Thermal severity on brazilian lettuce crops under two global climate change scenarios

Severidade térmica nas culturas de alface brasileiras em dois cenários de mudança climática global

Gravedad térmica en los cultivos de lechuga brasileños en dos escenarios de cambio climático global

DOI: 10.54033/cadpedv22n11-105

Originals received: 8/8/2025
Acceptance for publication: 9/3/2025

Carlos Eduardo Pacheco Lima
PhD in Soils and Plant Nutrition
Institution: Embrapa Vegetables - CNPq Productivity Fellow in Technological Development and Innovative Extension – Level C
Address: Brasília, Distrito Federal, Brazil
E-mail: carlos.pacheco-lima@embrapa.br

Mariana Rodrigues Fontenelle
Doctor in in Agricultural Microbiology
Institution: Embrapa Vegetables
Address: Brasília, Distrito Federal, Brazil
E-mail: mariana.fontenelle@embrapa.br

Marcos Brandão Braga
Doctor in Irrigation and Drainage
Institution: Embrapa Vegetables
Address: Brasília, Distrito Federal, Brazil
E-mail: marcos.braga@embrapa.br

Fábio Akiyoshi Suinaga
PhD in Genetics and Plant Breeding
Institution: Embrapa Vegetables - CNPq Productivity Fellow in Technological Development and Innovative Extension – Level 2
Address: Brasília, Distrito Federal, Brazil
E-mail: fabio.suinaga@embrapa.br

Ítalo Moraes Rocha Guedes
Doctor in Soils and Plant Nutrition
Institution: Embrapa Vegetables
Address: Brasília, Distrito Federal, Brazil
E-mail: italo.guedes@embrapa.br

Juscimar da Silva
Doctor in Soils and Plant Nutrition
Institution: Embrapa Vegetables
Address: Brasília, Distrito Federal, Brazil
E-mail: juscimar.silva@embrapa.br

ABSTRACT

Lettuce (*Lactuca sativa* L.) is one of the most produced and consumed vegetables in Brazil. As a crop of Mediterranean origin and therefore adapted to cool and/or mild climates, it is strongly affected by high temperatures. Morphophysiological disorders such as premature bolting and tipburn are examples of these impacts. Such problems are expected to worsen under projected scenarios of global warming and climate change. Therefore, this study aimed to assess the vulnerability of Brazilian lettuce production to two global climate change scenarios (RCP 4.5 and RCP 8.5) throughout the 21st century, using the regional climate model ETA-HadGEM2-ES, as well as the impacts of what we defined here as the *Thermal Severity Index*, calculated by summing the vulnerability indices of mean temperature and maximum temperature. Projections of mean temperature (Tmean) and maximum temperature (Tmax) were analyzed for the four seasons of the year, generating thematic maps of climate vulnerability and the Thermal Severity Index (IS), which integrates both variables. The results indicate a generalized warming trend, more pronounced under the RCP 8.5 scenario, with significant impacts on lettuce production, especially in the Central-West, Northeast, and Northern regions. Impacts will be greatest during summer and spring. By the end of the century, in both scenarios, almost the entire country, across all seasons, will present high to very high IS values. Only the Southern region and parts of mountainous areas showed high suitability for lettuce cultivation. The urgent adoption of climate change adaptation strategies and improvements in production system resilience is therefore necessary. As lettuce cultivation is highly associated with family farming—largely neglected in current climate change actions, this also becomes a matter of climate justice.

Keywords: Climate Emergency. Climate Vulnerability of Agricultural Crops. Climate Resilience. Adaptation to Global Climate Change. Climate Modeling.

RESUMO

A alface (*Lactuca sativa L.*) é uma das hortaliças mais produzidas e consumidas no Brasil. Por ser uma cultura de origem mediterrânea e, consequentemente, de clima frio e/ou ameno, tende a sofrer forte impacto em razão da ocorrência de elevadas temperaturas. Desordens morfofisiológicas como pendoamento precoce e queima-de-bordas são exemplos desse impacto. Tais questões devem se agravar com os cenários de aquecimento global e mudanças climáticas projetadas. Assim, o presente trabalho teve como objetivo avaliar a vulnerabilidade da alfacicultura brasileira frente a dois cenários de mudanças climáticas globais (RCP 4.5 e RCP 8.5) ao longo do século XXI, utilizando o modelo climático regional ETA-HadGEM2-ES, bem como os impactos do que aqui foi denominado como índice de severidade térmica, calculado pela soma dos índices de vulnerabilidade à temperatura média e à temperatura máxima. Foram analisadas projeções de temperatura média (Tmed) e máxima (Tmax) para as quatro estações do ano, gerando mapas temáticos de vulnerabilidade climática e do Índice de Severidade Térmica (IS) que integra ambas as variáveis. Os resultados indicam tendência de aquecimento generalizado, mais intenso no cenário RCP 8.5, com impactos significativos sobre a produção de alface, especialmente nas regiões Centro-Oeste, Nordeste e Norte. Os impactos serão maiores durante o verão e a primavera. Ao final do século, em ambos os cenários, praticamente todo o país, em todas as estações do ano, apresentarão IS alto a muito alto. Apenas a região Sul e partes das regiões serranas brasileiras apresentaram elevada aptidão para os cultivos. Faz-se necessário a urgente adoção de estratégias de adaptação às mudanças climáticas e melhoria da resiliência dos sistemas produtivos. Por se tratar de um cultivo agrícola muito associado a agricultura familiar, pouco englobada pelas ações atuais referentes às mudanças climáticas, torna-se também uma questão de justiça climática.

Palavras-chave: Emergência Climática. Vulnerabilidade Climática de Cultivos Agrícolas. Resiliência Climática. Adaptação às Mudanças Climáticas Globais. Modelagem Climática.

RESUMEN

La lechuga (*Lactuca sativa* L.) es una de las hortalizas más producidas y consumidas en Brasil. Al ser un cultivo de origen mediterráneo y, por lo tanto, adaptado a climas frescos y/o templados, se ve muy afectado por las altas temperaturas. Los trastornos morfofisiológicos, como el espigado prematuro y el quemado de las puntas, son ejemplos de estos impactos. Se prevé que estos problemas empeoren en los escenarios previstos de calentamiento global y cambio climático. Por lo tanto, el objetivo de este estudio fue evaluar la vulnerabilidad de la producción brasileña de lechuga ante dos escenarios de cambio climático global (RCP 4.5 y RCP 8.5) a lo largo del siglo XXI, utilizando el modelo climático regional ETA-HadGEM2-ES, así como los impactos de lo que aquí definimos como Índice de Severidad Térmica, calculado sumando los índices de vulnerabilidad de la temperatura media y la temperatura máxima. Se analizaron las proyecciones de la temperatura media (Tmean) y la temperatura máxima (Tmax) para las cuatro estaciones del año, generando mapas temáticos de vulnerabilidad climática y el Índice de Severidad Térmica (IS), que integra ambas variables. Los resultados indican una tendencia generalizada al calentamiento, más pronunciada en el escenario RCP 8.5, con impactos significativos en la producción de lechuga, especialmente en las regiones Centro-Oeste, Nordeste y Norte. Los impactos serán mayores durante el verano y la primavera. A finales de siglo, en ambos escenarios, casi todo el país, en todas las estaciones, presentará valores de IS altos o muy altos. Solo la región meridional y algunas zonas montañosas mostraron una alta idoneidad para el cultivo de lechuga. Por lo tanto, es necesario adoptar urgentemente estrategias de adaptación al cambio climático y mejorar la resiliencia de los sistemas de producción. Dado que el cultivo de lechuga está muy relacionado con la agricultura familiar, que en gran medida se ha descuidado en las medidas actuales contra el cambio climático, esto también se convierte en una cuestión de justicia climática.

Palabras clave: Emergencia Climática. Vulnerabilidad Climática de los Cultivos Agrícolas. Resiliencia Climática. Adaptación al Cambio Climático Global. Modelización Climática.

1 INTRODUCTION

Lettuce (*Lactuca sativa* L.) is one of the most produced and consumed vegetables in Brazil and worldwide (CNA, 2017). Among leafy vegetables, it is the most important globally (Sala & Costa, 2012). Several indicators highlight its relevance to horticulture, such as being the second crop in fertilizer revenue, averaging US$ 90.33 million, and representing 15% of the total value for this group of crops. The financial turnover of the vegetable chain with seeds and seedlings amounts to US$ 17.07 million for seeds and US$ 52.48 million for seedlings, with the majority (70%) commercially obtained as seedlings. The cultivated area in Brazil is 91,172 hectares, the second largest among vegetables, with an average yield of 18.6 tons per hectare and total production of 1,701,872 tons (CNA, 2017). Lettuce holds high socioeconomic importance, strongly linked to family farming but also present in large-scale agribusiness, generating around five jobs per hectare (Resende *et al.*, 2007), which corresponds to a labor/cost ratio of 17% (CNA, 2017).

This crop is of Mediterranean origin, later domesticated and adapted to tropical conditions. Although studies such as Lafta *et al*. (2017) indicate that lettuce achieves its best development under cooler climates (±18 °C), lettuce production has been adapted to tropical environments through adjustments in production systems, such as the development and availability of heat-tolerant genetic material (Sala & Costa, 2012). Plant breeding is also a crucial factor for adaptation to Global Climate Change (GCC).

According to Embrapa (2019), lettuce cultivation in tropical regions should be conducted under temperatures between 15 °C and 25 °C. Temperatures above 25 °C and long photoperiods may reduce the time to reach the reproductive stage, thus inducing premature bolting (Resende *et al*., 2007), while temperatures below 15 °C can limit plant growth (Ket *et al*., 2018). Another aspect to consider regarding GCC is the potential for increased prevalence or even emergence of phytopathogens. For example, temperatures between 22 °C and 26 °C associated with elevated atmospheric CO_2 levels may favor the development of *Allophoma tropica*, a fungal species that could emerge under GCC conditions. Furthermore, damages caused by this pathogen may become more severe due to the interaction between high temperatures and increased CO_2 concentration (Gullino *et al*., 2017). Temperatures above 30 °C can inhibit seed germination, promote premature bolting, tipburn, and poor plant development (Lafta *et al*., 2021).

