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ARTICLE

Empirical evidence of economic and climatic impacts on Proagro claims in Southern Brazil (2013-2023)

Evidências empíricas dos impactos econômicos e climáticos nos acionamentos do Proagro na região Sul do Brasil (2013-2023)

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Abstract: Brazilian agribusiness accounts for more than 26% of the country's Gross Domestic Product (GDP), yet it faces increasing climate-related risks that threaten its performance. This study analyzed the determinants of claims under the Agricultural Activity Guarantee Program (Proagro) in Southern Brazil between 2013 and 2023, focusing on corn, soybean, and wheat crops. A panel data methodology was employed, using fixed-effects models corrected for heteroskedasticity and autocorrelation. The results revealed that the *La Niña* phenomenon significantly impacts claims, increasing claim values by 168% for corn and 87.4% for soybeans, while reducing it by 166.4% for wheat. Average temperature showed a negative relationship with soybean claims (-4.35%), and corn prices presented a positive elasticity of 5.1%. Average productivity was statistically significant for corn and wheat. These findings highlight distinct patterns of climate vulnerability across crops and indicate challenges for the financial sustainability of the Program amid intensifying extreme weather events.

Keywords: Proagro, agricultural insurance, climate risks, *La Niña*, financial sustainability.

Resumo: O agronegócio brasileiro representa mais de 26% do Produto Interno Bruto (PIB) nacional, mas enfrenta crescentes riscos climáticos que ameaçam seu desempenho. Este estudo analisou os determinantes dos acionamentos do Programa de Garantia da Atividade Agropecuária (Proagro) na região Sul do Brasil entre os anos 2013 e 2023, focando nas culturas de milho, soja e trigo. Utilizou-se metodologia de dados em painel com modelos de efeito fixo corrigidos para heterocedasticidade e autocorrelação. Os resultados revelaram que o fenômeno *La Niña* impacta significativamente os acionamentos, aumentando em 168% o valor acionado para o milho e 87,4% para a soja, enquanto reduz em 166,4% para o trigo. A temperatura média mostrou relação negativa com os acionamentos da soja (-4,35%), e o preço do milho apresentou elasticidade positiva de 5,1%. A produtividade média foi estatisticamente significativa para o milho e o trigo. Os achados evidenciam padrões distintos de vulnerabilidade climática entre as culturas e indicam desafios para a sustentabilidade financeira do Programa diante da intensificação de eventos extremos.

Palavras-chave: Proagro, seguro agrícola, riscos climáticos, *La Niña,* sustentabilidade financeira.

1 Introduction

Climate-related risks have become a persistent global concern across a wide range of sectors, with particularly pronounced implications for agriculture. Their impacts extend from heightened price volatility (Faccia et al., 2021; Kotz et al., 2024) and growing concerns over mitigation policies and their potential effects on food access (Hasegawa et al., 2018), to broader systemic risks, including rising economic inequality, increased pressure on healthcare systems, and the potential destabilization of monetary and political systems (Kotz et al., 2025).

This scenario underscores the complexity of the issue, reflecting a clear dichotomy: it is already recognized that prices will be affected and, consequently, that food security among the most vulnerable populations will be compromised, whether as a result of mitigation efforts or due to supply constraints arising from climate-related risks.

In monetary terms, aggregate global losses between 1991 and 2021 amounted to US$ 3.8 trillion, corresponding to an annual average of US$ 123 billion. This represents approximately 5% of global agricultural GDP and nearly 300 million tons of cumulative losses per year (Food and Agriculture Organization, 2023). These figures are significant, particularly when considered in the context of global food security.

Brazil has played a pivotal role in the global food market, a position that became particularly evident during the COVID-19 pandemic, as the country emerged as one of the world's leading producers and suppliers. During the first two years of the pandemic, Brazilian agribusiness generated export revenues totaling US$ 120.6 billion, representing a 24% increase compared to 2019 (Brasil, 2025c). By exporting food and agricultural inputs to countries facing natural resource constraints, Brazil contributes directly to the maintenance of global food security, particularly in contexts characterized by significant production losses (Neves, 2023).

In the context of food security, global food production is highly susceptible to climate-related risks. In response to recurrent losses and the inherent uncertainties of agricultural activity, Brazil has implemented public policies aimed at mitigating these impacts. The development of rural credit, initiated in 1937, was institutionalized in 1965 with the enactment of Law No. 4,829, which established the National Rural Credit System (Sistema Nacional de Crédito Rural – SNCR) (Brasil, 1965).

With regard to risk management, the National Agricultural Insurance Company (Companhia Nacional de Seguros Agrícolas) was established in 1954 following the enactment of Law No. 2,168, which instituted agricultural insurance in Brazil (Brasil, 1954). Both frameworks have subsequently evolved in tandem with legislative developments, including the Federal Constitution, particularly Article 187, item V (Brasil, 1988), and Law No. 8,171 and its amendments, which established Brazil's Agricultural Policy (Brasil, 1991).

The objective of this study is to analyze the Agricultural Activity Guarantee Program (Programa de Garantia da Atividade Agropecuária – Proagro), established by Law No. 5,969 of 1973 (Brasil, 1973), along with its subsequent amendments[1]. Implemented in 1975, Proagro was designed to protect rural producers, in cases of income loss caused by natural adversities, by relieving them of financial obligations associated with rural production credit operations.

Proagro may be understood as a form of public insurance; however, its regulation, guidelines, and oversight do not fall under the authority of the National Council of Private Insurance (Conselho Nacional de Seguros Privados – CNSP) or the Superintendence of Private Insurance (Superintendência de Seguros Privados – SUSEP), but rather that of the Central Bank of Brazil (Brisolara, 2013).

