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

EL NIÑO, LA NIÑA E AGRICULTURA: VARIABILIDADE CLIMÁTICA E VULNERABILIDADE PRODUTIVA NA REGIÃO NORTE PIONEIRO DO PARANÁ, BRASIL

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ABSTRACT

This study investigates the effects of the El Niño and La Niña climate phenomena on agriculture in the Norte Pioneiro region of Paraná, focusing on the municipalities of Jacarezinho and Cornélio Procópio. The analysis addresses the main crops of the region — soya (first and second harvest), wheat and irrigated rice — which are directly influenced by seasonal climate variations. Data were obtained from reliable sources, such as the Secretaria de Estado de Agricultura e Abastecimento (SEAB), the Departamento de Economia Rural (DERAL) and the National Oceanic and Atmospheric Administration (NOAA), in addition to an extensive bibliographic review. The research seeks to explore how climate phenomena affect agricultural productivity and the local historical and social contexts, relating them to public policies and the adaptation strategies adopted by farmers. The results show that the phases of the El Niño-Southern Oscillation (ENSO) exert a direct influence on agricultural yields, underscoring the importance of climate monitoring and adaptive planning to ensure productive, environmental and socio-economic security.

Keywords: El Niño. La Niña. Agriculture. Climate Variability. Paraná.

RESUMO

Este estudo investiga os efeitos dos fenómenos climáticos El Niño e La Niña sobre a agricultura na região do Norte Pioneiro do Paraná, com enfoque nos municípios de Jacarezinho e Cornélio Procópio. A análise aborda as principais culturas da região — soja (primeira e segunda safra), trigo e arroz irrigado — directamente influenciadas pelas variações climáticas sazonais. Os dados foram obtidos a partir de fontes fiáveis, tais como a Secretaria de Estado de Agricultura e Abastecimento (SEAB), o Departamento de Economia Rural (DERAL) e a National Oceanic and Atmospheric Administration (NOAA), além de uma extensa revisão bibliográfica. A pesquisa procura explorar como os fenómenos climáticos afectam a produtividade agrícola e os contextos históricos e sociais locais, relacionando-os com as políticas públicas e as estratégias de adaptação adoptadas pelos agricultores. Os resultados evidenciam que as fases do El Niño-Oscilação Sul (ENOS) exercem influência directa sobre os rendimentos agrícolas, reforçando a importância do monitoramento

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climático e do planeamento adaptativo para garantir segurança produtiva, ambiental e socioeconómica.

Palavras-chave: El Niño. La Niña. Agricultura. Variabilidade Climática. Paraná.

RESUMEN
Este estudio investiga los efectos de los fenómenos climáticos El Niño y La Niña sobre la agricultura en la región del Norte Pionero de Paraná, centrándose en los municipios de Jacarezinho y Cornélio Procópio. El análisis aborda los principales cultivos de la región —soja (primera y segunda cosecha), trigo y arroz de riego—, directamente influenciados por las variaciones climáticas estacionales. Los datos se obtuvieron de fuentes confiables, tales como la Secretaria de Estado de Agricultura e Abastecimento (SEAB), el Departamento de Economia Rural (DERAL) y la National Oceanic and Atmospheric Administration (NOAA), además de una extensa revisión bibliográfica. La investigación busca explorar cómo los fenómenos climáticos afectan la productividad agrícola y los contextos históricos y sociales locales, relacionándolos con las políticas públicas y las estrategias de adaptación adoptadas por los agricultores. Los resultados evidencian que las fases del El Niño-Oscilación del Sur (ENOS) ejercen una influencia directa sobre los rendimientos agrícolas, reforzando la importancia del monitoreo climático y de la planificación adaptativa para garantizar seguridad productiva, ambiental y socioeconómica.

Palabras clave: El Niño. La Niña. Agricultura. Variabilidad Climática. Paraná.

1 INTRODUCTION

Research on the effects of the El Niño and La Niña climate phenomena on agriculture in the Norte Pioneiro region of Paraná offers a detailed perspective on productive fluctuations and the challenges faced by local agricultural producers. Centred on the municipalities of Jacarezinho and Cornélio Procópio, the analysis focuses on the main crops of the region — soya (first and second harvest), wheat and irrigated rice — which are directly influenced by seasonal climate variations. For this analysis, data obtained from reliable sources were used, such as the Secretaria de Estado de Agricultura e Abastecimento (SEAB), the Departamento de Economia Rural (DERAL) and the National Oceanic and Atmospheric Administration (NOAA), in addition to an extensive bibliographic review of scientific articles and specialised books, with the purpose of providing a solid basis of data and interpretations.

Organised into thematic sections, the present work aims to discuss the complex relationship between climate and agriculture, climate change on a broader scale, as well as to deepen the understanding of the El Niño and La Niña phenomena and their specific effects on harvests in two municipalities located in the northern portion of the state of Paraná. The impact of El Niño and La Niña on agriculture transcends strictly productive issues, being reflected also in the economic and social dimensions, especially in a region where agriculture constitutes a fundamental activity.

The research seeks to explore how climate phenomena affect agricultural productivity and the local historical and social contexts, relating them to public policies and the adaptation strategies adopted by farmers. Likewise, it analyses climate vulnerability and resilience in rural daily life and in the regional economy. The study examines the direct impacts of climate variations, such as droughts and floods, on productive cycles. It also investigates the modifications in management practices and in crop selection, highlighting the relationship between extreme climate patterns and agricultural productivity.

The study area of this work comprises the municipalities of Cornélio Procópio (Figure 1) and Jacarezinho (Figure 2), located in the north of the state of Paraná. Cornélio Procópio has approximately 47,000 inhabitants and a territorial area close to 635 km². Agriculture constitutes one of the pillars of the municipal economy, with the cultivation of soya, maize, wheat and, historically, coffee standing out, a crop that has shaped the economic and social identity of the region. This diversified agricultural structure, associated with investments in agricultural technology, seeks to increase productivity and strengthen the local economic base.