Lima *et al*. (2024), when evaluating the performance of 11 commercial tropicalized cultivars targeted to the Brazilian market, found that only three showed satisfactory commercial yield when grown under 30 °C/25 °C day/night temperatures and a 12-hour photoperiod for 45 days. These conditions simulated the mean temperature (Tmean) projected for Brazil under GCC by the end of the century. The main morphophysiological disorders observed were leaf chlorosis, premature bolting, tipburn, generalized necrosis, and plant death. Fernandes *et al*. (2019) also observed distinct adaptability among cultivars to heat, reinforcing cultivar selection as a strategy to increase resilience and adaptation to climate change.

Representative Concentration Pathways (RCPs) were proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014). These scenarios are based on greenhouse gas (GHG) concentration pathways in the atmosphere and their associated radiative forcing (expressed in W/m^2 by 2100). For this study, we selected the moderate emissions scenario RCP 4.5 (global mean temperature increase between 2.0 °C and 3.0 °C) and the high emissions scenario RCP 8.5 (increase between 4.0 °C and 5.5 °C), compared with the historical baseline (Climate Projections, 2025). However, these values reflect global averages; regional or local projections require adapted climate models. For understanding GCC impacts on the economic activities of a country or region, projections at regional or local scales are therefore essential (Chou *et al*., 2014a).

Indeed, observed data already indicate an increase in global mean temperature. Between 2011 and 2020, compared to the pre-industrial period

(1850–1900), the rise reached 1.1 °C (IPCC, 2023). The Paris Agreement set a limit of 1.5 °C to avoid climate collapse (IPCC, 2018). However, 2024 was the first year to surpass this limit, reaching 1.6 °C globally (Copernicus, 2025a), and January 2025 registered 1.75 °C (Copernicus, 2025b), raising concerns about losing this critical window of opportunity.

For Brazil, projections are concerning, and observed trends already point to intensified warming. Marengo (2018) reported a marked increase in climate extremes in recent decades. In 2019, capitals in the Central-West and South registered temperatures up to 9 °C above the historical average. Cardoso *et al*. (2022), when projecting future climate scenarios for southern Rio Grande do Sul, found annual temperature increases reaching 0.95 °C.

Assad & Assad (2024) noted that at the local scale, significant changes have occurred in variables such as precipitation, maximum (Tmax), mean, and minimum temperatures, relative humidity, and surface winds. They highlight that higher temperatures exert stronger negative impacts on C3 photosynthetic plants than on C4 plants. Lettuce, like most vegetables, belongs to the first group.

The ETA Regional Climate Model, used by the National Institute for Space Research (INPE), provides spatial resolution for South America and the Caribbean ranging from 5 km to 40 km, offering greater detail than Global Circulation Models (GCMs) (Chou *et al*., 2014a). By increasing spatial and temporal resolution, regional models refine the scenarios provided by GCMs, making them widely used to assess GCC impacts on water resource management, ecosystems, and agriculture at regional scales (Marengo, 2007). Through the Climate Projections portal (INPE, 2025), INPE makes available the generation and download of GeoTIFF maps produced by the ETA model coupled with GCMs, covering the historical period (1961–2005), near future (present–2040), mid-century (2041–2070), and end-of-century (2071–2100), under RCP 4.5 and RCP 8.5, thus facilitating impact assessments using Geographic Information Systems (GIS).

Given this context, the objective of the present study was to evaluate the impacts of projected thermal severity under two climate change scenarios (RCP

4.5 and RCP 8.5) throughout the 21st century on lettuce crops in Brazil, using the regional model ETA-HadGEM2-ES.

2 MATERIAL AND METHODS

2.1 SOFTWARE AND DATA ACQUISITION

For this study, we used the open-source software QGIS version 3.42.3. Climate modeling was carried out using the regional model ETA-HadGEM2-ES, which has been widely applied for the Brazilian territory (Chou, 2025). This model allows more detailed forecasting of phenomena associated with fronts, orography, sea breezes, and severe storms, which can be summarized as mesoscale systems (Chou, 2025).

Regarding its applicability for climate change projections, Chou *et al*. (2014a) reported that the model operates with a spatial resolution of 20 km for most of South America, Central America, and the Caribbean. A finer 5 km resolution is possible but limited due to high computational demand. GCMs such as HadGEM2-ES are used to enable downscaling (INPE, 2025). Simulations with the ETA model are available on the Climate Projections Platform (http://pclima.inpe.br/analise/), where they can be downloaded as raster GeoTIFF images.

For this work, GeoTIFF images were downloaded under the following scenarios: historical, RCP 4.5, and RCP 8.5, including values of mean and maximum temperature up to 2100. Seasonal frequency was considered: summer, autumn, winter, and spring. The generation of thematic maps for each variable constituted the first processing stage.

2.2 CLIMATE VULNERABILITY MAPPING

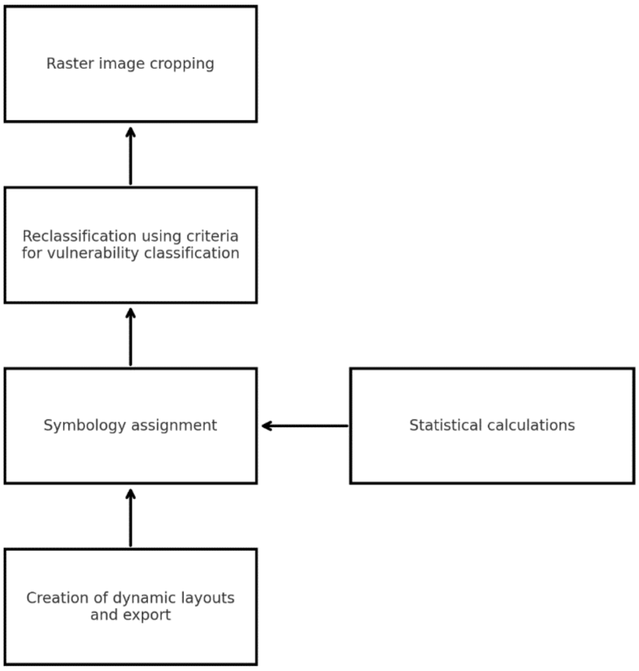
The second stage consisted of producing lettuce crop vulnerability maps based on mean and maximum temperature. We adopted the assumption that most lettuce production systems in Brazil are conventional and field-based (Henz

& Suinaga, 2009; Santos, 2018), which increases their exposure to projected climate conditions. Furthermore, much of the production is carried out by family farmers, who generally have limited resources for resilience-building and climate adaptation.

The vulnerability maps were generated through an automated workflow using Python scripts developed with the support of Generative Artificial Intelligence tools (AI – ChatGPT and GitHub Copilot). Scripts were executed in the PyQGIS environment to produce thematic maps. The automation process for generating vulnerability maps, along with the scripts produced via Prompt Engineering and Command Chaining, is described in Figure 1. Processing was conducted in batches of maps for each scenario, period, and season, which increased productivity and reduced working time.

Following FAIR principles (Findable, Accessible, Interoperable, and Reusable) of open science (Go FAIR, 2016; Fick & Hijmans, 2017), all scripts used are available in a Zenodo repository (Lima *et al*., 2025a). Thematic maps of temperature are available in Lima *et al*. (2025b). Scripts were registered under an open BSD 3-Clause license. As input layers, we used GeoTIFF images from climate projections and, for masking, the boundaries of Brazilian territory downloaded from the Brazilian Institute of Geography and Statistics (IBGE – https://www.ibge.gov.br/geociencias/cartas-e-mapas/mapas-de-referencia/15816-politico.html?=&t=downloads). An example of a Python script developed with AI support and applied in the processing workflow is shown in Table 1.

Figure 1. Workflow processes used in the automated generation of lettuce vulnerability maps to minimum, mean, and maximum temperature in Brazil.



Source: Authors (2025).

Table 1. Example of a Python script developed with AI and collaborative platforms for automating the generation of vulnerability maps used in this study.

import os
from qgis.core import (
QgsProject,
QgsProcessingFeedback,
QgsRasterLayer)
import qgis.utils
import processing
Permite ao usuário selecionar manualmente uma camada raster no QGIS
raster_layer = qgis.utils.iface.activeLayer()
Verifica se a camada selecionada é um raster
if raster_layer is None or not isinstance(raster_layer, QgsRasterLayer):
print("Erro: Nenhuma camada raster válida selecionada. Selecione uma camada raster no painel de camadas do QGIS e tente novamente.")
else:
print(f"Raster selecionado: {raster_layer.name()}")
Extrai o nome do arquivo raster sem extensão
raster_source = raster_layer.source()
raster_filename = os.path.basename(raster_source)
raster_name_without_ext = os.path.splitext(raster_filename)[0]
Define o caminho de saída
output_directory = "E:/Mudanças Climáticas/Nova geografia da produção de hortaliças/Imagens Raster BR/Vulnerabilidade"
os.makedirs(output_directory, exist_ok=True)
output_filename = f"{raster_name_without_ext}_vulnerabilidade.tif"
output_path = os.path.join(output_directory, output_filename)
Prepara o nome da banda para a expressão da calculadora raster

raster_calc_name = f'"{raster_layer.name()}@1"'
Expressão para reclassificação por faixas de temperatura
expression = (
f"(({raster_calc_name} >= 0.0000 AND {raster_calc_name} <= 5.0000) * 5) + "
f"(({raster_calc_name} > 5.0000 AND {raster_calc_name} <= 10.0000) * 4) + "
f"(({raster_calc_name} > 10.0000 AND {raster_calc_name} <= 15.0000) * 2) + "f"(({raster_calc_name} > 15.0000 AND {raster_calc_name} <= 25.0000) * 1) + "
f"(({raster_calc_name} > 25.0000 AND {raster_calc_name} <= 30.0000) * 3) + "
f"(({raster_calc_name} > 30.0000 AND {raster_calc_name} <= 35.0000) * 4) + "
f"(({raster_calc_name} > 35.0000 AND {raster_calc_name} <= 50.0000) * 5)")
Configuração dos parâmetros para o processamento
params = {
'EXPRESSION': expression,
'LAYERS': raster_layer,
'CELLSIZE': 0,
'EXTENT': raster_layer.extent(),
'CRS': raster_layer.crs(),
'OUTPUT': output_path}
Execução do processamento no QGIS
try:
feedback = QgsProcessingFeedback()
result = processing.run("qgis:rastercalculator", params, feedback=feedback)
if result and 'OUTPUT' in result:
output_layer = QgsRasterLayer(output_path, f"{raster_name_without_ext}_vulnerabilidade")
QgsProject.instance().addMapLayer(output_layer)
print(f"Processo concluído com sucesso! O raster reclassificado foi salvo como: {output_filename}")
print("Arquivo carregado no QGIS automaticamente.")
else:
print("Erro: O processamento não retornou saída válida.")
except Exception as e:
print(f"Erro no processamento: {str(e)}")

Source: Authors (2025).