Due to the increasing frequency of climate phenomena such as *El Niño* and *La Niña*, a consistent rise has been observed in the number of claims filed under the program for agricultural production losses and, consequently, in the volume of government subsidies. Between the 2013/2014 and 2022/2023 crop years, the amount covered by the program increased from BRL 10 billion to BRL 31 billion (Banco Central do Brasil, 2024).

Moreover, a widening gap has been observed between the average premium rate applied and the program's equilibrium rate (Abreu, 2025), revealing a significant imbalance that may prove unsustainable in the long term. In light of this scenario, the following research question arises: to what extent has Proagro responded to climate and financial risks in Southern Brazil?

[1] Proagro Mais, created in 2004 through Resolution No. 3,234 of August 31, is a subprogram of Proagro aimed at PRONAF beneficiaries, that is, producers participating in the National Program for Strengthening Family Agriculture (Programa Nacional de Fortalecimento da Agricultura Familiar – PRONAF). Producers who do not fall within this category and enroll in Proagro are covered under what is referred to as Traditional Proagro. This study considers both modalities

To address this question, this study employs panel data models to analyze the effects of climatic and economic variables on program claims across the states of the region.

2 Theoretical Foundation

2.1 Risks, Climate, and the Financial Sustainability of Proagro

The literature draws a clear conceptual distinction between risk and uncertainty. Knight (1921) defines risk as a situation in which the probabilities of outcomes can be estimated based on prior data or past experience. Uncertainty, by contrast, refers to scenarios in which such probabilities cannot be measured or estimated, either due to insufficient information or the singular nature of the event.

Climate risk can be understood as the probability of losses arising from unpredictable events, differing from pure uncertainty in that it allows for probabilistic quantification, as conceptualized by Knight (1921). In the agricultural context, such risks are systemic, affecting multiple producers simultaneously and thus requiring collective mitigation instruments, such as insurance mechanisms that transform potentially high future losses into predictable premiums, thereby promoting income stabilization and economic efficiency (Ozaki et al., 2007; Ozaki & Dias, 2009; Coble & Barnett, 2013; Wang et al., 2020).

Globally, agricultural insurance, initially developed within private markets in the United States and Europe, has evolved into subsidized models with annual costs exceeding US$20 billion, adapting to contexts characterized by high climate variability (World Bank, 2005; Smith & Glauber, 2012; Costa, 2023).

Risk in agricultural production can be classified into three categories: idiosyncratic risk, which refers to frequent but low-impact losses affecting individuals or small groups, such as losses on a single farm; intermediate risk, which encompasses less frequent events with more substantial losses, such as hail, frost, or floods affecting several farms within the same region; and catastrophic risk, associated with extreme and systemic events, such as prolonged droughts or widespread flooding, which affect large areas and populations (Ceballos et al., 2025).

Dependence on insurance may act as a disincentive to the adoption of sound agricultural practices, as farmers may increasingly rely on insurance coverage to offset financial losses. Consequently, they may be less inclined to implement risk-mitigating strategies, such as crop diversification, sustainable management practices, or investments in technologies such as irrigation systems. In this sense, insurance can function as a buffer that obscures the underlying effects of climate change by attenuating its economic impacts (Dolan, 2001).

A counterpoint highlighted in the literature concerns the potential for agricultural insurance to generate adverse environmental implications by influencing farmers' behavior and diminishing incentives for the adoption of sustainable management practices. Baumgärtner & Quaas (2008) theoretically argue that financial insurance may lead to the substitution of natural risk mitigation strategies, such as the use of agrobiodiversity, with market-based solutions.

Within this context, moral hazard arises when producers, supported by insurance coverage, choose to assume excessive risks, such as cultivating in areas with higher climate vulnerability (Wu et al., 2020), which may increase the frequency of claims and generate additional costs for the system.

Information asymmetry arises from disparities in knowledge between producers and insurers, facilitating adverse selection and even fraud, thereby increasing operational costs and compromising the long-term viability of such programs. The presence of these challenges reinforces the need for reforms that balance program benefits with their inherent risks (Ozaki & Dias, 2009; Mota et al., 2020; Wu et al., 2020; Dal Pozzo et al., 2025).

In Brazil, Agricultural Policy integrates planning, financing, and risk management through instruments such as rural credit, the Minimum Price Guarantee Policy (Política de Garantia de Preços Mínimos – PGPM), and agricultural insurance, with particular emphasis on the Rural Insurance Premium Subsidy Program (Programa de Subvenção ao Prêmio do Seguro Rural – PSR) and the Agricultural Activity Guarantee Program (Programa de Garantia da Atividade Agropecuária – Proagro) (Ramos & Martha Junior, 2010; Pintor et al., 2015; Vieira Filho & Fishlow, 2017; Wedekin, 2019).

Proagro, established in 1975 as a guarantee mechanism for rural credit operations, operates as a public insurance scheme managed by the Central Bank of Brazil (BACEN). It covers losses arising from climatic and phytosanitary events affecting financed crops, with a particular focus on small-scale producers, especially those engaged in family farming (Rodrigues et al., 2023; Oñate-Paredes & Ozaki, 2025).