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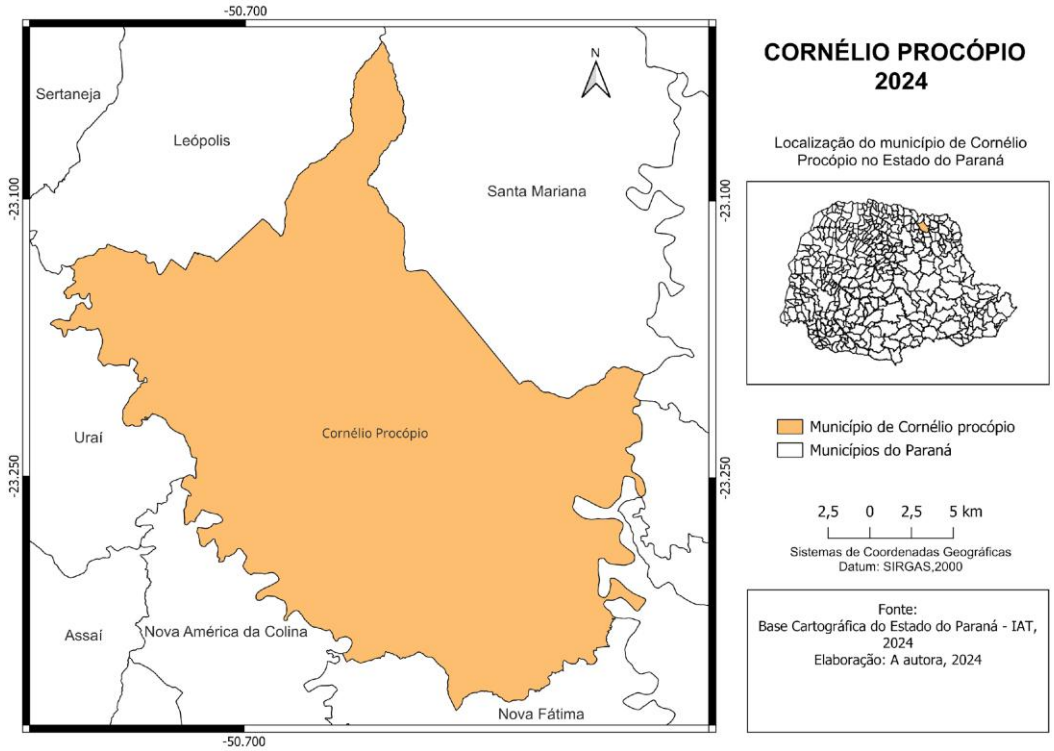
The municipality of Jacarezinho, with approximately 40,000 inhabitants and a territorial extension of around 602 km², also has an economy strongly linked to the agricultural sector, especially to the cultivation of sugar cane, soya and coffee. Like Cornélio Procópio, Jacarezinho has invested in agricultural practices aimed at increasing productivity and consolidating its economic potential. The city also presents an important livestock activity, including the production of milk and bovine meat, which complements the agricultural sector.

The relevance of this study is not limited solely to the analysis of climate impacts on crops, but also encompasses the identification of adaptation strategies capable of minimising losses and maximising the resilience of the agricultural sector. Among these strategies, the use of advanced technologies, crop diversification and the strengthening of agricultural cooperatives stand out, which have played a fundamental role in providing technical and financial support to rural producers. These measures, associated with effective public policies and investments in climate prediction systems, are essential to promote the economic and environmental sustainability of the region.

Figure 1

Location of the Municipality of Cornélio Procópio, State of Paraná, Brazil



Source: prepared by the authors.

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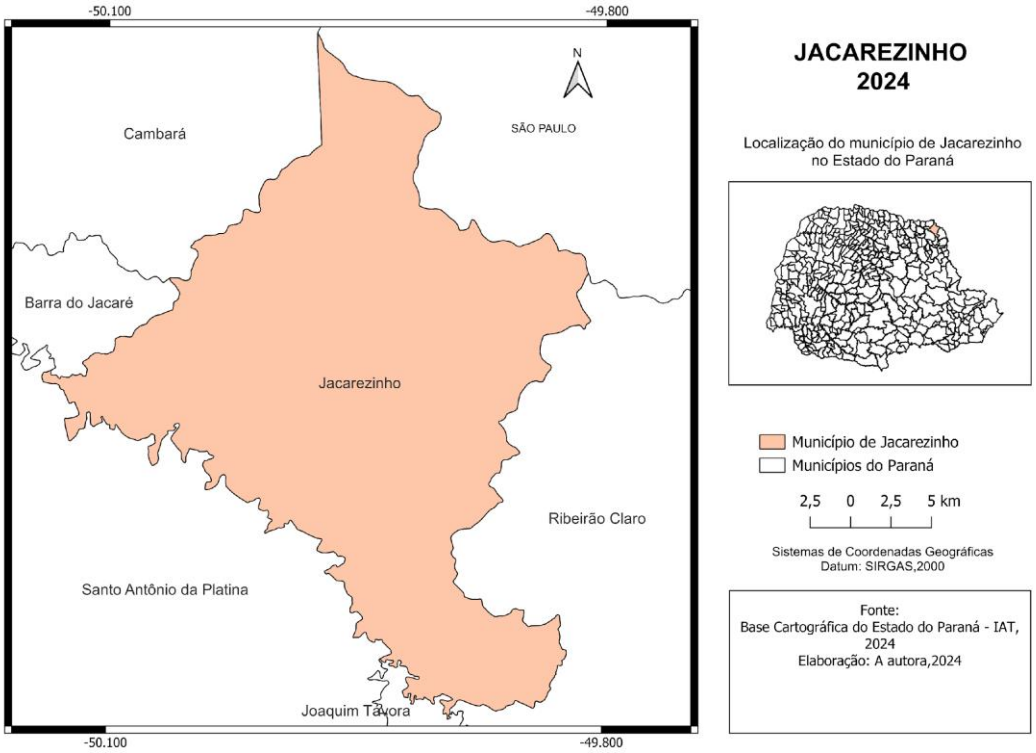
Figure 2

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



Source: prepared by the authors.

