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EL NIÑO, LA NIÑA Y AGRICULTURA: VARIABILIDAD CLIMÁTICA Y VULNERABILIDAD PRODUCTIVA EN LA REGIÓN NORTE PIONERA DE PARANÁ, BRASIL

EL NIÑO, LA NIÑA AND AGRICULTURE: CLIMATE VARIABILITY AND PRODUCTIVE VULNERABILITY IN THE NORTHERN PIONEER REGION OF PARANÁ, BRAZIL

EL NIÑO, LA NIÑA E AGRICULTURA: INFLUÊNCIAS DA VARIABILIDADE CLIMÁTICA SOBRE A VULNERABILIDADE PRODUTIVA NO NORTE PIONEIRO DO PARANÁ

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RESUMEN

La agricultura constituye una de las actividades económicas más dependientes de las condiciones climáticas, siendo especialmente sensible a las variaciones de temperatura, precipitación y disponibilidad hídrica. En este contexto, los fenómenos El Niño y La Niña, componentes del sistema El Niño-Oscilación del Sur (ENOS), se destacan como importantes mecanismos de variabilidad climática interanual capaces de influir significativamente en los patrones atmosféricos de distintas regiones del planeta. El presente estudio tuvo como objetivo analizar la influencia de estos fenómenos sobre la producción agrícola en los municipios de Cornélio Procópio y Jacarezinho, ubicados en la región Norte Pionero del estado de Paraná, Brasil, con el propósito de comprender las relaciones entre las anomalías climáticas asociadas al ENOS y el desempeño productivo de los principales cultivos regionales. La investigación se desarrolló mediante revisión bibliográfica y análisis de datos climáticos y agrícolas, considerando información relativa a los cultivos de soja, trigo y arroz de riego, así como registros meteorológicos e índices oceánicos relacionados con las fases del ENOS. Los resultados evidenciaron que las alteraciones en los patrones de temperatura y precipitación asociadas a los eventos El Niño y La Niña ejercen una influencia significativa sobre el desarrollo de los cultivos, pudiendo ocasionar tanto incrementos como reducciones en la productividad, dependiendo de la intensidad de los fenómenos, de las características fisiológicas de cada cultivo y de las condiciones ambientales locales. Asimismo, se constató que la variabilidad climática asociada al ENOS representa un importante factor de riesgo para el sector agropecuario regional, destacando la necesidad de integrar información climatológica en los procesos de planificación y gestión agrícola. Se concluye que el monitoreo climático y la adopción de estrategias adaptativas fundamentadas en el conocimiento científico constituyen herramientas esenciales para reducir vulnerabilidades, fortalecer la resiliencia de los sistemas productivos y promover una agricultura más sostenible frente a los desafíos impuestos por el cambio climático contemporáneo.

Palabras clave: El Niño. La Niña. Variabilidad Climática. Agricultura. Norte Pionero de Paraná. Climatología Agrícola.

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ABSTRACT
Agriculture is one of the economic activities most dependent on climatic conditions, being particularly sensitive to variations in temperature, precipitation, and water availability. In this context, the El Niño and La Niña phenomena, which are components of the El Niño-Southern Oscillation (ENSO) system, stand out as important mechanisms of interannual climate variability capable of significantly influencing atmospheric patterns in different regions of the world. This study aimed to analyze the influence of these phenomena on agricultural production in the municipalities of Cornélio Procópio and Jacarezinho, located in the Northern Pioneer Region of Paraná State, Brazil, seeking to understand the relationships between ENSO-related climatic anomalies and the productive performance of the main regional crops. The research was conducted through a bibliographic review and the analysis of climatic and agricultural data, including information on soybean, wheat, and irrigated rice production, as well as meteorological records and oceanic indices associated with ENSO phases. The results demonstrated that changes in temperature and precipitation patterns associated with El Niño and La Niña events exert a significant influence on crop development, leading to either increases or reductions in productivity depending on the intensity of the phenomena, the physiological characteristics of each crop, and local environmental conditions. Furthermore, ENSO-related climate variability was identified as a major risk factor for regional agricultural systems, highlighting the importance of integrating climatological information into agricultural planning and decision-making processes. It is concluded that climate monitoring and the adoption of adaptive strategies based on scientific knowledge are essential tools for reducing vulnerabilities, strengthening the resilience of agricultural systems, and promoting more sustainable agricultural practices in the face of contemporary climate change challenges.

Keywords: El Niño. La Niña. Climate Variability. Agriculture. Norte Pionero de Paraná. Agricultural Climatology.

RESUMO
A agricultura configura-se como uma das atividades econômicas mais dependentes das condições climáticas, sendo particularmente sensível às variações de temperatura, precipitação e disponibilidade hídrica. Nesse contexto, os fenômenos El Niño e La Niña, componentes do sistema El Niño-Oscilação Sul (ENOS), destacam-se como importantes mecanismos de variabilidade climática interanual, capazes de influenciar significativamente os padrões atmosféricos em diferentes regiões do planeta. O presente estudo teve como objetivo analisar a influência desses fenômenos sobre a produção agrícola nos municípios de Cornélio Procópio e Jacarezinho, localizados na região do Norte Pioneiro do Paraná, buscando compreender as relações entre as anomalias climáticas associadas ao ENOS e o desempenho produtivo das principais culturas agrícolas regionais. A pesquisa foi desenvolvida por meio de revisão bibliográfica e análise de dados climáticos e agrícolas, considerando informações referentes às culturas de soja, trigo e arroz irrigado, bem como registros meteorológicos e índices oceânicos relacionados às fases do ENOS. Os resultados evidenciaram que as alterações nos padrões de temperatura e precipitação associadas aos eventos El Niño e La Niña exercem influência significativa sobre o desenvolvimento das culturas agrícolas, podendo ocasionar tanto incrementos quanto reduções na produtividade, dependendo da intensidade dos fenômenos, das características fisiológicas das culturas e das condições ambientais locais. Constatou-se ainda que a variabilidade climática associada ao ENOS representa um importante fator de risco para o setor agropecuário regional, reforçando a necessidade de integração entre informações climatológicas e planejamento agrícola. Conclui-se que o monitoramento climático e a incorporação de estratégias adaptativas fundamentadas no conhecimento científico constituem ferramentas essenciais para a redução de vulnerabilidades, o fortalecimento da resiliência dos sistemas produtivos

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e a promoção de uma agricultura mais sustentável diante dos desafios impostos pelas mudanças climáticas contemporâneas.

Palavras-chave: El Niño. La Niña. Variabilidade Climática. Agricultura. Norte Pioneiro do Paraná. Climatologia Agrícola.