Unlike the Rural Insurance Premium Subsidy Program (PSR), which subsidizes premiums for private insurance primarily targeting large-scale producers, Proagro provides coverage by charging a rate applied to the financed amount. The three Southern states (Paraná, Santa Catarina, and Rio Grande do Sul) account for 84.8% of total coverage, with soybean, corn, and wheat representing 32.9%, 27.5%, and 13.2% of the value covered by Proagro, respectively (Loyola et al., 2016; Loyola & Schwantes, 2020; Brasil, 2025c; Torres et al., 2024).

The implementation of Proagro and rural insurance in the Brazilian context has yielded notable advances, including the stabilization of producers' income and the mitigation of climate-related losses, thereby contributing to the resilience of the agricultural sector. However, these instruments also present significant challenges that affect their effectiveness and financial sustainability, particularly with regard to moral hazard and information asymmetry.

Studies indicate that Proagro mitigates climate-related impacts, such as those associated with *El Niño* and *La Niña*, by stabilizing income and encouraging investment; however, it has been subject to criticism due to structural inefficiencies, including default and a reliance on fiscal subsidies (Instituto de Pesquisa Econômica Aplicada, 1993; Oliveira, 1995; Silveira et al., 2008; Oliveira & Pereira, 2025).

In Southern Brazil, Proagro stands out as a key instrument for safeguarding agribusiness, concentrating the majority of coverage and supporting the maintenance of competitiveness in a region highly exposed to adverse conditions, particularly climatic ones. Spatial analyses indicate high levels of participation in areas of intensive soybean, corn, and wheat production, reinforcing its role in fostering more secure agricultural practices and attracting local investment (Mota et al., 2020; Silva & Gosmann, 2024; Torres et al., 2024).

Nevertheless, despite its benefits, analyses based on data from the Central Bank of Brazil (BACEN) for the period 2013 to 2023 reveal a concerning trend. Owing to the increasing frequency of climate phenomena such as *El Niño* and *La Niña*, a sustained rise has been observed in the number of claims filed under the program.

Furthermore, a widening gap has been observed between the average premium rate applied and the program's equilibrium rate. While the equilibrium rate, defined as the rate required to ensure the program's financial sustainability, was estimated at 37.8% for wheat during the analyzed period, the average rate actually applied was 7%. This discrepancy requires the allocation of public funds to sustain the program's financial viability (Abreu, 2025).

The highest number of claims throughout the analyzed period was associated with the following loss-causing events: excessive rainfall, rainfall during harvest, disease or pest outbreaks, flooding, hail, frost, other natural phenomena, lightning, drought, waterspouts, extreme temperature variation, windstorms, strong winds, and cold winds. Data summarized in Figure 1 indicate that drought and excessive rainfall are the primary drivers of program claims related to crop losses in Southern Brazil (Banco Central do Brasil, 2024).

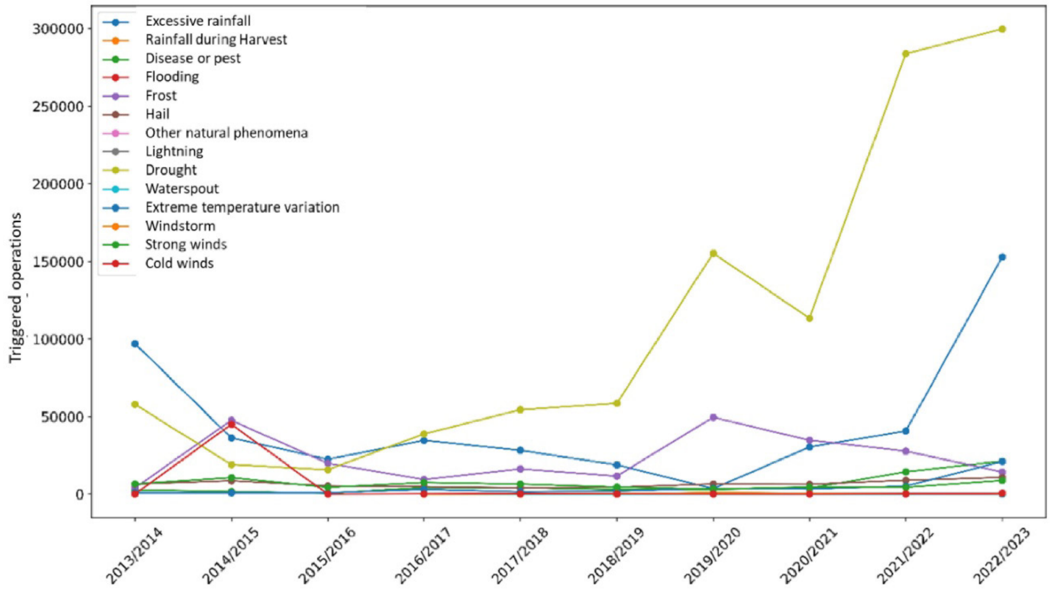

Figure 1. Number of claims in the states of SC, PR, and RS, by loss-causing event.
Note: *Crop year refers to the period from July 1st of a given year to June 30th of the following year.
Source: prepared by the authors based on data from Banco Central do Brasil (2024).

In their analysis of productivity across municipalities in Paraná between 1990 and 2002, Ozaki and Dias (2009) highlight that adverse climate events, such as droughts or frosts, tend to affect large areas simultaneously. This finding helps explain the high number of claims observed in the Southern states, given their geographic proximity.

Extreme climate events, such as droughts, frosts, and floods, have led to significant economic contractions, including an approximate 1.8% decline in GDP in 2022 and projections of a further 3.5% decrease in 2024, driven by losses in key crops such as corn (12.26% reduction), soybeans (4.67%), and wheat (32% in Paraná) (Assad & Assad, 2024; Universidade de São Paulo, 2024). These impacts extend beyond isolated economic fluctuations, reflecting a broader global trend of increasing frequency and intensity of natural disasters, which are responsible for annual losses exceeding BRL 11 billion in Brazil, equivalent to approximately 1% of agricultural GDP, with drought accounting for 84% of total sectoral losses between 2003 and 2013 (Arias et al., 2015; Food and Agriculture Organization, 2015).

