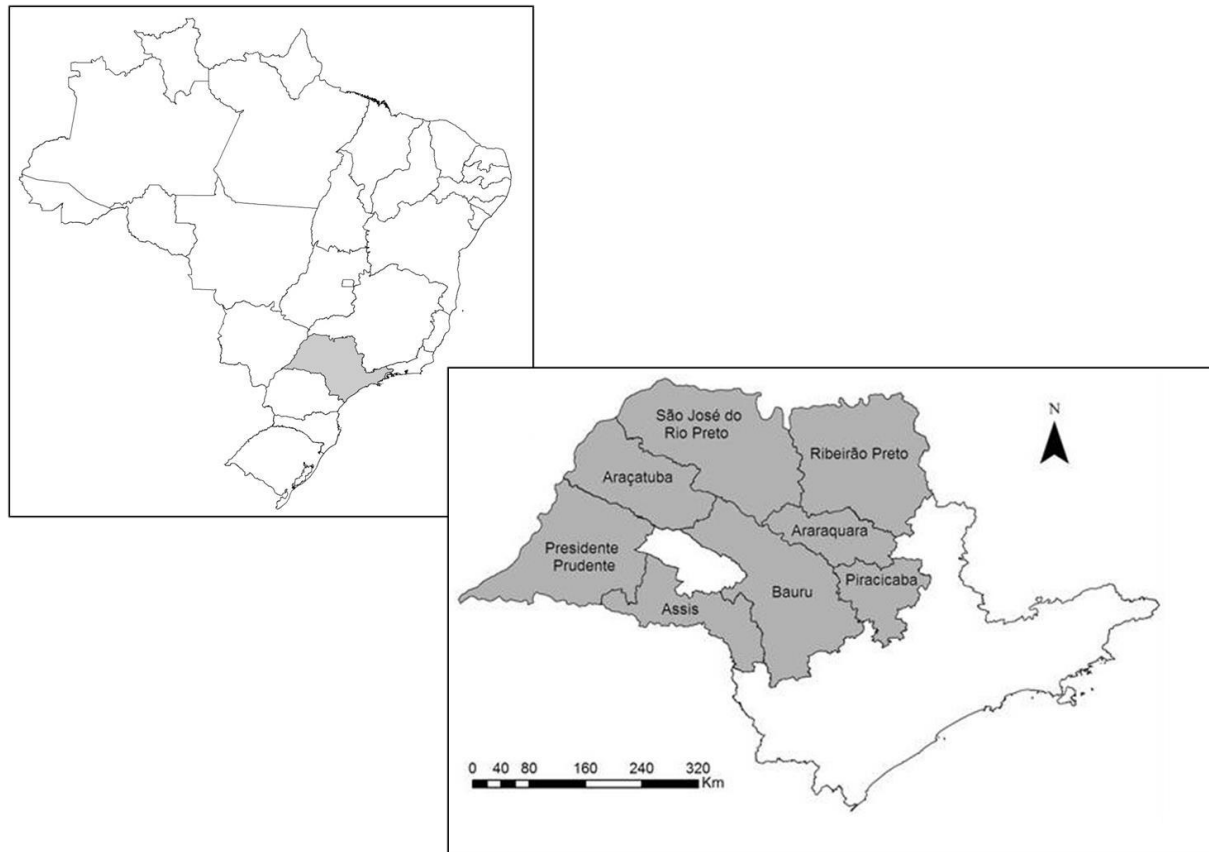
**Figure 1** - Location of the main sugarcane-producing areas of the provinces of Salta, Jujuy, and Tucumán, Argentina.



Source: Authors.

The sugarcane production in Brazil is 752,895,389 ton (FAO, 2019) and it is distributed throughout the country, but the State of São Paulo is the main producer with 51.8% of the country (CANA, 2021). The production in the state is concentrated in the following mesoregions: Araçatuba, Araraquara, Assis, Bauru, Piracicaba, Presidente Prudente, Ribeirão Preto, and São José do Rio Preto (Figure 2).

**Figure 2** - Location of the main sugarcane-producing areas of the State of São Paulo, Brazil.



Source: Authors.

The sugarcane crop becomes more susceptible to orange rust infestation from December to March (Araújo et al., 2013; Rago et al., 2012). The impacts of climate change were analyzed adopting the Idrisi GIS tool, considering the geographic database of climate information for Argentina and Brazil, obtained from the projections of climate scenarios of the global climate models of IPCC. The climatic variables mean air temperature and leaf wetness duration were selected, the latter being obtained from relative humidity, according to Hamada et al. (2008). In addition, two greenhouse gas emission scenarios were adopted, A2 and B1. These scenarios are called respectively “pessimistic” and “optimistic”, being the extreme scenarios, so that adaptation strategies can be proposed with a higher margin of safety based on the assessment of the impacts of climate change on the occurrence of plant disease.

This case study adopts a computer-based crop disease risk simulation which modelling approach is known as mechanistic or process-based, according to Juroszek et al. (2022). The prospective analysis of climate change on sugarcane orange rust considered the knowledge of the literature and experience of the authors, who incorporated the implicit effects of the interaction of the virulent pathogen, susceptible host, and predisposing environmental characteristics to define the climatic favorability for the occurrence of the disease. Adopting mathematical logic criteria of GIS, the ranges, were structured and applied to data of the normal climate (1961-1990) of the Climate Research Unit (2015) and to the future climate (2011-2040, 2041-2070, and 2071-2100), from the Data Distribution Center of the IPCC (2015).