2.3 RECLASSIFICATION FOR CLIMATE VULNERABILITY MAPS

For generating future climate vulnerability maps, spatial algebra reclassification was applied to the raster layers. Reclassification for mean and maximum temperature followed the criteria shown in Tables 2 and 3. The reclassified rasters were then renamed and assigned standardized color palettes. Layouts for each vulnerability map were produced and deposited on Embrapa's GeoInfo platform (https://geoinfo.dados.embrapa.br/) and in a Zenodo repository (Lima *et al*., 2025c).

The vulnerability classes for Tmean (Table 2) and Tmax (Table 3) are listed below. For classification, we considered the predominance of tropicalized lettuce cultivars in most of the country.

Table 2. Classes of mean temperature used to determine the vulnerability of Brazilian lettuce cultivation to this climatic variable.

Mean temperature (°C)	Vulnerability class
≤ 5.00	Very high
> 5.01 – ≤ 10.00	High
> 10.01 – ≤ 15.00	Low
> 15.01 – ≤ 25.00	Very low
> 25.01 – ≤ 30.00	Moderate
> 30.01 – ≤ 35.00	High
> 35.00	Very high

Source: Authors (2025).

Table 3. Classes of maximum temperature used to determine the vulnerability of Brazilian lettuce cultivation to this climatic variable.

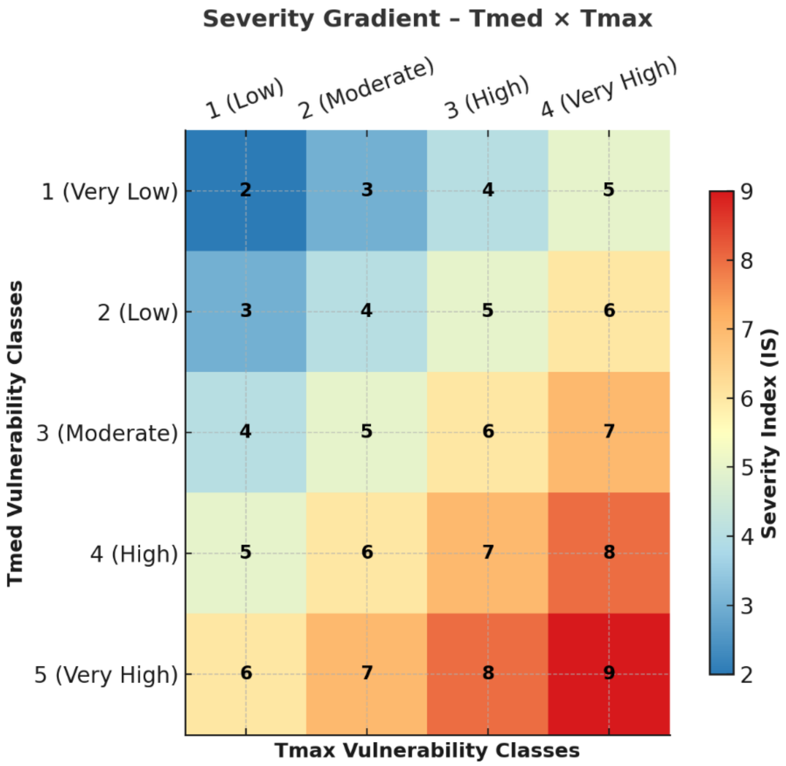
Maximum temperature (°C)	Vulnerability class
≤ 25.00	Low
> 25.01 – ≤ 30.00	Moderate
> 30.01 – ≤ 35.00	High
> 35.00	Very high

Source: Authors (2025).

2.4 CALCULATION AND MAPPING OF THE THERMAL SEVERITY INDEX

The *Thermal Severity Index* (SI) was designed to integrate both variables analyzed (Tmean and Tmax), providing greater robustness to the vulnerability assessment of lettuce production under climate change. The formula used for IS calculation is provided below. Thermal severity maps were also deposited in the GEOINFO platform and in a Zenodo repository (Lima *et al*., 2025c). Mapping procedures followed the same methodology described previously.

Figure 2. Diagram showing the relationship between vulnerability to average temperature (Tmed) and maximum temperature (Tmax), as well as the classification of the Thermal Severity Index (IS).



Source: Authors (2025).

2.5 USE OF ARTIFICIAL INTELLIGENCE TOOLS AND STATISTICAL ANALYSES

As mentioned earlier, AI tools were used to support the automated mapping workflow through Python script generation. They were also applied to assist in analyzing large datasets, using specific prompts. The AI tool used was Data Analyst (OpenAI). In total, 56 temperature maps, 56 vulnerability maps, and 28 IS maps were generated, amounting to 140 maps, in addition to 140 accompanying *.txt* files containing statistical data for each map, totaling 280 files analyzed. AI was also used as a support tool for generating charts and tables, as well as preliminary technical interpretations. However, it is important to emphasize that all processes are supervised, adjusted, and corrected by humans when necessary. Finally, AI tools are used as support to translate the text for English.

3 RESULTS AND DISCUSSION

The results reveal a concerning scenario, with significant increases in both climatic variables analyzed and, consequently, their negative effects on lettuce production systems. A generalized warming trend was observed across all evaluated periods and for all four seasons of the year. Below, we briefly discuss the projections for mean temperature (Tmean) and maximum temperature (Tmax), as these results have already been the focus of several other studies (Hamada, 2015; Soares, 2015; Silva *et al*., 2023; Valverde *et al*., 2023). Recent IPCC reports also point to this trend (IPCC, 2021; 2023). The following discussion emphasizes the consequences of these climatic anomalies for Brazilian lettuce production and explores possible strategies for strengthening resilience and adaptation.

Projections from the regional ETA-HadGEM2-ES model for the entire Brazilian territory indicated substantial increases in Tmean and Tmax anomalies throughout the 21st century under both scenarios (Figures 2 and 3). Seasonal variations were pronounced, with greater intensity under the RCP 8.5 scenario. Similar patterns were observed by Cardoso *et al*. (2022), who evaluated Tmean and precipitation under RCP 4.5 and RCP 8.5 using the ETA model coupled with three global models for southern Rio Grande do Sul. Other studies, such as Silva *et al*. (2020) and Valverde *et al*. (2023), also reported comparable outcomes.

The analysis of Tmean projections showed values close to or even exceeding 6 °C across all seasons under RCP 8.5 by the end of the century. Under RCP 4.5, values surpassed 3 °C in autumn and approached this threshold in the other seasons. Tmax projections indicated increases close to 8 °C in summer and above 7 °C in the other seasons under the high-emission scenario. For RCP 4.5, values were near or above 3 °C by the end of the century. These results are consistent with Hamada (2015) and Soares (2015).

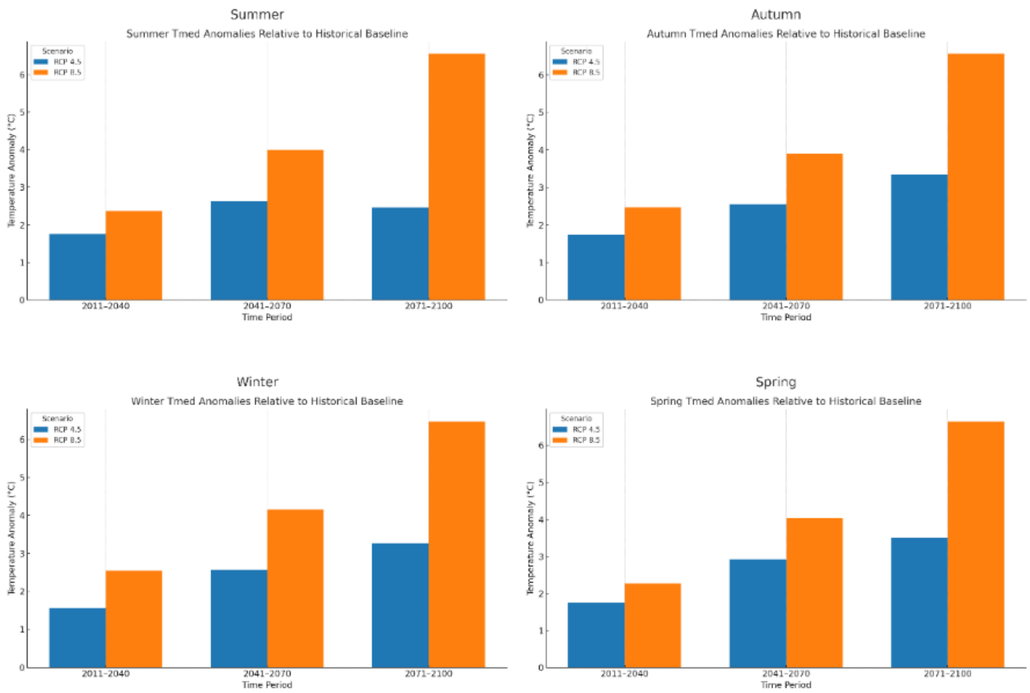
In practical terms, average Tmean and Tmax at the end of the century may reach the following values in RCP4.5: **Tmean;** summer – 27.61 °C (min. 18.71 °C; max. 34.39 °C); autumn – 26.77 °C (15.94–32.55 °C); winter – 25.44 °C (11.16–30.55 °C); spring – 28.51 °C (15.08–33.91 °C). **Tmax;** summer – 33.07

°C (23.04–41.17 °C); autumn – 32.17 °C (21.20–38.85 °C); winter – 31.39 °C (15.35–37.12 °C); spring – 34.75 °C (19.77–40.38 °C). For RCP 8.5, projected values were: **Tmean;** summer – 30.87 °C (20.84–38.01 °C); autumn – 29.99 °C (18.40–35.53 °C); winter – 28.65 °C (13.75–33.98 °C); spring – 31.65 °C (17.83–37.45 °C). **Tmax;** summer – 37.07 °C (25.42–45.05 °C); autumn – 36.00 °C (23.99–42.50 °C); winter – 34.89 °C (17.94–40.46 °C); spring – 38.42 °C (21.10–44.58 °C).

