Mercator, Fortaleza, v. 23, e23019, 2024. ISSN:1984-2201

EVALUATION OF CLIMATE CHANGE IMPACTS ON SUGARCANE AND CITRUS CROPS IN BRAZIL

https://doi.org/10.4215/rm2024.e23019

Sousa, A.S. [a*] - Xavier, F. [b] - Galvani, E. [c] - Silva, R.F. [d] - Mostaço, G.M. [e] - Saraiva, A.M. [f]
Cugnasca, C.E. [g] - Ross, J.L.S. [h]

(a) Phd in Geography **ORCID:** https://orcid.org/0000-0002-3039-830X. **LATTES:** http://lattes.cnpq.br/4706064220093988.
(b) PhD in Electrical Engineering **ORCID:** http://orcid.org/0000-0001-5797-7339. **LATTES:** http://lattes.cnpq.br/6644552602614357.
(c) Phd in Agronomy. **ORCID:** https://orcid.org/0000-0002-8082-5963. **LATTES:** http://lattes.cnpq.br/2026434763745090.
(d) PhD in Electrical Engineering. **ORCID:** http://orcid.org/0000-0002-9792-0553. **LATTES:** http://lattes.cnpq.br/8941366680536142.
(e) PhD Student in Electrical Engineering. **ORCID:** http://orcid.org/0000-0003-0984-4421. **LATTES:** http://lattes.cnpq.br/5479446295078583.
(f) PhD in Electrical Engineering. **ORCID:** https://orcid.org/0000-0003-2283-1123. **LATTES:** http://lattes.cnpq.br/0725312844547101.
(g) PhD in Electrical Engineering. **ORCID:** https://orcid.org/0000-0001-8306-9342. **LATTES:** http://lattes.cnpq.br/6040855194699192.
(h) PhD in Geography **ORCID:** https://orcid.org/0000-0002-7726-2960. **LATTES:** http://lattes.cnpq.br/1197390306069415.

Article history:
Received 17 June, 2024
Accepted 24 July, 2024
Published 10 September, 2024

(*) CORRESPONDING AUTHOR
Address: USP. Avenida Professor Lineu Prestes, 338 - Cidade Universitária - São Paulo - SP - CEP 05508-000 Phone: 55 (11) 3091-3769
E-mail: alexgeopro86@gmail.com

Abstract

Agricultural production is directly related to environmental conditions. Favorable conditions can lead to higher productivity and product quality. However, climate change may pose a threat to agricultural production worldwide, as an increase in temperature may cause a decrease in the extent of suitable areas for growing certain crops. Using spatial analysis and data from future climate change scenarios developed by the Intergovernmental Panel on Climate Change, this study aimed to evaluate the impact of climate change on sugarcane and citrus plantations in the state of São Paulo using agroclimatic zoning mapping. The results of this study demonstrate that both crops can suffer major reductions in areas suitable for cultivation if there are severe changes in the climate regime. These findings can assist managers and researchers to mitigate these potential impacts and clarify how climate change affects life on the planet, with a potential reduction in food and bioenergy production.

Keywords: Agroclimatic zoning, Climate change, Sugarcane, Citrus, Bioenergy.

Resumo / Resumen

AVALIAÇÃO DOS IMPACTOS DAS MUDANÇAS CLIMÁTICAS NAS CULTURAS DE CANA-DE-AÇÚCAR E CÍTRICOS NO BRASIL

A produção agrícola está diretamente relacionada às condições ambientais. Condições favoráveis podem levar a maior produtividade e qualidade do produto. No entanto, as alterações climáticas podem representar uma ameaça para a produção agrícola em todo o mundo, uma vez que um aumento da temperatura pode causar uma diminuição na extensão de áreas adequadas para o cultivo de certas culturas. Utilizando análises espaciais e dados de cenários futuros de mudanças climáticas desenvolvidos pelo Painel Intergovernamental sobre Mudanças Climáticas, este estudo teve como objetivo avaliar o impacto das mudanças climáticas nas plantações de cana-de-açúcar e citros no estado de São Paulo por meio do mapeamento do zoneamento agroclimático. Os resultados deste estudo demonstram que ambas as culturas podem sofrer grandes reduções nas áreas aptas ao cultivo caso haja mudanças severas no regime climático. Essas descobertas podem auxiliar gestores e pesquisadores a mitigar esses potenciais impactos e esclarecer como as mudanças climáticas afetam a vida no planeta, com potencial redução na produção de alimentos e bioenergia.

Palavras-chave: Zoneamento agroclimático, Mudanças climáticas, Cana-de-açúcar, Citros, Bioenergia.

EVALUACIÓN DE LOS IMPACTOS DEL CAMBIO CLIMÁTICO EN CULTIVOS DE CAÑA DE AZÚCAR Y CÍTRICOS EN BRASIL

La producción agrícola está directamente relacionada con las condiciones ambientales. Las condiciones favorables pueden conducir a una mayor productividad y calidad del producto. Sin embargo, el cambio climático puede representar una amenaza para la producción agrícola en todo el mundo, ya que un aumento de la temperatura puede causar una disminución en la extensión de las áreas adecuadas para el cultivo de ciertos cultivos. Utilizando análisis espaciales y datos de escenarios futuros de cambio climático desarrollados por el Panel Intergubernamental sobre Cambio Climático, este estudio tuvo como objetivo evaluar el impacto del cambio climático en las plantaciones de caña de azúcar y cítricos en el estado de São Paulo mediante mapeo de zonificación agroclimática. Los resultados de este estudio demuestran que ambos cultivos pueden sufrir importantes reducciones en las superficies aptas para el cultivo si se producen cambios severos en el régimen climático. Estos hallazgos pueden ayudar a los administradores e investigadores a mitigar estos impactos potenciales y aclarar cómo el cambio climático afecta la vida en el planeta, con una reducción potencial en la producción de alimentos y bioenergía.

