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Three Decades of Agricultural Land Use Transformation in Brazil in the Context of Bioeconomy and Climate Change

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Abstract

Brazilian agriculture has undergone major changes in land use over the past three decades, alongside climate change and the expansion of commodity production. This study assessed changes in cultivated area and their associations with climate variability across Brazil's five macroregions from 1995 to 2025, considering their implications for the bioeconomy. Official data on 23 agricultural crops were classified into commodities, staple food crops, other food crops, and mixed-use crops, while temperature and precipitation data were obtained from ERA5-Land. Temporal trends, correlations, first differences, detrended

series, lagged relationships, regional regressions, and sensitivity to maize classification were analyzed. Commodity crop area increased from approximately 19 to more than 60 million hectares, while staple food crop area declined from 12 to 6 million hectares. Consequently, the commodity share of the combined area of these two groups increased from approximately 62% to over 90%, regardless of maize classification. All five macroregions exhibited significant warming trends ranging from 0.23 to 0.34 °C per decade ($p < 0.01$). Commodity crop share was positively associated with temperature in first annual differences ($r = 0.26$; $p = 0.001$), with the strongest association observed in the Northeast, whereas precipitation relationships were less consistent. Although these associations do not establish causality, the findings reveal a long-term shift toward commodity-oriented agriculture alongside regional warming, highlighting the need to reconcile agricultural production with food security, diversification, ecosystem conservation, and climate resilience.

Keywords: food security; agricultural commoditization; staple food crops; climate variability; cropland dynamics; agricultural expansion; ERA5-Land

1. Introduction

Climate change, agricultural land use, and the bioeconomy are closely interconnected dimensions of global sustainable development. The transformation of agri-food systems presents a major challenge for reconciling agricultural production, food security, and environmental sustainability. Over recent decades, global agriculture has undergone substantial changes in land use, driven by market integration, shifting consumption patterns, technological advances, and increasing demand for food, animal feed, and bioenergy [1]. These transformations have occurred alongside climate change, which is modifying the environmental conditions under which agricultural systems have historically developed [2]. Studies conducted in Brazilian biomes, including the Amazon [3–6], Cerrado [7–9], and Caatinga [10–13], have demonstrated the importance of natural ecosystems for regional carbon and water balances and the environmental implications of their conversion into productive systems [14,15]. These interactions highlight the challenge of expanding agricultural production while limiting environmental degradation and climate-related impacts.

Brazil provides an important example of these transformations. Over the past three decades, its agricultural sector has experienced substantial expansion, intensification, and integration into domestic and international commodity markets [16]. Grain production has increased considerably, particularly through soybean expansion and successive cropping systems such as soybean–maize rotations. Agricultural frontiers have advanced mainly in the Central-West and parts of the North and Northeast, while both cropland expansion and multiple cropping have contributed to changes in agricultural production [16]. Soybean cultivation has played a central role in this process, with some of the highest expansion rates occurring along Brazil's emerging agricultural frontiers [16]. However, agricultural expansion also involves different land-use trajectories, whose environmental consequences depend on previous land use, production systems, and management practices. Studies in the Amazon–Cerrado transition and at the national scale have identified variations in soil carbon responses and agricultural soil carbon debt [17,18], reinforcing the importance of distinguishing changes in reported cultivated area from direct conversion of natural vegetation.

The expansion of commodity-oriented agriculture must also be considered alongside changes in crops intended primarily for domestic food consumption. Changes in cultivated area may reflect both increases in agricultural production and the redistribution of agricultural activities among different functions of the food system [1]. Such transformations have

implications for food availability, accessibility, and stability, although their effects depend on productivity, trade, income, technology, and public policies [2]. Recent studies have emphasized the connections between agricultural land-use change, family farming, monoculture expansion, and food security, indicating that agricultural restructuring may generate different socioeconomic and environmental consequences across Brazilian regions [2,19,20]. These relationships reinforce the need to examine agricultural transformation beyond aggregate production indicators.

Alongside these structural changes, climate variability represents an additional challenge for Brazilian agriculture. Rising temperatures, changes in precipitation patterns, and increasingly adverse hydroclimatic conditions can affect crop productivity, production stability, and agricultural suitability [21–24]. These effects may be especially relevant to family-based farming systems, which often face greater financial and technological constraints on adaptation. In the Amazon–Cerrado agricultural frontier, exceptionally dry conditions and increasing aridity have been associated with yield reductions and shifts in the climatic suitability of agricultural areas [25]. Nevertheless, climatic impacts differ among crops, production systems, and regions, emphasizing the importance of regional analyses and agricultural management practices [26–28]. Understanding these differences is essential for assessing the relationships between agricultural land-use dynamics and climate variability.