Furthermore, the sensitivity of soybean, corn, and wheat crops to climatic conditions constitutes a key driver of production uncertainty, affecting both yield and crop quality. Studies indicate that variations in temperature and precipitation, associated with phenomena such as *El Niño* and *La Niña*, alter rainfall and temperature patterns in Southern Brazil, compromising entire harvests and generating losses of up to 23.9 million tons, as observed during the 2015/2016 crop season (Confederação da Agricultura e Pecuária do Brasil, 2016; Ray et al., 2019; Torres et al., 2024; Zambrano-Medina et al., 2024).

El Niño intensifies excessive rainfall and elevated temperatures, whereas *La Niña* is associated with prolonged droughts, directly affecting rainfall and temperature patterns in states such as Paraná, Santa Catarina, and Rio Grande do Sul. This climate variability not only reduces average productivity, with potential impacts on up to 20% of global crop yields already affected by global warming, but also exacerbates international price volatility, thereby undermining rural income and the economic stability of the sector (Tao et al., 2016; Santos et al., 2021; Kumari et al., 2024; Martínez, 2024).

In the Brazilian context, projections indicate that climate change may reduce the productivity of wheat, corn, and soybeans by up to 30% in certain regions, underscoring the need for the implementation of adaptation strategies, such as agricultural zoning and the monitoring of changes in precipitation patterns (Siqueira et al., 1994; Sanches et al., 2014; Santos & Martins, 2016; Luiz & Silva, 2024).

Table 1 shows that the value covered by the program increases at a substantially faster rate than the size of the covered area. For the 2013/2014 and 2014/2015 crop years, there are no records for the area variable in the Proagro database (Banco Central do Brasil, 2024).

Table 1. Covered area, covered value, and growth rate of Proagro operations in the states of SC, PR, and RS, for all crops.

Year*	Covered area (hectares)	Covered value (BRL)	Growth rate of covered area (%)**	Growth rate of covered value (%)
2013/2014	ND	1,589,135,646.14	-	-
2014/2015	ND	1,393,877,733.49	-	-12.29
2015/2016	509,188.76	968,350,664.36	-	-30.53
2016/2017	943,435.33	1,639,288,361.80	85%	69.29
2017/2018	940,789.91	1,713,187,718.11	0%	4.51
2018/2019	882,941.85	1,966,493,711.01	-6%	14.79
2019/2020	1,611,354.85	3,966,187,721.57	82%	101.69
2020/2021	1,094,172.07	3,691,065,477.58	-32%	-6.94
2021/2022	1,962,648.53	9,274,231,406.28	79%	151.26
2022/2023	2,782,502.63	15,552,792,229.83	42%	67.70
Total	**10,727,033.93**	**41,754,610,670.17**	**250%**	**359%**

Notes: *Crop year refers to the period from July 1st of a given year to June 30th of the following year; **The growth rate was calculated based on the ratio ((analyzed crop year / previous crop year) -1).
Source: prepared by the authors based on data from Banco Central do Brasil (2024).

In light of these risks, the management of climate and financial uncertainties becomes essential for the sustainability of agribusiness, helping to prevent disparities in competitiveness, credit constraints, and declines in producers' income (Medeiros, 2013; Silva et al., 2014; Tabosa & Vieira Filho, 2021b).

3 Methodology

3.1 Data

This study uses the data presented in Table 2, drawing primarily from the Agricultural Decision Support System (Sistema de Suporte à Decisão na Agropecuária – SISDAGRO) (Brasil, 2025b), the Proagro data matrix (Banco Central do Brasil, 2024), the Agricultural Information Portal (Brasil, 2025a), the Climate Prediction Center, the Municipal Agricultural Production survey (Produção Agrícola Municipal – PAM/IBGE) (Instituto Brasileiro de Geografia e Estatistica, 2024), and data on anomalies or deviations in sea surface temperature (SST) relative to the mean, measured through buoys distributed across the ocean and monitored by the National Oceanic and Atmospheric Administration (NOAA) (National Oceanic Atmospheric Administration, 2025).

The data cover the period from 2013 to 2023, as Circular No. 3,620, issued by BACEN on December 21, 2012, established that all rural credit operations must be registered in the Rural Credit and Proagro Operations System (Sistema de Operações do Crédito Rural e do Proagro – SICOR) as of January 1, 2013.

The states of Paraná, Rio Grande do Sul, and Santa Catarina were selected as the geographical scope for analyzing the determinants of Proagro claims. This choice is justified by the significant concentration of program enrollments and claims in the Southern region, reflecting the vulnerability of local producers to adverse climate events (Banco Central do Brasil, 2024.

Table 2. Description of the variables used in the panel.

