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Local-scale mapping of future climate scenarios for the Lower São Francisco (SE–AL): implications for climate justice and just transition

Mapeamento em escala local de cenários climáticos futuros para o Baixo São Francisco (SE–AL): implicações para a justiça climática e a transição justa

Cartografía a escala local de los escenarios climáticos futuros para el Bajo São Francisco (SE–AL): implicaciones para la justicia climática y la transición justa

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ABSTRACT: This study presents local-scale (1 km²) climate projections for the Lower São Francisco region, located between the states of Sergipe and Alagoas (Brazil). Projections were derived from the ACCESS-CM2 model using the WorldClim database. The exclusive use of ACCESS-CM2 is justified by its physical consistency for the Brazilian territory. Key climatic variables - minimum temperature (Tmin), maximum temperature (Tmax), and precipitation (Prec) - were mapped for four SSPs scenarios up to 2100. The methodology was based on automated workflows developed with the support of generative artificial intelligence and collaborative platforms, which were used to build Python scripts executed in PyQGIS. FAIR and open science principles were adopted with all data deposited on public Zenodo repositories. Results indicate a strong warming trend, with Tmax increases up to 6°C and Tmin up to 5°C, accompanied by reductions in annual precipitation exceeding 250 mm. The rainy season may be shortened from five to three months. These changes pose severe risks to water availability, agricultural productivity, and farmers' livelihoods, potentially leading to food, nutritional and water insecurity in this socioeconomically and climate vulnerable region. There is urgent need to adopt resilient and adapted strategies. Climate-smart public policies and agricultural systems must be developed, implemented and piloted. As this is a socioeconomically and climatically vulnerable region, this study serves as support for the IPCC climate justice and just transition frameworks.

Keywords: ACCESS-CM2, climate emergency, semi-arid regions, water security, family farming adaptation, food and nutritional insecurity.

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1 INTRODUCTION

Global climate change (GCC) poses an unprecedented challenge to ecosystems and human societies, particularly in the Semi-arid of Northeast Brazil (NEB). Projections from IPCC/CMIP6 and IPCC/CMIP5 models indicate rising temperatures and reduced precipitation in the NEB, with the possibility of desertification in part of the area. (Brasil, 2016; IPCC, 2023). Thus, these changes are expected to intensify drought events, increasing the risks to water security, agricultural productivity, and food systems (Freitas *et al*., 2021; Marengo *et al*., 2021).

In Brazil, climate variability has increased drought risk and reduced water availability in the São Francisco River Basin (SFRB) (Almeida *et al*., 2020; Moraes *et al*., 2022; ANA, 2024). Projections indicate temperature rises of 2–2.5°C by 2050 and rainfall reductions up to 20%, with water availability in the basin's northeast possibly falling by 40% by 2040 (Silveira *et al*., 2016; ANA, 2024). Deforestation further aggravates warming and disrupts the hydrological cycle (Gomes *et al*., 2022). Nóbrega *et al*. (2022), when evaluating the application of CMIP6 models to determine an Aridity Index for the extended São Francisco River basin, found that these models performed satisfactorily compared to regional models such as CORDEX (Coordinated Regional Climate Downscaling Experiment), whose use is already well established in Brazil. The limitation in that case was the lower spatial resolution for CMIP6 models, a fact that is not present in our study because we used a downscaled database at local level. The data they found indicated a clear trend toward increased aridity, further restricting the already low regional water availability.

The LSF/SE-AL is particularly vulnerable due to the prevalence of family farming and its dependence on irrigation water (Silva *et al*., 2021; Nóbrega, 2022; Pontes *et al*., 2023). The predominant agricultural systems are linked to smallholder production, with most farmers being socioeconomically vulnerable (Silva *et al*., 2022) and engaged in activities such as sugarcane, cassava, corn, irrigated rice, dwarf and giant coconut, aquaculture (marine shrimp and Nile tilapia), and vegetables like okra, coriander, onion, and sweet pepper (IBGE, 2025). Water scarcity and climate change threaten production stability, especially during droughts (Castro, 2022). Therefore, rational water use and the adoption of climate-resilient strategies are essential to sustain agricultural livelihoods. These characteristics closely align this study with the concepts of climate justice and just transition, as defined by the Intergovernmental Panel on Climate Change (IPCC, 2023). These frameworks emphasize equity, social justice, and the inclusion of communities that are least responsible for greenhouse gas emissions yet most vulnerable to the impacts of GCC.

Despite this, climate scenarios for the Lower São Francisco region between the states of Sergipe and Alagoas are not being developed, especially with CMIP6 models and high spatial resolution (at the local level). The development of future climate scenarios with advanced tools – such as high-resolution open data, AI, and GIS – is strategic for increasing the rapid development and adoption of strategies to plan and execute resilient, adapted, and sustainable agricultural practices (Fick & Hijmans, 2017; Reichstein *et al*., 2019; Bommasani *et al*., 2021). Generative AI and prompt engineering have enhanced geospatial data analysis and climate modeling (Liu *et al*., 2023; Zhang *et al*., 2024), while open science and Findable, Accessible, Interoperable, and Reusable (FAIR) principles ensure transparency and reusability (Wilkinson *et al*., 2016; Taddeo *et al*., 2021).

In general, state-of-the-art CMIP6 models show difficulties in simulating climate variability over Northeastern Brazil (Firpo *et al*., 2022). Although HadGEM3 has been identified as the model with the best performance for precipitation for integrated Brazilian regions, its unavailability for the SSP3-7.0 scenario in WorldClim v.2.1, database used in this study, restricted its use. In this context, the ACCESS family emerges as a robust alternative. Firpo *et al*. (2022) identified ACCESS-ESM1-5 as the second-best model for reproducing monthly precipitation, most important climate variable for the study area. ACCESS-ESM1-5 is closely related to ACCESS-CM2, which is available in the database used and shares the same modeling lineage and physical consistency (Bi *et al*., 2020; Ziehn *et al*., 2020). Recent evaluations have highlighted the suitability of ACCESS models for long-term climate projections, demonstrating stable pre-industrial control runs and consistent performance across emission scenarios (Law *et al*., 2017; Schroeter *et al*., 2024). Moreover, ACCESS-CM2 is available for all SSP scenarios in high spatial resolution (1 km^2 – at local level) in WorldClim v.2.1 which is critical for supporting local-level agricultural and water management assessments. For these reasons, ACCESS-CM2 was adopted in this study as model for developing fine-scale climate projections in the LSF.