Palabras-clave: Zonificación agroclimática, Cambio climático, Caña de azúcar, Cítricos, Bioenergía.

ARTICLE

INTRODUCTION

Climate change has been the subject of research in several areas, given its unprecedented potential impact on the planet (NATIONS, 2019). Changes in the climate can cause various problems, such as biodiversity loss, population migrations, and reduction in the quality and quantity of food for people (WHITMEE et al., 2015). Analyzing future scenarios can be useful for planning activities and decision-making, both to reduce the impacts on the planet caused by human actions and increase our resilience to possible changes.

Several studies have been conducted to analyze future scenarios, such as those of the Intergovernmental Panel on Climate Change (IPCC), which collaborates with researchers worldwide. Many of these studies have predicted future scenarios that can serve as the basis for assessing the impacts of climate change on the planet (RIBEIRO et al., 2024; CASSAMO et al., 2023; TAYYEBI et al., 2023).

In addition to analyzing future scenarios, these studies were used to evaluate current actions and their impacts on the planet, such as pollutant emissions (ALAHMAD et al., 2023). This type of assessment is useful for creating or improving public policies including reducing pollutant emissions, developing and implementing "clean" energy alternatives such as bioenergy, and combating deforestation.

In agriculture, climate change can have many impacts, whether due to disasters such as floods, gales, frosts, or sudden temperature changes, with the potential to destroy or reduce productivity. For example, a change in the average temperature may result in several areas being unsuitable for multiple crops (FAROOQ et al., 2023).

With a decrease in planting areas, food production across the planet may be affected, causing hunger and disease in the most vulnerable populations (NGCAMU, 2023). In addition to socioeconomic problems, the impact of climate change on food production can lead to public health problems. Another issue is the production of bioenergy, which can be greatly affected.

This study aimed to analyze the impact of climate change on two most important crops produced in the state of São Paulo, Brazil: sugarcane and citrus. For this, agroclimatic zoning mapping was used, which considers the climatic conditions favorable for the cultivation of these crops. A comparison between the agroclimatic maps prepared for the current conditions and three possible climate change scenarios is demonstrated. This study is expected to contribute to research by showing, through agroclimatic zoning, evidence of how climate change can affect life on the planet, particularly in areas suitable for food and bioenergy production. The hypothesis verified in this study was that climate change may cause a reduction in suitable areas for sugarcane and citrus cultivation.

Suitable areas for citrus and sugarcane cultivation are defined by factors such as annual water deficit (Da) and average annual temperature (Ta). Agroclimatic zones can be established by spatializing these values.

SUGARCANE CROP

In contrast to other short-cycle crops such as rice and cotton, sugarcane crops can be planted year-round. The difference in the climatic requirements for this crop lies in the desired end products: sugar, sugarcane liquor, and fodder. Climatic conditions are more demanding for sugar production than for other purposes (CIIAGRO, 2019a).

The climatic limitations for sugarcane production are as follows (SÃO PAULO, Secretaria da Agricultura, 1974):

Average Annual Temperature (Ta)	Annual Water Deficit (Da)	Conditions
≥ 21 °C	-	Suitable
< 21 °C and > 19 °C	-	Suitable with low thermal restriction
< 19 °C and > 18 °C	-	Marginal for liquor and forage; Unsuitable for sugar industry; Thermal restriction
< 18 °C	-	Unsuitable for any production type
-	> 140 mm	Marginal; Requires irrigation

Table 1 - Climatic parameters for sugarcane cultivation

CITRUS CROP

Citrus crops are typically tropical and humid crops, and their climatic requirements may vary according to the type and species. The climatic conditions necessary for citrus production are classified as follows (SÃO PAULO, Secretaria da Agricultura, 1974):

Average Annual Temperature (Ta)	Annual Water Deficit (Da)	Conditions
> 17 °C	> 0 and ≤ 60 mm	Suitable
> 17 °C	> 60 mm	Water restrictions
< 17 °C	-	Suitable for robust types only (Sicilian lemon and sour orange)
-	0	Unsuitable or marginal with phytosanitary problems; Difficulties in maturation and harvest
> 20 °C	0	Unsuitable for most citrus; Suitable for others (tangerines, tangerines and ponkan, pomelo and Tahiti lemon)

Table 2 - Climatic parameters for citrus cultivation

RELATED WORK

Given the importance of the environment in agricultural production, studies have been conducted to evaluate future climate change scenarios. For example, in certain scenarios, a decrease in adequate areas to produce corn and coffee was identified in the state of São Paulo (ZULLO JUNIOR et al., 2006). In another study conducted on bean cultivation in the southern states of Brazil, future scenarios of climate change indicated a possible reduction in suitable areas for cultivation (MASSIGNAM et al., 2017). For sugarcane production in the state of São Paulo, one study found no productivity loss under different climate change scenarios (PINTO et al., 2018).

A study on the effects of climate change in the city of Piracicaba reported that soybean production could increase or decrease, based on the conditions used in the simulation (increased temperature and carbon dioxide) (SILVA et al., 2018).