Variable	Acronym	Unit	Description	Source
Average monthly temperature	AMT	Degrees Celsius (°C)	Value calculated as the average of temperatures recorded across the months of each crop year in the sample	Brasil (2025b)
Average monthly precipitation	AMP	Millimeters (mm)	Value calculated as the average precipitation recorded across the months of each crop year in the sample, followed by the sum of the monthly accumulated values	Brasil (2025b)
Average productivity for each crop	APC APS APW	Kilograms per hectare (Kg/ha)	Quantity produced per hectare	Instituto Brasileiro de Geografia e Estatistica (2024)
Price for each crop	PC PS PW	Brazilian Real (BRL)	Price paid to the producer for a 60 kg unit of the product[1] (soybean, corn, and wheat)	Brasil (2025a)
El Niño	*El Niño*	Dummy	Dummy variable indicating the presence of *El Niño* during the crop years in the sample	National Oceanic Atmospheric Administration (2025)
La Niña	*La Niña*	Dummy	Dummy variable indicating the presence of *La Niña* during the crop years in the sample	National Oceanic Atmospheric Administration (2025)
Claim amount for each crop	CAC CAS CAW	Brazilian Real (BRL)	Amount financed by the farmer for which a coverage claim was filed under Proagro	Banco Central do Brasil (2024)

Notes: [1]For the wheat crop, the average price used was calculated as the mean of grain wheat prices, wheat pH 75, and wheat pH 78. The crops considered are soybean, corn, and wheat.
Source: prepared by the authors (2025).

The dependent variable (y) selected was the claim amount, that is, the amount submitted for coverage under Proagro. This choice is grounded in the program's operational framework, in which not all claimed amounts are ultimately indemnified. Deductions from the payable amount may occur due to the absence of proof of input purchases, revenue obtained from product commercialization, and areas not verified as effectively cultivated. The claim amount was obtained from the Proagro Data Matrix (Banco Central do Brasil, 2024).

3.2 Methods

To simultaneously analyze the temporal evolution of Proagro and examine the impact of different variables across the three states, a panel data methodology was adopted. Given the range of variables employed, the model accounts for their idiosyncratic characteristics, thereby increasing the degrees of freedom and allowing greater flexibility in handling data heterogeneity (Greene, 2008, pp. 181–182). In general terms, the model is specified by Equations 1 and 2 (Baltagi, 2005; Greene, 2008).

$$yit = x\,^\wedge\,'it\beta + W\,^\wedge\,'i\alpha + \varepsilon it \tag{1}$$

$$= x\,^\wedge\,'it\beta + ci + \varepsilon it \tag{2}$$

where: i denotes the individual index (i = 1, 2... n), t denotes time (t= 1, 2,... T), x' is a row vector of regressors excluding the intercept, o $W'i$ captures heterogeneity, including the intercept; ci captures unobserved heterogeneity; εit is the error term.

According to Greene (2008), panel data analysis can be conducted using different approaches, including pooled, fixed effects (FE), random effects (RE), and random parameters (RP) models. In the pooled model, all data are treated as homogeneous, meaning that differences (heterogeneity) among individuals (states) are not explicitly accounted for, and estimation is performed using Ordinary Least Squares (OLS).

The Fixed Effects (FE) model allows for the identification of heterogeneity among the individuals under analysis, assuming that each state has its own specific characteristics that remain constant over time. Estimation is also performed using Ordinary Least Squares (OLS). The Random Effects (RE) model, in turn, assumes that differences among individuals are not correlated with the independent variables; it is more appropriate when the individuals or groups under analysis represent a random sample drawn from a larger population (Baltagi, 2005). Finally, the Random Parameters (RP) model assumes that each individual may have a distinct slope coefficient (Greene, 2008).

To determine the most appropriate model for panel data analysis, a series of preliminary tests was conducted, as detailed in Table 3. The initial choice between the pooled model and the Fixed Effects (FE) model is guided by the Chow test. The null hypothesis of this test assumes the absence of heterogeneity, which supports the adoption of the pooled model. If this hypothesis is rejected, the use of the Fixed Effects (FE) model is recommended (Greene, 2008).

Table 3. Procedures for panel data models.

Test	Description	Hypotheses
Chow	Pooled x FE	H_0: Pooled model; H_1: Fixed Effects (FE) model
Hausman	RE x FE	H_0: Random Effects (RE) model; H_1: Fixed Effects (FE) model
Mundlak ourSuest	RE x FE	H_0: Random Effects (RE) model; H_1: Fixed Effects (FE) model
Breusch and Pagan	Pooled x R	H_0: Pooled model; H_1: Random Effects (RE) model
Wald	Identify heteroskedasticity in the FE model	H_0: Homoskedasticity; H_1: Heteroskedasticity
Wooldridge	Autocorrelation	H_0: No autocorrelation; H_1: Autocorrelation
Pesaran CD and LM	Contemporaneous correlation	H_0: Cross-sectional independence; H_1: Contemporaneous correlation
Fisher	Identify the order of integration	H_0: Non-stationary; H_1: Stationary
Pedroni	Existence of a long-run equilibrium relationship	H_0: No cointegration; H_1: Cointegration

Source: prepared by the authors (2025).

In the selection between the pooled model and the Random Effects (RE) model, the Breusch–Pagan test is employed. The null hypothesis of this test indicates the absence of significant variation in unobserved effects, thereby supporting the pooled model (Greene, 2008).

The distinction between the Random Effects (RE) and Fixed Effects (FE) models is established through the Hausman, Mundlak, or Suest tests. The Hausman test is preferred in the absence of violations of the assumptions of homoskedasticity, autocorrelation, and contemporaneous correlation. Conversely, the Mundlak test serves as an alternative when these prerequisites are not met (Greene, 2008). In both tests, the null hypothesis supports the adequacy of the RE model. Rejection of this hypothesis leads to the conclusion that the FE model is the more appropriate choice.