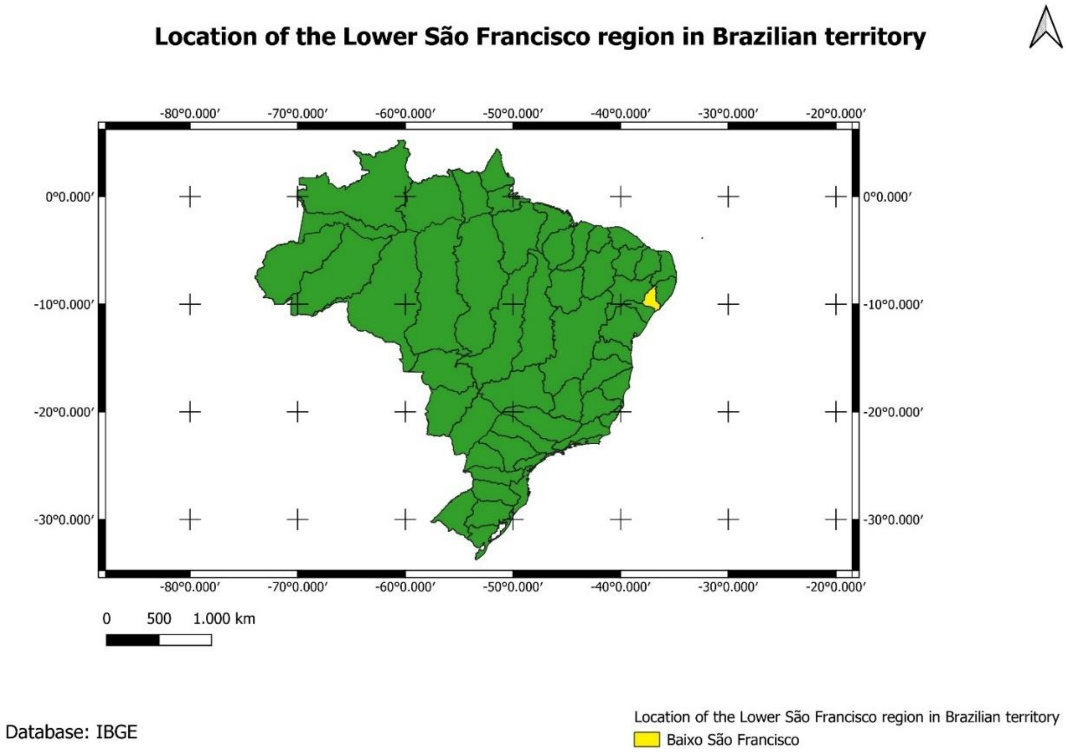
Therefore, this study aimed to develop future climate scenarios for the LSF/SE-AL using Open Science and digital technologies with a focus on supporting climate resilience and adaptation, as well as sustainability, aiming to promote a climate-smart and sustainable agriculture in a socio-economic vulnerable are of Brazil, to provide subsidies for climate justice and a just transition

2 MATERIALS AND METHODS

2.1 Study Area

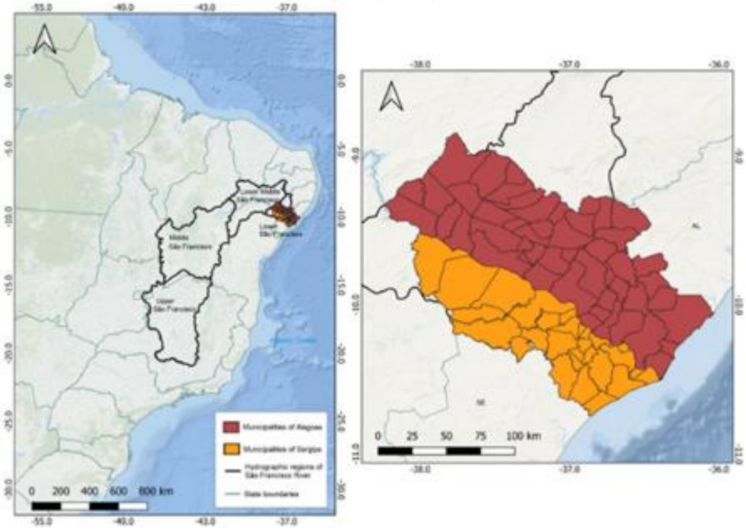
This study was conducted for the LSF region (Figure 1), covering part of the states of Sergipe (SE) and Alagoas (AL) – and represented herein by LSF/SE-AL – which belongs to the Lower São Francisco River Sub-basin (LSFRS), Brazil, and includes several municipalities with regional representation in both irrigated and rainfed agriculture (Figure 2).

Figure 1. Location of the Lower São Francisco (LSF) region in the Northeast of Brazil.



Source: The authors.

Figure 2. Detailed geographical location of the study area – Part of the Lower São Francisco region (LSF), which covers areas of the states of Sergipe (SE) and Alagoas (AL) and is referred herein as LSF/SE-AL, in Northeast Brazil (NEB).



Source: The authors.

The study area has a climate that varies from semi-arid, in the Sertão, to tropical humid, in the Zona da Mata and Coastal Zone (Medeiros *et al*., 2014; Marengo *et al*., 2021) – with high water dependency, mainly in the Semi-arid and in the Agreste regions. In this study, the time frame covered a historical period (1970–2000) and 20-years projections until 2100 (Present–2040, 2041–2060, 2061–2080 and 2081–2100). Climate modeling used Shared Socioeconomic Pathways (SSPs) (IPCC, 2021; IPCC, 2023). It was used SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

2.2 Data, Database and Climate Model

Three main climate variables were analyzed: minimum temperature (Tmin), maximum temperature (Tmax), and precipitation (Prec). It is mapped using the ACCESS-CM2 climate model, part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) consortium validated for applications in Brazil (Almeida *et al*., 2022) and presents satisfactory performance for mapping precipitation in Brazilian territory. The choice of ACCESS-CM2 was justified in introduction section of this paper. The data, in multiband raster format (Geotiff), was obtained from the WorldClim v2.1 platform (Fick & Hijmans, 2017), with a spatial resolution of 1 km^2.