Despite growing research on agricultural expansion and climate change, many studies in Brazil have concentrated on individual crops, particularly soybean and maize, agricultural productivity, specific expansion frontiers, or projections under future climate scenarios [29–31]. Comparatively less attention has been devoted to long-term assessments of changes in the composition of cultivated areas that distinguish commodity crops, staple food crops, and dual-purpose crops while examining their associations with observed temperature and precipitation variability across Brazil's five macroregions. A recent study [2] investigated the transition from traditional crops to commodities in Northern Brazil and identified heterogeneous relationships with climatic conditions. Extending this approach to the national scale provides an opportunity to determine whether these transformations are regionally restricted or reflect broader changes in Brazilian agriculture.

Based on this research gap, three hypotheses were examined. H1: The composition of cultivated areas in Brazil changed between 1995 and 2025, with an increasing relative share of commodity crops and a declining relative share of staple food crops among the selected agricultural groups. H2: The magnitude and temporal patterns of these changes differed among Brazil's five macroregions. H3: Interannual variations in temperature and precipitation were statistically associated with changes in agricultural crop composition, with associations differing among agricultural indicators and macroregions. The sensitivity of the observed agricultural trends to alternative classifications of maize was also examined.

Therefore, this study aims to assess three decades of agricultural land use transformation in Brazil (1995–2025), quantifying changes in the relative importance of food crops and commodities and investigating their associations with climate variability. Specifically, the objectives are to: (i) reconstruct the temporal evolution of cultivated areas across major agricultural crop groups; (ii) quantify absolute and relative changes in commodity and staple food crop areas; (iii) identify the crops and regions contributing most to agricultural expansion or contraction; (iv) evaluate the sensitivity of the observed trends to the classification of maize as a dual-purpose crop, commodity, or staple food crop; and (v) investigate associations between agricultural changes and air temperature and precipitation across Brazil's five macroregions.

Within the broader context of the Brazilian bioeconomy, these transformations reflect the increasing integration of biological resources into food production, animal feed, energy,

industrial processing, and global markets. Assessing their implications for agricultural diversification, food security, and climate resilience is essential for understanding the sustainability challenges associated with Brazil's evolving agricultural production systems.

2. Materials and Methods

2.1. Characterization of Study Area

The study covers the entire Brazilian territory, encompassing its five official geographic macroregions: North, Northeast, Central-West, Southeast, and South (Figure 1). Brazil extends over approximately 8.5 million km^2, from 5°16′ N to 33°45′ S and from 34°48′ W to 73°59′ W, exhibiting substantial climatic, ecological, and agricultural diversity. These macroregions were selected as spatial units to assess changes in agricultural land use and their associations with climate variability between 1995 and 2025.