In this way, the study seeks to offer a relevant contribution to the understanding of the dynamics of agricultural production in a scenario of constant climate change, providing a geographical analysis of the impacts of El Niño and La Niña in the north of the state of Paraná. Based on contextualised data, the aim is to broaden knowledge about the vulnerability of the main crops of the region to these phenomena, promoting a reflection on the adaptation strategies adopted by farmers over the years. This approach does not have as its purpose to provide direct bases for the formulation of public policies, but to contribute academically to future research and to a broader understanding of the relationship between climate and agriculture in 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 theoretical review based on books and scientific articles was carried out with the objective of understanding the relationship between the El Niño and La Niña climate phenomena and their impacts on agriculture. This review provided the theoretical basis necessary to interpret the data collected and to establish correlations between climate events and the crops analysed.

Data were collected on the production of soya (first and second harvest), wheat and irrigated rice during the period between 1996 and 2023, considering years influenced by El Niño, La Niña and climatically neutral conditions. These data were systematised in order to facilitate the identification of patterns and trends over time. This organisation made it possible to develop a detailed analysis of the productive variations as a function of climate conditions.

The analysis was structured by means of tables that organised the information by crop and year, highlighting the climate influences observed in each period. These tables constituted the main tool for comparing agricultural yields under different climate contexts, allowing a detailed assessment of the impacts and of the patterns identified.

From this systematisation, it was possible to carry out a comparative analysis that integrated the climate and agricultural data, highlighting how the El Niño and La Niña phenomena directly affected the productivity of the crops. The methodology adopted ensured clarity and scientific rigour both in the collection and in the interpretation of the data, contributing to a deeper understanding of the climate dynamics and of their implications for local agriculture.

2 CLIMATE, AGRICULTURE AND CLIMATE CHANGE

Ayoade (2004) highlights the intrinsic relationship between climate and agriculture, emphasising that climate exerts a direct influence on agricultural practices. Climate conditions are determinant for the suitability of a region for agricultural activities. Elements such as temperature, precipitation and humidity directly influence 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) also tends to cause droughts in some regions, such as Australia and parts of Southeast Asia, while it may cause excessive precipitation in others, such as the western coast of South America. These patterns significantly alter agricultural yields, requiring the adaptation of management and planning practices to mitigate the negative impacts.

According to Fritsche-Neto and Borém (2015), in the context of climate change, agriculture encompasses a wide range of crops and soil management practices oriented towards food production, such as vegetables, fruits and cereals. Understanding these changes is indispensable owing to the close dependence of human societies on climate conditions. According to Melo and Oliveira (2010), agriculture constitutes a fundamental element for food security, which is exposed to climate variations and to their potentially drastic effects. Since climate is the result of atmospheric dynamics, extreme phenomena such as

droughts, floods and anomalous temperatures may generate food insecurity, causing social, environmental and economic consequences.

Marengo *et al.* (2009) point out that the increase in the frequency of extreme climate events, such as heat waves and intense precipitation, has caused floods, landslides and droughts in various regions. Agriculture is particularly sensitive to these variations, which translates into important social and economic impacts, as Lima (2001) highlights. The Intergovernmental Panel on Climate Change (IPCC, 2021) points out that atmospheric alterations have intensified these phenomena, causing significant damage to agriculture, including crop losses and reduction of production.

In this context, climate transformations have generated a growing concern. In Brazil and Latin America, there is an increasing concern that short-term climate variability and medium- and long-term climate change will have significant negative impacts on landscapes, agriculture, economic growth and associated livelihoods (Assad e Pinto, 2008; Margulis e Dubeux, 2010).

Likewise, Magalhães *et al.* (2021, p. 10) state that “temperature and the amount of precipitation are the main climate variables that will impact global agriculture as a consequence of climate change”. In this sense, when precipitation is excessive, the soil may become saturated if it does not have sufficient capacity to absorb water, causing leaching processes that affect the dynamics of nutrients 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 (CFC), are gaseous substances present in the atmosphere that absorb infrared radiation and retain heat, contributing to the greenhouse effect. This phenomenon produces the warming of the terrestrial surface and of the atmosphere, playing a fundamental role in the processes of climate change.

Greenhouse gases may cause significant alterations in atmospheric dynamics. According to the data of the Second Brazilian Inventory of Emissions and Removals of Greenhouse Gases, published in 2009, Brazil emitted a total of 2,203,362 gigagrams of carbon dioxide equivalent in the year 2005. Of the total emissions, the agricultural and livestock sector was responsible for 22%, while land use and management represented 57.5%. Consequently, climate and agriculture coexist in a dynamic relationship in which both mutually influence each 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 of the climate attributable directly or indirectly to

human activities that modify the composition of the global atmosphere and that is added to the natural climate variability observed during comparable periods. Therefore, climate change does not only affect present atmospheric conditions, but also climate dynamics over days, months and in different regions of the planet. It is worth highlighting that human interactions with the natural environment modify environmental systems at different spatial and temporal scales.

Ayoade (1998) holds that climate influences human societies in various ways and, in turn, human activities influence climate. Almeida (2018) highlights that climate changes are shaped by various historical contexts. McNeill (2000) observes that the Industrial Revolution accelerated the burning of fossil fuels, intensifying the emission of greenhouse gases. Lovelock (2006) complements this perspective by pointing out that such emissions contribute significantly to climate change. Although anthropic actions do not produce immediate effects, their consequences manifest themselves globally with the passing of time, evidencing the impact of human activities on the climate system.