2.3 Geoprocessing Processes

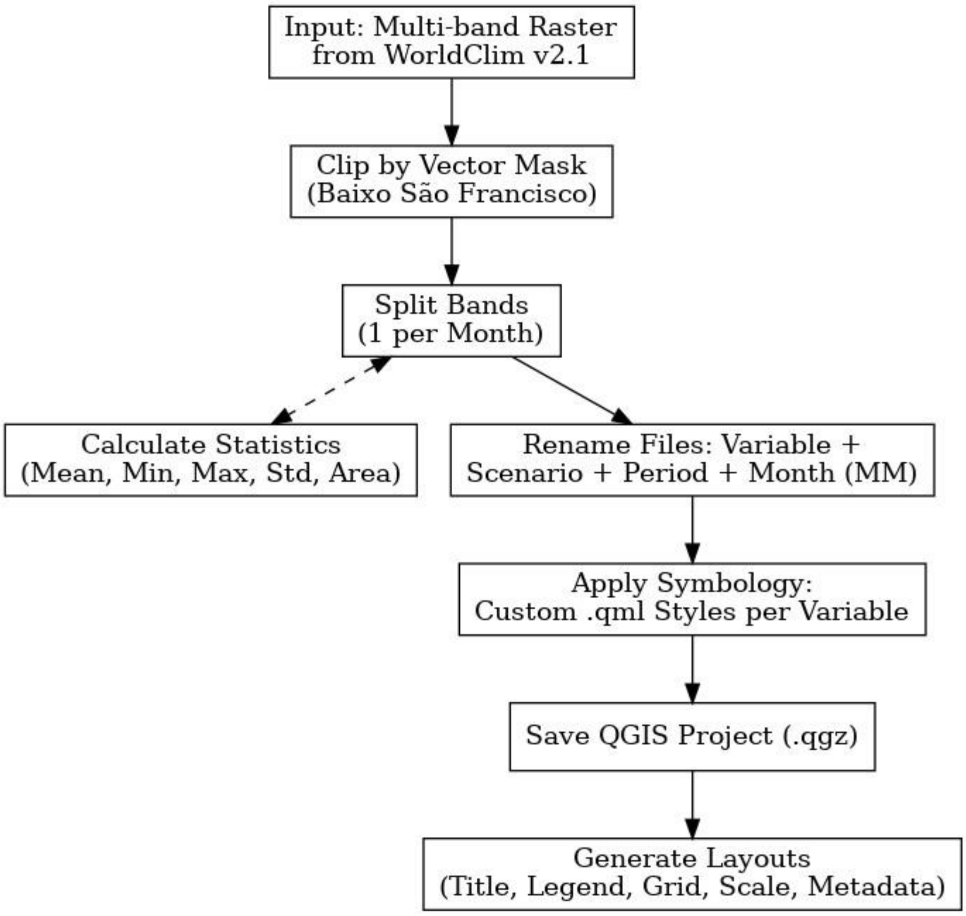
Geospatial data were processed in the QGIS 3.42.3. The scripts were run using PyQGIS. First the scripts were elaborated with the support of ChatGPT and then refined using GitHub Copilot, Google Colab and Visual Studio Code as listed below.

2.4 AI use for Geoprocessing Processes and Data Analysis

For geoprocessing processes an automation process using Python language was used. The development of Python scripts was conducted with support of generative AI (ChatGPT and GitHub Copilot), collaborative platforms such as Google Colab and programming software (Visual Studio Code). Full automation processes by Prompt Engineering can be found in Lima *et al*. (2025a). A complete automation processing was developed for each IPCC scenario and period. Scripts were developed for executing the following processes: split raster images by mask; band separation; batch renomination; batch symbology attribution; save .qgz files; batch statistical analysis with exportation as .txt files; and dynamics layouts production with exportation as PNG files; basic statistical calculation. Figure 3 shows the workflow of this process. All processes, except the split raster images and band separation, were performed in batches of 12 QGIS layers. All scripts are available on three Zenodo repositories (Lima *et al*., 2025b; Lima *et al*., 2025c; Lima *et al*., 2025d).

AI (Data Analyst – OpenAI) was also used as support to data analysis, generation of figures, graphics and tables, and to improve these visual elements. The translation from Portuguese to English also involved the use of AI tools.

Figure 3. Workflow of the automated geoprocessing used for study data determination.



Source: The authors.

3 RESULTS AND DISCUSSION

As a result of this study, around 300 Python scripts were generated to automate the geospatial processing. The scripts were used to produce 720 climate scenario maps for the LSF/SE-Al. Due to the large volume of data generated, these are not included in this article, except for a few examples. Also, to disseminate Open Science, all the results mentioned have been deposited on the Zenodo platform, with a specific DOI (Lima *et al*., 2025a-g). The cartographic assets were also deposited in Embrapa's Spatial Data Infrastructure (Geoinfo). All scripts have been licensed under the BSD-3 Clauses, while the other materials have been registered under the Creative Commons 4.0 International license revised. This is in line with the FAIR principles (Wilkinson *et al*., 2016). It is important to emphasize that digital tools were used in this study as a methodological strategy and that, in due course, they will form the basis of a new paper on the subject.

The automation of climate scenarios in GIS environments significantly reduces processing time and increases productivity. It also reduces human error occurrence and increases the scalability and accuracy of data processing. (Esri, 2023) to enhance the resilience and sustainability of agricultural systems, as well as helping to establish public policies such as the National Policy on Climate Change (Law 12.187/2009), the National Adaptation Plan (Brazil, 2016), the National Water Resources Policy (Brazilian Law 9.433/1997), the National Irrigation Policy (Brazilian Law 12.787/2013) and the ABC+ Plan (Brazil, 2021). In addition, this work is aligned with the UN's 2030 agenda, contributing to Sustainable Development Goals (SDGs) 2 (Zero hunger), 6 (Clean water and sanitation) and 13 (Climate Action).

Regarding the modeling, although the exclusive use of the ACCESS-CM2 model limits the diversity of projections, the decision to use it was based on the availability of data in local spatial resolution (1 km^2) in WorlClim v.2.1 (Fick & Hijmans, 2017), necessary to make a detailed analyses to the study area, and the results found by Firpo *et al*. (2022) demonstrated the excellent performance of an ACCESS family model for estimating precipitation projections for Brazil. This variable is the main one for this study as it is a mostly semi-arid region. It is also important to emphasize that the WorldClim platform already features bias correction (Fick & Hijmans, 2017), which facilitates and accelerates the process of mapping future climate scenarios.