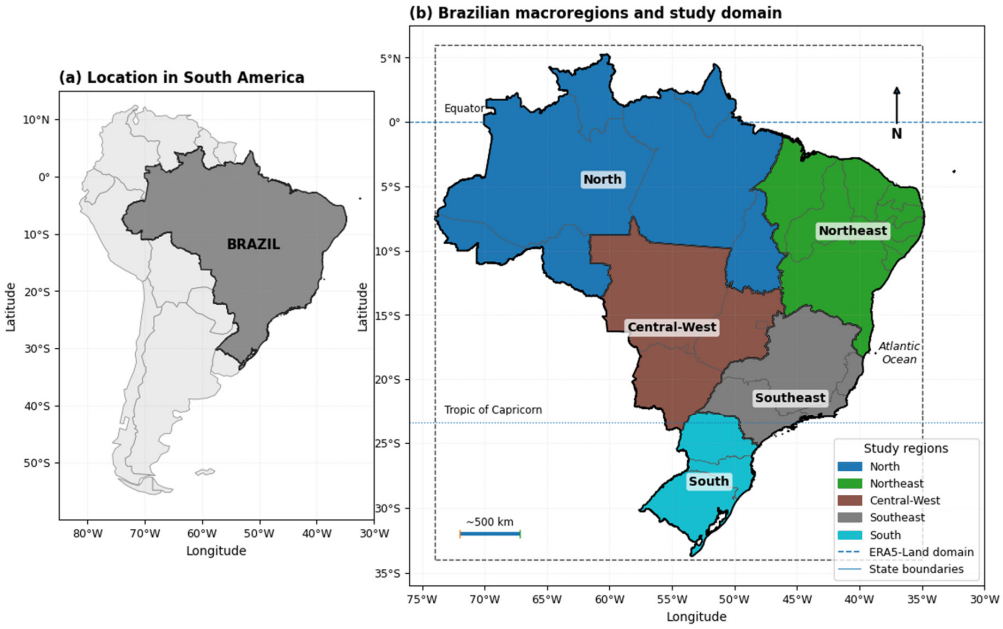

Figure 1. Location of the study area and the five Brazilian macroregions considered in the analyses of changes in agricultural land use and climate variability between 1995 and 2025. (**a**) Location of Brazil in South America. (**b**) Boundaries of the North, Northeast, Central-West, Southeast, and South regions, including internal state boundaries. The dashed rectangle represents the spatial domain of the ERA5-Land climate data used to derive the air temperature and precipitation time series. The Equator and the Tropic of Capricorn are shown as geographic references. Geodetic reference system: SIRGAS 2000 (EPSG:4674).

The five macroregions encompass different climatic regimes, ecosystems, and agricultural production systems (Table 1). The North is predominantly characterized by the Amazon biome and hot, humid conditions, whereas the Northeast includes humid coastal environments and extensive semiarid areas dominated by the Caatinga. The Central-West comprises large areas of Cerrado, with pronounced wet and dry seasons, as well as portions of the Amazon and Pantanal biomes. The Southeast includes Atlantic Forest and Cerrado ecosystems, with tropical and subtropical climatic conditions, while the South encompasses Atlantic Forest and Pampa landscapes, with greater seasonal temperature variability. These environmental differences influence agricultural suitability, production calendars, and regional patterns of agricultural development.

Table 1. General climatic, ecological, and agricultural characteristics of Brazil's five geographic macroregions.

Macroregion	Predominant Climate	Main Biomes	Agricultural Characteristics
North	Equatorial and tropical; predominantly hot and humid	Amazon, Cerrado	Cassava, açaí, soybean, maize, and expanding agricultural frontiers
Northeast	Tropical humid to semiarid; high rainfall variability	Caatinga, Atlantic Forest, Cerrado	Cassava, beans, sugarcane, soybean, and fruit crops
Central-West	Tropical savanna; distinct wet and dry seasons	Cerrado, Pantanal, Amazon	Large-scale soybean, maize, sorghum, and sugarcane production
Southeast	Tropical and subtropical; seasonal rainfall	Atlantic Forest, Cerrado	Coffee, sugarcane, citrus, soybean, and diversified food crops
South	Subtropical and temperate; pronounced thermal seasonality	Atlantic Forest, Pampa	Soybean, maize, rice, beans, and diversified agricultural systems

Agricultural production also differs among regions. Commodity-oriented agriculture has expanded considerably in the Central-West and parts of the North and Northeast, particularly through soybean and maize production. The Southeast combines major commercial crops, including sugarcane and coffee, with diversified food production, while the South is characterized by intensive agricultural systems involving both commodity and food crops. These regional differences provide an important context for interpreting changes in cultivated area and their associations with climatic conditions.

For the analyses, agricultural data from the Brazilian Institute of Geography and Statistics (IBGE) were aggregated according to the five official macroregional boundaries. Air temperature and precipitation data from ERA5-Land were spatially aggregated using the same geographic divisions. This procedure established a consistent spatial and temporal framework for comparing agricultural land-use dynamics and climate variability across Brazil from January 1995 to December 2025.

The five macroregions exhibit distinct characteristics in terms of climatic conditions, the organization of agricultural systems, and the historical dynamics of land occupation and use. The Northern region comprises a large part of the Brazilian Amazon, characterized predominantly by hot and humid conditions and by an agricultural frontier that has expanded significantly in recent decades. The Northeast exhibits high climatic diversity, ranging from humid coastal areas to extensive semiarid zones in the interior, where irregular rainfall constitutes a major constraint on agricultural production.

The Midwest, which includes a significant portion of the Brazilian Cerrado, has established itself as one of the country's leading regions for large-scale agricultural production, particularly of crops integrated into national and international commodity chains. The Southeast and South regions have historically more established and diversified agricultural systems. The Southeast is home to major production areas for cash crops, such as coffee and sugarcane, while also maintaining significant production of various food crops.