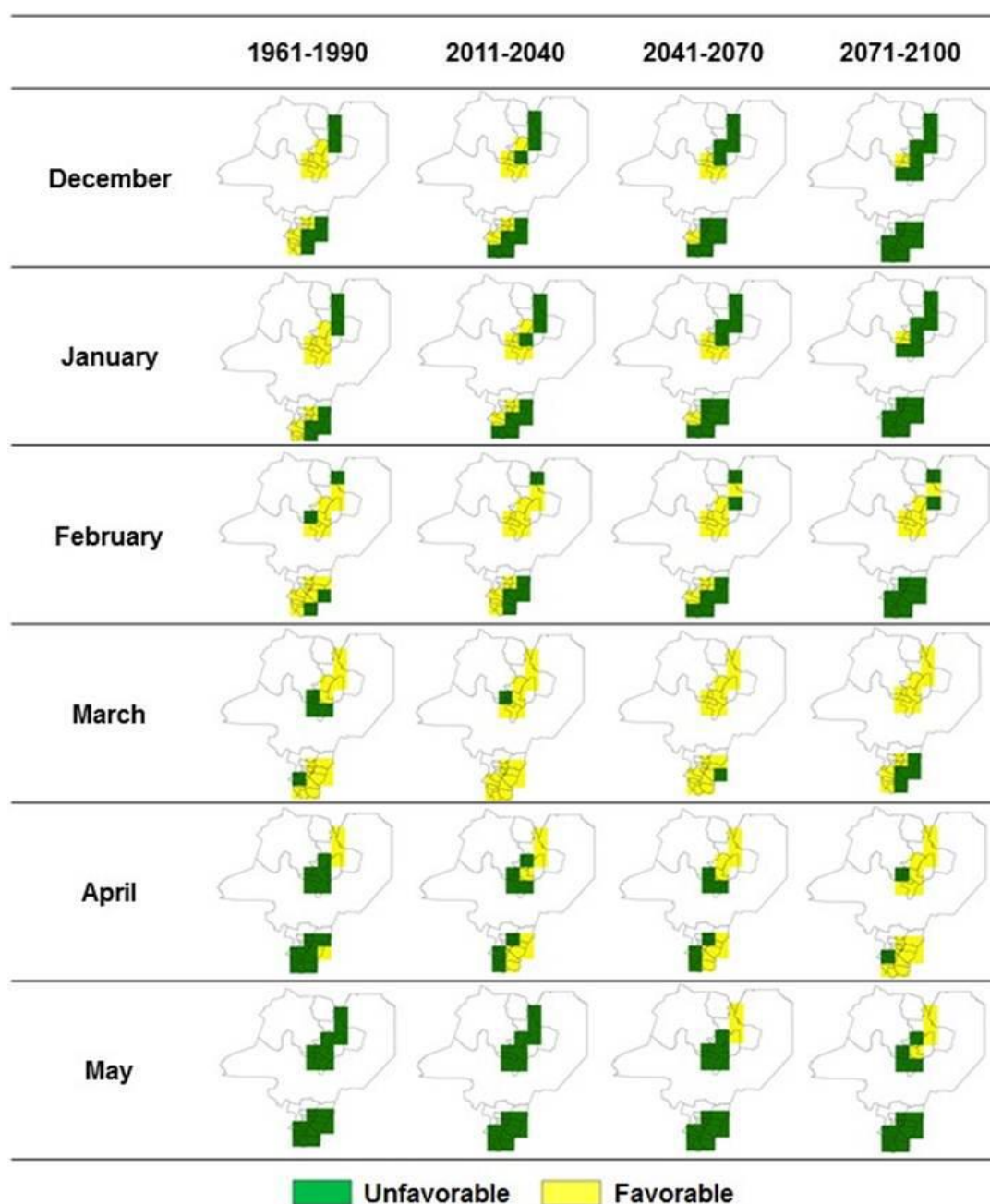
The combined climatic variables ranges were defined in two classes. The favorable conditions for the occurrence of the disease occur with temperature between 20 °C and 25 °C, regardless of leaf wetness duration, or temperature higher than 25 °C and leaf wetness above 8 h day<sup>-1</sup>. Unfavorable climatic conditions occur with an average temperature below 20 °C, for any leaf wetness condition, or with average temperature above 25 °C, and leaf wetness below 8 h day<sup>-1</sup>.

### 3. Results and Discussion

The risk simulation of sugarcane orange rust considered the climatic favorability to occurrence of the crop disease for the sugarcane-producing regions of Argentina and Brazil in future scenarios.

