Resilience of Brazil's Soybean Supply Chain: Structural Breaks, Climate Shocks, and Regional Disparities

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Abstract: This study investigates the resilience of Brazil's soybean supply chain to climatic and economic shocks by identifying structural breaks in production, yields, and price trends from 2006 to 2024. Using econometric techniques such as Bai-Perron multiple break tests, as well as stationarity diagnostics (ADF, CUSUM), the analysis reveals that climate induced disruptions can be key drivers of volatility in soybean prices and yields. Four structural breaks were detected in October 2008, June 2012, February 2016, and November 2020, aligning with global crises, severe droughts, and supply chain disruptions. Results highlight strong regional disparities: Southern states (Rio Grande do Sul, Paraná) exhibit increasing vulnerability to droughts and reduced resilience, while the Central-West (notably Mato Grosso) demonstrates adaptive capacity supported by investments in irrigation and climate smart agriculture. These findings emphasize the need for region specific adaptation strategies and policies that integrate climate risk management, infrastructure, and sustainable production practices. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Keywords: soybean production, resilience, structural breaks, climate change, regional disparities

This research involves econometric modeling, break tests, and multi-dimensional datasets, whose complexity benefits from graphical communication. Visual elements, such as structural break plots, heatmaps of production losses, and inter and intra harvest correlation matrices, facilitate the interpretation of results and highlight regional heterogeneity. An interactive poster format enables readers to explore supplementary datasets through QR code, strengthening transparency and reproducibility.

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Problem Statement

Brazil supplies over 50% of global soybean exports, consolidating its centrality in global food systems and in the geopolitics of agricultural commodities (FAO, 2025; USDA, 2024). However, this leadership is increasingly challenged by structural vulnerabilities. On the one hand, recurrent extreme climate events, such as prolonged droughts, floods, and temperature anomalies, have imposed severe constraints on yields and production stability, particularly in the Southern states, historically pioneers in soybean cultivation (Noia-Junior et al., 2025; Bonetti, 1981). On the other hand, economic and geopolitical shocks, ranging from the 2008 financial crisis to the COVID-19 pandemic and the Russia–Ukraine war, have generated price volatility and disrupted global trade flows (Deese; Reeder, 2007; Anderson; Mitchell; Maples, 2024).

Analyses aggregated at national level tend to obscure these heterogeneous regional responses. While the Central-West exhibits greater adaptive capacity due to technological investment in irrigation, soil management, and climate-smart practices (Toloi et al., 2021; Vieira Filho, 2024), the South has shown declining resilience, with rising frequency of crop failures linked to climate extremes (Ferreira et al., 2024; Noia-Junior; Christo; Pezzopane, 2025). This asymmetry highlights that resilience is unevenly distributed across Brazilian territory and cannot be understood as a uniform attribute.

Given this context, a critical research gap emerges: to what extent are structural breaks in soybean production and price dynamics driven by climatic extremes as opposed to economic shocks, and how do regional disparities condition the resilience of the production chain? Addressing this question requires combining econometric tests of structural breaks (Bai; Perron, 1998; Zeileis et al., 2002) with climate and production data (INMET, CONAB, IBGE), enabling the identification of breakpoints and their correspondence with extreme events and systemic disruptions.

Methods and Materials

The methodological framework integrates data preprocessing, econometric modeling, and resilience analysis, structured in five stages. The dataset integrates multiple sources covering the 2006–2024 period.

Climate: Daily precipitation (mm) and temperature (mean, maximum, minimum, °C) records from the Brazilian National Institute of Meteorology (INMET), aggregated at the state level. Extremes were classified as:

- *Drought:* precipitation < 30 mm/month
- *Excess rainfall:* precipitation > 95th percentile
- *Extreme cold:* minimum temperature < 10th percentile
- *Extreme heat:* maximum temperature > 90th percentile

Production: Data from Brazilian National Supply Company (CONAB) and Brazilian Institute of Geography and Statistics (IBGE), including planted area, harvested area, total production, yields, and area losses (hectares).

Prices: Monthly soybean futures prices (p_t^{nom}) from the Chicago Board of Trade (CBOT) covering September 2006 to August 2024 were deflated using the U.S. Consumer Price Index (i_t) to obtain real prices (p_t^{real}):

$$y_t = p_t^{real} = \frac{p_t^{nom}}{i_t} \times 100 \qquad \textbf{(1)}$$

Summary statistics (mean, standard deviation, minimum, maximum) were computed for prices, yields, precipitation, and temperature. A moving average was applied to soybean futures prices to highlight short-term cycles. The Augmented Dickey-Fuller (ADF) test was used to assess the presence of a unit root:

$$\Delta y_t = \alpha + \beta_t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \quad \textbf{(2)}$$

where $\gamma = 0$ indicates a unit root (non-stationarity) and $\gamma < 0$ indicates stationarity (Enders, 2015).