1 INTRODUCTION

Research on the effects of the climatic phenomena El Niño and La Niña on agriculture in the Northern Pioneer Region of Paraná provides an in-depth perspective on productive fluctuations and the challenges faced by local agricultural producers. Focusing on the municipalities of Jacarezinho and Cornélio Procópio, the analysis centers on the region’s principal crops—soybean (first and second harvests), wheat, and irrigated rice—which are directly influenced by seasonal climatic variations. To support this analysis, data were obtained from reliable sources, including the Paraná State Secretariat of Agriculture and Supply (SEAB), the Department of Rural Economy (DERAL), and the National Oceanic and Atmospheric Administration (NOAA). These data were complemented by an extensive bibliographic review of specialized books and scientific articles, providing a robust foundation for data interpretation and analysis.

Organized into thematic sections, this study aims to discuss the complex relationship between climate and agriculture, the broader context of climate change, and the specific effects of the El Niño and La Niña phenomena on agricultural production in two municipalities located in the northern portion of Paraná State. The impacts of El Niño and La Niña on agriculture extend beyond purely productive aspects, also affecting economic and social dimensions, particularly in a region where agriculture constitutes a fundamental economic activity.

This research seeks to examine how climatic phenomena affect agricultural productivity and local historical and social contexts, relating these influences to public policies and farmers’ adaptation strategies. It analyzes climatic vulnerability and resilience within rural livelihoods and the regional economy. Furthermore, the study investigates the direct impacts of climatic variations, such as droughts and floods, on production cycles and explores changes in management practices and crop selection, highlighting the relationship between extreme climatic patterns and agricultural productivity.

The study area encompasses the municipalities of Cornélio Procópio (Figure 1) and Jacarezinho (Figure 2), both located in northern Paraná State, Brazil. Cornélio Procópio has an estimated population of approximately 47,000 inhabitants and a territorial area of about 635 km². Agriculture represents one of the pillars of the municipality’s economy, with soybean, corn, wheat, and historically coffee cultivation playing prominent roles. Coffee production, in particular, has significantly shaped the region’s economic and social identity. This diversified agricultural structure, combined with investments in agricultural technology, seeks to enhance productivity and strengthen the local economic base.

The municipality of Jacarezinho, with an estimated population of approximately 40,000 inhabitants and a territorial area of around 602 km², also has an economy strongly linked to the agricultural sector, particularly sugarcane, soybean, and coffee production. Similar to Cornélio Procópio, Jacarezinho has invested in agricultural practices aimed at increasing productivity and consolidating its economic potential. The municipality also maintains a significant livestock sector, including dairy and beef cattle production, which complements its agricultural activities.

The relevance of this study extends beyond the analysis of climatic impacts on crop production, encompassing the identification of adaptation strategies capable of minimizing losses and maximizing the resilience of the agricultural sector. Among these strategies, the adoption of advanced technologies, crop diversification, and the strengthening of agricultural cooperatives stand out as crucial mechanisms for providing technical and financial support to farmers. Such measures, when combined with effective public policies and investments in climate forecasting, are essential for promoting the economic and environmental sustainability of the region.