Almeida (2018) states that climate changes are driven both by internal factors, such as variations of the solar system, astronomical effects and volcanic activity, and by external factors related to the interaction between climate, atmosphere, oceans and terrestrial surface. Silva (2012) highlights that the definitions of climate and climate change are not completely consensual in the scientific literature. Table 1 presents a temporal scale of climate, showing climate transformations at different levels: geological, historical and contemporary.

Table 1

Temporal scale of variability and of climate change in different periods

Classification	Temporal Scale	Predominant Causal Factors
Climate fluctuation	Less than 10 years	Ocean-atmosphere interaction
Climate variability	From 10 years to 100,000 years	Volcanic activity and variations in solar emission
Climate change	From 100,000 years to 10 million years	Changes in the orbit of translation and in the inclination of the terrestrial axis
Anthropic climate alteration	Very short	Anthropic activities; urbanisation, deforestation, river diversion, among others

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

The gases derived from activities driven by human beings, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), retain solar heat in the atmosphere, causing imbalances in the global climate system. As Silva (2012, p. 3) points out, the elements and,

above all, the factors of climate are, on many occasions, so complex, variable, highly dynamic and characterised by chaotic behaviours that it is impossible to define their functioning with precision. In this sense, climate constitutes a complex phenomenon that, under certain circumstances, presents anomalies, as occurs with the El Niño and La Niña climate phenomena. These events do not possess a fixed periodicity of occurrence and their magnitudes may be intensified or modified by the influence of human activities.

Although these changes are also part of long-duration natural cycles, as Conti (2000) points out, currently they are intensified by anthropic action. The significant increase of global temperature, resulting from the combination of natural and anthropogenic factors, contributes to a complex and multifaceted climate dynamics. These complexities are not limited solely to thermal variations, but involve multiple responses and interactions in different components of the terrestrial system. The understanding of these processes is fundamental to interpret the impacts of global warming, including the climate patterns associated with the El Niño-Southern Oscillation (ENSO) phenomenon, which significantly influence global climate variability at different temporal scales, as well as agricultural activities, as analysed in the present study.

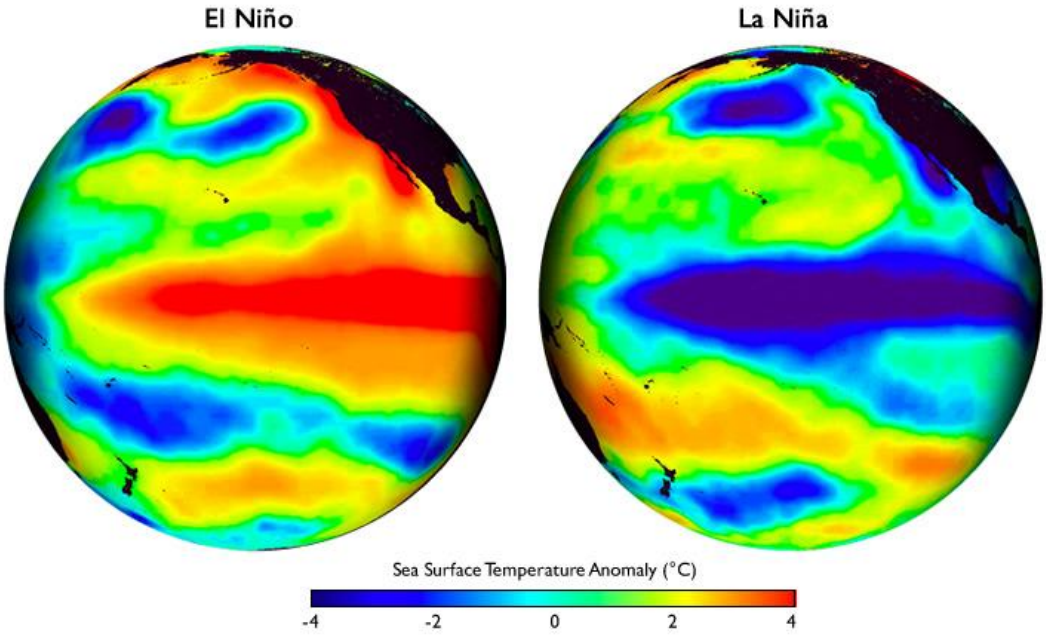
3 EL NIÑO AND LA NIÑA

The ENSO phenomenon (El Niño-Southern Oscillation) presents two main phases: the warm one, known as El Niño, and the cold one, called La Niña, both associated with variations in the surface temperature of the tropical Pacific Ocean. According to Glantz (2001), these alterations, accompanied by changes in the atmospheric pressure fields represented by the Southern Oscillation Index, affect the general circulation of the atmosphere and influence the climate of various regions of the world. Viegas (2018) highlights ENSO as the best-known phenomenon of interannual climate variability, responsible for anomalous patterns in atmospheric dynamics and in the precipitation regimes of tropical, subtropical and extratropical areas, particularly affecting South America.

Furthermore, Oliveira (2015) points out that ENSO weakens the trade winds in the equatorial region, altering atmospheric currents. This weakening generates differentiated patterns of precipitation and periods of drought in various regions. During the cooling of the oceanic surface, the modifications in the winds cause the displacement of the warm waters from east to west, significantly influencing the global climate. Figure 3 presents a representation of the warming and cooling of the waters of the Pacific Ocean on the western coast of the Americas during the different phases of the ENSO phenomenon.

Figure 3

Representation of the thermal anomalies of the Pacific Ocean associated with the El Niño and La Niña phases of the ENSO phenomenon



Source: observatório Histórico - Geográfico (2015).