The method proposed by Bai and Perron (1998) was adopted for the endogenous identification of structural breaks and the estimation of multiple structural breaks in univariate or multivariate time series. This approach is based on the estimation of segmented models, in which the structural parameters vary between regimes separated by endogenous breakpoints. To formalize this framework, an autoregressive model with $\mu + 1$ regimes is considered, as adapted from Enders (1948):

$$y_t = \alpha + \sum_{i=1}^{p} \beta_i y_{t-1} + \sum_{j=1}^{p} \phi_{jt}\left(\gamma_1 + y_{t-1}\right) + \varepsilon_t \qquad \textbf{(3)}$$

where ϕ_{jt} represents a dummy variable that assumes the value 0 before the j^{th} break and the value 1 after it. The breaks are interpreted as discrete changes in the parameters of the data-generating function, reflecting structural changes in the dynamics of the series.

Pearson's correlation was applied to measure associations between climatic variables (precipitation, temperatures), production losses ($losses$), and soybean prices (y_t):

$$\rho XY = \frac{Cov(X,Y)}{\sigma X \sigma Y} \qquad \textbf{(4)}$$

Correlation matrices were estimated for intra-harvest (same season) and inter-harvest (losses in one season versus prices in the subsequent season) dynamics.

To facilitate the visualization of the analyses, was made heatmaps, represented losses by state during planting and harvest phases, with vertical dashed lines marking identified structural breaks. Extreme climate events (drought, excessive rainfall, extreme heat/cold) were classified using percentile thresholds (P_{95}, P_{90}, P_{10}) and overlaid as point markers, and correlation plots, illustrated intra- and inter-harvest associations between production shocks and price responses.

All empirical analyses were conducted in R software (R Project, 2025), using the strucchange (Zeileis et al., 2024), urca (Pfaff et al., 2024) and ggplot2 (Wickham et al., 2025) packages, which support estimation routines, structural stability tests, seasonal decomposition, graphical visualization and time series processing.

Results

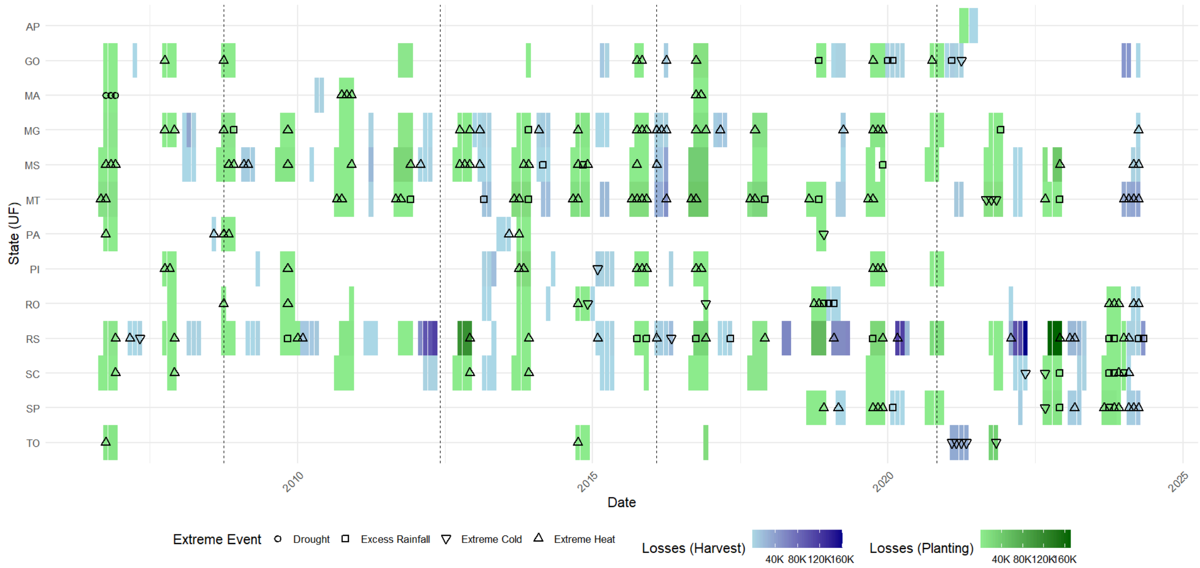
The spatiotemporal panel shows, by state, area losses during sowing (green) and harvesting (blue), with overlapping extreme events (symbols: drought = circle; excessive rainfall = square; extreme cold = inverted triangle; extreme heat = triangle). The dotted vertical lines mark the four structural breaks dated by the Bai-Perron tests.