Figure 1

Geographic Location of Cornélio Procópio, Paraná State, Brazil

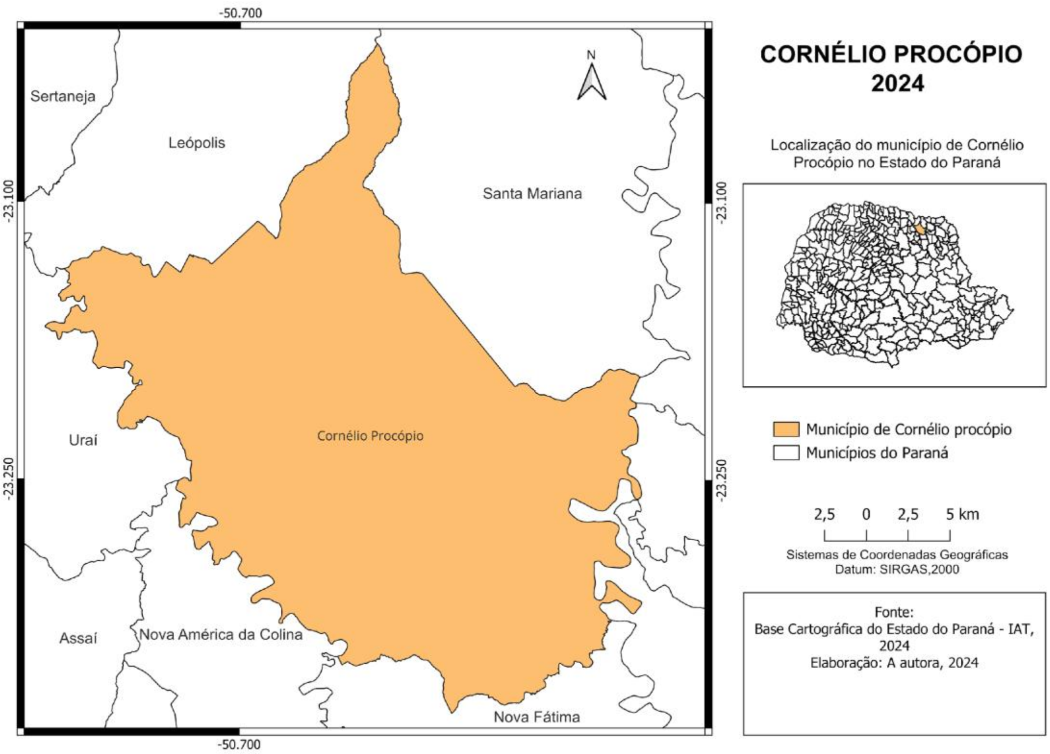

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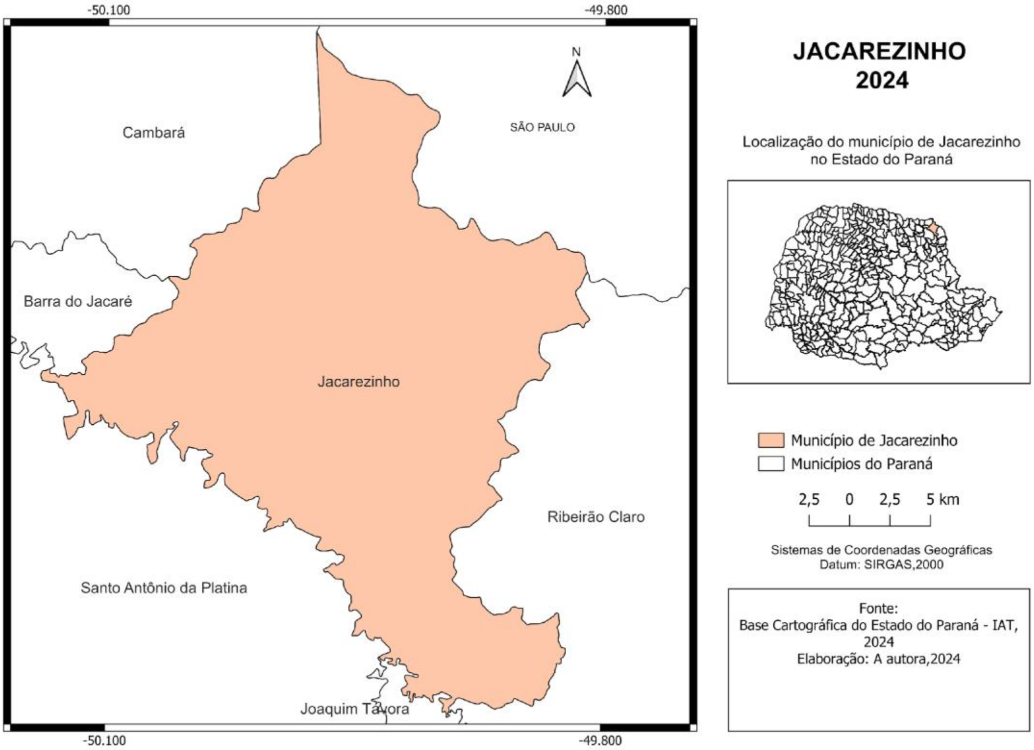
Figure 2

Geographic Location of the Municipality of Jacarezinho, Paraná State, Brazil



In this context, the present study seeks to provide a meaningful contribution to the understanding of agricultural production dynamics under conditions of ongoing climate variability, offering a geographical analysis of the impacts of El Niño and La Niña in northern Paraná State. Through the use of contextualized data, this research aims to expand knowledge regarding the vulnerability of the region's principal crops to these climatic phenomena while encouraging reflection on the adaptation strategies adopted by farmers over time. Rather than serving as a direct basis for public policy formulation, this study seeks to contribute academically to future research and to a broader understanding of the relationship between climate and agriculture within the regional context.

The methodological procedures adopted in this study combined bibliographic research with the analysis of quantitative and qualitative data related to agricultural production in the municipalities of Cornélio Procópio and Jacarezinho. Initially, a comprehensive review of books and scientific articles was conducted to understand the relationship between the climatic phenomena El Niño and La Niña and their impacts on agricultural systems. This review provided the theoretical foundation necessary for interpreting the collected data and establishing correlations between climatic events and the agricultural crops analyzed.

Data on the production of soybean (first and second harvests), wheat, and irrigated rice were collected for the period from 1996 to 2023, encompassing years influenced by El

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Niño, La Niña, and climatically neutral conditions. These data were systematically organized to facilitate the identification of patterns and trends over time. Such organization enabled an in-depth examination of productive variations associated with different climatic conditions.

The analysis was structured through tables that organized production data according to crop type and year, highlighting climatic influences during each period. These tables served as the primary analytical tool for comparing agricultural yields under different climatic scenarios, allowing for a detailed assessment of the impacts and patterns observed.

Based on this systematization, a comparative analysis was conducted integrating climatic and agricultural data, emphasizing how El Niño and La Niña events directly affected crop productivity. The methodological approach ensured consistency, clarity, and scientific rigor in both data collection and interpretation, contributing to a comprehensive understanding of climatic dynamics and their implications for local agricultural systems.

2 CLIMATE, AGRICULTURE, AND CLIMATE CHANGE

Ayoade (2004) emphasizes the intrinsic relationship between climate and agriculture, highlighting that climate exerts a direct influence on agricultural practices. Climatic conditions are decisive factors in determining the suitability of a region for agricultural activities. Elements such as temperature, precipitation, and humidity directly affect plant growth, water availability, and the development of agricultural pests and diseases. Furthermore, according to Glantz (2001), the ENSO phenomenon (El Niño and La Niña) tends to cause droughts in certain regions, such as Australia and parts of Southeast Asia, while producing excessive rainfall in others, including the western coast of South America. These patterns significantly alter agricultural yields, requiring adaptations in management practices and planning strategies to mitigate adverse impacts.

According to Fritsche-Neto and Borém (2015), within the context of climate change, agriculture encompasses a broad range of crops and soil management practices aimed at food production, including vegetables, fruits, and grains. Understanding such changes is essential, given the extent to which human societies depend on them. Melo and Oliveira (2010) argue that agriculture is a critical component of food security and is highly susceptible to drastic climatic variations. Since climate results from the dynamics of the atmosphere, extreme events such as droughts, floods, and abnormal temperatures may contribute to food insecurity, generating social, environmental, and economic consequences.

Marengo *et al.* (2009) point out that the increasing frequency of extreme climatic events, such as heat waves and intense precipitation, has resulted in floods, landslides, and droughts across several regions. Agriculture is particularly sensitive to such variations, leading to significant social and economic impacts, as noted by Lima (2001). The Intergovernmental Panel on Climate Change (IPCC, 2021) highlights that atmospheric changes have intensified these phenomena, causing substantial damage to agricultural systems, including crop and production losses.

In this regard, climatic changes have become a growing source of concern. In Brazil and throughout Latin America, there is increasing apprehension that short-term climate variability and medium- to long-term climate change will have significant adverse effects on landscapes, agricultural production, national economic growth, and associated livelihoods (Assad & Pinto, 2008; Margulis & Dubeux, 2010).

Furthermore, Magalhães *et al.* (2021, p. 10) state that “temperature and rainfall are the principal climatic variables that will affect global agriculture as a consequence of climate change.” Thus, excessive rainfall may saturate soils when their water absorption capacity is exceeded, leading to soil leaching, a process that plays an important role in nutrient dynamics and soil fertility.

According to Mendonça and Danni-Oliveira (2007), greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) are gaseous substances present in the atmosphere that absorb infrared radiation and retain heat, thereby contributing to the greenhouse effect. This phenomenon results in the warming of the Earth’s surface and atmosphere, playing a crucial role in contemporary climate change processes.

Greenhouse gases can significantly alter atmospheric dynamics. According to data from the Second Brazilian Inventory of Greenhouse Gas Emissions and Removals, published in 2009, Brazil emitted a total of 2,203,362 gigagrams of carbon dioxide equivalent in 2005. Of these emissions, agriculture accounted for 22%, while land use and land-use change were responsible for 57.5%. Consequently, climate and agriculture coexist in a dynamic relationship in which each influences the other, contributing to the transformation of landscapes.