The ACCESS-CM2 shares the same atmospheric and oceanic core as the ACCESS - ESM1-5, used by Firpo *et al*. (2022) to evaluate the performance of CMIP6 models for Brazil. ACCESS-ESM1-5 and ACCESS-CM2 differ mainly in the inclusion of carbon cycle components and minor parameterization adjustments (Bi *et al*., 2020; Ziehn *et al*., 2020). Nóbrega *et al*. (2022) showed that both CMIP6 and CORDEX frameworks satisfactorily reproduced the Aridity Index in the extended São Francisco Basin. Despite ACCESS-CM2 presents intermediated performance in this last study, it remains a scientifically sound choice for local-scale studies because it integrates updated atmospheric and land components and has demonstrated physical consistency when compared to observations (Bi *et al*., 2020). Furthermore, the use of ACCESS-CM2 is justified, beyond it one of the most performance for Brazilian territory (Firpo *et al*., 2022), because it is the only member of the ACCESS family currently available in the WorldClim v.2.1 database at 1 km^2 spatial resolution, enabling detailed and more effective analyses of water resources and agricultural activities required for local assessments in the LSF/SE-AL (Soares-Filho *et al*., 2013; Fick & Hijmans, 2017),

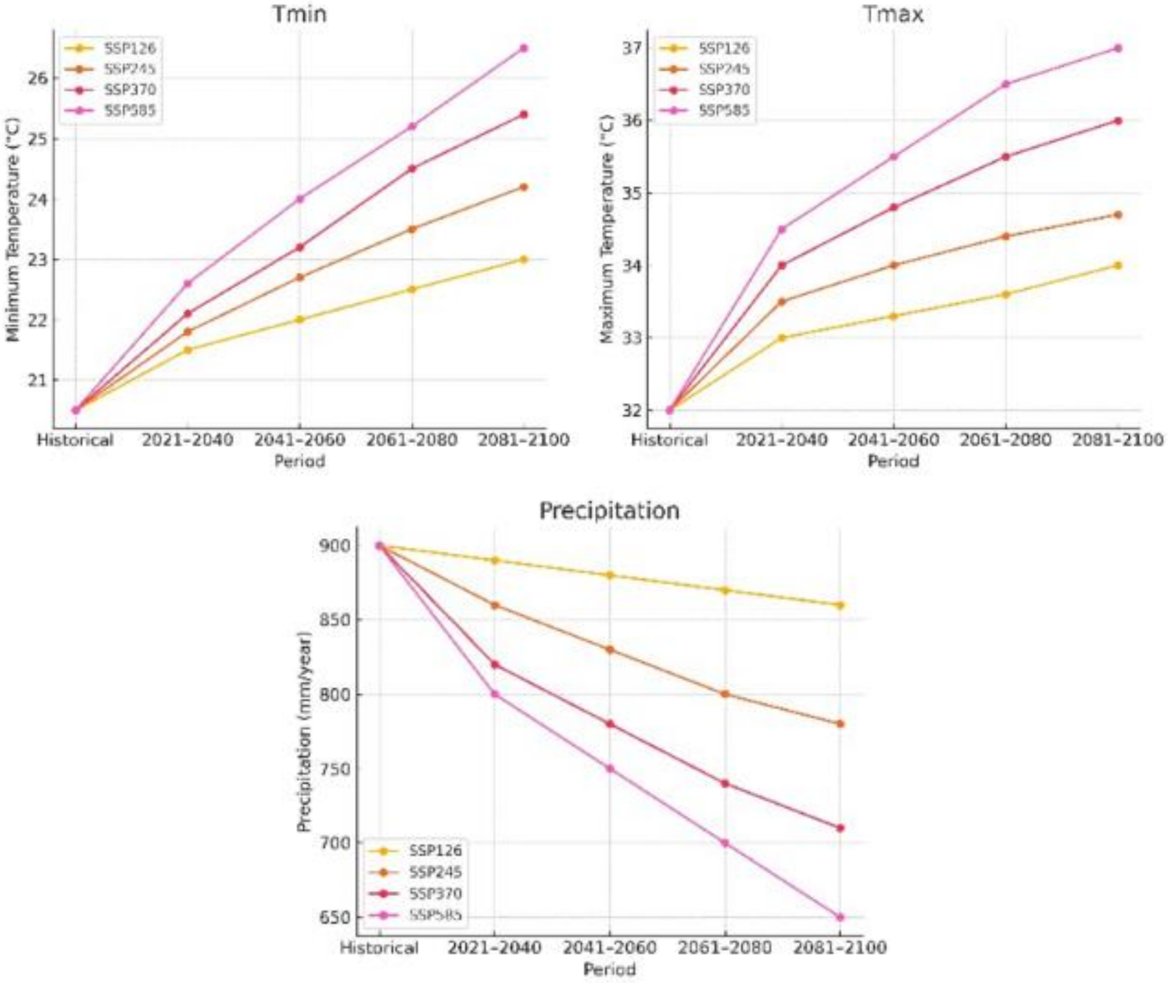
Analysis of future climate projections for the LSF/SE-AL area indicates warmth and decrease of precipitation (Prec), in all IPCC scenarios (Figure 4), over the 21st. century, using 20-years averages. However, the intensity is higher for pessimistic scenarios (SSP3 7.0 and SSP5 8.5). Minimum and maximum temperatures are expected to increase with the highest intensity in SSP5 8.5. In this scenario, the minimum temperature (Tmin) is expected to rise from 20.5°C (historical average, 1970–2000) to around 27.5°C. The maximum temperature (Tmax), in this same scenario, could exceed 37°C. Other studies have recorded similar behavior for the semi-arid and inland regions (Salman *et al*., 2022; Almeida *et al*., 2022; Marengo *et al*., 2021).

The increase in minimum temperature (Tmin) is expected to affect night-time evapotranspiration, increasing crop water demand. Furthermore, this scenario may compromise the nocturnal physiological recovery of plants, affecting production systems for crops such as sugarcane, vegetables, and fruit trees (Silva *et al*., 2023). These results are in accordance with other studies that have found similar behavior in vulnerable areas, imposing challenges for the ecological biodiversity and agriculture activities, as well as reinforcing results from models adjusted for Brazil and NEB (Marengo *et al*., 2021; Almeida *et al*., 2022). In addition, the rise in Tmin interferes in agricultural climate stability, worsening the already restricted water balance in the sub-basin (Castro, 2022; ANA, 2024).