Based on these studies and the IPCC scenarios, an analysis was conducted on the consequences of citrus and sugarcane cultivation.

MATERIALS AND METHODS

STUDY AREA

São Paulo (Figure 1) is the most populous state in Brazil, with 45.5 million inhabitants, and located in the southeast of the country (IBGE, 2019). According to the Brazilian Ministry of Agriculture, the value of agricultural production in the state of São Paulo represented approximately 12 % of the country's production in 2023 (approximately 1,142 trillion Brazilian reais) (BRASIL, 2023).

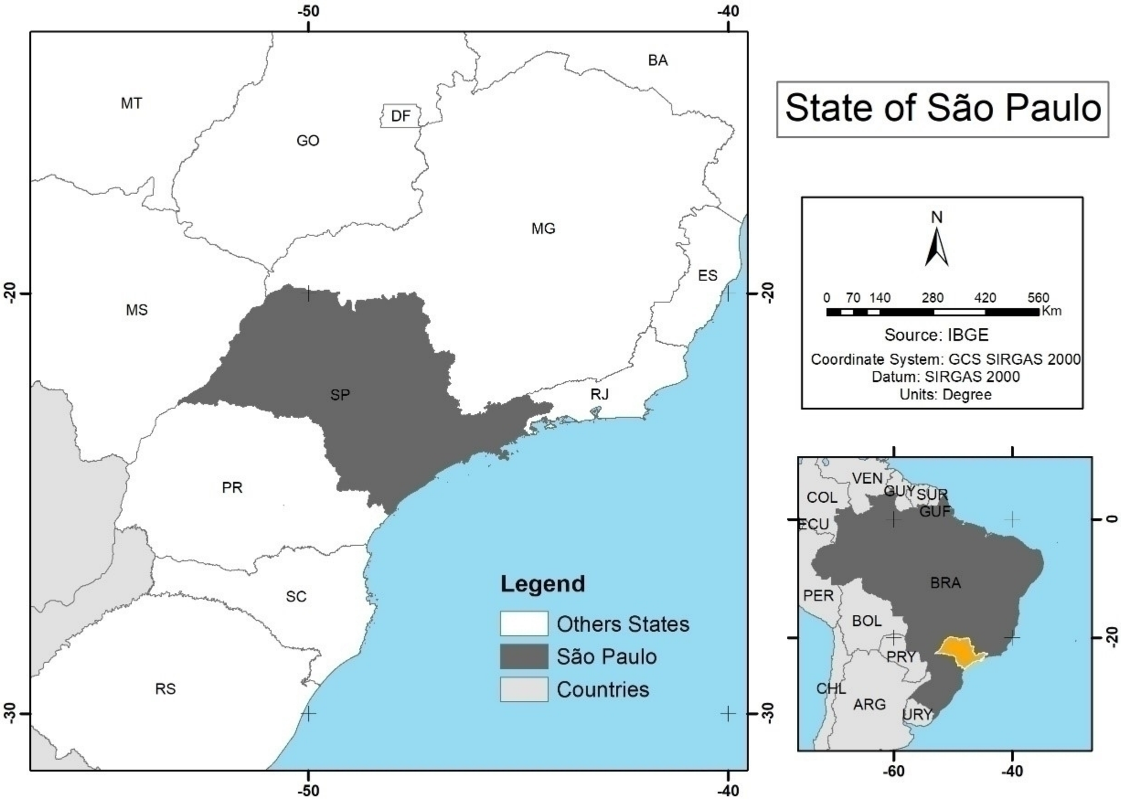

Figure 1 - São Paulo State - Brazil

Concerning the sugarcane production, the value produced in the state of São Paulo represents approximately 54 % of the total production in Brazil (713.2 million tons), whereas, for the orange crops, production in this state represents approximately 77 % of the total production in the country (16,929,631 tons) (CONAB, 2024; IBGE, 2022). The State is part of the citrus belt, which is one of the world's largest producers of orange juice.

METHODS

Based on Köppen studies (ABREU, 1983), who analyzed and classified climate types, significant advances were made in the systematization of climatic information, along with a considerable increase in the production of knowledge. Penck contributed by delineating morphoclimatic zones, establishing the relationship between climatic zones and terrain morphology (ROSS et al., 2022). With the advancement of techniques such as the use of aerial photography, concepts like land system and land units emerged, enabling a more detailed analysis of the interaction between climate and landscape (ZONNEVELD, 1989). This growing understanding of the relationship between climate and landform made agroclimatic zoning a crucial tool for optimizing agricultural production by applying climatic knowledge.

In the context of agroclimatic zoning, the state of São Paulo has different climatic characteristics, making the spatialization of this information essential for analyzing the impacts of climate change. Understanding how different regions of the state are affected requires precise climate data and spatial techniques to model these variations accurately.

For this study, the meteorological time series of 267 cities in the State of São Paulo were obtained from the Brazilian climatic database (EMBRAPA, 2019), including the data of the "average annual and monthly temperature in degree Celsius" and "annual and monthly precipitation volume in millimeters."

From this dataset, a macro was prepared using Microsoft Excel to calculate the water balance and obtain the annual water deficit for each municipality. After the calculations were performed, the data were spatialized into a point-shaped shapefile. Each point was located in the central area of the respective municipality. From this shapefile, the data were spatialized for the entire state using the kriging method with GIS tool.

São Paulo shows high climatic variability, with marked differences in temperature and precipitation across its regions. Figure 2 illustrates the temperature and precipitation characteristics in this state.