These results are consistent with the likelihood of extreme temperature events suggested by Fontolan *et al*. (2019), who evaluated such events in Campinas, São Paulo, using two regional models. Resulting vulnerability indices are particularly alarming. The spatial distribution of these data can be found in the maps deposited in the Zenodo repository (Lima *et al*., 2025b).

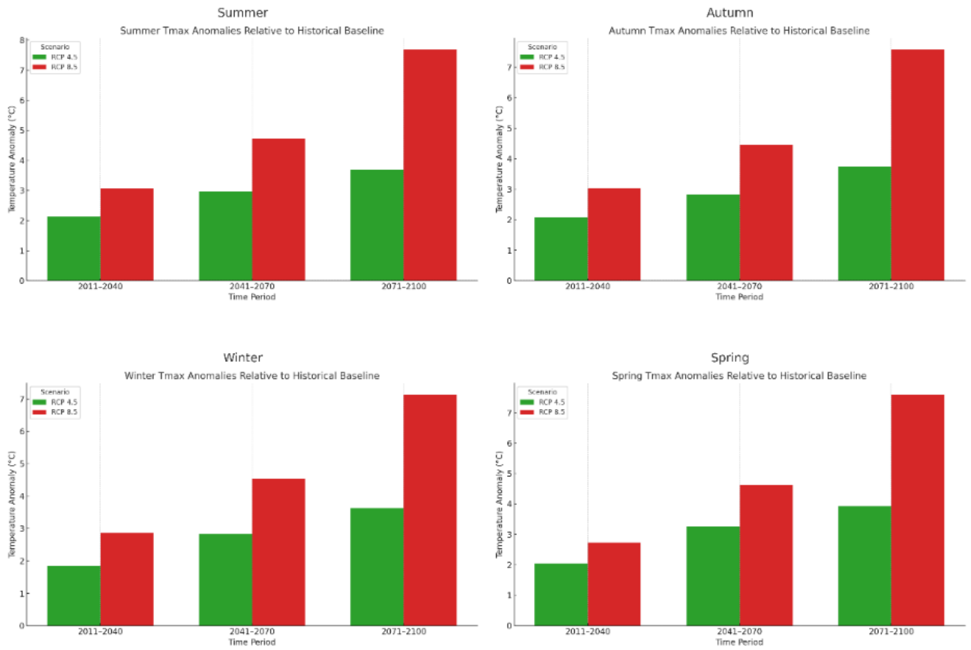
An example of Tmax evolution over the century in the RCP 8.5 spring scenario is shown in Figure 4. Spatial patterns of Tmean and Tmax across all scenarios and periods followed a consistent trend, with the greatest increases occurring across the Central-West, Northeast, and Northern regions. The lowest temperatures are expected in the South, with some mountainous areas in the Southeast showing similar conditions. However, even for the South, Tmax projections indicated a substantial increase (3.82 °C) by the end of the century compared to the historical baseline. Results from Santos *et al*. (2020) support these findings, with higher temperatures projected for the Central-West, Northeast, and North, exceeding 4 °C. Figures 3 and 4 illustrate projected anomalies of mean and maximum temperature across Brazil under different periods and RCP scenarios, compared with the historical baseline.

Figure 3. Average temperature anomalies projected by the ETA-HADGEM2-ES model for Brazil in the three periods evaluated (2011–2040; 2041–2070; 2071–2100) under moderate greenhouse gas emissions (RCP 4.5) and high emissions (RCP 8.5), compared to the historical baseline (1961–2005).



Source: Authors (2025).

Figure 4. Maximum temperature anomalies projected by the ETA-HADGEM2-ES model for Brazil in the three periods evaluated (2011–2040; 2041–2070; 2071–2100) under moderate greenhouse gas emissions (RCP 4.5) and high emissions (RCP 8.5), compared to the historical baseline (1961–2005).



Source: Authors (2025).

3.1 VULNERABILITY TO MEAN TEMPERATURE (TMEAN)

Future vulnerability of Brazilian lettuce production to mean temperature under both climate change scenarios and across all four seasons and three time periods is presented in Tables 4. The full set of maps is available on the GeoInfo platform and in a Zenodo repository under CC BY 4.0 license (Lima *et al*., 2025c).

Table 4. Evolution of projected vulnerability classes throughout the 21st century for Brazilian lettuce crops to projected average temperature for the four seasons of the year in the RCP 4.5 and RCP 8.5 scenarios, determined from projections using the ETA-HADGEM2-ES model.

Scenario	**Period**	**Very low**	**Low**	**Moderate**	**High**	**Very high**
			Summer			
-	Historical	56.02	0	43.98	0	0
RCP 4.5	Present to 2040	12.28	0	82.15	5.56	0
RCP 4.5	2041 to 2070	5.08	0	74.27	20.29	0.36
RCP 4.5	2071 to 2100	4.76	0	83.93	11.32	0
RCP 8.5	Present to 2040	10.72	0	81.15	8.13	0
RCP 8.5	2041 to 2070	5.08	0	74.27	20.29	0.36
RCP 8.5	2071 to 2100	0.86	0	19.34	74.03	5.77
			Autumn			
-	Histórico	71.85	0.06	28.09	0	0
RCP 4.5	Present to 2040	24.4	0.01	74.38	1.22	0
RCP 4.5	2041 to 2070	13.37	0	81.98	4.64	0
RCP 4.5	2071 to 2100	16.08	0	80.84	3.08	0
RCP 8.5	Present to 2040	16.62	0	80.74	2.64	0
RCP 8.5	2041 to 2070	10.75	0	79.94	9.31	0
RCP 8.5	2071 to 2100	4.03	0	28.28	65.95	1.74
			Winter			
-	Histórico	75.84	4.06	20.07	0.03	0
RCP 4.5	Present to 2040	37.36	1.22	61.42	0	0
RCP 4.5	2041 to 2070	31.55	0.63	67.69	0.13	0
RCP 4.5	2071 to 2100	27.52	0.62	71.38	0.48	0
RCP 8.5	Present to 2040	30.22	0.66	69.06	0.06	0

RCP 8.5	2041 to 2070	20.89	0.24	72.83	6.04	0
RCP 8.5	2071 to 2100	12.32	0.03	31.2	56.46	0
Spring						
-	Histórico	26.45	0.08	73.25	0.22	0
RCP 4.5	Present to 2040	17.85	0.01	70.21	11.93	0
RCP 4.5	2041 to 2070	13.71	0	54.58	31.71	0
RCP 4.5	2071 to 2100	11.57	0	43.09	45.34	0
RCP 8.5	Present to 2040	16.82	0	63.02	20.16	0
RCP 8.5	2041 to 2070	11.62	0	33.09	55.17	0.11
RCP 8.5	2071 to 2100	5.44	0	15.78	57.74	21.04

Source: Authors (2025).

Data showed that under RCP 4.5, the effects of Tmean on lettuce crops are significantly constrained. By 2100, in summer, projections indicate predominance of moderate vulnerability (83.93% of the national area), with 4.76% classified as very low and 11.32% as high. Under RCP 8.5, high vulnerability areas dominate, reaching 74.03%.

For RCP 4.5, moderate vulnerability predominates across all seasons (80.84% in autumn; 71.3% in winter), except spring, where high vulnerability dominates (45.39%) by the end of the century. Under RCP 8.5, high vulnerability predominates by 2100 in autumn (65.95%), winter (56.45%), and spring (57.74%). In spring, a considerable share of the territory (21.04%) is classified as very high vulnerability, while autumn and winter also retain relevant portions classified as moderate (31.2% and 28.28%, respectively).

3.2 VULNERABILITY TO MAXIMUM TEMPERATURE (TMAX)

The vulnerability to Tmax showed an even more concerning evolution under both RCP scenarios (Table 5). Under RCP 4.5, by 2100, 79.66% of the territory is projected as high vulnerability in summer, 75.9% in autumn, and 64.15% in winter. In spring, very high vulnerability predominates, reaching 62.6%.

Table 5. Evolution of projected vulnerability classes throughout the 21st century for Brazilian lettuce crops to maximum temperature for the four seasons of the year in the RCP 4.5 and RCP 8.5 scenarios, determined from projections using the ETA-HADGEM2-ES model.

Scenario	Period	Low	Moderate	High	Very high
			Summer		
-	Histórico	0.82	57.36	40.44	1.38
RCP 4.5	Present to 2040	0.04	11.75	79.88	8.32
RCP 4.5	2041 to 2070	0.03	4.92	83.4	11.65
RCP 4.5	2071 to 2100	0.01	2.89	79.66	17.44
RCP 8.5	Present to 2040	0.04	5.87	79.87	14.22
RCP 8.5	2041 to 2070	0.01	2.23	59.34	38.42
RCP 8.5	2071 to 2100	0	0.39	11.89	87.72
			Autumn		
-	Histórico	5.32	70.33	23.99	0.36
RCP 4.5	Present to 2040	0.91	24.41	70.95	3.73
RCP 4.5	2041 to 2070	0.61	16.77	75.91	6.71
RCP 4.5	2071 to 2100	0.31	10.58	75.9	13.21
RCP 8.5	Present to 2040	0.38	14.1	76.93	8.59
RCP 8.5	2041 to 2070	0.2	7.51	72.22	20.06
RCP 8.5	2071 to 2100	0.02	2.17	22.91	74.9
			Winter		
-	Histórico	12.83	52.33	34.84	0
RCP 4.5	Present to 2040	8.18	27.48	64.15	0.19
RCP 4.5	2041 to 2070	7.09	18.69	68.32	5.9
RCP 4.5	2071 to 2100	6.55	14.24	64.15	15.06
RCP 8.5	Present to 2040	6.66	18.07	68.83	6.44
RCP 8.5	2041 to 2070	5.41	10.18	55.11	29.3
RCP 8.5	2071 to 2100	3.49	5.75	25.53	65.22
			Spring		
-	Histórico	4.45	18.83	68.75	7.97
RCP 4.5	Present to 2040	1.93	10.54	55.85	31.68
RCP 4.5	2041 to 2070	1.52	7.2	39.2	52.07
RCP 4.5	2071 to 2100	1.42	6.5	29.48	62.6

RCP 8.5	Present to 2040	1.71	9.06	44.52	44.71
RCP 8.5	2041 to 2070	1.17	5.85	22.73	70.25
RCP 8.5	2071 to 2100	0.36	3.59	11.42	84.63

Source: Authors (2025).