The spatial distribution of Tmin, as exemplified in Figure 5, shows an increase in heterogeneity until 2041–2060. Subsequently, in the period 2061–2100, there is a clear trend towards homogenization of the area, with higher Tmin prevailing. Areas close to the São Francisco River show higher temperatures compared to the distant ones. This corroborates with other studies (Thompson *et al*., 2021; Michel *et al*., 2022; Guo *et al*., 2023; Gzinska & Sojka, 2023; Zhi *et al*., 2023; Johnson *et al*., 2024; White *et al*., 2025) whose findings indicate more pronounced warming in rivers and adjacent areas due to GCC. According to those authors, the primary mechanisms driving this warming include reduced water levels and surface area; urbanization; deforestation; increased direct solar radiation and decreased groundwater recharge, which naturally cools rivers; changes in land use and land cover; other microclimatic effects; and the overarching impacts of GCC.

Maximum temperature (Tmax) projections follow a similar pattern to those observed for minimum temperatures, with increases in all SSP scenarios by the end of the century, but with varying intensities. Similarly to Tmin, and as expected, the highest values were observed for the pessimistic scenarios (IPCC, 2021). Strong mitigation scenarios, such as SSP1 2.6, can significantly reduce projected warming levels. The warming in the pessimistic scenarios is expected to intensify from 2041-2060. Similar trends for semi-arid and arid zones of the world and of the NEB were also found by Silveira *et al*. (2016), Marengo *et al*. (2021), and Salman *et al*. (2022).

Figure 4. 20-years averages of minimum temperature (Tmin), maximum temperature (Tmax), and rainfall (Prec), respectively, for the Lower São Francisco region over 21st. century in all SSPs scenarios.

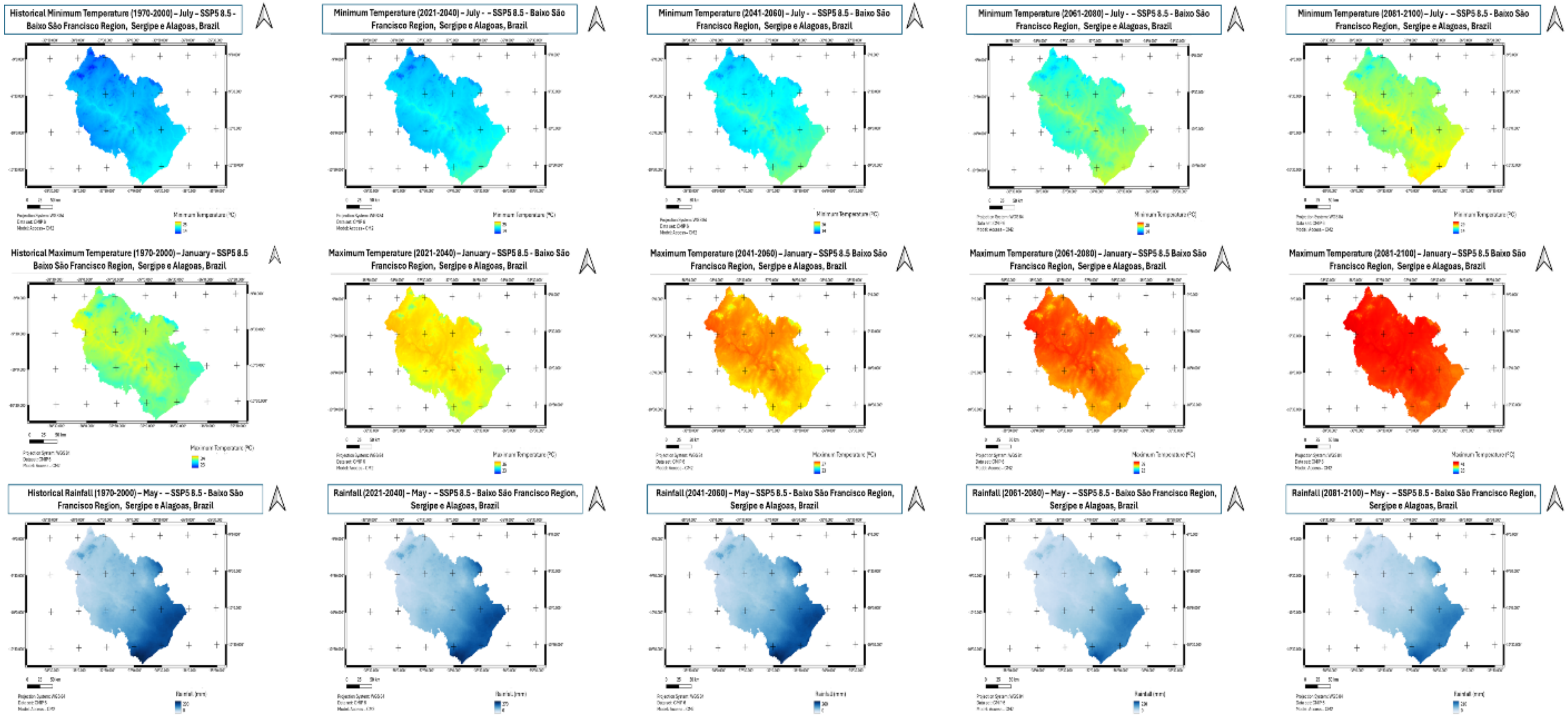


Source: The authors.

The maximum temperature (Tmax) is related to the occurrence of heat waves, a phenomenon that has become more intense and frequent because of GCC. (Perkins-Kirkpatrick & Lewis, 2020; Russo *et al*., 2019). Recent research by Perkins-Kirkpatrick & Lewis (2020) and Oliveira *et al*. (2021a) indicates that an increase in daily Tmax leads to a higher probability of extreme events such as heat waves, with significant impacts on agriculture, public health, and water resources. It is also estimated that heat stress caused by heat waves can cause yield losses of up to 60%, affecting the physiology of cultivated plants, causing damage to growth, photosynthesis, reproductive development, seed, and fruit formation (Liu *et al*., 2019; Paul & Nandha, 2023; Huang *et al*., 2024), and leading to food and nutritional insecurity (Zhao *et al*., 2021; Kroeger, 2023; Singh *et al*., 2023).

The precipitation (Prec) behavior shows a downward trend over the century in all SSPs. In the pessimistic scenario, this decline could reach 250 mm. The spatial distribution of Prec shows uniformity during the dry season and heterogeneity in the wet season. The coastal region and Zona da Mata should concentrate Prec, possibly through extreme rainfall events. The Agreste and semi-arid regions should continue to be the driest regions, but with an intensification of this phenomenon, in accordance with information from other studies (Silveira *et al*., 2016; Marengo *et al*., 2021; Nóbrega *et al*., 2022). These characteristics may lead to threats to water and food security (Silva *et al*., 2023; Pontes *et al*., 2023).