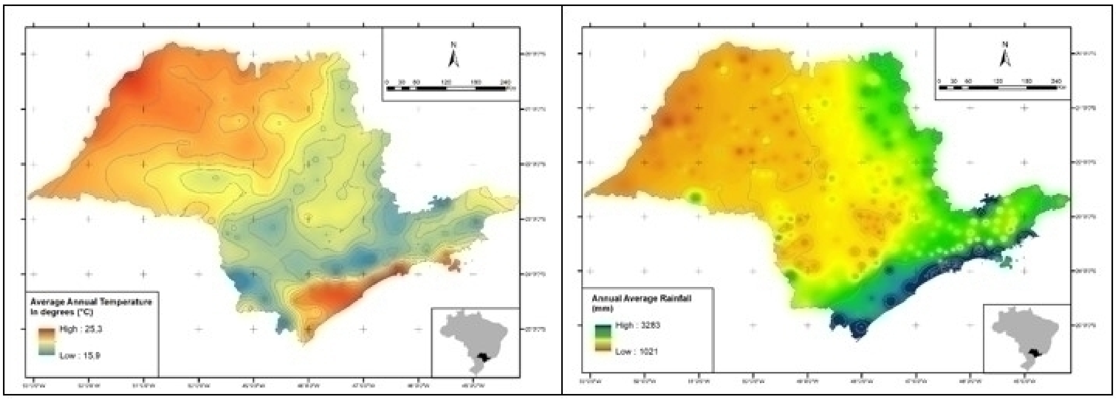

Figure 2 - Average annual temperature and precipitation for the state of São Paulo. Source: Authors, based on data from EMBRAPA (2019)

Table 3 presents four climate scenarios. "Normal" scenario is the period that considers the average of the historical series. "IPCC1" scenario involves an increase of 1 ºC in temperature and 15 % in rainfall. "IPCC2" scenario involves an increase of 3 ºC in temperature and 15 % in rainfall. "IPCC3" scenario involves an increase of 5.8 ºC and 15 % in rainfall.

Eight maps were created to present the agroclimatic zoning for the two crops (sugarcane and citrus), considering each of the four scenarios described.

The future scenarios described in Table 3 (IPCC1, IPCC2, and IPCC3) are the same as those used in the study by ZULLO JUNIOR et al. (2006), in which the impacts of climate change on corn and coffee productions were analyzed.

Scenario	Description
Normal	Current conditions obtained from the historical series of meteorological data
IPCC1	Increase of 1 ºC in Ta and 15 % in annual precipitation volume
IPCC2	Increase of 3 ºC in Ta and 15 % in annual precipitation volume
IPCC3	Increase of 5.8 ºC in Ta and 15 % in annual precipitation volume

Table 3 - Scenarios to evaluate suitability for citrus and sugarcane crops

With the climate scenarios established, defining the agroclimatic zones is also necessary. These were defined based on parameters from the Integrated Center for Agrometeorological Information for both sugarcane (CIIAGRO, 2019a) and citrus (CIIAGRO, 2019b). Five agroclimatic zones were created for citrus (Table 4) and six for sugarcane (Table 5) cultivations.

Classification	Description
Zone 1	Suitable
Zone 2	Suitable with water restrictions
Zone 3	Suitable for some robust types
Zone 4	Unsuitable or marginal fitness with phytosanitary problems
Zone 5	Unsuitable for most citrus types

Table 4 - Suitability classification for citrus crop

Classification	Description
Zone 1	Suitable - optimum for cultivation
Zone 2	Suitable with low thermal restriction
Zone 3	Marginal - seasonal water deficit area; Irrigation required
Zone 4	Marginal - absence of dry period; Difficulties in maturation and harvest
Zone 5	Marginal for brandy and forage; Unsuitable for sugar industry; Thermal Restriction
Zone 6	Unsuitable

Table 5 - Suitability classification for sugarcane crop

Based on the defined climate scenarios and criteria for the agroclimatic zones, it was possible to define the spatialization of these zones in the state of São Paulo. For this, interpolation data of “Ta” and “Da” were used for both the studied crops throughout the State. The intervals of each of the agroclimatic zones were defined in a GIS based on the values of "Ta" and "Da" (Tables 1 and 2), enabling their adequate delimitation.

RESULTS AND DISCUSSIONS

STATISTICAL ANALYSIS

For citriculture (Figure 3), a predominance of Zones 1 and 2 was observed. The other zones occupy 70 % of the territory and, in IPCC3, it covers >95 %.