According to the United Nations Framework Convention on Climate Change (1992), climate change is defined as any alteration in climate that is directly or indirectly attributable to human activities that modify the composition of the global atmosphere and that is additional to natural climate variability observed over comparable periods. Therefore, climate change influences not only the immediate state of the atmosphere but also its dynamics over days, months, and across diverse regions. It is important to emphasize that human interactions with the natural environment modify it at multiple spatial and temporal scales.

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Ayoade (1998) argues that climate influences human societies in various ways and, conversely, that human activities influence climate. Almeida (2018) emphasizes that climate change is shaped by diverse historical contexts. McNeill (2000) observes that the Industrial Revolution accelerated the combustion of fossil fuels, intensifying greenhouse gas emissions. Lovelock (2006) further notes that these emissions contribute substantially to climate change. Although anthropogenic actions may not produce immediate effects, their impacts become evident globally over time, demonstrating the significant influence of human activities on the climate system.

Almeida (2018) states that climate change is driven by internal factors, such as variations in the solar system, astronomical effects, and volcanic activity, as well as by external factors, including interactions among the climate system, atmosphere, oceans, and the Earth's surface. Silva (2012) highlights that there is no complete consensus regarding the definitions of climate and climate change. Table 1 presents a temporal scale of climate, illustrating climatic changes at different levels: geological, historical, and contemporary.

Table 1

Temporal Scale of Climate Across Different Time Periods

Classification	Time Scale	Causes
Climate Fluctuation	Less than 10 years	Ocean–atmosphere interactions
Climate Variability	10 years to 100,000 years	Volcanic activity and variations in solar radiation
Climate Change	100,000 years to 10 million years	Changes in Earth's orbital parameters and axial tilt
Anthropogenic Climate Change	Very short-term	Human activities, including urbanization, deforestation, river diversion, and land-use change

Source: modified from Rubens Leite Vianello & Adil Rainier Alves (2012).

Greenhouse gases generated by human activities, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), retain solar heat within the atmosphere, contributing to an imbalance in the global climate system. As noted by Silva (2012, p. 3), climatic elements and, above all, climatic factors are often so complex, variable, highly dynamic, and characterized by chaotic behavior that defining their precise functioning becomes exceedingly difficult. In this sense, climate itself constitutes a complex phenomenon that occasionally exhibits anomalies, such as the El Niño and La Niña events, which do not occur according to a fixed schedule and whose magnitude may be intensified or modified by anthropogenic influences.

Although climatic changes are also part of long-term natural cycles, as highlighted by Conti (2000), they are currently being intensified by human activities. The marked increase in global temperatures, resulting from the combined effects of anthropogenic and natural factors, contributes to a highly dynamic and multifaceted climatic system. These complexities extend beyond simple temperature changes, encompassing a wide range of interactions and responses across different components of the Earth system. Understanding such processes is essential for interpreting the impacts of global warming, including climate patterns associated with the El Niño–Southern Oscillation (ENSO), which exert a profound influence on global climate variability across multiple temporal scales and significantly affect agricultural activities, as discussed throughout this study.

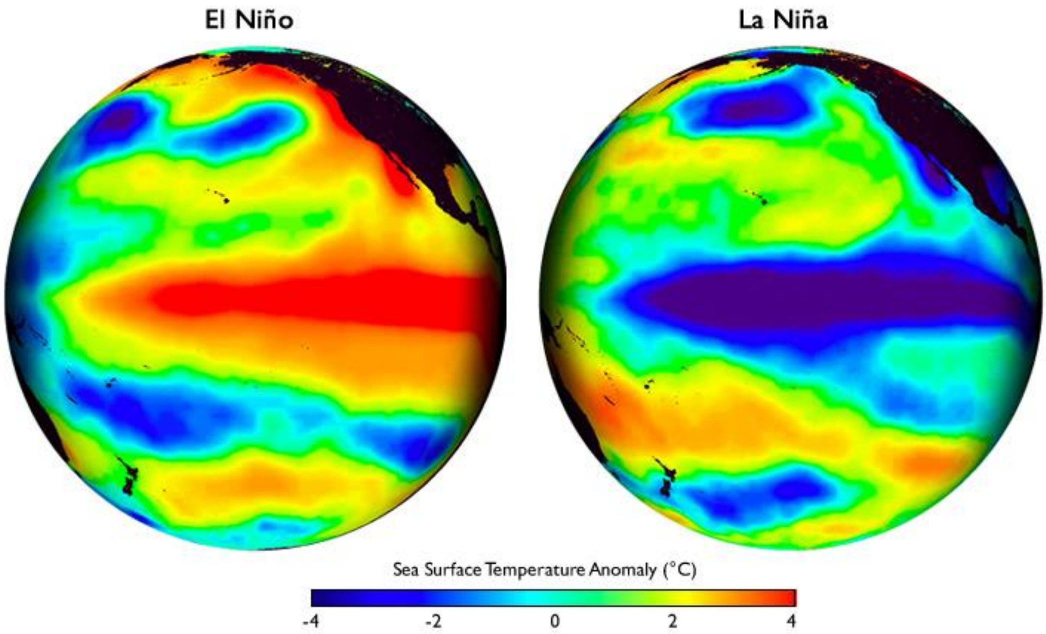
3 EL NIÑO AND LA NIÑA

The ENSO (El Niño–Southern Oscillation) phenomenon comprises two principal phases: the warm phase, known as El Niño, and the cold phase, known as La Niña. Both are associated with variations in sea surface temperatures across the tropical Pacific Ocean. According to Glantz (2001), these changes, accompanied by fluctuations in atmospheric pressure fields represented by the Southern Oscillation Index (SOI), affect the general circulation of the atmosphere and influence climatic conditions in numerous regions around the world. Viegas (2018) identifies ENSO as the most widely recognized phenomenon of interannual climate variability, responsible for anomalous patterns in atmospheric dynamics and precipitation across tropical, subtropical, and extratropical regions, particularly affecting South America.

Furthermore, Oliveira (2015) notes that ENSO weakens the trade winds in the equatorial region, thereby altering atmospheric circulation patterns. This weakening results in distinct precipitation regimes and drought periods in various regions. During episodes of sea surface cooling, changes in wind patterns cause warm ocean waters to be displaced from east to west, influencing climate conditions on a global scale. Figure 3 illustrates the warming and cooling of Pacific Ocean waters along the western coast of the Americas, corresponding respectively to El Niño and La Niña events.

Figure 3

Schematic Representation of Sea Surface Temperature Anomalies in the Tropical Pacific Ocean During El Niño and La Niña Events



Source: adapted from Observatório Histórico - Geográfico (2015).