In addition to model selection tests, diagnostic tests were conducted to assess the presence of heteroskedasticity, autocorrelation, and contemporaneous correlation. Heteroskedasticity was evaluated using the Wald test; autocorrelation was tested using the Wooldridge test; and contemporaneous correlation was examined using the Pesaran test and its CD and LM variants (Greene, 2008).

The classification of panels as short or long is determined by the relationship between the number of individuals and the length of the observed time period. Short panels consist of many individuals observed over a limited number of time periods, whereas long panels involve a smaller number of individuals observed over an extended period (Cameron & Trivedi, 2010, p. 697). In long panels, appropriate model specification is crucial for accurately analyzing groups of individuals separately (Baltagi, 2005; Greene, 2008).

Finally, to assess whether a panel dataset is stationary, that is, whether its mean and variance remain constant over time, the Fisher test was employed to determine the order of panel integration. In stationary series, both the mean and variance are constant over time, whereas a random pattern indicates the presence of a unit root, making forecasting less reliable. Although the test proposed by Maddala & Wu (1999) has the advantage of not requiring a balanced panel, its application is more appropriate for long panels.

Equations 3, 4 and 5 describe the models estimated for corn, soybean, and wheat crops, respectively. It is important to note that the variables were observed on a monthly basis for the three states under analysis and, due to the different units of measurement, were log-transformed.

$$lnvam_{it} = \alpha_0 + \beta_1 lnPm_{it} + \beta_2 lnPMM_{it} + \beta_3\ elnino_{it} + \beta_4 lanina_{it} + \beta_5 \ln AMP_{it} + \beta_6 \ln AMT_{it} + u_{it} \quad (3)$$

$$lnvas_{it} = \alpha_0 + \beta_1 lnPS_{it} + \beta_2 lnPMS_{it} + \beta_3\ elnino_{it} + \beta_4 lanina_{it} + \beta_5 \ln AMP_{it} + \beta_6 \ln AMT_{it} + u_{it} \quad (4)$$

$$lnvat_{it} = \alpha_0 + \beta_1 lnPT_{it} + \beta_2 lnPMT_{it} + \beta_3\ elnino_{it} + \beta_4 lanina_{it} + \beta_5 \ln AMP_{it} + \beta_6 \ln AMT_{it} + u_{it} \quad (5)$$

the variables were observed on a monthly basis for the three states under analysis and were log-transformed: $lncac_{it}$ represents the claim amount for corn, $lnPCit$ denotes the price of corn, ln APC it is the average productivity of corn, $elnino_{it}$ is a dummy variable indicating the presence of *El Niño;* $lanina_{it}$ is a dummy variable indicating the occurrence of *La Niña*; $lnAMP_{it}$ is average monthly precipitation; $lnAMT_{it}$ is average monthly temperature; $lncasit$ represents the claim amount for soybeans, $lnPSit$ denotes the price of soybeans, lnAPSit is the average productivity of soybeans; lncawit represents the claim amount for wheat, lnPWit denotes the price of wheat, lnAPWit is the average productivity of wheat.

4 Results and Discussion

Table 4 summarizes the results obtained from the unit root tests of the variables. The test was not performed for the dummy variables (el_nino and la_nina), as their values are binary (0 or 1). Based on the Fisher test, derived from the Augmented Dickey–Fuller (ADF) test, the stationary variables are ln_CAC, ln_CAS, ln_APS, ln_CAW, ln_APW, ln_AMT, and ln_AMP.

The variables ln_PC, ln_APC, ln_PS, and ln_PW were found to be non-stationary; therefore, first differencing was applied to render them stationary. Given that the Pedroni test indicated the presence of cointegration among the variables in the three models under study, a standard regression modeling approach was adopted, and error correction models were not deemed necessary. It is also worth noting that, due to the different units of measurement among the variables, standardization was applied, and all variables were log-transformed.

For model selection, the tests described in Table 5 were performed. The indicated model is the Fixed Effects model for both crops, according to the Chow test, which rejected the pooled specification (null hypothesis) (p-value: 0.0000), and the Suest test, which rejected the null hypothesis of Random Effects (p-value: 0.0049). Although the Breusch–Pagan test did not reject the null hypothesis (p-value: 1.0000), suggesting the pooled model, the Chow test, by ruling out the pooled specification, led to the selection of the Fixed Effects model as the most appropriate.

Table 4. Unit root and cointegration test statistics and p-values for the Fisher test (based on the Augmented Dickey–Fuller – ADF tes).

Variable	p-value	Diagnosis
ln_CAC	0.0000	Stationary
ln_PC	0.6911	Non-stationary
ln_APC	0.1336	Non-stationary
ln_CAS	0.0827	Stationary**
ln_PS	0.9531	Non-stationary
ln_APS	0.0643	Stationary**
ln_CAW	0.0000	Stationary
ln_PW	0.9418	Non-stationary
ln_APW	0.0000	Stationary
ln_AMT	0.0000	Stationary
ln_AMP	0.0000	Stationary

Notes: *tests were conducted without a trend; ** variables are stationary at the 10% significance level; ***the test was performed using the variables in first differences when non-stationary.
Source: prepared by the authors (2025).

Table 5. Test statistics and hypotheses for panel data models for corn, soybean, and wheat crops.