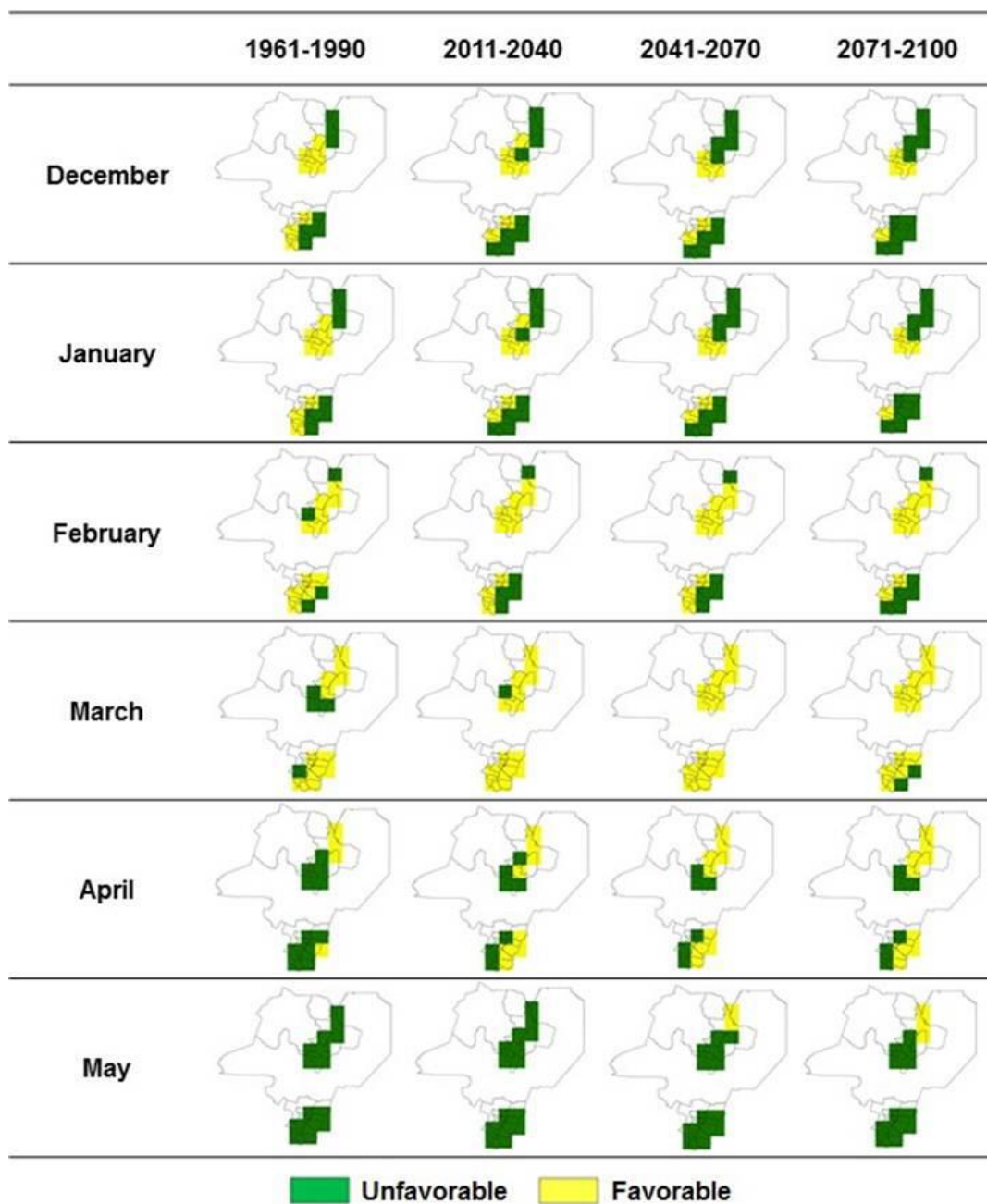
The geographical distribution maps of favorability to Argentina are shown in Figures 3 and 4. The quantitative of areas of favorability classes is shown in Figure 5. The favorability for the occurrence of sugarcane orange rust in the main producing departments of the provinces of Jujuy, Salta, and Tucumán varied throughout the months of December, January, February, March, April, and May, in the reference period (1961-1990) and the future scenarios.

**Figure 3** - Climatic favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing departments of the provinces of Jujuy, Salta, and Tucumán in Argentina, from December to May, for normal climate (1961-1990) and for future climate (2011-2040, 2041-2070 and 2071-2100) in the scenario A2.



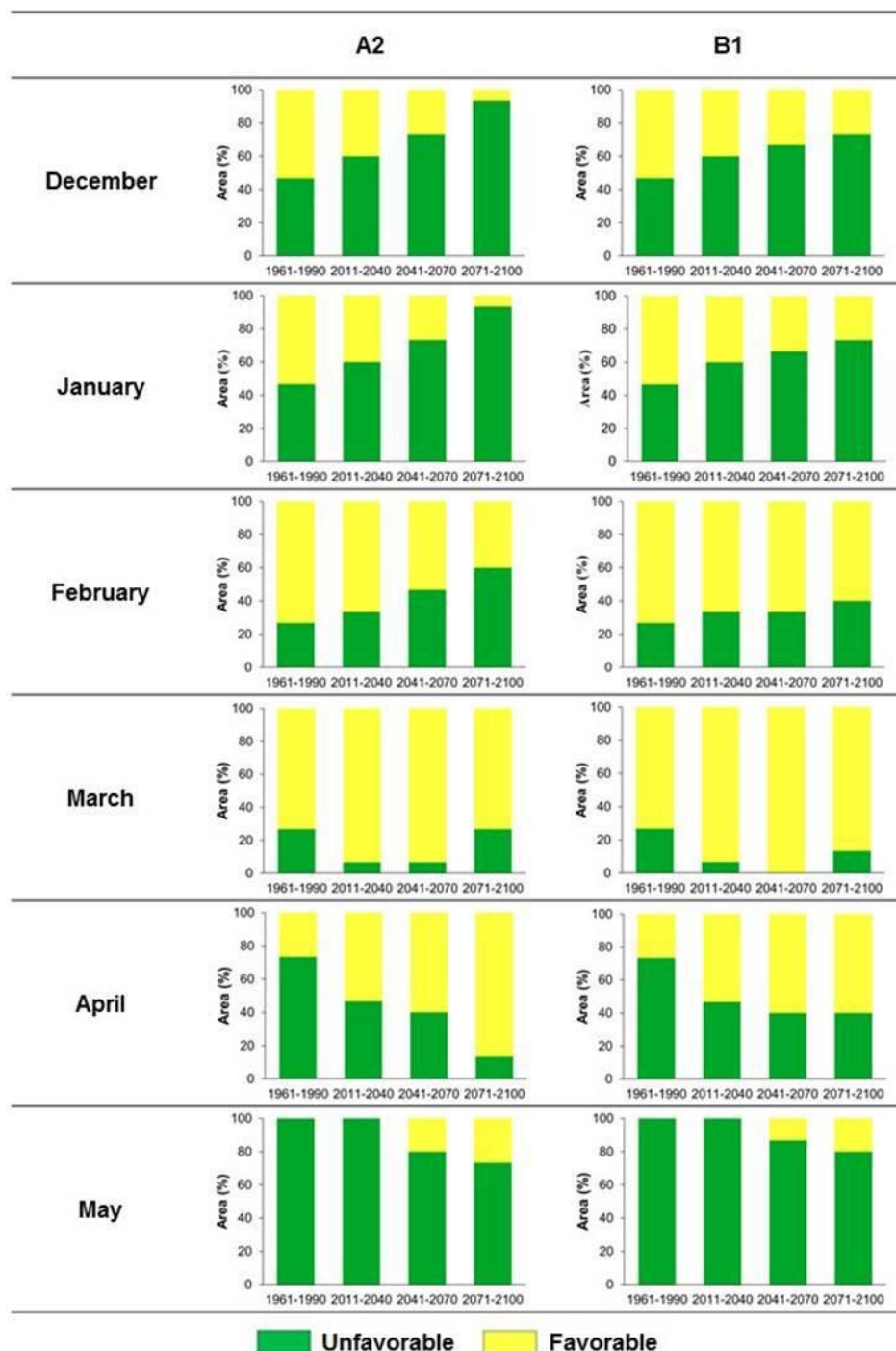
Source: Authors.