Figure 5. Maps examples of monthly projected climate drawn up in this study for minimum temperature (Tmin), maximum temperature (Tmax), and precipitation (Prec), respectively. The maps scenarios exemplify an analysis of temporal evolution in the SSP5 8.5 scenario.



Historical Minimum Temperature (1970-2000) – July – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Minimum Temperature (2021-2040) – July - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Minimum Temperature (2041-2060) – July - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Minimum Temperature (2061-2080) – July - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Minimum Temperature (2081-2100) – July - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Historical Maximum Temperature (1970-2000) – January – SSP5 8.5 Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Maximum Temperature (2021-2040) – January – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Maximum Temperature (2041-2060) – January – SSP5 8.5 Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Maximum Temperature (2061-2080) – January – SSP5 8.5 Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Maximum Temperature (2081-2100) – January – SSP5 8.5 Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Historical Rainfall (1970-2000) – May - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Rainfall (2021-2040) – May - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Rainfall (2041-2060) – May – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Rainfall (2061-2080) – May - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

Rainfall (2081-2100) – May - – SSP5 8.5 - Baixo São Francisco Region, Sergipe e Alagoas, Brazil

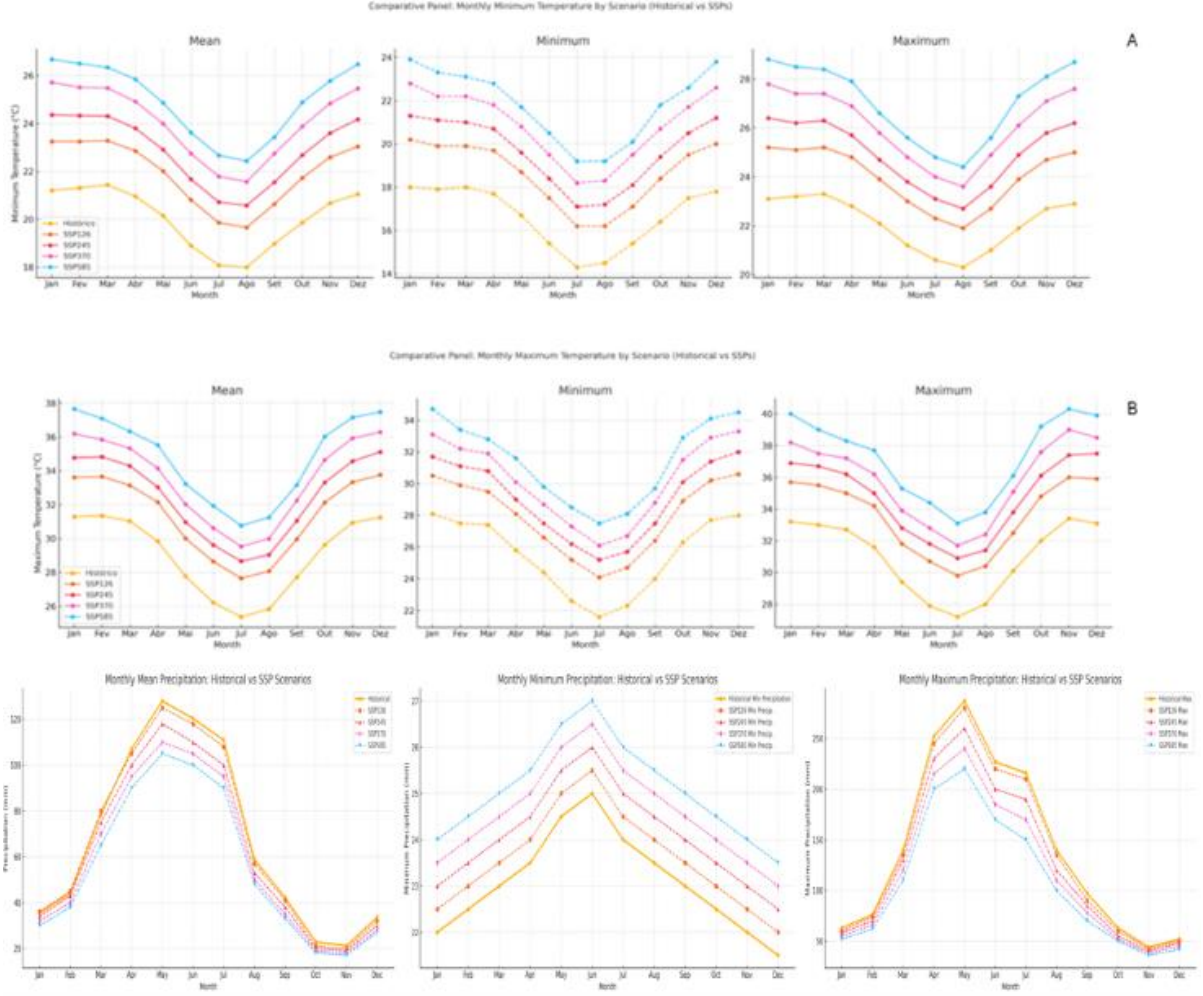
Source: The authors.

The statistics for the monthly analysis of the three variables, comparing the projected averages for (2081–2100) with those observed historically, were also determined using a specific Python script capable of extracting the data recorded in the raster images. Graphs were also constructed comparing the monthly behavior for the average, minimum and maximum values determined for each variable, for the same period, for all months and the SSP scenarios (Figure 6). In general, the temperature increase was greater for Tmax than for Tmin, with anomalies reaching values above 6ºC between November and January in the SSP5 8.5 scenario. For all other months, Tmax reaches values above 5ºC.

Nevertheless, the projected anomalies for Tmin are significant, with values above 5ºC between October and February. In the other months, these anomalies are always above 4ºC in the SSP5 8.5 scenario. In the optimistic scenario (SSP1 2.6), an increase of more than 2ºC (Tmax) and 1.5ºC (Tmin) is expected for all months of the year by the end of the century, while for the intermediate scenario (SSP2 4.5) these anomalies should reach values above 3ºC (Tmax) and 2ºC (Tmin). Prec levels could fall by 28.6% for SSP1 2.6 and 38.98% for SSP5 8.5, both observed in November. All scenarios point to an increase in temperature, while the intensity of this is greater in the higher atmospheric greenhouse gas emissions scenarios.