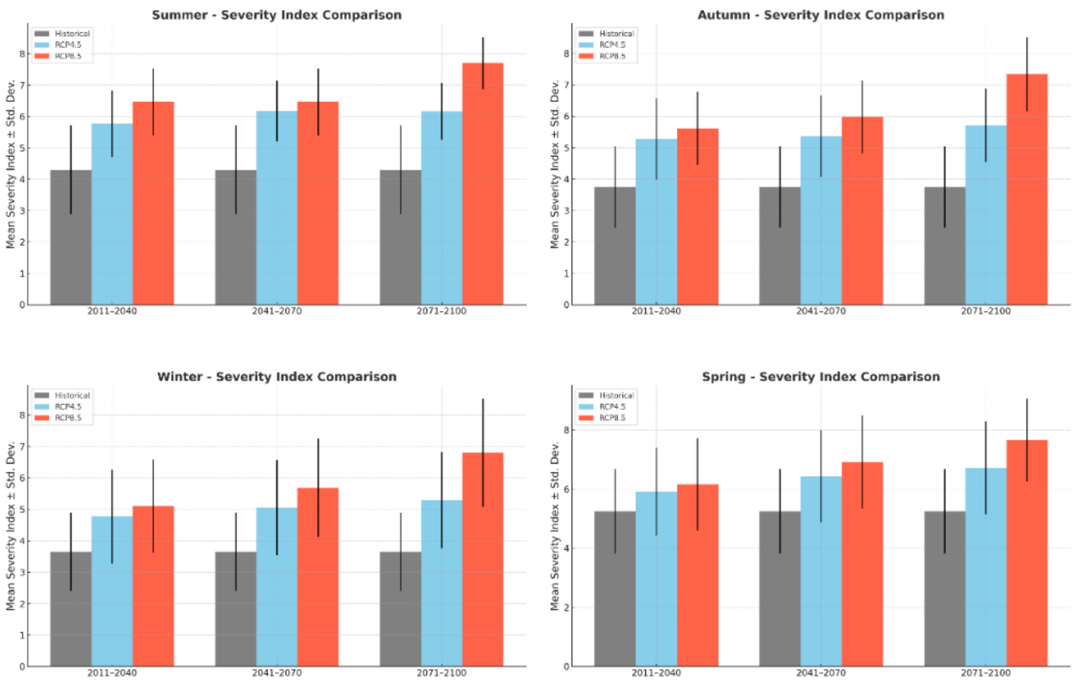
Under RCP 8.5, very high vulnerability predominates across all seasons by the end of the century (87.72% in summer; 74.9% in autumn; 65.22% in winter; and 84.63% in spring).

These results reveal a clear worsening of climate risks for lettuce production in Brazil, unless measures to enhance resilience and adaptation to climate change are adopted.

3.3 THERMAL SEVERITY INDEX (IS)

The severity of these risks is further confirmed by the Thermal Severity Index (IS), which combines Tmean vulnerability (1–5 scale) and Tmax vulnerability (1–4 scale). Figure 6 shows the evolution of IS values across the 21st century for all seasons and both RCP scenarios compared with the historical baseline.

Figure 6. Temporal evolution of the Severity Index (IS) throughout the 21st century under climate change scenarios for the four annual seasons in Brazil.



Source: Authors (2025).

There is a consistent trend of increasing IS throughout the century, regardless of season or scenario. By 2071–2100, IS values reached 6.72 in spring under RCP 4.5 and 7.70 in summer under RCP 8.5 (Table 7). The lowest values were observed in winter (5.29 in RCP 4.5; 6.80 in RCP 8.5). The largest increases relative to the historical period were found in autumn for both scenarios (+1.97 in RCP 4.5; +3.60 in RCP 8.5). These findings demonstrate that although lettuce production is significantly affected in both scenarios, impacts are considerably reduced under moderate emissions (RCP 4.5).

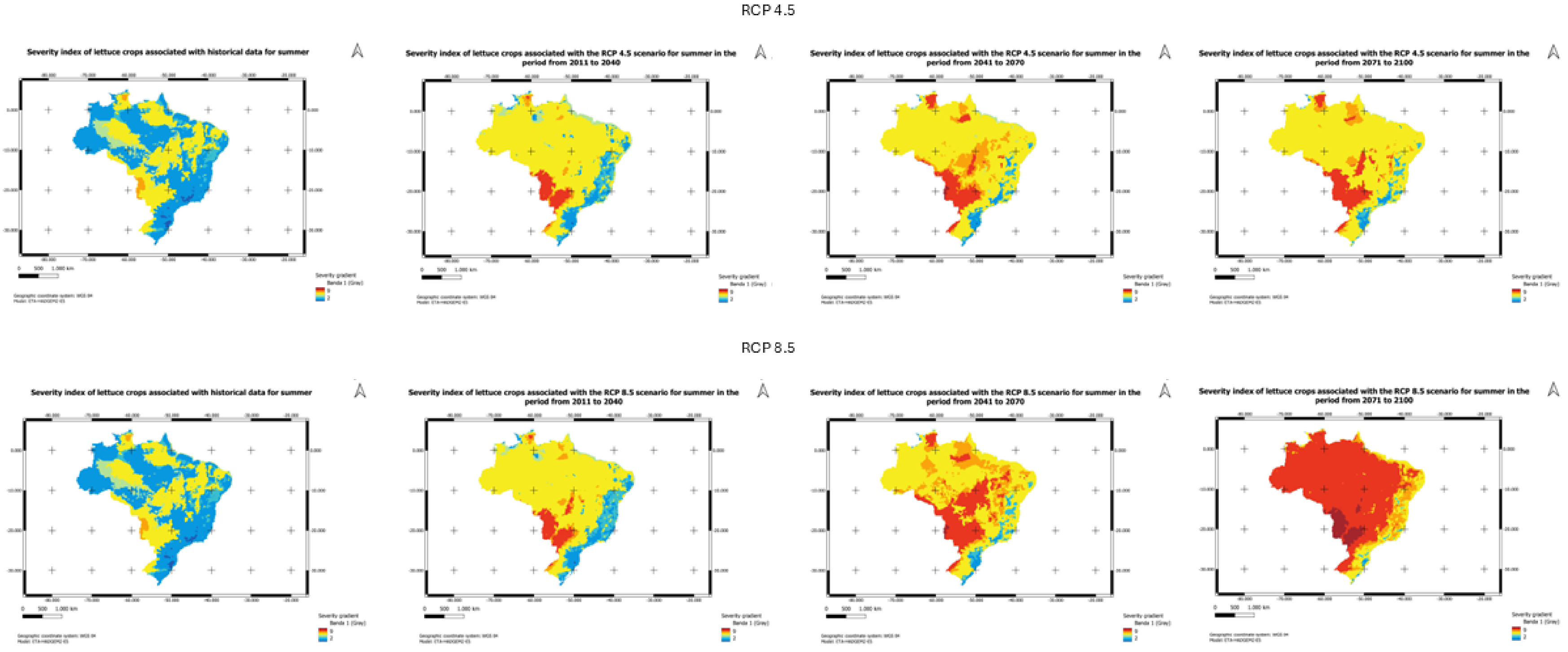
Table 7. Comparison of severity indices between values determined for the end of the century in different scenarios and the historical period.

Season	Historical	RCP 4.5	RCP 8.5	RCP4.5 vs Historical	RCP8.5 vs Historical
Summer	4.30	6.16	7.70	+1.86	+3.40
Autumn	3.74	5.71	7.34	+1.97	+3.60
Winter	3.65	5.29	6.80	+1.64	+3.15
Spring	5.25	6.72	7.66	+1.47	+2.41

Source: Authors (2025).