During El Niño events, sea surface waters in the equatorial Pacific Ocean become warmer than average, represented by the red-shaded areas, altering atmospheric circulation patterns and triggering climatic changes on a global scale, such as intense rainfall in some regions and drought conditions in others. In contrast, during La Niña events, sea surface temperatures in the same region fall below average, indicated by the dark blue areas, strengthening the trade winds and producing climatic effects generally opposite to those associated with El Niño. As a result, regions that typically experience increased rainfall during El Niño may face drought conditions during La Niña, and vice versa. These climatic oscillations directly affect agriculture, precipitation regimes, and temperature patterns across many parts of the world, including Brazil.

The El Niño phenomenon results largely from interactions between the atmosphere and the ocean, producing impacts that extend across multiple components of the Earth system on a global scale through the warming of ocean waters. According to data from the Federal University of Pelotas [n.d.], sea surface temperatures during El Niño events may reach, on average, up to 4°C above normal conditions. Conversely, La Niña is characterized by anomalously cooler waters in the tropical Pacific Ocean. It is important to emphasize that both phenomena occur within the same geographical region, although they differ in terms of characteristics and intensity. As noted by Oliveira (2001), the climatic phenomena known as

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El Niño and La Niña generally occur within alternating cycles lasting approximately three to seven years, although the interval between successive events may vary from one to ten years.

A comprehensive understanding of ENSO requires consideration not only of its global-scale consequences but also of its local impacts. One example is the fishing industry along the Peruvian coast, which may be profoundly affected during La Niña events. According to Oliveira (1999), when trade winds weaken over the Pacific Ocean, ocean currents decrease in velocity, causing surface waters to become more stationary and consequently warmer.

In the Brazilian context, Oliveira (1999) further notes that during La Niña events, southern Brazil tends to experience cooler summer temperatures, while the Northeast region often records a substantial increase in rainfall. In the Amazon Basin, river discharge generally increases, making the region more susceptible to flooding. During winter, southern Brazil tends to become drier when compared to El Niño periods, which are typically characterized by frequent and intense rainfall. Consequently, ENSO events influence multiple dimensions of society and environmental systems.

A study conducted by Salini (2011) analyzed 61 years of climatic data from the Taquari-Antas River Basin, located in the Taquari Valley within the municipality of Estrela, Rio Grande do Sul, and recorded a total of 31 flood events. During El Niño periods, which accounted for 182 months, only 10 floods were observed. In contrast, during neutral conditions, totaling 349 months, 15 floods occurred. During the 201 months classified as La Niña periods, only six floods were recorded. These findings indicate a variable distribution of flooding events across different climatic phases, representing 32.25% of occurrences during El Niño, 48.38% during neutral periods, and 19.35% during La Niña conditions (Salini, 2011).

Another example of ENSO-related impacts occurred during a low-intensity El Niño event between December 2 and December 9, 2018, when southerly winds with velocities ranging from 11 to 13 meters per second displaced significant volumes of ocean water toward the coast of Rio Grande do Sul. This phenomenon resulted in increased salinity levels in the Patos Lagoon (Wills, 2002). Milliman and Farnsworth (2001) argue that elevated salinity may negatively affect coastal ecosystems by increasing stress on species adapted to freshwater environments, thereby compromising their survival and reproductive capacity. Furthermore, high salinity levels may adversely affect agriculture by intensifying the salinization of irrigated soils, reducing the productivity of crops sensitive to saline conditions.

Similarly, Castro (2001) reports that El Niño episodes have occurred with relative frequency along the coast of Paracuru, in the state of Ceará, over a 41-year period. These events are characterized by low precipitation indices. During such periods, strong aeolian transport of sediments occurs, resulting in intense sediment mobilization. According to Castro (2001), this process promotes the displacement of transverse mobile dunes, which may bury coastal lagoons, agricultural lands, and portions of the coastal plain, thereby causing damage to agricultural activities and aquatic environments. It is also important to note that excessive soil moisture may lead to root asphyxiation, impairing the absorption of nutrients and oxygen. Consequently, crop quality and yield may decline, while susceptibility to fungal diseases and other plant pathologies increases.

Furthermore, Alves (2000) highlights that high relative humidity and persistent rainfall during harvest periods contribute to the deterioration of grain quality, reducing both yield and market value. Such impacts demonstrate the vulnerability of agricultural systems to atmospheric alterations and reinforce the importance of adopting appropriate land-use and management strategies to mitigate the adverse effects associated with ENSO-related climatic variability.

4 CLIMATIC INFLUENCES ON SOYBEAN, WHEAT, AND IRRIGATED RICE PRODUCTION IN THE MUNICIPALITIES OF CORNÉLIO PROCÓPIO AND JACAREZINHO, PARANÁ STATE, BRAZIL

Agriculture, as an activity highly dependent on climatic conditions, may experience significant impacts resulting from climate variability and climate change, generating considerable social, environmental, and economic consequences (Lima, 2001). Several factors, including plant physiology, water availability, soil fertility, soil erosion, pest and disease dynamics, and soil salinization, can be directly influenced by climatic alterations (Pritchard & Amthor, 2005).

According to Farias *et al.* (2007), climatic factors play a crucial role in soybean cultivation, particularly temperature, which is one of the most important meteorological variables affecting crop growth and development. Studies indicate that soybean achieves optimal development under thermal conditions ranging from 20°C to 30°C, with a base temperature of 10°C and a maximum threshold of 40°C. Temperatures exceeding 40°C during the flowering period may cause significant damage, impairing pod retention and consequently reducing productivity.

Furthermore, Neumaier *et al.* (2000) emphasize that during the initial developmental stages, which are particularly sensitive, temperatures above 35°C combined with the absence of wind and cloud cover may cause excessive heating of the soil surface, reaching

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temperatures of up to 55°C. Such conditions may result in physiological lodging and severe stress to soybean plants.

In this context, soybean sensitivity to thermal conditions becomes especially relevant when considering El Niño events. During El Niño years, global temperatures tend to increase, potentially intensifying heat stress effects on soybean crops. Consequently, El Niño may exacerbate problems associated with soil overheating and negatively affect plant development and productivity.

Similarly, air temperature is one of the most influential factors in wheat development, a crop that depends on cooler thermal conditions to induce flowering through a process known as vernalization (Streck *et al.*, 2003). Wheat cultivars are classified according to their vernalization requirements, with winter varieties exhibiting a greater dependence on this process, whereas spring varieties require less exposure to low temperatures. According to Walter *et al.* (2009), spring wheat cultivars are predominantly grown in Brazil, particularly in the southern region, where autumn climatic conditions are more favorable for cultivation, since the Brazilian environment generally does not provide adequate conditions for the flowering of winter wheat varieties.