Tests	P-value corn	P-value soybean	P-value wheat
Chow	0.0000**	0.0000**	0.0000**
Suest***	0.0049**	0.0005**	0.0000**
Breusch and Pagan	1.0000	1.0000	1.0000
Wald	0.0261*	0.0002*	0.0565*
Wooldridge	0.0000**	0.0000**	0.0000**
Pesaran CD	0.0012**	0.0000**	0.0000**
Pedroni (corn model)***	H0: Not cointegrated H1: Cointegrated	0.0006	Cointegrated
Pedroni (wheat model)***	H0: Not cointegrated H1: Cointegrated	0.0329	Cointegrated
Pedroni (soybean model)***	H0: Not cointegrated H1: Cointegrated	0.0454	Cointegrated

Notes: *the tests were conducted without a trend; ** the variables are stationary at the 10% significance level; *** the test was performed using the non-stationary variables in first differences.
Source: prepared by the authors (2025).

As shown in Table 6, corn price (lnPC), average productivity (lnAPC), and the occurrence of the *La Niña* phenomenon were statistically significant at the 5% level. The model explained 19.31% of the variation in the Corn Claim Amount (CAC). The occurrence of *La Niña* implies an estimated increase of 168% in the claimed amount, while a 1% increase in price and productivity is associated with increases of 5.1% and 7.1%, respectively.

For soybeans, the *La Niña* phenomenon and average temperature were statistically significant at the 5% level. *La Niña* was associated with an approximate increase of 87.4% in the claimed amount, while a 1% increase in average temperature was associated with a decrease of about 4.35% in the Soybean Claim Amount (CAS). The model explained 19.74% of the variation in CAS. These results are presented in Table 7.

For wheat, as shown in Table 8, average productivity (positive) and *La Niña* (negative) were statistically significant at the 5% level. *La Niña* was associated with a decrease of 166.4% in the claimed amount, while a 1% increase in average productivity resulted in an increase of 6.28%. The model exhibited the highest R^2 among the three, explaining 23.23% of the variation in wheat claims.

Table 6. Results of panel data models for the corn crop.

Variable	Fixed Effects Model	Corrected Fixed Effects Model
$lnPCD1_{it}$	5.145* (0.003)	5.145* (0.024)
$lnAPCD1_{it}$	7.075* (0.001)	7.075* (0.013)
$elnino_{it}$	-0.006 (0.983)	-0.006 (0.975)
$lanina_{it}$	1.686* (0.000)	1.686* (0.015)
ln_AMP_{it}	-0.041 (0.806)	-0.041 (0.789)
ln_AMT	-1.697* (0.015)	-1.697 (0.728)
$const$	19.837 (0.000)	19.837 (0.268)
R^2	19.31%	19.31%

Notes: *parameter significant at the 5% significance level; **parameter significant at the 10% significance level.
Source: prepared by the authors (2025).

Table 7. Results of panel data models for the soybean crop.

Variable	Fixed Effects Model	Corrected Fixed Effects Model
$lnPSD1_{it}$	3.474 (0.208)	3,474 (0.280)
$lnAPS_{it}$	-1.188* (0.121)	-1,188 (0.156)
$elnino_{it}$	0.136 (0.696)	0.136 (0.797)
$lanina_{it}$	0.874* (0.007)	0.874* (0.045)
ln_AMP_{it}	-0.617* (0.001)	-0.617 (0.125)
ln_AMT	-4.353* (0.000)	-4.353* (0.035)
$const$	39.694* (0.000)	39.694* (0.005)
R^2	19.74%	19.74%

Notes: *parameter significant at the 5% significance level; **parameter significant at the 10% significance level.
Fonte: prepared by the authors (2025).

Table 8. Results of panel data models for the wheat crop.

Variable	Fixed Effects Model	Corrected Fixed Effects Model
$lnPWD1_{it}$	5.934* (0.010)	5.934** (0.102)
$lnAPW_{it}$	6.282* (0.000)	6.282* (0.048)
$elnino_{it}$	-0.926* (0.003)	-0.926 (0.128)
$lanina_{it}$	-1.664* (0.000)	-1.664* (0.042)
ln_AMP_{it}	-0.141 (0.404)	-0.141 (0.219)
ln_AMT	1.819* (0.010)	1.819 (0.418)
$const$	-38.536* (0.000)	-38.536** (0.065)
R^2	23.23%	23.23%

Notes: *parameter significant at the 5% significance level; **parameter significant at the 10% significance level.
Source: prepared by the authors (2025).

The panel data analysis for the period from 2013 to 2023 revealed significant relationships between climatic, economic, and production variables and Proagro claims for corn, soybeans, and wheat in Southern Brazil (Paraná, Santa Catarina, and Rio Grande do Sul). The use of robust models corrected for heteroskedasticity and autocorrelation enhances the reliability of the findings (Baltagi, 2005; Greene, 2008).

The *El Niño* variable was not statistically significant in explaining variations in claims for any of the crops, contrasting with studies such as Luiz & Silva (2024), which identified negative effects on soybeans, and Carvalho (2020), which associated extreme climate events, including *El Niño*, with substantial agricultural losses. This suggests that, in this context, other climatic factors may be more influential or that the impacts of *El Niño* are less pronounced in the analyzed region (Carvalho, 2020; Luiz & Silva, 2024).

On the other hand, the occurrence of *La Niña* showed a positive and statistically significant association with increases in claims for corn and soybeans, raising the claimed amounts by approximately 168% and 87.4%, respectively. In contrast, for wheat, an average reduction of 166.4% was observed, aligning with evidence of asymmetric impacts of extreme events on agriculture in Southern Brazil (Berlato et al., 2005; Torres et al., 2024; Zambrano-Medina et al., 2024).