During El Niño events, the surface waters of the equatorial Pacific present temperatures higher than normal, represented by the areas in red, which modifies atmospheric circulation and causes climate alterations on a global scale, such as intense precipitation in some regions and droughts in others. In contrast, during La Niña episodes, the surface temperatures in the same region are located below the average, represented by the areas in dark blue, intensifying the trade winds and influencing the climate in an opposite manner. Generally, these conditions generate droughts in regions where El Niño favours abundant rains and, conversely, increase precipitation where normally drier conditions predominate. These climate oscillations directly affect agriculture, precipitation patterns and temperature in various parts of the world, including Brazil.

The El Niño phenomenon results, to a large extent, from the interaction between the atmosphere and the ocean, generating impacts that extend to multiple components of the global climate system owing to the warming of the surface waters. According to data from the Universidade Federal de Pelotas [n.d.], during El Niño episodes the temperature of the surface waters may reach values of up to 4 °C above the usual average. On the contrary, La Niña constitutes an anomaly characterised by the cooling of the tropical waters of the Pacific Ocean. It is important to highlight that both phenomena occur in the same oceanic region, although they present different characteristics and intensities. According to Oliveira (2001),

the climate phenomena known as El Niño and La Niña usually alternate in cycles with an average duration of between three and seven years, although the interval between one event and another may vary from one to ten years.

The understanding of the ENSO phenomenon requires a perspective that transcends its global consequences and also considers its impacts on a local scale. An example of this is the fishing activity on the coast of Peru, which may be profoundly altered by the occurrence of these phenomena. According to Oliveira (1999), when the trade winds lose intensity in the Pacific Ocean, the marine currents diminish their speed and the surface waters remain more stationary, increasing their temperature and modifying the marine ecological conditions.

In the Brazilian context, Oliveira (1999) points out that during La Niña episodes the south of Brazil usually experiences lower temperatures during summer, while the Nordeste region registers a considerable increase of precipitation. In Amazonia, an increase in the flow of the rivers is observed, which favours the occurrence of floods. During winter, the South region tends to present drier conditions in comparison with El Niño periods, characterised by intense and frequent rains. Consequently, these phenomena affect multiple dimensions of social, economic and environmental organisation.

The study carried out by Salini (2011) demonstrated that, over 61 years of climate records in the basin of the Taquari-Antas river, located in the Vale do Taquari, municipality of Estrela, 31 flood events were recorded. During the El Niño periods, which covered a total of 182 months, only 10 floods occurred. In contrast, during the periods of climate neutrality, which totalled 349 months, 15 floods were recorded. In turn, during the 201 months associated with La Niña, only six flood events were recorded. These results evidence a differentiated distribution of the floods according to the predominant climate phase, representing 32.25% of the events during El Niño, 48.38% during neutral periods and 19.35% during La Niña (Salini, 2011).

Another example of the impacts associated with ENSO occurred during a low-intensity El Niño episode recorded between 2 and 9 December 2018. During this period, winds coming from the southern quadrant, with speeds between 11 and 13 m/s, displaced large volumes of oceanic water towards the coast of the state of Rio Grande do Sul. This phenomenon caused an increase in salinity in the Laguna dos Patos (Wills, 2002). Milliman and Farnsworth (2001) hold that the increase in salinity may negatively affect coastal ecosystems by increasing the levels of physiological stress in species adapted to freshwater environments, compromising their survival and reproductive capacity. Furthermore, high salinity may harm agriculture by

intensifying the salinisation processes of irrigated soils, reducing the productivity of crops sensitive to these conditions.

Similarly, Castro (2001) points out that on the littoral of Paracuru, in the state of Ceará, El Niño episodes have occurred with relative frequency over a period of 41 years. These events are characterised by low pluviometric indices and by an intense mobilisation of sediments transported by the wind. According to the author, this process favours the displacement of transverse mobile dunes, capable of burying coastal lagoons, agricultural areas and sectors of the coastal plain, causing harm both to agriculture and to aquatic ecosystems. Likewise, it is important to highlight that the excess of water in the soil may cause root asphyxia, impeding the adequate absorption of nutrients and oxygen by the plants. As a consequence, both the quality and the quantity of agricultural production diminish and the susceptibility of crops to fungal diseases and other pathologies increases.

Furthermore, Alves (2000) highlights that high relative humidity and persistent precipitation during the harvest period contribute to the deterioration of grain quality, reducing both the yield and the commercial value of production. These impacts make evident the vulnerability of agriculture to atmospheric alterations and reinforce the importance of implementing adequate strategies of agricultural management and soil conservation to minimise the intensity of the adverse effects associated with the El Niño and La Niña climate phenomena.

4 INFLUENCE OF CLIMATE ON THE PRODUCTION OF SOYA, WHEAT AND IRRIGATED RICE IN THE MUNICIPALITIES OF CORNÉLIO PROCÓPIO AND JACAREZINHO, STATE OF PARANÁ, BRAZIL

Agriculture, being an activity highly dependent on climate conditions, may experience significant impacts as a consequence of climate variations and changes, generating important social, environmental and economic repercussions (Lima, 2001). Various factors, such as plant physiology, water availability, soil fertility and erosion, the dynamics of pests and diseases, as well as soil salinisation, may be directly influenced by these climate alterations (Pritchard & Amthor, 2005).

According to Farias *et al.* (2007), climate factors play a fundamental role in the cultivation of soya, especially temperature, considered one of the most determinant meteorological variables for its growth and development. Various studies indicate that soya presents better performance under thermal conditions ranging between 20 °C and 30 °C, with a base temperature of 10 °C and a maximum temperature of 40 °C. Temperatures higher

than 40 °C during the flowering period may cause significant damage, negatively affecting the capacity for pod retention and reducing crop yield.