Streck and Alberto (2006) investigated the impacts of climate change on wheat yields in Santa Maria, Rio Grande do Sul, by simulating scenarios involving increased temperatures and atmospheric CO_2 concentrations. Their results indicated that temperature increases ranging from 3°C to 6°C, combined with atmospheric CO_2 concentrations of 700 ppm, offset the potential positive effects of CO_2 fertilization on wheat productivity, with the most severe impacts occurring under warming scenarios of 5°C and 6°C. Conversely, some scenarios indicated potential yield increases. Siqueira *et al.* (2001) also reported that rising temperatures accelerate wheat developmental cycles, leading to reduced productivity due to shortened growth periods.

Accordingly, based on the findings of Streck and Alberto (2006), when these effects are associated with La Niña events, the impacts on wheat cultivation may become even more complex. During La Niña episodes, lower temperatures may favor the vernalization requirements of winter wheat varieties in regions where such conditions would not normally occur. However, increased precipitation in certain areas may result in excessive soil moisture, negatively affecting crop yields. Therefore, the influence of La Niña on wheat production depends on a delicate interaction between temperature and precipitation, which varies according to geographic location and the wheat cultivar being grown.

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According to Monteiro (2009), irrigated rice cultivated under controlled flooding systems is widely grown in southern Brazil, particularly in the states of Rio Grande do Sul and Santa Catarina, and is highly sensitive to climatic conditions, especially temperature. Yoshida and Parao (1976) report that the cardinal temperatures for rice development range from 7°C to 20°C (base), 20°C to 35°C (optimum), and 30°C to 45°C (maximum), with the reproductive stage being the most vulnerable phase of development. During flowering, temperatures exceeding 33°C may interrupt reproductive processes. Yamakawa *et al.* (2007) observed that elevated temperatures, such as 33°C during grain filling and maturation, reduce grain weight and increase the occurrence of chalky grains, thereby compromising grain quality.

Therefore, temperature constitutes a critical factor for soybean, wheat, and rice cultivation in Brazil. El Niño, characterized by the warming of Pacific Ocean waters, tends to increase temperatures, potentially impairing soybean development during flowering and rice production when thermal thresholds exceed optimal levels. In contrast, La Niña may favor wheat vernalization processes while simultaneously increasing precipitation, which may negatively affect certain crops depending on local conditions. Understanding the impacts of these climatic phenomena is essential for developing adaptive agricultural practices capable of minimizing economic losses and enhancing agricultural resilience. Table 2 presents data regarding the occurrence of ENSO phases from 1996 onward, including El Niño, La Niña, and neutral years.

Table 2

El Niño and La Niña Events Since 1996, Neutral Periods, and Their Respective Onset and Termination Dates

Years	ENSO Phase	Onset and Termination Months
1996–1997	Neutral Phase	January 1996 to April 1997
1997–1998	El Niño	May 1997 to May 1998
1998–2000	La Niña	July 1998 to December 2000
2001–2002	Neutral Phase	January 2001 to May 2002
2002	El Niño	July 2002 to December 2002
2003–2004	Neutral Phase	January 2003 to June 2004
2004	El Niño	July 2004 to December 2004
2005–2007	Neutral Phase	January 2005 to May 2007
2007–2008	La Niña	June 2007 to June 2008
2009	El Niño	July 2009 to December 2009
2010–2011	La Niña	June 2010 to December 2011

2012–2014	Neutral Phase	January 2012 to December 2014
2015	El Niño	January 2015 to December 2015
2016	La Niña	August 2016 to December 2016
2017–2018	Neutral Phase	January 2017 to December 2018
2019–2020	El Niño	January 2019 to July 2020
2020–2022	La Niña	August 2020 to December 2022
2023	El Niño	May 2023 to December 2023

Source: nOAA - National Oceanic and Atmospheric Administration. Historical El Niño/La Niña episodes (1950-present) based on the ONI (Oceanic Niño Index).

The following data present agricultural production records for soybean (first and second harvests), wheat, and irrigated rice in the municipalities of Jacarezinho and Cornélio Procópio between 1997 and 2023 (Tables 3 and 4). These data illustrate variations in agricultural production over time, reflecting how climatic cycles and meteorological phenomena, such as El Niño and La Niña, may influence the performance of these economically important crops. Furthermore, the comparative analysis between the two municipalities enables the identification of regional differences in agricultural productivity, highlighting the distinct responses of local production systems to climatic variability and environmental conditions.

Table 3

Agricultural Production of Soybean (First and Second Harvests), Wheat, and Irrigated Rice in Cornélio Procópio, Paraná State, Brazil, 1997–2023 (tons)

Crop Year	Soybean (t)	Wheat (t)	Irrigated Rice (t)
1996 - 1997	435.904,00	176.578,00	7.750,00
1997 - 1998	409.684,00	230.060,00	6.110,00
1998 - 1999	490.416,00	202.410,00	4.423,00
1999 - 2000	358.700,00	83.833,00	2.620,00
2000 - 2001	555.550,00	262.904,00	2.956,50
2001 - 2002	501.927,00	237.420,00	3.681,10
2002 - 2003	665.300,00	525.540,00	4.260,50
2003 - 2004	691.120,00	500.650,00	3.361,00
2004 - 2005	544.240,00	443.100,00	2.178,60
2005 - 2006	609.062,00	46.512,20	2.145,00
2006 - 2007	728.120,00	238.837,00	2.450,15
2007 - 2008	740.523,50	495.186,90	2.349,85
2008 - 2009	515.634,62	240.336,00	1.551,80
2009 - 2010	870.092,00	354.614,80	1.645,40

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2010 - 2011	1.055.112,50	183.523,42	1.409,91
2011 - 2012	753.852,30	201.836,90	1.184,21
2012 - 2013	1.090.884,00	119.871,26	970,02
2013 - 2014	577.621,20	373.252,20	716,30
2014 - 2015	1.019.434,20	399.286,88	630,12
2015 - 2016	978.672,00	346.436,10	302,40
2016 - 2017	1.252.081,20	315.301,80	273,60
2017 - 2018	1.129.248,00	177.081,00	340,28
2018 - 2019	950.235,00	250.012,80	230,40
2019 - 2020	1.183.951,80	284.820,00	239,04
2020 - 2021	1.205.133,00	170.994,60	233,28
2021 - 2022	939.644,80	258.039,60	241,92
2022 - 2023	1.259.353,20	287.992,80	230,40

Source: secretaria da Agricultura e do Abastecimento - Historical Time Series of Agricultural Production by Municipality (1997 a 2023).