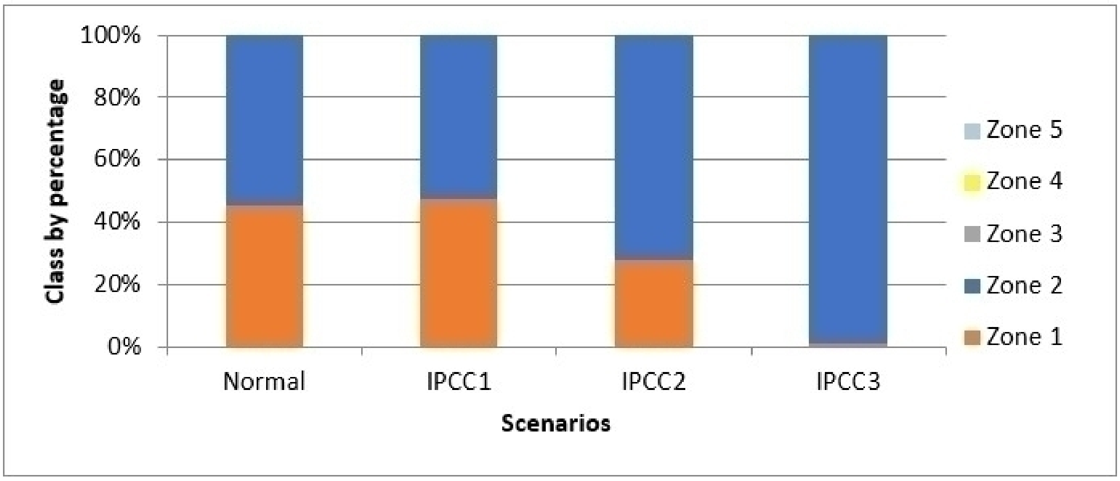

Figure 3 - Distribution of agroclimatic zones for citrus crops under different climate scenarios

For sugarcane cultivation (Figure 4), under current conditions, >50 % of the area stays in Zone 1, approximately 20 % in Zone 2, just over 20 % in Zone 3, and

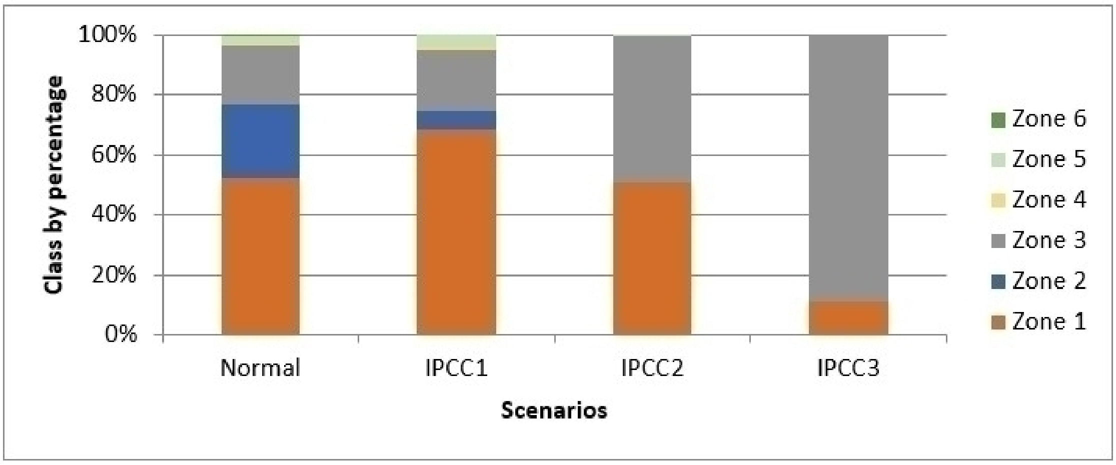

Figure 4 - Distribution of agroclimatic zones for sugarcane crops under different climate scenarios

SPATIAL ANALYSIS

For citriculture, notably, in the current scenario, the state of São Paulo is particularly suitable for cultivation (Figure 5 - A), which explains its significant participation in the total production of the country. Most of its territory is defined as Zone 1 or Zone 2. Both were suitable for citrus; however, Zone 2 presented water restrictions. In the southernmost section, where coastal zone predominated, there were areas defined as Zone 5, owing to the high temperature and humidity conditions, making it suitable for only some types of citrus, and Zone 4, where high humidity predominated, favors the development of phytosanitary problems. A small area, defined as Zone 3, is located in the coldest region of São Paulo, Brazil.