The South, meanwhile, is characterized by intensive and diversified agriculture, with significant contributions from both crops intended directly for food and those linked to commodity chains. These differences mean that trends in cultivated area and their possible association with climatic conditions are not necessarily uniform across Brazil. The country's latitudinal span and physiographic diversity also give rise to distinct temperature and precipitation patterns. While much of the North and Northeast regions experience high average temperatures throughout the year, the South and part of the Southeast exhibit greater seasonal temperature variation. Similarly, total precipitation amounts and seasonal

distribution vary substantially among regions, ranging from the high rainfall volumes in much of the Amazon to the conditions of greater water scarcity and interannual variability observed in the northeastern semiarid region.

In the Midwest and parts of the Southeast, the marked alternation between wet and dry seasons plays an important role in determining agricultural calendars and cropping systems. This heterogeneity makes Brazil a particularly suitable area for investigating the long-term transformation of the composition of agricultural areas and its association with climate variability. For this study, the five macroregions served as the spatial units used to integrate agricultural and climate data for the period from January 1995 to December 2025.

Data on cultivated area were aggregated regionally, while the climatic variables of air temperature and precipitation from ERA5-Land were spatially delimited and aggregated using the same regional boundaries. Thus, a consistent spatial and temporal framework was constructed, allowing for a comparison of the trajectories of food crops and agricultural commodities under different climatic and productive contexts across Brazil.

2.2. Meteorological Data

The meteorological data used in this study were obtained from the ERA5-Land reanalysis (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview, accessed on 25 August 2026), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) through the Copernicus Climate Change Service; this product has already been validated in many regions of Brazil by other studies [32]. The variables used were 2-m air temperature and total precipitation, covering the period from 1995 to 2025, consistent with the time series of the agricultural data analyzed. The original data had a spatial resolution of 0.1° × 0.1°, covering the area between 6° N and 34° S and 74° W and 35° W, which encompasses Brazilian territory.

Total precipitation, originally expressed in meters of water equivalent, was converted to millimeters (mm). Given the temporal structure of the data sets used—in which precipitation is presented as a cumulative total over the course of the day—the value corresponding to the final 24-h total was used to estimate daily precipitation and, subsequently, monthly totals. The 2-m air temperature data from ERA5-Land were initially converted from Kelvin (K) to degrees Celsius (°C) and aggregated into monthly averages. The ERA5-Land grid cells were spatially associated with the five macroregions using their respective geographic boundaries. For each region, the monthly temperature was obtained by spatially averaging the valid grid cells located within its polygon. These data provide better support for this type of analysis, given the low density of weather stations in many regions of Brazil, such as the Northern Region [33,34].

Annual temperature anomalies were calculated separately for each macroregion relative to the average temperature for the same period. Thus, positive values represent warmer years, and negative values represent colder years relative to the region's own average reference condition. The annual temperature anomaly was calculated using the following equation:

$$T'_{r,y} = \overline{T}_{r,y} - \frac{1}{N}\sum_{k=1995}^{2025} \overline{T}_{r,k} \quad (1)$$

where $T'_{r,y}$ represents the annual temperature anomaly (°C) for region r in year y; $\overline{T}_{r,y}$ corresponds to the average annual temperature of region r in year y; and N represents the number of years in the time series. The value zero represents the average temperature of the reference period for each region.

To ensure spatial alignment with the agricultural data, the ERA5-Land grid was intersected with the geographic boundaries of the five Brazilian macroregions. Only the grid cells that spatially belonged to each region were considered. This procedure resulted in

31,481 cells for the North, 12,764 for the Northeast, 13,546 for the Central-West, 7980 for the Southeast, and 5160 for the South.

The monthly values were then spatially aggregated to represent the average weather conditions for each macroregion. To integrate them with the annual data on cultivated area, the monthly time series were subsequently aggregated on an annual scale. Annual temperature was calculated as the average of the monthly temperatures, while annual precipitation corresponded to the sum of the monthly precipitation totals. This procedure produced a 31-year time series for each of the five macroregions, totaling 155 region–year observations, with no temporal gaps in the analyzed period. Besides absolute values, climate anomalies were calculated to allow for comparisons between regions with different climatic regimes.

The use of the same reanalysis data set, spatial resolution, and aggregation procedure for all regions ensured consistency in the spatiotemporal comparison of meteorological conditions. The resulting regional time series were subsequently integrated with agricultural land use data to investigate the associations between temperature and precipitation variability and interannual changes in the proportion and extent of land allocated to food crops and agricultural commodities in Brazil.