**Figure 4** - Climatic favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing departments of the provinces of Jujuy, Salta, and Tucumán in Argentina, from December to May, for normal climate (1961-1990) and for future climate (2011-2040, 2041-2070 and 2071-2100) in the scenario B1.



Source: Authors.

**Figure 5** - Percentage of area occupied by favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing departments of the provinces of Jujuy, Salta, and Tucumán in Argentina, from March to May, in the periods of normal climate (1961–1990) and future climate (2011–2040, 2041–2070 and 2071–2100) in scenarios A2 and B1.



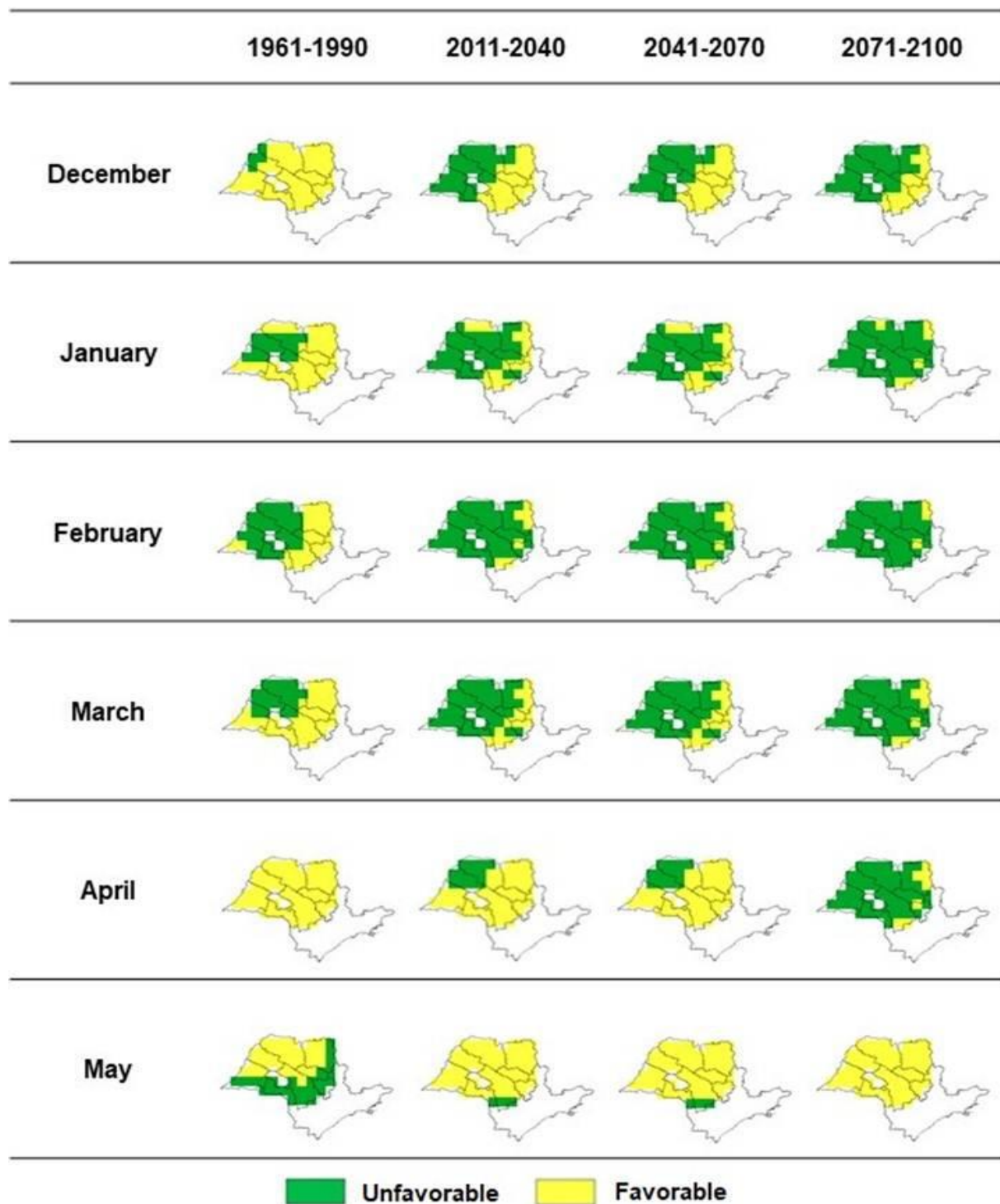
Source: Authors.