These results show that there should be a smaller temperature amplitude in the future, with Tmax and Tmin values much higher than at present, leading to an increase in evapotranspiration, which, combined with the significant drop in rainfall levels, should lead to a worsening of the region's fragile water situation.

Figure 6. Comparison between mean, minimum, and maximum values of maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (Prec) projected for the end of the century in all SSP scenarios with the historical average (1970–2000).



Source: The authors.

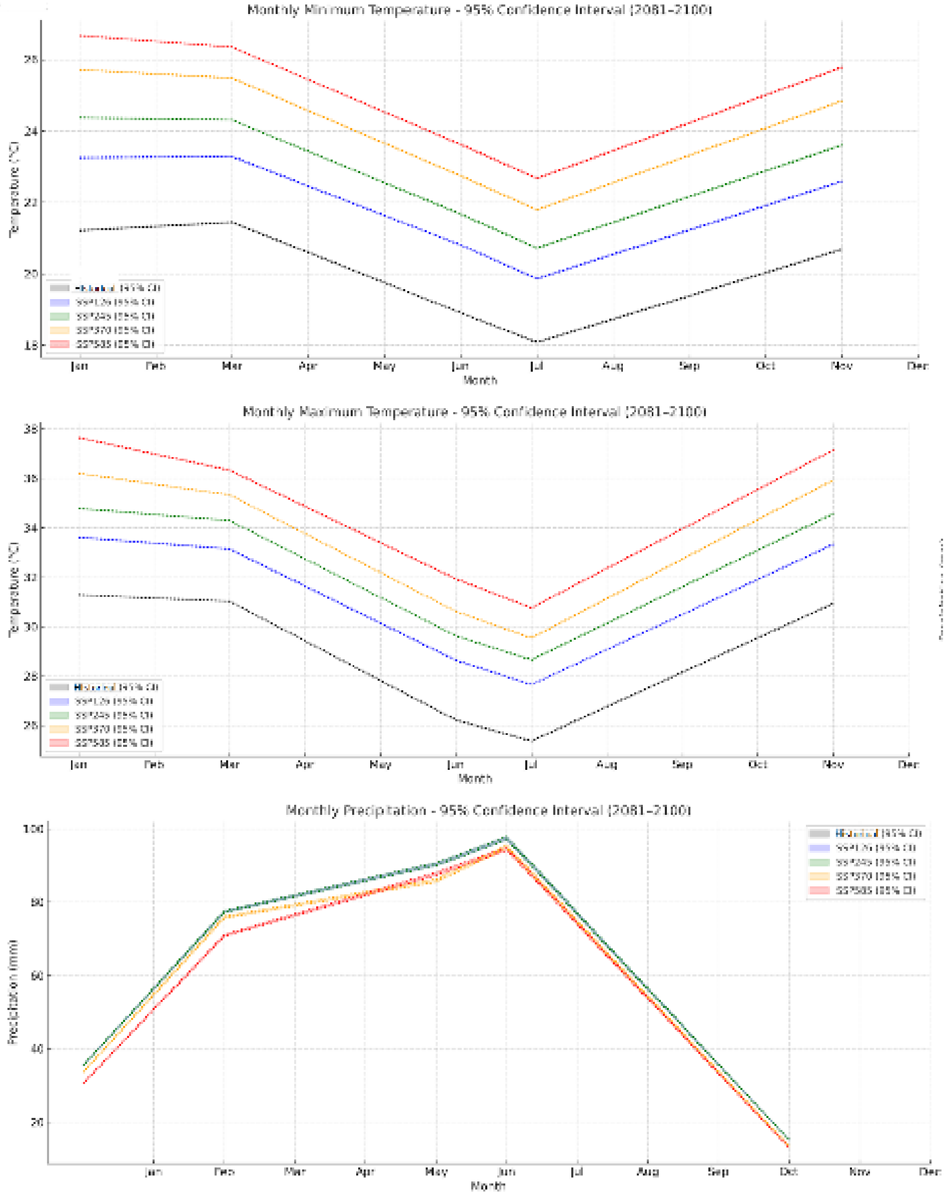
It is important to note that the National Water Resources Policy (Brazilian Law 9.433/1997) prioritizes the use of water for human supply and animal watering, leaving irrigated agriculture – the largest water consumer (over 50%) (ANA, 2024) –, vulnerable during water crisis. This scenario leads to an increase in food and nutritional insecurity, as well as climate injustice, since the most vulnerable communities, such as family farmers, are likely to suffer the worst impacts (Santos *et al*., 2022; Souza *et al*., 2023; Oliveira *et al*., 2025).

Figure 6 also shows that significant variations between the SSPs are projected for the period 2081–2100, with a tendency for average rainfall levels to decrease in all SSP scenarios compared to the historical period. On the other hand, the minimum monthly Prec points to an increase in rainfall levels as the SSP scenario becomes more severe, probably linked to the occurrence of intense rainfall events. Finally, the maximum monthly Prec values point to a significant decrease, especially in the SSP3 7.0 and SSP5 8.5 scenarios. SSP1 2.6 shows projected maximum Prec values like those of historical Prec, making it the scenario with the least impact, followed by SSP2 4.5.

The graphs of the 95% confidence intervals (CI) for 2081–2100, compared to the historical period, confirm the trend of an increase in minimum and maximum temperatures, as well as a reduction in rainfall levels. However, there is a clear widening of the curves as the projections are made in the higher emission scenarios (SSP3 7.0 and SSP5 8.5) than in the optimistic scenario (SSP1 2.6), indicating that in the former there is greater uncertainty regarding climate projections. This becomes clearer for Prec CI, when the curves for the historical scenario, SSP1 2.6, and SSP2 4.5 practically overlap. Apparently, the projected temperature data is more uncertain than the projected precipitation data, which may have something to do with the small variation expected, especially for the months of July to October, which are traditionally the driest months, especially in semi-arid zones. The CI increases during the rainy season, between March and July. These statements are further supported by Figure 8, which shows the variation in the mean rainy season (mean Prec $\geq$ 60 mm) in 2081–2100 compared to the historical period. In the SSP1 2.6 scenario, there are five rainy months, as in the historical average. This scenario worsens as the scenario becomes more pessimistic, with projections pointing to a reduction of one rainy month in the SSP2 4.5 scenario, one and a half rainy months in the SSP3 7.0 scenario, and two rainy months in the SSP5 8.5 scenario.