This dynamic reflects the association of *La Niña* with reduced rainfall and the intensification of cold fronts, resulting in a higher frequency of droughts and frosts, which affect crops differently depending on their growing seasons (Carvalho, 2020; Climate Prediction Center, 2025). Corn and soybeans, primarily cultivated during the spring–summer season, exhibit greater vulnerability to reduced precipitation during critical stages such as flowering and grain filling, thereby increasing production risks and the likelihood of claims. This is supported by Oñate-Paredes & Ozaki (2025) and Carvalho (2020), who identify water deficit as the main factor driving yield losses in corn (Carvalho, 2020; Oñate-Paredes & Ozaki, 2025). Conversely, wheat, sown in the autumn–winter period and harvested in the spring, shows lower susceptibility, as drier conditions may favor grain quality, as discussed by Chagas et al. (2021), thereby explaining the reduction in claims (Carvalho, 2020; Chagas et al., 2021).

Regarding agricultural prices, a 1% increase in the average price of corn is associated with an approximately 5.1% increase in Proagro claims, holding other variables constant. This suggests the presence of moral hazard, whereby producers may adjust their decisions to maximize indemnities in high-price scenarios, potentially filing claims for partial losses to secure more attractive returns (Wu et al., 2020; Dal Pozzo et al., 2025).

This behavior is intensified in subsidized insurance programs such as Proagro, where premium subsidies ranging from 35% to 45% may encourage opportunistic behavior (Tabosa & Vieira Filho, 2021a; Dal Pozzo et al., 2025). Conversely, declines in prices may also lead to an increase in claims, as sales revenues may fail to cover production costs, making insurance claims more advantageous than continuing production (Wu et al., 2020; Dal Pozzo et al., 2025).

Average productivity was a significant factor for corn and wheat, with increases associated with higher levels of claims, reflecting the expansion of insured areas and agricultural investments that increase the number of insured operations and exposure to systemic risks (Pimenta, 2020).

High-productivity regions, such as Southern Brazil, concentrate Proagro coverage, creating a cycle in which greater productivity and increased credit uptake heighten vulnerability to adverse climate events, affecting large areas and resulting in more substantial claims. This dynamic has been highlighted by Ozaki & Dias (2009) and Torres et al. (2024), who emphasize the challenges to the financial sustainability of programs such as Proagro due to geographic concentration and exposure to catastrophic risks (Ozaki & Dias, 2009; Pimenta, 2020; Tabosa & Vieira Filho, 2021a; Torres et al., 2024).

Regarding average temperature, a negative relationship was observed for soybeans, which may be attributed to the crop's thermal resilience, as it optimizes physiological processes and reduces losses (Siqueira et al., 1994; Tao et al., 2016). However, variables such as temperature and precipitation were not significant for corn, suggesting that macro-scale phenomena such as *La Niña* exert a dominant influence, overriding these effects, as noted by Amaral et al. (2023), who highlight atmospheric complexity and the limiting role of water constraints under drought conditions (Siqueira et al., 1994; Tao et al., 2016; Amaral et al., 2023). Thus, while elevated temperatures alone may benefit certain crops, reduced rainfall, particularly during *La Niña* events, drives losses and claims, reinforcing the predominance of water availability as a key determinant (Siqueira et al., 1994; Tao et al., 2016).

In summary, the results confirm that *La Niña*, commodity prices, and productivity are key determinants of Proagro claims. These findings are consistent with the international literature, in which public agricultural insurance programs, such as the United States Federal Crop Insurance Program, face similar challenges related to financial sustainability and the behavioral effects induced by subsidies (Smith & Glauber, 2012).

5 Conclusions

The results of this study demonstrate that both climatic and economic factors exert a significant influence on Proagro claims, with important variations across the crops analyzed in Southern Brazil. The occurrence of *La Niña* showed a heterogeneous impact, increasing claims for corn and soybeans while reducing them in the case of wheat, thereby reinforcing the need for differentiated policies tailored to each crop type. Furthermore, the roles of price and productivity point to potential moral hazard effects and highlight the interaction between insurance, rural credit, and production intensification.

These findings gain further relevance in the current context of climate change and the ongoing transformations affecting Proagro. The increasing rigidity in access to the program occurs alongside rising climate and financial risks, which may ultimately compromise its effectiveness. It is therefore necessary to rethink the structure and design of Proagro by integrating criteria related to climate risk, financial risk, and fiscal sustainability.

Proagro has become more restrictive in terms of access, while climate phenomena have intensified. As a result, the program appears to be drifting away from its original objective of protecting producers from risk, despite the reservations highlighted in the literature regarding different types of risk.

Given Brazil's strategic role in global food security, it is essential that public policies such as Proagro keep pace with transformations in the agricultural sector, strengthening producers' resilience and ensuring adequate protection against adverse conditions, particularly for smallholder farmers, who are more vulnerable to losses.

The effects associated with climate phenomena may vary across locations and crop groups. Future research could include studies conducted in other regions of Brazil to better understand how agricultural systems in different areas respond to climate change.

Additional research could also examine losses in geographically defined areas, particularly in relation to programs such as the Agricultural Climate Risk Zoning (Zoneamento Agrícola de Risco Climático – ZARC) and regions not recommended for specific crops. Analyses of climatic factors may also contribute to the improvement of policies beyond Proagro, including agricultural insurance more broadly, rural credit, and agricultural zoning.

Authors' contributions

NTLA: Análise formal, Conceptualization, Data curation, Writing – original draft, Writing – review & editing. AF: Writing – review & editing, Validation. GCM: Writing – review & editing, Validation. EP: Formal analysis, Writing – review & editing, Validation.

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Conflicts of interest:

Nothing to declare.

Ethics approval:

Not applicable.

Data availability

The research data are publicly available and accessible for public consultation.

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