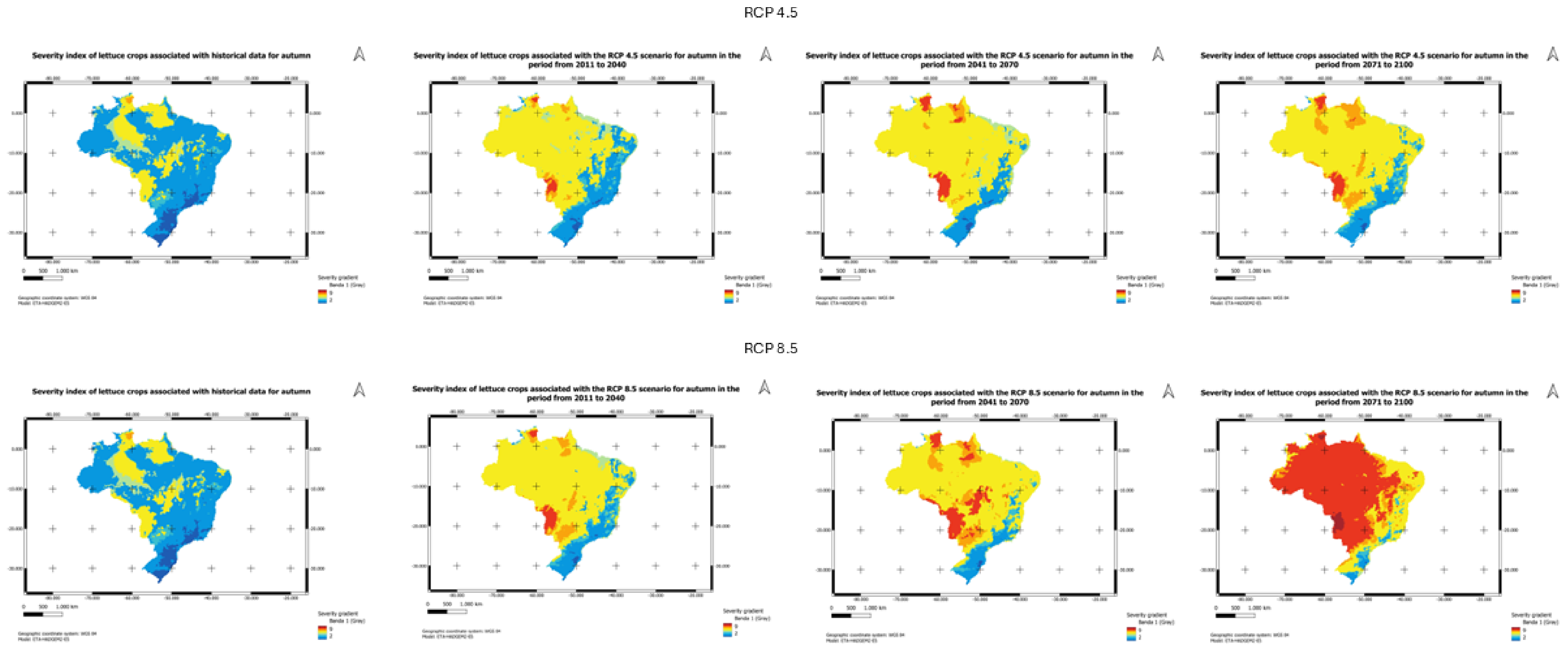
Spatial distribution of IS maps (Figures 7–10) reinforces these findings: under RCP 4.5, thermal impacts are significantly mitigated in summer, autumn, and winter, but spring projections remain concerning. Under RCP 8.5, large red zones dominate almost the entire country in all seasons by the end of the century. In spring and summer, these critical conditions appear as early as the mid-century period (2041–2070).

Figure 7. Comparison between projected severity indices for lettuce crops in summer during the historical period, 2011–2040, 2041–2070, and 2071–2100, under the RCP 4.5 and RCP 8.5 scenarios in Brazil.



Source: Authors (2025).

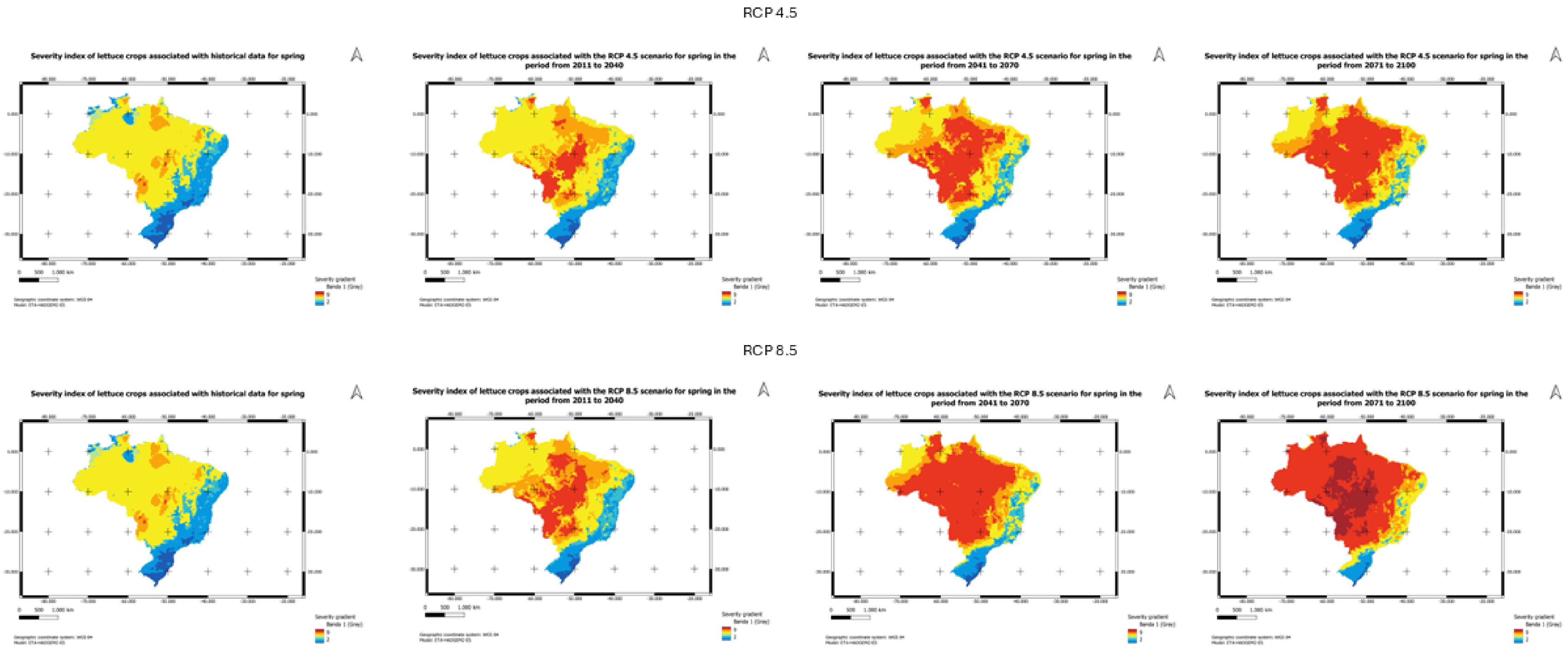
Figure 8. Comparison between projected severity indices for lettuce crops in autumn during the historical period, 2011–2040, 2041–2070, and 2071–2100, under the RCP 4.5 and RCP 8.5 scenarios in Brazil.



Source: Authors (2025).

ISSN: 1983-0882

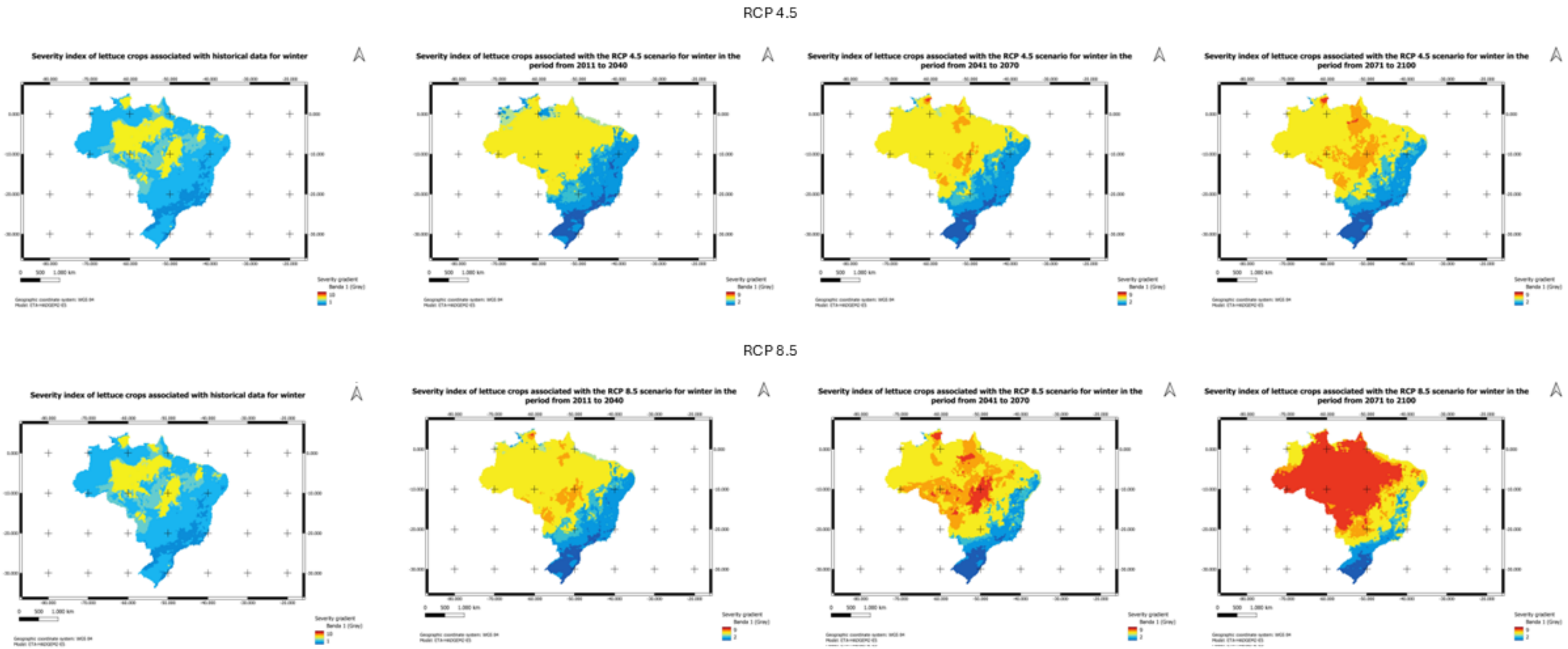
Figure 9. Comparison between projected severity indices for lettuce crops in spring during the historical period, 2011–2040, 2041–2070, and 2071–2100, under the RCP 4.5 and RCP 8.5 scenarios in Brazil.



Source: Authors (2025).

REVISTA CADERNO PEDAGÓGICO – Studies Publicações Ltda.
ISSN: 1983-0882

Figure 10. Comparison between projected severity indices for lettuce crops in winter during the historical period, 2011–2040, 2041–2070, and 2071–2100, under the RCP 4.5 and RCP 8.5 scenarios in Brazil.



Source: Authors (2025).

It is not an exaggeration to state that a new geography of lettuce cultivation must be considered for Brazil under climate change scenarios. Major producing regions, such as those in the South and Southeast, will be heavily impacted, with production restricted by the end of the century (especially under RCP 8.5) to mountainous areas and the far south of the country, unless mitigation, resilience, and adaptation strategies are implemented. Other important production areas, such as the Federal District, where lettuce is the leading vegetable in cultivated area (Emater-DF, 2024), will be even more affected, as they are in the Central-West—a region projected to face severe impacts.