Main findings:

(i) Clusters of extreme events (mainly droughts and excessive rainfall) are observed near the breaks of 2008, 2012, and 2020, with an increase in the intensity of losses in several states, suggesting synchrony between climate shocks and regime shifts (Figura 1).

(ii) The Southern Region (RS, PR, and, to a lesser extent, SC) experiences greater recurrence of drought during planting/harvesting and denser blocks of losses, demonstrating a reduction in productive resilience in the final period of the sample (Figura 1).

Figure 1: Heatmap of losses and extreme events by state



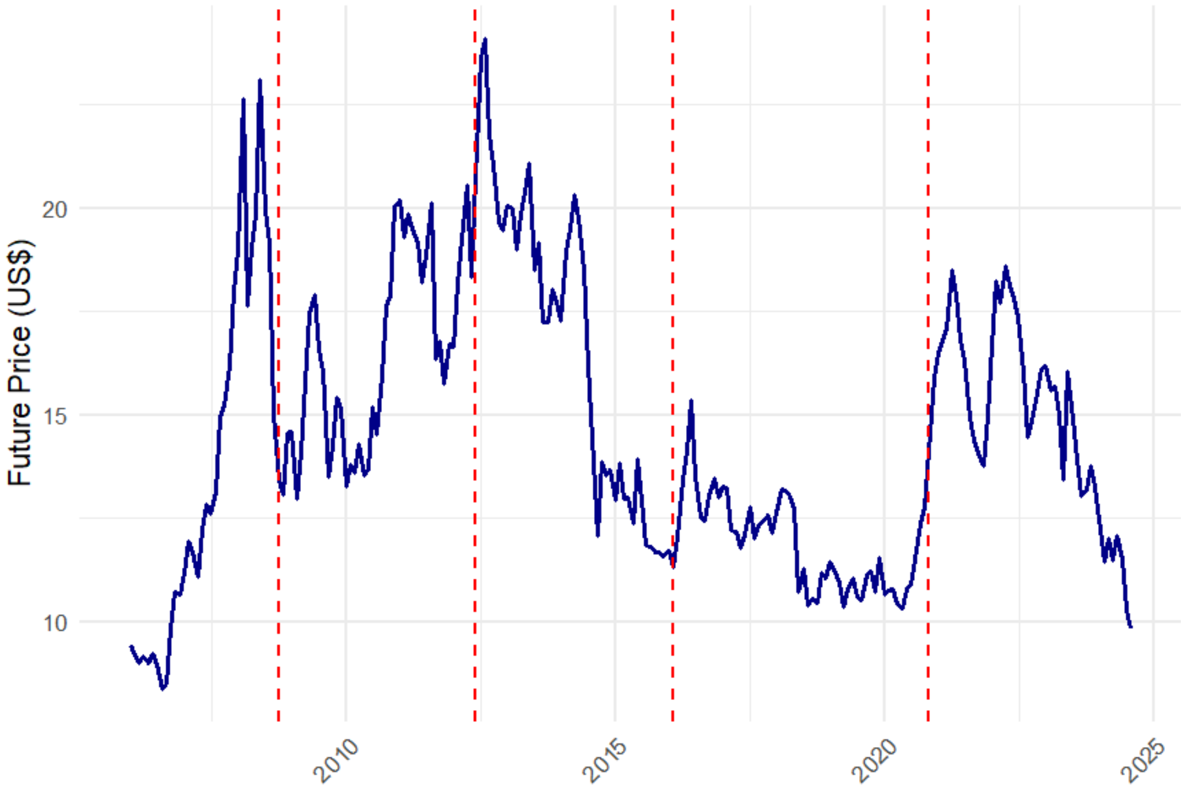
Source: Prepared by the author based on data from CBOT, CONAB, IBGE and INMET.

(iii) In the Central-West (MT, MS, GO), extreme events are recorded, but with generally less extensive and more scattered losses, consistent with greater adaptive capacity, irrigation, soil management, and climate-smart practices (Figura 1).

(iv) The temporal overlap between extremes and losses reinforces the role of climate shocks as a transmission mechanism for supply instability, an element that reappears in price dynamics (Figura 1).