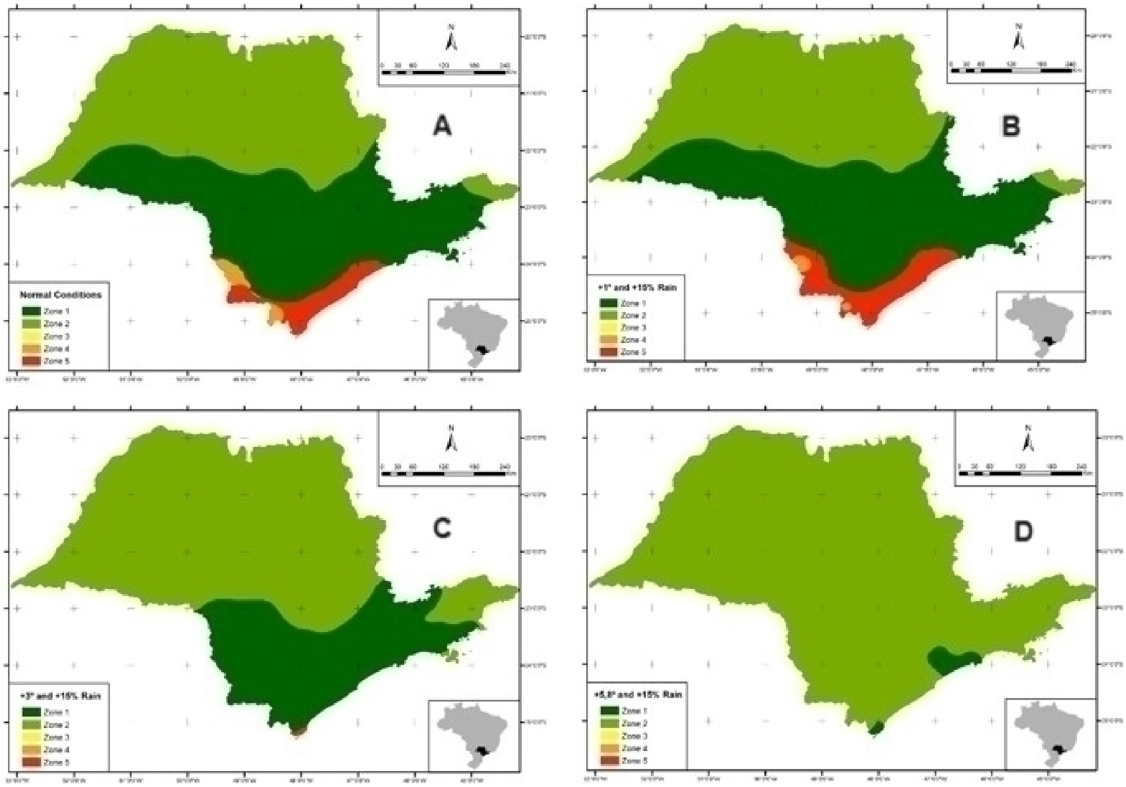

Figure 5 - Suitability analysis for citrus crop in: A - Scenario 1 (normal conditions); B - Scenario 2 (IPCC1); C - Scenario 3 (IPCC2); and D – Scenario 4 (IPCC3).

In the second scenario (IPCC1), where there is an increase of 1 ºC in temperature and 15 % in precipitation (Figure 5 - B), two changes were observed. First is a slight expansion of Zone 1 over Zone 2, and second is the advancement of Zone 5 over Zone 1. This is because of the high humidity and air temperature. Zone 5 advances because of increased water availability caused by increased rainfall. A retraction in Zone 3 is observed, owing to the increase in temperature.

In the third scenario (IPCC2), where there is an increase of 3 ºC in temperature and 15 % in precipitation (Figure 5 - C), Zone 2 expands over Zone 1, which in turn, advances over other Zones, leaving only remnants of Zone 5. This is because of the increased temperature, which resulted in an increased water deficit throughout the state.

In the fourth scenario (IPCC3), where there is an increase of 5.8 ºC in temperature and 15 % in precipitation (Figure 5 - D), Zone 2 consolidates its expansion over Zone 1, and as a result 95 % of the state remains in Zone 2.

A study in China that analyzed the IPCC climate change scenarios indicated an expansion in suitable areas for citrus production. Key climatic factors, particularly temperature and humidity, from July to December are projected to change in ways that enhance citrus yield across most regions, despite some variations in quality. These findings suggest that future climatic conditions will favor increased citrus yields (WANG et al., 2022).

For sugarcane cultivation, notably, in the current scenario (Normal), the state of São Paulo presents a predominance of suitable areas (Figure 6 - A), defined by Zones 1, 2, and 3. Zone 3, located further north of the state and requires irrigation. Zone 4 is concentrated in the south of the state, the most humid area associated with the coast, and is characterized by difficulties in crop maturation. Zone 6 is a small area in the coldest region of the state. Zone 5, in turn, is associated with some areas of Zones 2 and 6.

The second scenario (IPCC1) presented in Figure 6 - B shows an expansion of Zone 1 over Zone 2, significantly reducing the suitable low thermal area, which becomes a suitable unrestricted area consolidating Zone 4. Zone 5 ceased to have a significant presence, and Zone 6 retracted due to the increased temperatures.

The third scenario (IPCC2) presented in Figure 6 - C shows an advancement of Zone 1 over the remnants of Zone 2, and areas of Zones 4 and 6. At the same time, Zone 3 advances over Zone 1, allowing the entire state to cultivate sugarcane, with half of its area in need of irrigation due to water restrictions.

The fourth scenario (IPCC3) presented in Figure 6 - D, shows a consolidation of the expansion of Zone 3 over Zone 1, and >85 % of the state belongs to Zone 3, suitable for sugarcane cultivation but with water restrictions. The remaining area belongs to Zone 1 and is suitable for cultivation.

Although there may be a decrease in the suitable areas for sugarcane cultivation, this does not necessarily imply a loss of productivity. According to PINTO et al. (2018), sugarcane productivity models did not show productivity loss under several climate change scenarios. However, as shown in Figure 6, climate change can increase the demand for sugarcane irrigation in most areas of the state of São Paulo, which can be an economic and environmental problem for the sugarcane cultivation.

A study conducted using data from the Muzaffarnagar district of India analyzed various climatic variables to assess the effects of climate change on sugarcane production area. Each climatic scenario was found to potentially increase the sugarcane production in some areas and decrease it in others (VERMA et al., 2023).