Likewise, Neumaier *et al.* (2000) point out that during the initial stages of development, particularly sensitive to environmental conditions, temperatures higher than 35 °C combined with absence of wind and cloud cover may cause excessive warming of the soil surface, reaching values of up to 55 °C. These conditions may lead to the physiological lodging of the plants and seriously compromise their development.

In this context, the sensitivity of soya to thermal conditions acquires special relevance when El Niño events are considered. During the years influenced by this phenomenon, global temperatures tend to increase, intensifying the effects of thermal stress on the cultivation of soya. Furthermore, El Niño may aggravate the problems associated with the overheating of the soil and limit the capacity for adequate development of the plants.

Similarly, air temperature constitutes one of the most influential factors in the development of wheat, a crop that depends on colder thermal conditions to induce flowering through a process known as vernalisation (Streck *et al.*, 2003). Wheat is classified according to its vernalisation requirements, with the winter varieties being those that present a greater dependence on this process, while the spring varieties require a more limited exposure to low temperatures. According to Walter *et al.* (2009), in Brazil the spring varieties predominate, especially in the South region, where the autumn climate conditions are more favourable for their cultivation, given that the Brazilian environment generally does not provide the conditions necessary for the adequate flowering of winter wheats.

Streck and Alberto (2006) investigated the impacts of climate change on wheat yield in Santa Maria, Rio Grande do Sul, simulating scenarios of increase of temperature and atmospheric concentration of CO_2. The results showed that increases of temperature between 3 °C and 6 °C, combined with CO_2 concentrations of 700 ppm, annulled the positive effects of carbon dioxide fertilisation on crop yield, with the most severe impacts being observed under thermal increases of 5 °C and 6 °C. On the other hand, some scenarios indicated increases in productivity. Likewise, Siqueira *et al.* (2001) pointed out that the increase of temperature accelerates the development cycle of wheat, reducing productivity owing to the shortening of its phenological cycle.

According to the results of Streck and Alberto (2006), when these effects are associated with the La Niña phenomenon, the impacts on wheat may become even more complex. During La Niña events, lower temperatures may favour the vernalisation of winter varieties in regions where the conditions necessary for this process would not normally occur.

However, the increase of precipitation in certain areas may cause excess humidity, negatively affecting yield. Consequently, the effects of La Niña on wheat depend on a complex interaction between temperature and precipitation, which varies according to geographical location and the variety cultivated.

According to Monteiro (2009), irrigated rice under controlled flooding systems is widely cultivated in the south of Brazil, especially in the states of Rio Grande do Sul and Santa Catarina, being highly sensitive to climate conditions, particularly to temperature. Yoshida and Parao (1976) point out that the cardinal temperatures for the development of rice oscillate between 7 °C and 20 °C (base temperature), between 20 °C and 35 °C (optimal temperature) and between 30 °C and 45 °C (maximum temperature), with the reproductive phase being the most vulnerable of the cycle. During flowering, temperatures higher than 33 °C may interrupt the reproductive processes. In turn, Yamakawa *et al.* (2007) observed that high temperatures, of the order of 33 °C during grain filling and ripening, reduce their weight and increase the incidence of grains with a chalky appearance, compromising their commercial quality.

Therefore, temperature constitutes a determinant factor for the cultivation of soya, wheat and rice in Brazil. The El Niño phenomenon, associated with the warming of the waters of the Pacific Ocean, tends to raise temperatures, negatively affecting soya during flowering and rice when the optimal thermal thresholds are exceeded. In turn, La Niña may favour the vernalisation processes of wheat, although it may also increase precipitation, generating adverse effects on certain crops. Understanding the impacts of these phenomena is essential for the adoption of adaptive agricultural practices capable of minimising economic losses and increasing the resilience of productive systems. Table 2 presents the data corresponding to the years of occurrence of the two phases of ENSO since 1996, as well as the climatically neutral periods.

Table 2

ENSO phases (El Niño and La Niña), neutral periods and respective start and end periods since 1996

Period	ENSO Phase	Start and end months
1996–1997	Neutral phase	From January 1996 to April 1997
1997–1998	El Niño	From May 1997 to May 1998
1998–2000	La Niña	From July 1998 to December 2000
2001–2002	Neutral phase	From January 2001 to May 2002
2002	El Niño	From July to December 2002

2003–2004	Neutral phase	From January 2003 to June 2004
2004	El Niño	From July to December 2004
2005–2007	Neutral phase	From January 2005 to May 2007
2007–2008	La Niña	From June 2007 to June 2008
2009	El Niño	From July to December 2009
2010–2011	La Niña	From June 2010 to December 2011
2012–2014	Neutral phase	From January 2012 to December 2014
2015	El Niño	From January to December 2015
2016	La Niña	From August to December 2016
2017–2018	Neutral phase	From January 2017 to December 2018
2019–2020	El Niño	From January 2019 to July 2020
2020–2022	La Niña	From August 2020 to December 2022
2023	El Niño	From May 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).

Below, data corresponding to the period between 1997 and 2023 are presented on the agricultural production of soya (first and second harvest), wheat and irrigated rice in the municipalities of Jacarezinho and Cornélio Procópio (Tables 2 and 3). The data illustrate the variations of production over the years, reflecting how climate cycles and meteorological phenomena, such as El Niño and La Niña, may influence the performance of these crops strategic for the regional economy. Likewise, the comparative analysis between both municipalities makes it possible to identify spatial differences in agricultural productivity, evidencing the different responses of the local productive systems to climate variability and to the predominant environmental conditions.

Table 3

Production of soya (first and second harvest), wheat and irrigated rice in Cornélio Procópio, Paraná, Brazil (1997–2023) (t)

Years	Soya Production (First and Second Harvest) (t)	Wheat Production (t)	Irrigated Rice Production (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
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 - Agricultural production by municipality: historical series (1997–2023).