3.4 MORPHOPHYSIOLOGICAL AND AGRONOMIC IMPACTS

Morphophysiological disorders observed under simulated GCC thermal regimes include premature bolting, leaf chlorosis, tipburn, leaf necrosis, and even stand loss (plant mortality) (Lima *et al*., 2024). Other studies have reported reduced mineral fertilizer efficiency (Bento *et al*., 2020), increased irrigation requirements (Eekhout *et al*., 2024), and difficulties in head formation in iceberg-type lettuces (Sala & Costa, 2012). Kobori *et al*. (2012) also reported poor seedling formation, irregular stands, low seed germination, seedling death, leaf bitterness due to latex accumulation, apical meristem loss, and boron deficiency symptoms.

3.5 ADAPTATION AND RESILIENCE STRATEGIES

Given this scenario, urgent strategies must be adopted to enhance the resilience and adaptation of lettuce production systems. Key recommendations must include:

- **Improved climate mapping**: Employing multiple GCMs alongside the ETA model and incorporating higher-resolution datasets such as Wor-ldClim v2.1 (1 km² resolution) (Fick & Hijmans, 2017), as well as more recent CMIP6 models;

- **Plant breeding**: Developing heat-tolerant cultivars with stable morphophysiological responses. Desirable traits include delayed flowering, bolting resistance, and lower susceptibility to physiological disorders (Pereira *et al*., 2024);
- **Production system adjustments**: Incorporating protected environments (e.g., shaded screens, controlled environments), improved irrigation and nutrient management, soil cover, conservation tillage, mulching, and microclimate adjustments to mitigate thermal stress (Pereira *et al*., 2024);
- **Use of biological inputs**: Arbuscular mycorrhizal fungi, rhizobacteria, and endophytic microorganisms have demonstrated potential to improve nutrient uptake, enhance photosynthetic efficiency, and promote antioxidant activity under heat stress (Junrami *et al*., 2022; Tang *et al*., 2022; Anand *et al*., 2023). For lettuce specifically, Bento *et al*. (2020) and Lima *et al*. (2024) showed positive impacts of biofertilizers in improving growth, vigor, and physiological resilience under heat stress.

3.6 POLICY AND SUSTAINABLE DEVELOPMENT IMPLICATIONS

This study aligns strongly with Brazilian public policies such as the ABC+ Plan (Sectoral Plan for Adaptation to Climate Change and Low-Carbon Emissions in Agriculture, 2020–2030), the National Adaptation Plan, and the National Climate Change Policy. It also contributes to the Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger and Sustainable Agriculture), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action).

4 CONCLUSIONS

The results obtained in this study are alarming and reinforce the urgent need for mitigation, adaptation, and resilience strategies in lettuce production systems across Brazil. Thermal projections indicate strong adverse effects on lettuce cultivation under both evaluated scenarios (RCP 4.5 and RCP 8.5), with greater intensity under the high-emission scenario (RCP 8.5). By the end of the century, almost the entire Brazilian territory will face high to very high levels of vulnerability, as expressed by the Thermal Severity Index (IS).

Spatially, the Central-West, Northeast, and Northern regions will be the most affected, followed by the Southeast. The Southern region and some mountainous areas will be less affected and may represent refuges for lettuce production. Seasonally, the greatest impacts will occur in summer and spring.

Therefore, it is not an exaggeration to state that a new geography of lettuce cultivation in Brazil will be necessary in the coming decades. Without adaptation, mitigation, and resilience measures, lettuce production—one of the country's main vegetable crops—will face increasing challenges, directly affecting family farming and food security.

Urgent adaptation measures include the development of heat-tolerant cultivars, the use of protected cultivation systems, improvements in soil and water management, and the use of bio-inputs. These measures must be integrated into agricultural public policies, aligned with the ABC+ Plan and the Sustainable Development Goals.

Finally, the study highlights that adaptation strategies in lettuce production are also a matter of climate justice: a large share of production is carried out by family farmers, who are highly vulnerable and often excluded from adaptation and resilience actions currently implemented in Brazil.

REFERENCES

ANAND, U.; PAL, T.; YADAV, N.; *et al*. Current scenario and future prospects of endophytic microbes: promising candidates for abiotic and biotic stress management for agricultural and environmental sustainability. Microbial Ecology, v. 86, p. 1455–1486, 2023. Disponível em: https://doi.org/10.1007/s00248-023-02190-1. Acesso em: 4 set. 2025.

ASSAD, Eduardo Delgado; ASSAD, Maria Leonor Ribeiro Casimiro Lopes. Mudanças do clima e agropecuária: impactos, mitigação e adaptação. Desafios e oportunidades. Estudos Avançados, São Paulo, v. 38, n. 112, p. 271–292, 2024. Disponível em: <https://doi.org/10.1590/s0103-4014.202438112.015>. Acesso em: 04 ago. 2025.

BENTO, B. M. da C.; FRANÇA, A. C.; OLIVEIRA, R. G.; SARDINHA, L. T.; LEAL, F. D. S. Organic fertilization attenuates heat stress in lettuce cultivation. Acta Agronómica, v. 69, n. 3, p. 219–227, 2020. ISSN 0120-2812. DOI: https://doi.org/10.15446/acag.v69n3.84267.

CARDOSO, Iulli Pitone; SIQUEIRA, Tirzah Moreira; TIMM, Luis Carlos; RODRIGUES, Aryane Araujo; NUNES, Andre Becker. Análise anual de temperatura média e precipitação para a região sul do Rio Grande do Sul. Revista Brasileira de Ciências Ambientais, v. 57, n. 1, p. 58–71, mar. 2022. DOI: https://doi.org/10.5327/Z2176-94781204..

CHOU, S. C.; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; NOBRE, P.; MARENGO, J. Evaluation of the Eta Simulations Nested in Three Global Climate Models. American Journal of Climate Change, v. 3, p. 438-454, 2014a. Disponível em: http://www.scirp.org/journal/PaperInformation.aspx?PaperID=52887#.VakHg_lViko.

CHOU, S. C.; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; MARENGO, J. Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. American Journal of Climate Change, v. 3, p. 512-527, 2014b. Disponível em: http://www.scirp.org/journal/PaperInformation.aspx?PaperID=52877#.VakIh_lVikp. DOI: 10.4236/ajcc.2014.35043. Acesso em: 15 ago. 2025.

CONFEDERAÇÃO NACIONAL DA AGRICULTURA E PECUÁRIA DO BRASIL - CNA. Mapeamento e quantificação da cadeia produtiva de hortaliças. 1 ed. Brasília: CNA, 79 p, 2017. Disponível em:https://www.cnabrasil.org.br/publicacoes/mapeamento-e-quantifica%C3%A7%C3%A3o-da-cadeia-produtiva-das-hortali%C3%A7as Aceso em 15 ago. 2025.

EEKHOUT, J. P. C. *et al*. How future changes in irrigation water supply and demand affect water security in a Mediterranean catchment. Agricultural Water Management, v. 297, 2024, p. 108818. ISSN 0378-3774. Disponível em: https://doi.org/10.1016/j.agwat.2024.108818. Acesso em: 14 ago. 2025.

EMPRESA DE ASSISTÊNCIA TÉCNICA E EXTENSÃO RURAL DO DISTRITO FEDERAL – EMATER-DF. Relatório de Informações Agropecuárias do Distrito Federal – RIA 2024. Brasília: EMATER-DF; SEAGRI-DF; Governo do Distrito Federal, 2024. Disponível em: https://www.emater.df.gov.br. Acesso em: 4 set. 2025.

FERNANDES, Gabriel Siqueira Tavares; LIMA, Edivania de Araujo; ALVES, Adriana Ursulino; BRITO, Victor Alves; SOARES, Lucas Carvalho. Condicionamento agrometeorológico em cultivares de alface. Revista Brasileira de Meteorologia, São Paulo, v. 34, n. 4, p. 505–514, 2019. Disponível em: <https://doi.org/10.1590/0102-7786344064>. Acesso em: 04 ago. 2025.

FICK, S.E.; HIJMANS, R.J. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, v.37, n.12, p.4302-4315, 2017. DOI: https://doi.org/10.1002/joc.5086.

FONTOLAN, Mariana; XAVIER, Ana Carolina Freitas; PEREIRA, Heloisa Ramos; BLAIN, Gabriel Constantino. Using climate change models to assess the probability of weather extremes events: a local scale study based on the generalized extreme value distribution. Bragantia, Campinas, v. 78, n. 1, p. 146-157, 2019. DOI: https://doi.org/10.1590/1678-4499.2018144.

GO FAIR. FAIR Principles: Findable, Accessible, Interoperable, Reusable. [S.l.]: GO FAIR Initiative, 2016. Disponível em: <https://www.go-fair.org/fair-principles/>. Acesso em: 31 jul. 2025.

GULLINO, Maria Lodovica; GILARDI, Giovanna; GARIBALDI, Angelo. Evaluating severity of leaf spot of lettuce, caused by Allophoma tropica, under a climate change scenario. Phytopathologia Mediterranea, v. 56, n. 2, p. 235–241, 2017. DOI: 10.14601/Phytopathol_Mediterr-20458. Disponível em: <www.fupress.com/pm>. Acesso em: 15 ago. 2025.

HAMADA, E. Methodologies for drawing up maps of future climate scenarios. In: Lima, C.E.P.; Fontenelle, M.R.; Braga, M.B (Ed.). Climate change and vegetable production: projections, impacts, adaptive and mitigating strategies. 1 ed. Brasília, Embrapa, 2015. 17-32.

HENZ, Gilmar Paulo; SUINAGA, Fábio. Tipos de alface cultivados no Brasil. Brasília, DF: Embrapa Hortaliças, nov. 2009. 7 p. (Comunicado Técnico, n. 75). ISSN 1414-9850. Disponível em: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/881897/tipos-de-alface-cultivados-no-brasil>. Acesso em: 04 ago. 2025.

HORTIFRUTI BRASIL. HORTIFRUTI/CEPEA: Quais são as frutas e hortaliças mais consumidas pelos brasileiros? Piracicaba: Hortifruti Brasil, 25 mar. 2021. Disponível em: https://www.hfbrasil.org.br/br/hortifruti-cepea-quais-sao-as-frutas-e-hortalicas-mais-consumidas-pelos-brasileiros.aspx. Acesso em: 13 ago. 2025.

INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE). Guia PROJETA: Projeções Climáticas para Estudos de Impacto e Adaptação no Brasil. São José dos Campos: INPE, 2025. Disponível em: https://ftp1.cptec.inpe.br/pesquisa/grpeta/petamdl/Download/PROJETA/Guia_Projeta_Final_01-10.pdf. Acesso em: 12 ago. 2025.

IPCC. AR 6 Synthesis Report: Climate Change 2023 - Summary for Policymakers. IPCC, 2023, 36 p.

IPCC. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva: IPCC, 2014. 151 p.

IPCC. Climate change 2021: the physical science basis - Summary for Policymakers. IPCC, 2021, 32 p.

IPCC. Global warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. [Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P. R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; Connors, S.; Matthews, J. B. R.; Chen, Y.; Zhou, X.; Gomis, M. I.; Lonnoy, E.; Maycock, T.; Tignor, M.; Waterfield, T. (eds.)]. Geneva: IPCC, 2018. 616 p. Disponível em: https://www.ipcc.ch/sr15/. Acesso em: 10 ago. 2025.

JUNRAMI, K.; BATHIA, V.S.; KATARIA, S.; ALAMRI, S.A.; SIDDIQUI, M.H.; RASTOGI, A. Inoculation with arbuscular mycorrhizal fungi alleviates the adverse effects of high temperature in soybean. Plants, 11, 2210, 2022.

KET, Pinnara; GARRÉ, Sarah; OEURNG, Chantha; HOK, Lyda; DEGRÉ, Aurore. Simulation of crop growth and water-saving irrigation scenarios for lettuce: a monsoon-climate case study in Kampong Chhnang, Cambodia. Water, v. 10, n. 666, p. 1-23, 2018.

KIST, Benno Bernardo; BELING, Romar Rudolfo; JUNGBLUT, Guido (trad.). Anuário brasileiro de Horti&Fruti 2024. Santa Cruz do Sul: Editora Gazeta Santa Cruz, 2023. 94 p. ISSN 2178-0897.

KOBORI, R.F.; BRUNELLI, K.R.; GIORIA, R. Potential impact of climate change on lettuce diseases in Brazil. In: Ghini, R.; Hamada, E.; Bertiol, W. (Ed.). Impacts of climate change on important crop diseases in Brazil. Jaguariúna: Embrapa Meio Ambiente, 2012, p. 129-144.

LAFTA, Abbas; SANDOYA, German; MOU, Beiquan. Genetic variation and genotype by environment interaction for heat tolerance in crisphead lettuce. HortScience, v. 56, n. 2, p. 126–135, 2021. DOI: 10.21273/HORTSCI15209-20.

Disponível em: https://doi.org/10.21273/HORTSCI15209-20. Acesso em: 09 ago. 2025.

LAFTA, Abbas; TURINI, Thomas; SANDOYA, German V.; MOU, Beiquan. Field evaluation of green and red leaf lettuce genotypes in the Imperial, San Joaquin, and Salinas Valleys of California for heat tolerance and extension of the growing seasons. HortScience, v. 52, n. 1, p. 40–48, 2017. DOI: 10.21273/HORTSCI10835-16. Disponível em: https://doi.org/10.21273/HORTSCI10835-16. Acesso em: 15 ago. 2025.

LIMA, C. E. P.; FONTENELLE, M. R.; BRAGA, M. B. Climate Projections of Tmin, Tmax and Tmean in Brazil (2011–2100) under RCP 4.5 & RCP 8.5 using Eta-HadGEM2-ES (v.1.1.0). Zenodo, 2025b. Disponível em: https://doi.org/10.5281/zenodo.16738108. Acesso em: 4 set. 2025.

LIMA, C. E. P.; FONTENELLE, M. R.; SUINAGA, F. A.; BRAGA, M. B.; GUEDES, I. M. R.; SILVA, J. Thermal Vulnerability Maps – v1.0.1 (v.1.0.1). Zenodo, 2025d. Disponível em: https://doi.org/10.5281/zenodo.17037290. Acesso em: 4 set. 2025.

LIMA, C. E. P.; FONTENELLE, M. R.; SUINAGA, F. A.; BRAGA, M. B.; GUEDES, I. M. R.; SILVA, J. Thermal Vulnerability Maps – v1.0.0 (v.1.1.0). Zenodo, 2025c. Disponível em: https://doi.org/10.5281/zenodo.16611961. Acesso em: 4 set. 2025.

LIMA, C. E. P.; FONTENELLE, M. R.; SUINAGA, F. A.; GUEDES, I. M. R.; SILVA, J.; BRAGA, M. B. Scripts para automação do mapeamento da vulnerabilidade da alfacicultura brasileira às mudanças climáticas elaborados com apoio de IAs generativas e aprendizado de máquinas (v.1.0.0). Zenodo, 2025a. Disponível em: https://doi.org/10.5281/zenodo.15284458. Acesso em: 4 set. 2025.

LIMA, Carlos Eduardo Pacheco; CAJAMARCA, Sabrina Magaly Navas; TRINDADE, Douglas Martins; FONTENELLE, Mariana Rodrigues; SUINAGA, Fábio Akioshy; FONSECA, Maria Esther de Noronha; BOITEUX, Leonardo Silva; PILON, Lucimeire; BRAGA, Marcos Brandão; GUEDES, Italo Moraes Rocha; SILVA, Juscimar da. Adaptation of lettuce cultivars to high temperatures and different types of fertilization: anticipating management strategies to mitigate the adverse effects of global climate change. Global Research in Environment and Sustainability, v. 2, n. 9, p. 32–51, dez. 2024.

MARENGO, J. A. *et al*. Mudanças climáticas globais e seus efeitos sobre a biodiversidade: caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI. 1. ed. Brasília: Ministério do Meio Ambiente, Secretaria de Biodiversidade e Florestas, Departamento de Conservação da Biodiversidade, 2007. Disponível em: https://www.mctic.gov.br/buscaintegrada. . Acesso em: 4 set. 2025.

MARENGO, Jose A. Mudanças climáticas, impactos e políticas públicas para reduzir impactos. ClimaCom Cultura Científica - Pesquisa, Jornalismo e Arte, ano 5, n. 13, dez. 2018. ISSN 2359-4705.

PELEG, Z.; BLUMWALD, E. Hormone balance and abiotic stress tolerance in crop plants. Current Opinion in Plant Biology, v. 14, n. 3, p. 290–295, 2011. Disponível em: https://doi.org/10.1016/j.pbi.2011.02.001. Acesso em: 4 set. 2025.

PEREIRA, Maryanne C.; SOUZA, Nara O. S.; NASCIMENTO, Warley M.; SILVA, Giovani O. da; SILVA, Caroline R. da; SUINAGA, Fabio A. Stability evaluation for heat tolerance in lettuce: implications and recommendations. Plants, v. 13, n. 11, p. 1546, 2024. Disponível em: https://doi.org/10.3390/plants13111546. Acesso em: 14 ago. 2025.

RESENDE, Francisco Vilela; SAMINÊZ, Tereza Cristina O.; VIDAL, Mariane Carvalho; SOUZA, Ronessa B. de; CLEMENTE, Flávia Maria V. Cultivo de alface em sistema orgânico de produção. Brasília: Embrapa Hortaliças, 2007. 40 p. (Circular Técnica, 56).

SALA, F. C.; COSTA, C. P. Retrospective and trend of Brazilian alfaciculture. Horticultura Brasileira, v. 30, p. 187–194, 2012.

SANTOS, Camila Regina dos. Sistema de produção de alface em cultivo convencional e cultivo hidropônico: alimento de qualidade? 2018. 40 f. Dissertação (Mestrado em Ciências Ambientais) – Universidade Estadual do Oeste do Paraná, Programa de Pós-Graduação em Ciências Ambientais, Toledo, 2018.

SANTOS, Diego Jatobá dos; PEDRA, George Ulguim; BARBOSA, Marcelo Guatura; JÚNIOR, Carlos Augusto Guimarães; ALVES, Lincoln Muniz; SAMPAIO, Gilvan; MARENGO, José Antônio. Future rainfall and temperature changes in Brazil under warming levels of 1.5ºC, 2ºC and 4ºC. Sustainability in Debate, Brasília, v. 11, n. 3, p. 57-73, dez. 2020. DOI: 10.18472/SustDeb.v11n3.2020.

SILVA, G. K. da; DUARTE, A. D. M. J.; LIMA, C. E. S.; SILVA, M. V. M.; SILVEIRA, C. da S. Eta Model and CMIP5 Climate Change Projections for the São Francisco and Paraíba do Sul River Basins, Brazil. Revista Brasileira de Meteorologia, v. 38, e38210072, 2023. Disponível em: http://dx.doi.org/10.1590/0102-77863810072. Acesso em: 10 jul. 2025.

SOARES, W.R. Climate change projections for Brazil at the end of the 21st century. In: Lima, C.E.P.; Fontenelle, M.R.; Braga, M.B (Ed.). Climate change and vegetable production: projections, impacts, adaptive and mitigating strategies. 1 ed. Brasília, Embrapa, 2015. 33-46.

TANG, H.; HASSAN, M. U.; FENG, L.; NAWAZ, M.; SHAH, A. N.; QARI, S. H.; LIU, Y.; MIAO, J. The critical role of arbuscular mycorrhizal fungi to improve drought tolerance and nitrogen use efficiency in crops. Frontiers in Plant Science, v. 13, p. 919166, 6 jul. 2022. Disponível em: https://doi.org/10.3389/fpls.2022.919166. Acesso em: 4 set. 2025.

VALVERDE, María Cleofé; CALADO, Bianca Nunes; CALADO, Gabrielle Gomes; KUROKI, Larissa Yumi; BRAMBILA, Ricardo; SOUSA, Aline Ramos de. Climate projections of precipitation and temperature in cities from ABC Paulista, in the Metropolitan Region of São Paulo-Brazil. Frontiers in Climate, v. 5, 2023. Disponível em: <https://doi.org/10.3389/fclim.2023.1127026>. Acesso em: 31 jul. 2025.