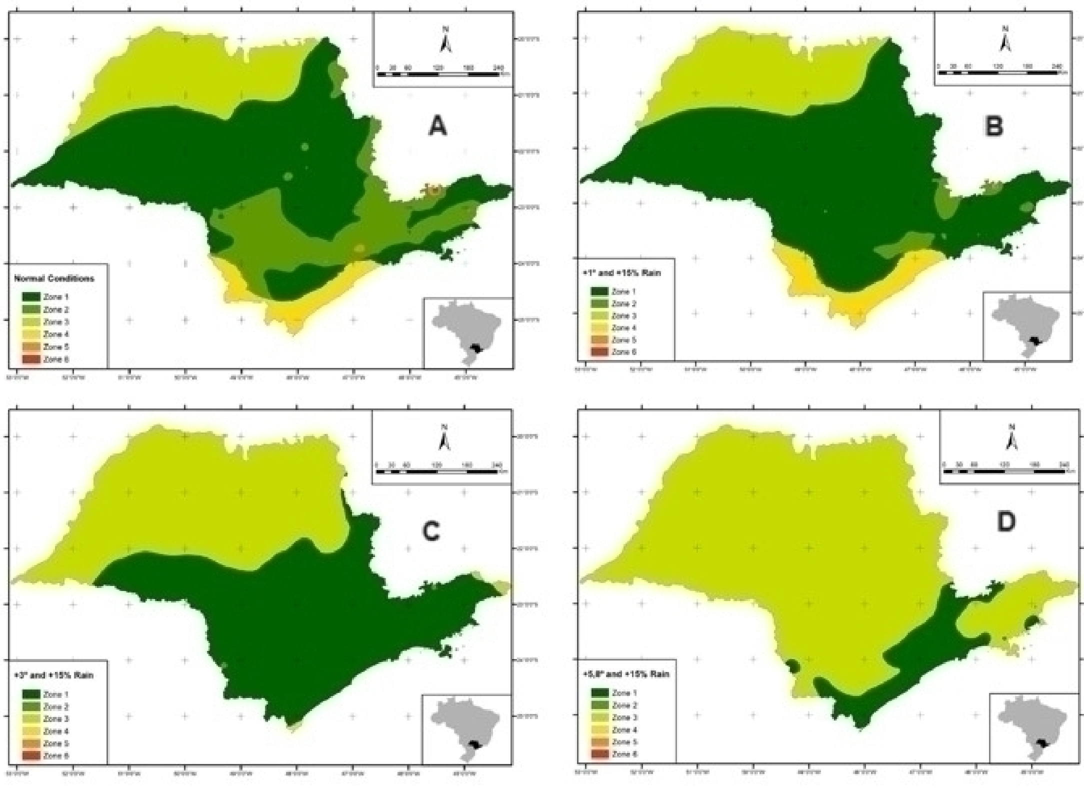

Figure 6 - Suitability analysis for sugarcane crop in: A - Scenario 1 (normal conditions); B - Scenario 2 (IPCC1); C - Scenario 3 (IPCC2); and D – Scenario 4 (IPCC3).

CONCLUSIONS

This study aimed to analyze the potential impacts of climate change on the suitability of sugarcane and citrus crops in different regions of the state of São Paulo. IPCC scenarios were used to classify the entire state of São Paulo based on the climatic data from 267 locations and their suitability

ARTICLE

for both the crops. Through interpolation of the results and spatial analysis, it was concluded that without further research to increase crop resilience to climate change, such as genetic improvement, there will be a reduction in areas naturally suitable for the cultivation of both the crops. This holds true for the three scenarios analyzed. We also observed an expansion of areas suitable for production with irrigation. The enhanced water requirements tend to make the production process expensive because of the increased need for natural resources and technical-productive adaptations. Moreover, highlighting the economic impacts to which the state is susceptible is important, as it is one of the largest producers of orange juice in the world and an important producer of sugarcane and its derivatives such as biofuels.

As a limitation, which may be addressed in future studies, we did not consider genetic modifications in the species or different varieties of species. Other sugarcane and citrus varieties may be more resilient to changes in temperature and precipitation.

The results of this study may be useful for future research by providing information on the impacts of climate change on agricultural production throughout the state of São Paulo. In addition, public policy managers can use these findings for action planning and decision-making to mitigate the future impacts of climate change.

ACKNOWLEDGMENTS

This work was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001; Itaú Unibanco S.A. through the Itaú Scholarship Program, at the Centro de Ciência de Dados (C2D), Universidade de São Paulo, Brazil; and National Council for Scientific and Technological Development (CNPq).

REFERENCES

ABREU, A. A. de., (1982). Análise Geomorfológica: Reflexão e Aplicação Tese (Livre Docência em Geografia), FFLCH – USP, São Paulo.

ALAHMAD, B., KHRAISHAH, H., ALTHALJI, K., BORCHERT, W., AL-MULLA, F., & KOUTRAKIS, P. (2023). Connections between air pollution, climate change, and cardiovascular health. Canadian Journal of Cardiology.

BRASIL. Valor da Produção Agropecuária é atualizado para R$ 1,142 trilhão este ano. https://www.gov.br/agricultura/pt-br/assuntos/noticias/valor-da-producao-agropecuaria-e-atualizado-para-r-1-142-trilhao-este-ano, 2023 (accessed on Jun 30).

CASSAMO, C. T., DRAPER, D., ROMEIRAS, M. M., et al. (2023). Impact of climate changes in the suitable areas for Coffea arabica L. production in Mozambique: Agroforestry as an alternative management system to strengthen crop sustainability. Agriculture, Ecosystems & Environment, 346, 108341.

CIIAGRO. Zoneamento macro - Aptidão ecológica da cultura da cana-de-açúcar.http://www.ciiagro.sp.gov.br/znmt_macro_10.html, 2009a (accessed on Jun 30).

CIIAGRO. Zoneamento macro - Aptidão ecológica da cultura da citrus. http://www.ciiagro.sp.gov.br/znmt_macro_12.html, 2019b (accessed on Jun 30).

CONAB. SAFRA 2023/24 CANA-DE-AÇÚCAR 4º LEVANTAMENTO https://www.conab.gov.br/info-agro/safras/cana, 2024 (accessed on Jun 30).