The maps of geographical distribution from December to February stand out with reduction of favorable areas for the provinces of Jujuy, Salta, and Tucumán (Figures 3 and 4). For March and April, there was an increase in favorability for the development of rust in the sugarcane-producing regions of Argentina. In May, for the departments (Figure 1) of Tucumán, the maps of geographic and temporal distribution did not show favorability for the occurrence of orange rust in the reference climate and in the future scenarios A2 and B1. Also in May, however, the departments of Orán and Santa Bárbara in A2 scenario and San Pedro, Orán, and Santa Barbara in B1scenario showed favorable conditions for the occurrence of the disease.

The percentage of the area occupied by favorability class in the main sugarcane-producing regions of Argentina indicates a greater favorability in scenarios A2 and B1 in February, March, and April (Figure 5). In the period 2041-2070, the area of favorable class a reach 93% of total area in March, and 100% of favorable area, in A2 and B1 scenarios, respectively. In May, in the period of normal climate (1961–1990) and 2011-2040 (scenarios A2 and B1) a 100% of unfavorable area for sugarcane orange rust is assessed.

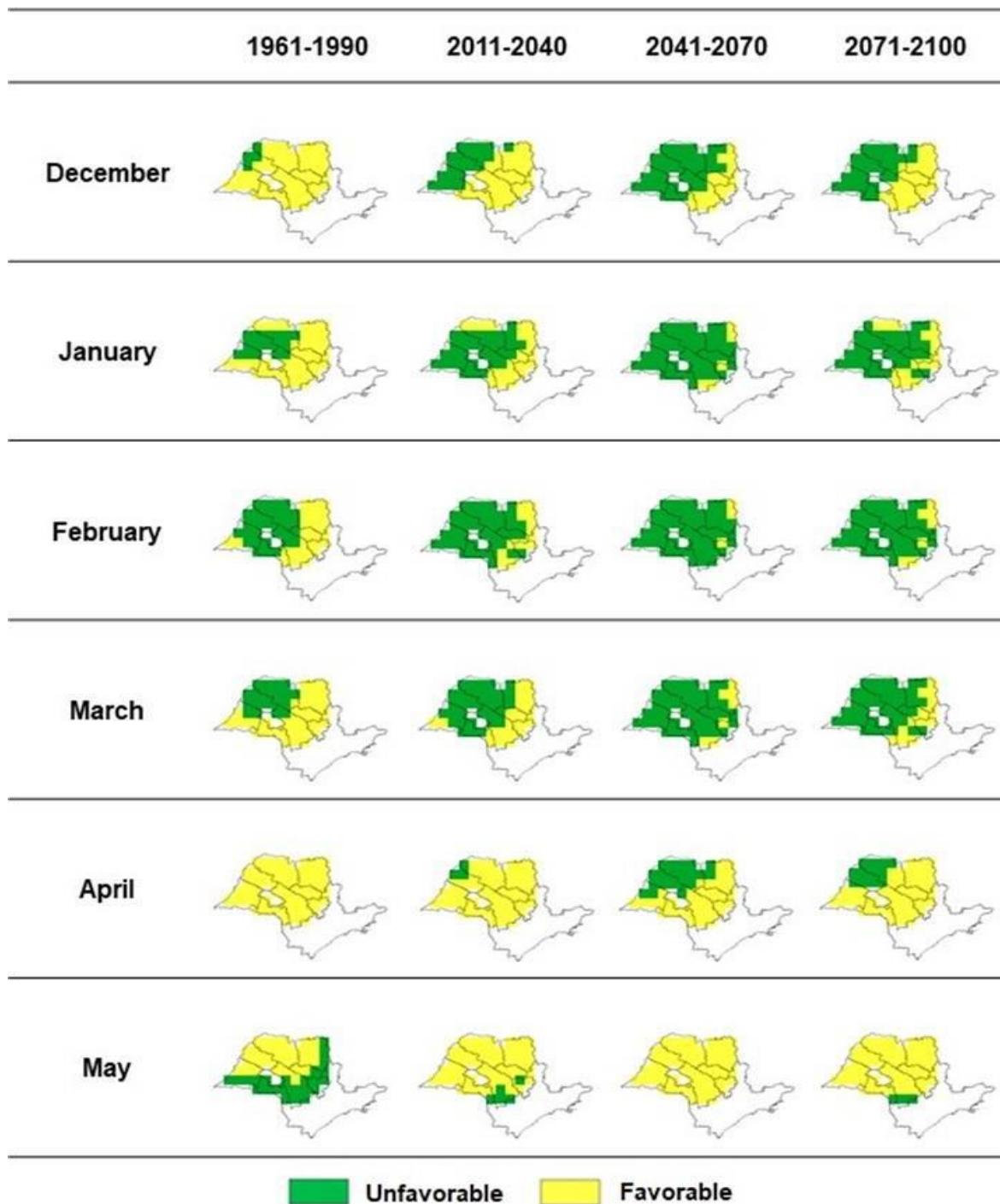
The geographical distribution maps of favorability to Brazil are shown in Figures 6 and 7, and the quantitative of areas of favorability classes is shown in Figure 8. In general, the favorability for the occurrence of sugarcane orange rust in the main producing mesoregions of the State of Sao Paulo varied along the months of December, January, February, March, April, and May, in the reference period (1961-1990) and the future scenarios, also occurred to Argentina.