Table 4

Production of soya (first and second harvest), wheat and irrigated rice in Jacarezinho, Paraná, Brazil (1997–2023) (t)

Years	Soya Production (First and Second Harvest) (t)	Wheat Production (t)	Irrigated Rice Production (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 - Agricultural production by municipality: historical series (1997–2023).

In Cornélio Procópio, soya production presented considerable variability over the years, reflecting the combined influence of climate phenomena and of agricultural policies. During the 1996–1997 campaign an approximate production of 435,904 tonnes was recorded, reducing to 409,684 tonnes in 1997–1998, a period marked by an intense El Niño event. This phenomenon, characterised by higher temperatures and alterations in the precipitation regimes, may have affected agricultural production by modifying the availability of humidity in the soil, an essential factor for the development of soya. According to Assad and Pinto (2008), El Niño usually causes an increase of precipitation in the south of Brazil, which may compromise crop yield.

Between 1998 and 2000, during the occurrence of La Niña, soya production increased to reach 490,416 tonnes in the 1998–1999 campaign, reflecting a phase of crop recovery favoured by greater atmospheric stability. Unlike El Niño, La Niña modifies regional climate patterns and may generate more favourable conditions for the development of soya in certain areas of the south of Brazil (Grimm, 2011). However, in the following campaign (1999–2000), production descended significantly to 358,700 tonnes, possibly the result of the combination between climate variability and economic difficulties associated with the devaluation of the Real in 1999, which increased the costs of agricultural inputs and reduced the profitability of producers.

During the 2002–2003 campaign, coinciding with a new El Niño episode, soya production increased to 665,300 tonnes, representing a considerable growth in relation to the previous years. This period coincided with the expansion of the use of more advanced agricultural technologies and with governmental incentives aimed at increasing the national production of soya oriented towards the international market (Furtado, 2004). In 2003–2004, under neutral climate conditions and a favourable economic context, production reached 691,120 tonnes. In this period, the increase of the global demand for soya, especially on the part of China, drove international prices and stimulated the expansion of the crop.

In 2015, a year characterised by a significant El Niño event, production reached 978,672 tonnes. Although this phenomenon usually generates unfavourable conditions for some agricultural regions, the technological advances and the adaptation capacity of the producers contributed to mitigating part of its adverse effects. Nevertheless, the Brazilian economy was going through a period of recession that limited access to credit and raised production costs, configuring a particularly challenging scenario for the agricultural sector (IPEA, 2015).

The 2019–2020 period, also influenced by El Niño, recorded an increase of production to 1,183,951.8 tonnes. This growth may be associated with various factors, among them the appreciation of soya in the international market and the incentives for a more intensive and sustainable production. Likewise, the trade tensions between the United States and China increased the demand for Brazilian soya, benefiting the producers of Cornélio Procópio and favouring the increase of production even under less favourable climate conditions.

During the 2021–2022 period, under the influence of La Niña, soya production was maintained at high levels, reaching 1,259,353.2 tonnes. In this stage, the adoption of agricultural practices adapted to the climate conditions and the increase of productive efficiency were fundamental factors for sustaining the growth. The incorporation of new technologies, combined with the experience accumulated by the farmers, made it possible to maintain high levels of productivity despite the climate limitations.

Wheat production also experienced important fluctuations, reflecting both the influence of climate phenomena and the challenges of the market. In 1996–1997, 176,578 tonnes were recorded, increasing to 230,060 tonnes in 1997–1998 thanks to governmental incentives aimed at diversifying agricultural production and reducing dependence on imports. However, the adverse climate conditions associated with El Niño caused a reduction to 202,410 tonnes in 1998–1999. This oscillating behaviour was frequent during the years affected by El Niño

owing to processes such as leaching and soil erosion, which negatively affect the crop (Grimm, 2011).

During the 2002–2003 period, with the return of El Niño, wheat production increased to 525,540 tonnes as a result of subsidy and support policies for national production. This growth, driven by federal programmes, had as its objective to reduce Brazilian dependence on wheat imports, a product fundamental for national feeding (IPEA, 2004).

During the La Niña event of 2007–2008, wheat production reached 495,186.9 tonnes. The thermal conditions recorded during this period favoured the development of the crop, allowing the producers to increase their productivity. However, in 2015–2016, coinciding with an El Niño event and a national economic recession, production descended to 346,436.1 tonnes, reflecting both the effects of the adverse climate conditions and the economic difficulties that affected the agricultural sector.

In turn, irrigated rice production reached 7,750 tonnes in 1996–1997, diminishing progressively over the years, although with some fluctuations. In 1999–2000, production was reduced to 2,620 tonnes, reflecting a transformation in the Brazilian agricultural structure, where more profitable crops, such as soya and wheat, came to occupy a priority position (Mendes, 2007). During the El Niño event of 2009–2010, irrigated rice production reached only 1,645.4 tonnes, a situation associated both with climate factors and with the reduction of institutional support for the crop. In 2022–2023, under La Niña conditions, production was reduced to barely 230.4 tonnes, evidencing the growing preference for crops of greater economic profitability.

These results suggest that the agriculture of Cornélio Procópio showed an important capacity for adaptation to the challenges imposed by climate variability and by economic conditions. The El Niño and La Niña phases exerted a direct influence on agricultural yields, especially in the soya and wheat crops, while the incentive policies, the subsidies and the incorporation of new technologies contributed to the diversification and modernisation of agricultural production. These responses evidence both the adaptive capacity of the producers and the importance of public policies in the configuration of the regional productive systems.

In the case of Jacarezinho, agricultural production also evidences the influence of climate phenomena such as El Niño and La Niña. The analysis of the data corresponding to the period 1996–2023 demonstrates that the fluctuations in the productivity of the main crops — soya (first and second harvest), wheat and irrigated rice — cannot be attributed exclusively to the meteorological conditions. Over almost three decades, economic, social and political

factors also played a fundamental role in the vulnerability and resilience of the agricultural systems to climate variability.