EMBRAPA. Banco de Dados Climáticos do Brasil. https://www.cnpm.embrapa.br/projetos/bdclima/balanco/index/index_sp.html, 2019 (accessed on Feb)

FAROOQ, A., Farooq, N., Akbar, H., Hassan, Z. U., & Gheewala, S. H. (2023). A critical review of climate change impact at a global scale on cereal crop production. Agronomy, 13(1), 162.

IBGE. IBGE: Brasil em Síntese | São Paulo | Panorama. https://cidades.ibge.gov.br/brasil/sp/panorama, 2019 (accessed on Jul 30).

IBGE. Produção de Laranja. https://www.ibge.gov.br/explica/producao-agropecuaria/laranja/br, 2022 (accessed on Jun 29).

MASSINGHAM, A. M., PANDOLFO, C., SANTI, A., CARAMORI, P. H., & VICARI, M. B. (2017). Impact of climate change on climatic zoning of common bean in the South of Brazil. Embrapa Trigo-Artigo em periódico indexado (ALICE).

NATIONS, U. Climate Change. https://www.un.org/en/sections/issues-depth/climate-change/, 2019 (accessed on Jul 20).

NGCAMU, B. S. (2023). Climate change effects on vulnerable populations in the Global South: a systematic review. Natural Hazards, 118(2), 977–991.

PINTO, H. M. S., SANTOS VIANNA, M., DA COSTA, L. G., & MARIN, F. R. (2018). Produtividade de cana-de-açúcar no Estado de São Paulo baseada em simulações multimodelos e mudanças climáticas. Agrometeoros, 26(1).

RIBEIRO, A. F., MARTINS, F. B., DOS SANTOS, D. F., TORRES, R. R., & FAGUNDES, F. F. A. (2024). Suitable areas for temperate fruit trees in a Brazilian hotspot area: Changes driven by new IPCC scenarios. European Journal of Agronomy, 155, 127110.

ROSS, J. L. S.; SOUSA, A. da S.; SANTOS, J. J. (2022). Relevo, paisagem e a tecnologia da informação. In: Paisagens da Geomorfologia: temas e conceitos no século XXI / organização Antonio Teixeira Guerra, Hugo Soares Alves Loureiro. Rio de Janeiro. Editora: Bertrand do Brasil

SÃO PAULO. Secretaria da Agricultura. Zoneamento agrícola do Estado de São Paulo. Secretaria da Agricultura, 1974.

SILVA, E. H. F. M., ALMEIDA PEREIRA, R. A., GONÇALVES, A. O., BORDIGNON, Á. J. Z., & MARIN, F. R. (2018). Simulação de produtividade futura de soja em Piracicaba-SP com base em projeções de mudanças climáticas. Agrometeoros, 25(1).

TAYYEBI, M., SHARAFATI, A., NAZIF, S., & RAZIEI, T. (2023). Assessment of adaptation scenarios for agriculture water allocation under climate change impact. Stochastic Environmental Research and Risk Assessment, 37(9), 3527–3549.

VERMA, A. K., GARG, P. K., PRASAD, K. H., & DADHWAL, V. K. (2023). Variety-specific sugarcane yield simulations and climate change impacts on sugarcane yield using DSSAT-CSM-CANEGRO model. Agricultural Water Management, 275, 108034.

WANG, S., XIE, W., & YAN, X. (2022). Effects of future climate change on citrus quality and yield in China. Sustainability, 14(15), 9366.

WHITMEE, S., HAINES, A., BEYRER, C., et al. (2015). Safeguarding human health in the Anthropocene epoch: Report of the Rockefeller Foundation-Lancet Commission on planetary health. The Lancet, 386(10007), 1973–2028.

ZONNEVELD, I. S. (1989). The Land Unit – A fundamental Concept in Landscape Ecology, and its Applications. Landscape Ecology, v.2, p. 67-86.

ZULLO JUNIOR, J., PINTO, H. S., & ASSAD, E. D. (2016). Impact assessment study of climate change on agricultural zoning. Meteorological Applications, 13(S1),69–80.

Author's Affiliation

Sousa, A.S. - University of São Paulo, São Paulo (SP), Brazil.
Xavier, F. - University of São Paulo, São Paulo (SP), Brazil.
Galvani, E. - Professor at University of São Paulo, São Paulo (SP), Brazil.

Silva, R.F. - Professor at the University of São Paulo, São Paulo (SP), Brazil.
Mostaço, G.M. - University of São Paulo, São Paulo (SP), Brazil.
Saraiva, A.M. - Professor at the University of São Paulo, São Paulo (SP), Brazil.
Cugnasca, C.E. - Professor at the University of São Paulo, São Paulo (SP), Brazil.
Ross, J.L.S. - Professor at the University of São Paulo, São Paulo (SP), Brazil.

Authors' Contribution

Sousa, A.S. - The author contributed to the elaboration, realization and manipulation of data and writing.
Xavier, F. - The author contributed to the elaboration, realization and manipulation of data and writing.
Galvani, E. - The author contributed to the elaboration, realization and manipulation of data and writing.
Silva, R.F. - The author contributed to the elaboration, realization and manipulation of data and writing.
Mostaço, G.M. - The author contributed to the elaboration, realization and manipulation of data and writing.
Saraiva, A.M. - The author contributed to the elaboration, realization and manipulation of data and writing.
Cugnasca, C.E. - The author contributed to the elaboration, realization and manipulation of data and writing.
Ross, J.L.S. - The author contributed to the elaboration, realization and manipulation of data and writing.

Editors in Charge

Alexandra Maria Oliveira
Alexandre Queiroz Pereira