Table 4

Soybean (First and Second Harvests), Wheat, and Irrigated Rice Production in Jacarezinho, Paraná State, Brazil, 1997–2023 (tons)

Year	Soybean (First and Second Harvests) (t)	Wheat (t)	Irrigated Rice (t)
1996 - 1997	62.692,00	28.866,00	7.995,00
1997 - 1998	49.417,00	52.462,00	9.615,00
1998 - 1999	77.247,10	37.814,80	9.879,00
1999 - 2000	64.238,00	12.648,00	8.007,00
2000 - 2001	84.666,50	36.521,00	4.404,00
2001 - 2002	95.732,00	22.032,50	5.600,00
2002 - 2003	116.852,00	81.957,10	5.270,60
2003 - 2004	185.680,00	125.875,00	6.622,00
2004 - 2005	162.994,15	81.507,49	4.809,50
2005 - 2006	156.051,69	15.558,40	7.799,60
2006 - 2007	161.995,00	40.581,60	5.113,00
2007 - 2008	164.496,73	111.908,23	5.063,00
2008 - 2009	179.987,60	78.926,10	6.433,40
2009 - 2010	285.207,65	84.694,16	3.670,00
2010 - 2011	351.355,20	68.902,56	4.455,00
2011 - 2012	260.994,20	94.210,20	3.835,00
2012 - 2013	406.636,10	57.909,50	4.515,00
2013 - 2014	324.740,40	208.861,00	2.525,00
2014 - 2015	495.236,40	129.249,90	3.650,00

2015 - 2016	490.488,24	135.193,50	1.816,00
2016 - 2017	640.598,00	162.407,00	2.254,00
2017 - 2018	616.532,50	123.711,60	952,50
2018 - 2019	542.580,50	70.281,40	631,75
2019 - 2020	574.609,00	139.657,00	638,00
2020 - 2021	669.223,70	136.095,00	816,00
2021 - 2022	631.319,00	142.891,00	1.340,00
2022 - 2023	683.116,30	188.592,50	1.474,00

Source: secretaria da Agricultura e do Abastecimento - Historical Time Series of Agricultural Production by Municipality (1997 a 2023).

In Cornélio Procópio, soybean production exhibited considerable variability over the years, reflecting the combined influence of climatic phenomena and agricultural policies. During the 1996–1997 growing season, production reached approximately 435,904 tons, declining to 409,684 tons in 1997–1998, a period marked by a strong El Niño event. This phenomenon, characterized by higher temperatures and alterations in precipitation patterns, may have negatively affected agricultural production by reducing soil moisture availability, a critical factor for soybean development. According to Assad and Pinto (2008), El Niño events are often associated with increased rainfall in southern Brazil, which can adversely affect crop performance.

Between 1998 and 2000, during a La Niña episode, soybean production increased to 490,416 tons in 1998–1999, reflecting a period of recovery associated with greater climatic stability. In contrast to El Niño, La Niña intensifies average temperatures in southern Brazil, creating more favorable conditions for soybean development (Grimm, 2011). However, in the following agricultural year (1999–2000), production declined sharply to 358,700 tons, likely reflecting climatic variability combined with economic challenges, including the devaluation of the Brazilian Real in 1999, which increased agricultural input costs and reduced producer profitability.

In 2002–2003, during another El Niño event, soybean production increased substantially to 665,300 tons. This period coincided with the expansion of advanced agricultural technologies and government incentives aimed at increasing soybean production to meet growing international demand (Furtado, 2004). In 2003–2004, under neutral climatic conditions and a favorable economic environment, production reached 691,120 tons. During this period, increasing global demand, particularly from China, contributed to higher soybean prices and stimulated cultivation.

In 2015, a year characterized by a significant El Niño event, soybean production reached 978,672 tons. Although El Niño conditions are often unfavorable in certain regions, advances in cultivation techniques and farmers' adaptive capacity helped mitigate part of the adverse climatic effects. Nevertheless, Brazil was experiencing a severe economic recession, which limited access to credit and increased production costs, creating additional challenges for agricultural producers (IPEA, 2015).

The 2019–2020 period, also influenced by El Niño conditions, recorded an increase in soybean production to 1,183,951.8 tons. This growth may be associated with several factors, including favorable international soybean prices and incentives promoting sustainable and intensive agricultural production. Furthermore, trade tensions between the United States and China increased global demand for Brazilian soybeans, benefiting producers in Cornélio Procópio and stimulating production growth despite unfavorable climatic conditions.

In 2021–2022, under La Niña conditions, soybean production remained high compared to previous years, reaching 1,259,353.2 tons. During this period, the adoption of climate-adapted agricultural practices and improvements in production efficiency played a crucial role in sustaining growth. Technological innovations, combined with the accumulated experience of local farmers, enabled high productivity levels despite climatic conditions that might otherwise have been unfavorable.

Wheat production also experienced significant fluctuations, reflecting both climatic influences and market-related challenges. In 1996–1997, wheat production totaled 176,578 tons, increasing to 230,060 tons in 1997–1998 due to governmental incentives aimed at diversifying agricultural production and reducing Brazil's dependence on wheat imports. However, adverse climatic conditions associated with El Niño in 1998–1999 contributed to a decline to 202,410 tons. Such fluctuations were common during El Niño years, partly due to increased soil leaching and erosion processes that negatively affected wheat cultivation (Grimm, 2011).

Nevertheless, during the 2002–2003 El Niño event, wheat production increased to 525,540 tons as a result of federal subsidy programs and support for wheat cultivation under managed agricultural conditions. This expansion was intended to stimulate domestic production and reduce dependence on imported wheat, a staple commodity within the Brazilian food system (IPEA, 2004).

During the 2007–2008 La Niña event, wheat production reached 495,186.9 tons. Increased temperatures provided favorable conditions for cultivation, allowing producers to improve productivity. However, during the 2015–2016 El Niño event, coinciding with a period

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of economic recession, wheat production declined to 346,436.1 tons, reflecting both adverse climatic conditions and economic constraints that increased production costs and limited access to financing.

Irrigated rice production, in contrast, totaled 7,750 tons in 1996–1997 and exhibited a gradual decline over subsequent years, despite some fluctuations. In 1999–2000, production fell to 2,620 tons, reflecting structural changes within Brazilian agriculture, in which more profitable crops such as soybean and wheat gained priority (Mendes, 2007). During the 2009–2010 El Niño event, irrigated rice production reached only 1,645.4 tons, a decline also associated with reduced institutional support for rice cultivation. By 2022–2023, under La Niña conditions, production had decreased further to 230.4 tons, reflecting producers' preference for more economically attractive crops.

Overall, the analysis suggests that agriculture in Cornélio Procópio demonstrated a significant capacity to respond to challenges imposed by climatic variability and economic conditions. El Niño and La Niña phases directly influenced soybean and wheat yields, while agricultural subsidies, technological innovations, and market incentives shaped the adoption of new production practices and crop diversification strategies. These responses highlight both the adaptive capacity of local producers and the important role of governmental policies in shaping agricultural production patterns in Brazil.