In relation to soya, the main crop of the region, the El Niño events evidenced significant impacts. Under neutral climate conditions, in 1996–1997 Jacarezinho produced approximately 62,692 tonnes of soya. However, during the intense El Niño episode of 1997–1998, production diminished to 49,417 tonnes. According to Neumaier (2017), the excess of humidity and the high precipitation during the reproductive phase may significantly reduce the productivity of soya, hindering the absorption of water and nutrients and generating less developed and less productive plants.

The arrival of La Niña in 1998–1999 modified this scenario, favouring the production of soya, which reached 77,247.1 tonnes. This increase reflects both the resilience of the crop to certain conditions of water deficit and the adaptation capacity of the local producers. During the following years high levels of production were maintained until the occurrence of a new El Niño event in 2002, which caused a slight reduction to 116,852 tonnes. This behaviour confirms the influence of the ENSO cycles on the regional agricultural dynamics.

Wheat, highly sensitive to the excess of humidity, also presented significant variations. During the El Niño event of 1997–1998, production reached 52,462 tonnes; however, the high humidity favoured the appearance of fungal diseases and hindered the harvest tasks. Subsequently, during La Niña in 1998–1999, production descended to 37,814.8 tonnes. These results evidence the vulnerability of the crop to climate variability, benefiting from moderately dry conditions, but being harmed by excessively rainy periods (Fontana & Berlato, 2000).

Irrigated rice, in turn, depends directly on water availability to maintain its productivity levels. During the El Niño years, such as 1997–1998, when an increase of precipitation was recorded, production reached 9,615 tonnes. However, during intense La Niña events, such as the one recorded in 2011–2012, the reduction of water availability significantly affected production, evidencing that access to water resources constitutes a determinant factor for the sustainability of the crop in the region.

The analysis of the productive data of Jacarezinho between 1996 and 2023 demonstrates that the ENSO phenomena directly influence regional agricultural production. However, such impacts must be interpreted considering also the Brazilian economic and social context. During the 2000s decade, the country experienced a period of economic growth that made it possible to broaden investments in agricultural infrastructure and agronomic research. Likewise, the expansion of rural credit policies and the strengthening of

EMBRAPA contributed to the modernisation of agricultural practices and to greater productive stability, even in years characterised by adverse climate conditions (Santos & Neves, 2015).

In recent years, the growing international demand for soya, particularly on the part of China, incentivised the expansion of the crop in regions more vulnerable to climate variability, such as Jacarezinho. The appreciation of the export markets stimulated the adoption of new technologies, more efficient management practices and varieties more resistant to water stress. Nevertheless, despite these advances, the producers continue to face difficulties in fully foreseeing and mitigating the effects of the events associated with ENSO.

The agricultural production of Jacarezinho has been profoundly influenced by the El Niño and La Niña phenomena, which directly affect crop performance. To reduce these impacts, it is fundamental to adopt strategies such as crop rotation, the adequacy of the agricultural calendars, the use of more resistant seeds and the implementation of conservationist practices, such as direct sowing and vegetal cover of the soil. These measures contribute to conserving soil humidity, minimising damage and preparing the productive systems to face adverse climate conditions.

Furthermore, the strengthening of agricultural cooperativism, combined with public policies oriented towards agricultural insurance and technical assistance, has been essential to increase the resilience of the sector. The investments in technology, infrastructure and early climate warning systems constitute indispensable tools to face the challenges imposed by El Niño and La Niña. In this sense, the integrated strategies and adaptive planning, as Assad and Pinto (2008) highlight, are fundamental to guarantee the sustainability and stability of agricultural production and to promote regional economic development in the face of scenarios of growing climate variability.

5 FINAL CONSIDERATIONS

The results obtained in this research evidence that the El Niño and La Niña climate phenomena exert a significant influence on the dynamics of agricultural production in the region of the Norte Pioneiro of the state of Paraná, especially in the municipalities of Cornélio Procópio and Jacarezinho. The variations in the patterns of temperature and precipitation associated with the different phases of ENSO (El Niño-Southern Oscillation) demonstrate a high potential to modify the productive performance of crops strategic for the regional economy, such as soya, wheat and irrigated rice.

The analysis of the data made it possible to identify that the impacts of these phenomena do not manifest themselves in a homogeneous manner among the different agricultural crops, since each species presents specific physiological requirements and

different levels of sensitivity to climate conditions. In this context, the periods characterised by thermal and pluviometric anomalies may favour certain agricultural activities and, simultaneously, compromise the development of others, evidencing the complexity of the existing interactions between climate and agriculture.

The results obtained reinforce the importance of climate monitoring and of the incorporation of meteorological and climatological information in the processes of agricultural planning. The anticipated knowledge of the conditions associated with the different phases of ENSO may contribute to the adoption of more efficient management strategies, reducing the productive risks and broadening the adaptation capacity of the agricultural systems to climate variability.

In addition to the direct impacts on productivity, the research makes evident that extreme climate events possess important economic and social implications, especially in regions whose productive structure presents a strong dependence on the agricultural and livestock sector. In this sense, understanding the relationships between climate variability and agricultural production is fundamental to support actions of territorial planning, risk management and strengthening of regional socio-economic resilience.

Finally, it is worth highlighting that the El Niño and La Niña phenomena constitute fundamental components of global climate variability, whose effects tend to acquire an increasingly greater relevance in a context characterised by the increase of the frequency and intensity of extreme events associated with contemporary climate change. Consequently, studies that integrate climatology, agriculture and regional development reveal themselves to be essential to broaden the understanding of the future challenges faced by the agricultural sector, contributing to the construction of adaptation and sustainability strategies capable of guaranteeing greater productive, environmental and socio-economic security for future generations.

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