**Figure 6** - Climatic favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing mesoregions of the State of São Paulo, from December to May, for the normal climate (1961-1990) and for the future climate (2011-2040, 2041-2070 and 2071-2100) in scenario A2.



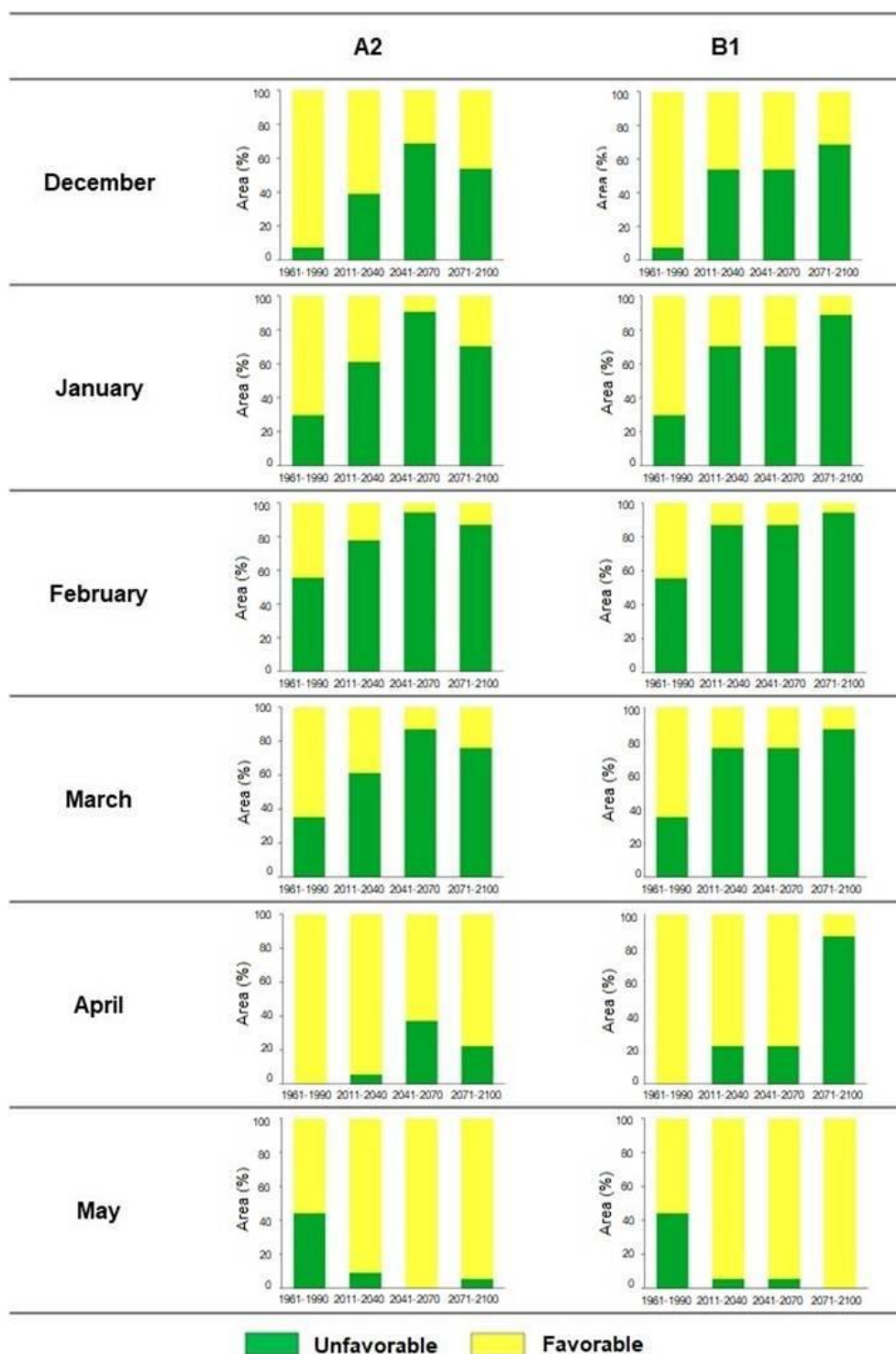
Source: Authors.

**Figure 7** - Climatic favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing mesoregions of the State of São Paulo, from December to May, for the normal climate (1961-1990) and for the future climate (2011-2040, 2041-2070 and 2071-2100) in scenario B1.



Source: Authors.

**Figure 8** - Percentage of area occupied by levels of favorability for sugarcane orange rust (*Puccinia kuehnii*) in the main producing mesoregions of the State of São Paulo, from December to February, in the periods of normal climate (1961–1990) and future climate (2011–2040, 2041–2070 and 2071–2100) in scenarios A2 and B1.



Source: Authors.

Under the future scenarios, there was a tendency of decrease in favorability in April for the mesoregions (Figure 2) of Araçatuba and São José do Rio Preto, in A2 scenario, for the 2071-2100 period (Figure 6). The same was observed in B1 scenario, for the 2011-2040 and 2041-2070 periods. In the 2071-2100 period, the unfavorable area increased in all sugarcane-producing mesoregions (Figure 7). From December to March, the reduction of favorable areas stands out in the different sugarcane-producing mesoregions. The months of December and April had greater favorability for the 1961-1990 period, with 92% and 100% of favorable area, respectively (Figure 8).