In Jacarezinho, agricultural production likewise provides evidence of the influence of climatic phenomena such as El Niño and La Niña. Analysis of production data from 1996 to 2023 reveals that fluctuations in the productivity of major crops—including soybean (first and second harvests), wheat, and irrigated rice—cannot be attributed solely to meteorological conditions. Over nearly three decades, social, economic, and agricultural policy factors also played fundamental roles in determining both the vulnerability and resilience of agricultural systems to climatic variability.

Soybean, the region's principal crop, exhibited substantial responses to El Niño events. Under neutral climatic conditions in 1996–1997, Jacarezinho produced approximately 62,692 tons of soybeans. However, during the strong El Niño event of 1997–1998, production declined significantly to 49,417 tons. Increased rainfall associated with this phenomenon created difficulties during critical stages of crop development. Neumaier (2017) notes that excessive rainfall and high humidity during the reproductive stage of soybean development may reduce productivity. Lower evaporative demand under such conditions can hinder water and nutrient uptake, resulting in smaller and less productive plants.

During intense El Niño episodes, excessive rainfall may further reduce soybean productivity by increasing the incidence of fungal diseases and complicating agricultural operations such as planting and harvesting. Conditions changed considerably with the onset of La Niña in 1998–1999, when reduced precipitation favored soybean production, which increased to 77,247.1 tons, representing a substantial improvement relative to the previous year.

La Niña is generally associated with climatic conditions opposite to those observed during El Niño, often contributing to drier conditions in southern Brazil and thereby favoring soybean cultivation. This increase in productivity reflects both the resilience of the crop under reduced moisture conditions and the capacity of local farmers to adapt to favorable climatic circumstances. In subsequent years, production remained relatively high until another El Niño event in 2002 contributed to a slight decline to 116,852 tons. This pattern reinforces the influence of ENSO cycles on agricultural dynamics and highlights the challenges they pose for agricultural planning and management.

Wheat cultivation, which is highly sensitive to excessive moisture, also exhibited considerable variability in Jacarezinho. During the 1997–1998 El Niño event, wheat production reached 52,462 tons. However, elevated humidity levels favored fungal diseases and delayed harvesting operations, reducing productivity. In the subsequent La Niña period (1998–1999), accompanied by intense rainfall, production declined to 37,814.8 tons. These observations demonstrate the vulnerability of wheat to climatic variability, as the crop benefits from moderate dry conditions but is highly susceptible to excessive rainfall (Fontana & Berlato, 2000).

Irrigated rice cultivation depends directly on water availability to sustain production levels. During El Niño years such as 1997–1998, when rainfall increased, rice production reached 9,615 tons, although excessive moisture created management challenges. Conversely, during more intense La Niña events, such as that of 2011–2012, reduced water availability significantly affected production, demonstrating that access to water resources remains a key determinant of the sustainability of irrigated rice cultivation in Jacarezinho.

The analysis of agricultural production data from Jacarezinho between 1996 and 2023 indicates that ENSO phenomena exert a direct influence on regional agricultural yields. However, these impacts must be interpreted within broader economic and social contexts. During the 2000s, Brazil experienced sustained economic growth, enabling increased investment in agricultural infrastructure and agronomic research. Agricultural credit programs and the strengthening of EMBRAPA contributed to the expansion and modernization of agricultural practices, promoting greater production stability even under challenging climatic conditions (Santos & Neves, 2015).

In recent years, growing international demand for soybeans, particularly from China, has encouraged the expansion of cultivation into regions more vulnerable to climatic variability, including Jacarezinho. Favorable export markets created incentives for soybean production despite the recurrent challenges posed by El Niño and La Niña events. The adoption of improved management techniques and technologies designed to increase resilience to climatic stressors, such as drought, has become increasingly common. Nevertheless, farmers continue to face difficulties in accurately anticipating and fully mitigating ENSO-related impacts.

Agricultural production in Jacarezinho has therefore been strongly influenced by El Niño and La Niña events, which directly affect crop performance. To reduce these impacts, farmers must adopt adaptive strategies such as crop rotation, adjustments to agricultural calendars, the use of stress-resistant seed varieties, and soil conservation practices including no-till farming and vegetative cover. These measures contribute to soil moisture conservation, reduce potential damages, and improve crop preparedness under adverse climatic conditions. Climate monitoring and crop diversification also play fundamental roles in reducing economic risks associated with extreme climatic events.

Furthermore, the strengthening of agricultural cooperatives, combined with public policies promoting crop insurance and technical assistance, has become essential for enhancing the resilience of the agricultural sector. Investments in technology, infrastructure, and climate early-warning systems are indispensable for addressing the challenges posed by El Niño and La Niña events. As emphasized by Assad and Pinto (2008), integrated strategies and adaptive planning are crucial for ensuring the sustainability and stability of agricultural production while supporting regional economic development under conditions of climatic variability.

5 FINAL CONSIDERATIONS

The results obtained in this study demonstrate that the climatic phenomena El Niño and La Niña exert a significant influence on agricultural production dynamics in the Northern Pioneer Region of Paraná State, particularly in the municipalities of Cornélio Procópio and Jacarezinho. Variations in temperature and precipitation patterns associated with the different phases of the El Niño–Southern Oscillation (ENSO) exhibit substantial potential to affect the productive performance of crops that are strategically important to the regional economy, including soybean, wheat, and irrigated rice.

The analysis revealed that the impacts of these phenomena are not homogeneous across agricultural crops, as each species presents distinct physiological requirements and varying degrees of sensitivity to climatic conditions. In this context, periods characterized by thermal and pluviometric anomalies may favor certain crops while simultaneously impairing the development of others, highlighting the complexity of interactions between climate and agricultural production.

The findings reinforce the importance of climate monitoring and the integration of meteorological and climatological information into agricultural planning processes. Prior knowledge of climatic conditions associated with ENSO phases can support the adoption of more efficient management strategies, reducing production risks and enhancing the adaptive capacity of agricultural systems in the face of climate variability.

Beyond their direct effects on productivity, the results indicate that extreme climatic events also generate significant economic and social implications, particularly in regions whose productive structures are strongly dependent on agricultural activities. Therefore, understanding the relationship between climate variability and agricultural production is essential for supporting territorial planning initiatives, risk management strategies, and the strengthening of regional socioeconomic resilience.

Finally, it should be emphasized that El Niño and La Niña constitute key components of global climate variability, whose effects are likely to become increasingly relevant in a context characterized by the growing frequency and intensity of extreme events associated with contemporary climate change. Consequently, studies that integrate climatology, agriculture, and regional development are essential for advancing the understanding of future challenges facing the agricultural sector and for supporting the development of adaptation and sustainability strategies capable of ensuring greater productive and environmental security for future generations.

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