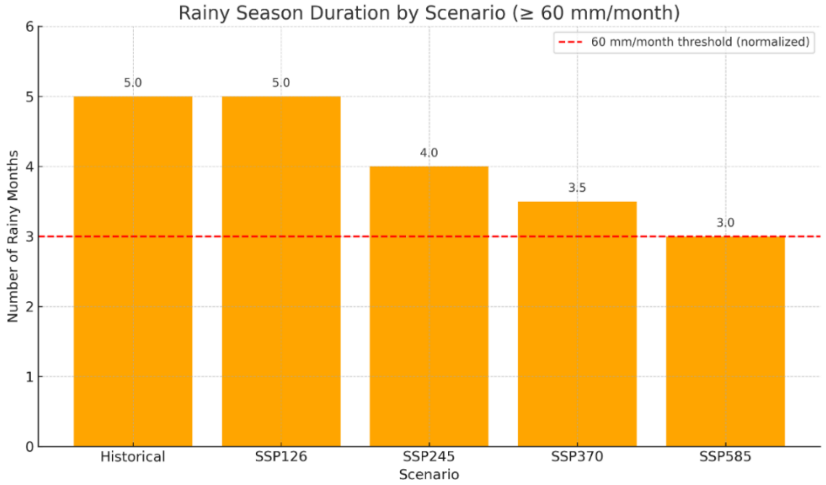
In this scenario, the adoption of sustainable, resilient, and adaptative agricultural practices and the rational use and management of water, as recommended by Freitas *et al*. (2021) and Reichstein *et al*. (2019), will be essential to promote the adaptation of the region's agricultural systems in the long term (Marengo *et al*., 2021). Strategic crops such as sugarcane and irrigated rice tend to suffer a reduction in photosynthetic efficiency at temperatures above 36°C (Silva *et al*., 2023). Important vegetables to family farming in the LSF/SE-AL as okra, coriander, onion, and sweet pepper presents different adaptation tolerance to hot climates and it is high irrigation dependent (Lima *et al*., 2015). Impacts such as reduced productivity, increased incidence of diseases and pests, emergence of pests and diseases that are not currently significant, loss of suitability of productive areas, negative effects on product quality (Dumitru *et al*., 2023), and damage to post-harvest logistics and other negative impacts must be observed (Mattos *et al*., 2014) in this drawn scenario. Additionally, the increase in evapotranspiration intensifies water demand, putting pressure on the availability of water for irrigation and supply (Castro, 2022; Silva *et al*., 2023; ANA, 2024) in a region that already suffers from water scarcity.

Figure 7. Maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (Prec) confidence interval (CI) projected for the end of the century in all SSP scenarios vs the historical period (1970–2000).



Source: The authors.

Figure 8. Rainy season duration by scenario measured by months with precipitation (Prec) levels higher than 60 mm month^{-1}.



Source: The authors.

In the face of these challenges, multidimensional strategic technical-political planning becomes essential, integrating bioclimatic monitoring, resilient agricultural systems and optimizing the use of water resources, as recommended by Reichstein *et al*. (2019), Freitas *et al*. (2021), Gomes *et al*. (2022), and. Zeri *et al*. (2021). Improved climate mapping, using other CMIP6 models and ensemble, use of climate-smart agriculture (CSA) as those that use Internet of Things (IoT), sensors, AI and climatization techniques to reduce climate negative impacts, adoption of regenerative systems, promote the development of more efficient irrigation methods, and improvement of plant breeding to produce heat tolerant and water efficient cultivars are essential to maintain the agricultural systems sustainability (Dumitru *et al*., 2023; Pereira *et al*., 2024). Adequate water resources management is also necessary, with development and application of public policies and adoption of strategies as degraded land recuperation and restoration of native vegetation, especially riparian forests.

Finally, family farming plays a crucial role in the LSF region, being the main provider of employment and earnings, as well as food and nutritional security, particularly among rural riverside communities. These communities are highly vulnerable socioeconomically, receive little technical assistance, and experience high rates of rural exodus, especially among young people. Currently, there are several environmental and production problems that hinder the sustainability of agricultural activity, such as water scarcity, soil salinization, marine intrusion in the São Francisco River—the region's main water resource—nitrate contamination, loss of native vegetation, and low use of regenerative systems and practices. Under projected climate change scenarios, these issues are anticipated to intensify. These populations are known to have a lower capacity to adapt your way of life and economics activities to climate change.

For all the above reasons, this study is not only a technical and scientific analysis, but also a way to create a basis for the adoption of climate justice and just transition measures, recognized benchmarks of the IPCC. It should be noted that the concept of climate justice recognizes that the impacts of climate change are not distributed equally, and that historical responsibilities and response capacities must be adequate to serve vulnerable populations. On the other hand, just transition can be defined as a set of policies, mechanisms, and processes designed to ensure that the transformation towards a low-carbon economy occurs in an equitable, inclusive, and socially responsible manner (IPCC, 2023).

4 CONCLUSIONS

Evidence of significant climate change in the Lower São Francisco (LSF/SE-AL) region has been observed. The maximum temperature (Tmax) at the end of the century is expected to increase above 6ºC in SSP5 8.5 and above 2ºC in SSP1 2,6. Tmin, in turn, should increase between 1.5ºC and 2ºC (SSP1 2.6) and between 4ºC and 5ºC (SSP5 8.5). The hottest period of the year is expected to be between November and February.

Annual precipitation (Prec) levels will fall by 6% (SSP1 2.6) and 30% (SSP5 8.5) in 2081–2100, reaching a 250 mm reduction. In some months of the year, however, the drop could reach almost 40% in SSP5 8.5. Even in dry months rainfall should decrease. There will also be a reduction in the number of rainy months, reaching, in the worst case, between 2 and 3 per year, with significantly lower values than in the historical period (1970–2000) registers.

All these changes lead to negative impacts on agricultural production systems. There is therefore an urgent need to adopt sustainable and resilient agricultural practices, processes and products. Systems such as no-till farming, agroforestry systems, rational irrigation management, heat and drought tolerant genetic materials, crop diversification, and even protected cultivation in controlled environments and soilless cultivation must be urgently considered as a strategy for maintaining agricultural sustainability in the region.

This work is also aligned with various national public policies and the United Nations's 2030 Agenda, as well as the climate justice and just transition of IPCC benchmarks.

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AUTHOR DECLARATIONS

Artificial intelligence tools were used to assist in language editing, data interpretation, figures, graphics and tables elaborated and programing code generation. All outputs were reviewed and validated by the authors. Details on the use of AI tools can be found in the materials and methods section.

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