Sugarcane orange rust is a relatively new disease in Argentina and Brazil (Barbasso et al., 2010; Funes et al., 2016). Environmental conditions, with average air temperatures between 23 °C and 25 °C, rainy days and prolonged dew periods, favor infections, the production of spores and dissemination of the disease in the field (Pérez-Vicente et al., 2010; Chapola et al., 2016). In Brazil, the greatest progress in orange rust was observed in March and April, which have the conditions presented above (Chapola et al., 2016). Temperature is an important climatic element in the occurrence of epidemics, and it may affect the components of the infection cycle. Studies indicate that temperatures above 28 °C can reduce the rate of infection, the expansion of the lesion and sporulation, as well as increasing the latent period of urediniospores of different rusts (Angelotti et al., 2014; Cheng et al., 2014). Sangel et al. (2019) also found that high summer temperatures negatively affected the development of orange rust. In this context, we found a reduction in favorability for the occurrence of this disease in the main sugarcane-producing regions of Argentina and Brazil, from December to February and from December to March, respectively, due to the increase in mean air temperature predicted for the periods 2011-2040, 2041-2070 and 2071-2100.

Climatic risk maps of *P. kuehnii* infection using monthly temperature and relative humidity data from 2008 to 2010 also showed variability of favorable conditions to orange rust for Brazil (Sumida et al., 2019). In this study, there was greater favorability for the occurrence of the disease from December to May; since the entire country of Brazil was considered, without distinction of the producing areas. In the United States, mathematical models have been developed for potential use in the quantitative assessment of risks of sugarcane rust epidemics (Chaulagain et al., 2020). Thus, different methodologies can be used to create maps of geographical and temporal distribution of plant diseases (Alberto et al., 2019; Angelotti et al., 2017; Bosso et al., 2017; Bisonard et al., 2020; Bhim et al., 2020). All these studies have in common is the use of an important tool for the identification of areas with favorable climatic conditions for the development of the pathogen. Therefore, the monitoring of these areas of risk for the occurrence of diseases, through maps of geographic and temporal distribution, can be a preventive measure, seeking actions to prevent the entry of the pathogen, as well as the indication of tolerant cultivars in areas with favorable environmental conditions (Sentelhas et al., 2016; Sumida et al., 2019). These measures should be adopted by the main sugarcane-producing areas of Argentina and Brazil. It is worth pointing out that, for the main producing regions of Argentina (provinces of Jujuy, Salta, and Tucumán), the pathogen has not yet been identified in sugarcane plantations, hence reinforcing the importance of preventive actions to control orange rust, avoiding the entry of the fungus in these areas. As verified in the maps of geographical and temporal distribution of the present study, this type of control measure will be strategic, because the main producing departments of the provinces of Jujuy, Salta, and Tucumán have favorable climatic conditions for the development of the disease throughout the sugarcane cultivation cycle (Figures 3 and 4).

Because of the limited information about the impact of climate change on sugarcane orange rust for Argentina and Brazil it is extremely important to obtain a systematized information on the risk for the occurrence of the crop disease for the adoption of control strategies, avoiding severe damage in the future. This type of predictive study, using maps of geographical and temporal distribution, guides the adoption of preventive control measures, in order to avoid the introduction of the pathogen in regions with no occurrence (Bosso et al., 2016). In addition, the internationalization of research strengthens actions for the protection of plant, and it contributes to the improvement of scientific bases, allowing the planning of phytosanitary policies, assisting the public policies makers focusing on food security (Bisonard et al., 2020).

## 4. Conclusion

The favorability for the occurrence of sugarcane orange rust in the main sugarcane-producing regions of Argentina and Brazil varied over the months of the cultivation cycle. For Argentina, the future climate scenarios point to a reduction in favorability for the occurrence of sugarcane orange rust from December to February and an increase in April. In Brazil, in the months from December to March shall have a reduction in the risk of occurrence and in May the favorability shall increase in the future.

In conclusion, the risk simulation approach of sugarcane orange rust is useful to support stakeholder decision in climate change scenarios. These findings are valid for the locations considered in this study and, therefore, extrapolate the results across locations is not advisable. Thus, further studies need to be conducted to validate to other regions of interest. Moreover, additional studies are desirable integrating and considering sustainable adaptation methods to reduce crop disease risk in future.

## Acknowledgments

Funding was provided by Brazilian Cooperation Agency (ABC) affiliated to the Ministry of External Relations and Fondo Argentino de Cooperación Sur-Sur y Triangular (FO.AR) Ministerio de Relaciones Exteriores, Comercio Internacional y Culto