Figure 2 shows the trajectory of real soybean futures prices traded on the CBOT from 2006 to 2024, highlighting the four structural breaks identified: **2008-10-01:** regime associated with the global financial crisis and reconfiguration of the soybean trade (Fousekis, 2023; Liu; Wang; Zhang, 2015; Deese; Reeder, 2007); **2012-06-01:** post-severe drought regime in North America and Brazil, with price adjustments (NOAA, 2012; Obergfell, 2012; Carvalho et al., 2020); **2016-02-01:** transition associated with the expansion of production in the US and supply-demand realignment (Gale; Valdés; Ash, 2019; Meade; Rosen; Stone, 2016; Wright, 2014); **2020-11-01:** regime linked to logistical disruptions and chain restructuring during COVID-19 (Anderson; Mitchell; Maples, 2024; Gao; Jiang; Zhou, 2024; Gao; Zhou; Jiang, 2024; WHO, 2020).

Figure 2: Futures Price Series and Structural Breaks



Source: Prepared by the author based on data from CBOT.

Figure 3: Inter-harvest Correlation

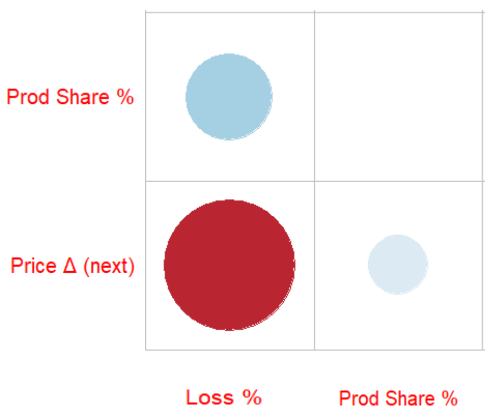
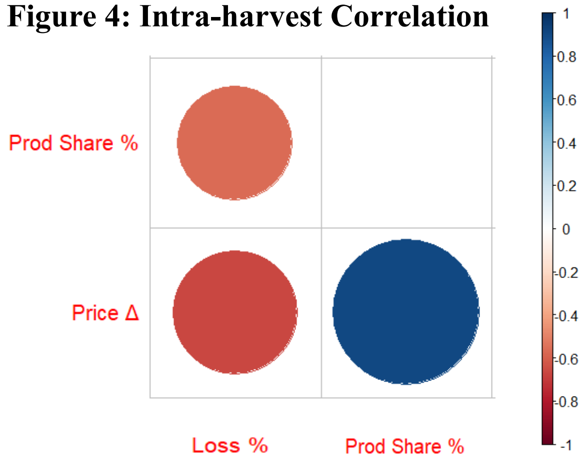


Figure 4: Intra-harvest Correlation



Source: Prepared by the author based on data from CBOT, CONAB, IBGE and INMET.

The inter-harvest matrix relates losses in harvest t and price variation in harvest $t + 1$. The result indicates a weak to moderate and heterogeneous association between states and periods, reflecting that intertemporal adjustment mechanisms (storage, substitution between origins, replenishment of external supply, and hedging positions) mitigate the pass-through of losses from one cycle to the price of the following harvest. In substantive terms, regime changes and expectations formed within the current cycle itself tend to dominate short-term price dynamics.

The intra-harvest matrix relates losses and price variation within the same cycle. A positive and more intense association is observed between greater losses and greater price variations during the period, consistent with the interpretation that prices respond immediately to shocks in production expectations and actual harvest results. In other words, production losses act as a trigger for price adjustments within the agricultural cycle itself.

The heatmap highlights the co-occurrence of extremes and losses in periods close to disruptions (disruptions identified by the Bai-Perron test), suggesting a plausible causal mechanism in which extreme weather events cause losses, reduce supply, and increase price volatility. The price response is stronger intra-harvest than inter-harvest, reflecting the formation of expectations in futures markets. Regionally, the South region shows increasing vulnerability to droughts, while the Central-West region is more resilient due to its greater adaptive capacity. From a public policy perspective, the results indicate the need for incentives for climate-adapted production techniques, the expansion of rural insurance calibrated for local risk, the use of hedging instruments, and investments in resilient infrastructure to mitigate losses and reduce volatility.

Conclusions and Considerations

In summary, the study demonstrates that the soybean production chain in Brazil is sensitive to climatic and economic shocks, with structural disruptions coinciding with severe droughts, trade conflicts, and global crises. The sector's resilience is heterogeneous: while the Central-West region has greater adaptive capacity, driven by more robust technologies and agricultural practices, the South region shows increasing fragility in the face of climate change. In this context, policies that encourage production techniques adapted to regional conditions, the expansion of agricultural insurance adjusted to local risks, the use of market risk management instruments, and investments in resilient infrastructure and sustainable practices stand out as essential. Such measures are essential to mitigate the impacts of climate change, reduce production losses, and ensure the maintenance of Brazil's strategic role in global food security.

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