## References

- Alberto, R.T., Isip, M. F., Biagtan, A. R., & Tagaca, R. C. (2019). Disease risk map of anthracnose twister of onion based on previous disease locations as a future predictor. *Spatial Information Research*, 27, 259-265.
- Angelotti, F., Scapin, C. R., Tessmann, D. J., Vida, J. B., & Canteri M. G. (2014). The effect of temperature, leaf wetness and light on development of grapevine rust. *Australasian Plant Pathology*, 43, 9-13.
- Angelotti, F., Hamada, E., Magalhães, E. E., Ghini, R., Garrido, L. R., & Pedro Júnior, M. (2017). Climate change and the occurrence of downy mildew in Brazilian grapevines. *Pesquisa Agropecuária Brasileira*, 52, 424-432.
- Araújo, K. L., Canteri, M. G., Gilio, T. A. S., Neubauer, R. A., Sanches, P. B., Sumida, C. H., & Giglioti, E. A. (2013). Resistência genotípica e monitoramento da favorabilidade para ocorrência da ferrugem alaranjada da cana-de-açúcar. *Summa Phytopathologica*, 39, 271-275.
- Barbasso, D., Jordão, H., Maccheroni, W., Boldini, J., Bressiani, J., & Sanguino, A. (2010). First report of *Puccinia kuehnii*, causal agent of orange rust of sugarcane, in Brazil. *Plant Disease*, 94, 1170.
- Benedetti, P. E. (2018). *Primer relevamiento del área cultivada con caña en Argentina a través de imágenes satelitales*. <https://inta.gob.ar/noticias/primer-relevamiento-del-area-cultivada-con-cana-en-argentina-a-traves-de-imagenes-satelitales>. Accessed 19 December 2020.
- Bisonard, E. M., Hamada, E., Angelotti, F., Gonçalves, R. R. V., & Rago, A. M. (2020). Evolução da mancha preta do amendoim nas principais regiões produtoras da Argentina e do Brasil frente às mudanças no clima. *Revista Brasileira de Geografia Física*, 13, 1778-1791.
- Bosso, L., Febraro, M., Cristinzio, G., Zoina, A., & Russo, D. (2016). Shedding light on the effects of climate change on the potential distribution of *Xylella fastidiosa*. *Biological Invasions*, 18, 1759-1768.
- Bosso, L., Luchi, N., Maresi, G., Cristinzio, G., Smeraldo, S., & Russo, D. (2017). Predicting current and future disease outbreaks of *Diplodia sapinea* shoot blight in Italy: species distribution models as a tool for forest management planning. *Forest Ecology and Management*, 400, 655-664.
- Cana (2021). *Agrianual 2021: anuário da agricultura brasileira*. FND.
- Chapola, R. G., Hoffmann, H. P., & Massola, N. S. (2016). Reaction of sugarcane varieties to orange rust (*Puccinia kuehnii*) and methods for rapid identification of resistant genotypes. *Tropical Plant Pathology*, 41, 139-146.
- Chaulagain, B., Small, I. M., Shine, J. M., Fraisse, C. W., Raid, R. N., & Rott, P. (2020). Weather-based predictive modeling of orange rust of sugarcane in Florida. *Phytopathology*, 110, 626-632.
- Cheng, P., Ma, Z., Wang, X., Wang, C., Li, Y., Wang, S., & Wang, H. (2014). Impact of UV-B radiation on aspects of germination and epidemiological components of three major physiological races of *Puccinia striiformis* f. sp. *tritici*. *Crop Protection*, 65, 6-14.
- Comstock, J. C., Sood, S. G., Glynn, N. C., Shineii, J., McKemy, J. M., & Castlebury, L. A. (2008). First report of *Puccinia kuehnii* butler, causal agent of orange rust of sugarcane in the United States and Western Hemisphere. *Plant Disease*, 92, 175.
- FAO - Food and Agriculture Organization of the United Nations. (2019). *FAOSTAT Database*. Rome, Italy: FAO. <http://www.fao.org/faostat/en/#home>

- Funes, C., Pérez Gómez, S. G., Henríquez, D. D., Pauli, V., Bertani, R. P., Fontana, D. P., Rago, A. M., Joya, M. C., Sopena, R. A., González, V., Babi, H., Erazzu, L. E., Cuenya, M. I., & Ploper, L. E. (2016). First report of orange rust of sugarcane caused by *Puccinia kuehnii* in Argentina. *Plant Disease*, 100, 861.
- Hamada, E., Ghini, R., Fernandes, J. L., & Pedro Júnior, M. J. (2008). Spatial and temporal variability of leaf wetness duration in the State of São Paulo, Brazil. *Scientia Agrícola*, 65, 26-31.
- Intergovernmental Panel on Climate Change. (2019). *Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems*. [https://www.ipcc.ch/site/assets/uploads/2019/08/2f.-Chapter-5\\_FINAL.pdf](https://www.ipcc.ch/site/assets/uploads/2019/08/2f.-Chapter-5_FINAL.pdf).
- Intergovernmental Panel on Climate Change. (2021). Summary for policymakers. In: *Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. In Press.
- Juroszek, P., Bartsch, L., Fontaine, J. F., Racca, P., & Kleinhenz, B. (2022). Summary of the worldwide available crop disease risk simulation studies that were driven by climate change scenarios and published during the past 20 years. *Plant Pathology*, 00, 1-24.
- Klosowski, A. C., Bespalhok Filho, J. C., Ruaro, L., Fragoso, R. B., & May de Mio, L. L. (2015). Reação de cultivares e época de avaliação da ferrugem alaranjada da cana-de-açúcar. *Bioscience Journal*, 31, 489-498.
- Nazir, N., Bilal, S., Bhat, K. A., Shah, T. A., Badri, Z. A., Bhat, F. A., Wani, T. A., Mugal, M. N., Parveen, S., & Dorjey, S. (2018). Effect of climate change on plant diseases. *International Journal of Current Microbiology and Applied Science*, 7, 250-256.
- Pérez-Vicent, L., Martín, E. L., Barroso, F., Martínez, E., Borrás, O., & Hernández, I. (2010). Definitive identification of orange rust of sugarcane caused by *Puccinia kuehnii* in Cuba. *Plant Pathology*, 59, 804.
- Rago, A. M., Pérez Gómez, S. G., & Fontana, P. D. (2012). Roya marrón. *Caña de azúcar*. Identificación y manejo de las enfermedades en Argentina (p. 9-13). INTA. Programa Nacional de Cultivos Industriales, Córdoba, Argentina.
- Sentelhas, P. C., Santos, D. L., Monteiro, L. A., Soares-Colletti, A. R., Pallone Filho, W. J., Donzelli, J. L., & Arrigoni, R. B. (2016). Agro-climatic favorability zones for sugarcane orange rust as a tool for cultivar choice and disease management. *Crop Protection*, 84, 88-97.
- Sumida, C. H., Fantin, L. H., Gonçalves, M., Canteri, M. G., Araújo, K. L., & Gigliotti, E. A. (2019). A system to map the risk of infection by *Puccinia kuehnii* in Brazil. *Acta Scientiarum Agronomy*, 41, e39905.