2.3. Agricultural Production Data

The agricultural production data used in this study were obtained from the Municipal Agricultural Production (PAM) database, made available by the Brazilian Institute of Geography and Statistics (IBGE) online (https://sidra.ibge.gov.br/pesquisa/pam/tabelas, accessed on 25 August 2026) for the same period covered by the time series. The PAM is an official nationwide database that provides annual information on various agricultural crops in Brazilian municipalities. Crops belonging to the categories of temporary and permanent crops were considered, selected based on their relevance to food production and to Brazil's major commercial agricultural supply chains.

The data were initially organized by crop, year, and geographic unit and subsequently aggregated for the five Brazilian macroregions. The main variable used was the planted agricultural area (for temporary crops) and the area designated for harvest (for permanent crops) associated with each crop, expressed in hectares (ha), as this variable is directly related to the objective of assessing long-term changes. For analytical purposes, the 23 crops were classified into four functional groups: commodity crops, staple food crops, other food crops, and mixed-use crops. The comparison between commodity crops and staple food crops constituted the primary focus of the analysis.

The classification was established for the purposes of this study based on the predominant role of each crop in Brazilian agricultural production and food systems, considering the economic and social relevance of agricultural products described by IBGE [35] and the distinction between food, feed, processing, and other uses adopted in FAO food balance sheet methodologies [36].

The category "other food crops" includes selected fruit crops and other agricultural products primarily associated with human consumption that were not included among the four staple food crops. This classification represents an analytical grouping developed by the authors rather than an official crop classification provided by IBGE. Because individual crops may participate in multiple markets and supply chains, these categories describe predominant functional roles and do not imply exclusive end uses.

The first category comprised crops predominantly associated with commercial and agroindustrial chains and commodity markets, while the second category included crops that play a significant role in food supply and domestic consumption. This classification made it possible not only to assess changes in individual crops but also to track the evolution

of the relative composition of agricultural land allocated to the two groups over the study period. Corn received special treatment due to its multifunctional nature. Although it is important for human consumption, a large portion of its production is integrated into animal feed, agribusiness, and commodity chains.

The exclusive classification of corn as a food crop or a commodity could therefore artificially influence the magnitude of the observed transition. To assess the robustness of the results, alternative classification scenarios were considered, treating corn as a dual-purpose crop and, in sensitivity analyses, as a commodity or as a staple food crop. This procedure made it possible to verify whether the identified trajectory of agricultural transformation remained consistent under different classification assumptions. Based on the annual data, the total area of commodity crops, the total area of staple food crops, and their respective shares of the total agricultural area were calculated for each macroregion.

The share of commodities was expressed as the ratio of the area devoted to crops classified in this group to the sum of the areas of the commodity and food crop groups, multiplied by 100. An equivalent procedure was used to determine the share of food crops. Absolute, relative, and percentage-point changes were also calculated between the initial and final years of the time series, making it possible to identify the crops and regions that contributed most to the transformation observed between 1995 and 2025. It is important to note that the sum of the areas of the different crops in the PAM does not necessarily represent an estimate of the single physical area occupied by the crop, since PAM data allow for successive crops in the same area.

A single area may be used for more than one crop during the same agricultural year, especially in successive cropping or second-crop systems. Therefore, in this study, changes are interpreted as alterations in the composition and extent of the cultivated/harvested areas reported for the different crops, rather than as direct and equivalent conversions of land cover. This distinction is important for interpreting the expansion of commodities and the decline of food crops without attributing physical land-use conversions based solely on PAM/IBGE data. After standardization and aggregation, the agricultural data were structured on an annual basis that was spatially and temporally compatible with the meteorological information. For each of the five macroregions, 31 annual observations were obtained, totaling 155 region–year combinations between 1995 and 2025.

This framework made it possible to analyze long-term trends in Brazil's agricultural composition and, subsequently, to integrate agricultural production data with regional temperature and precipitation time series derived from ERA5-Land. For analytical purposes, the 23 crops were classified into four functional groups: commodity crops, staple food crops, other food crops, and mixed-use crops (Table 2). Six crops were classified as commodities, four as staple food crops, twelve as other food crops, and corn was classified separately as a mixed-use crop due to its simultaneous use in human food, animal feed, and agro-industrial supply chains.

The classification adopted in this study reflects the predominant functional role of each crop within Brazilian agricultural production systems rather than an exclusive distinction between commercial and food uses. Commodity crops were defined according to their predominant association with commercial, agroindustrial, and commodity-oriented supply chains, whereas staple food crops were identified based on their importance in traditional domestic food consumption. Other food crops were maintained as a separate category, and maize was classified as a mixed-use crop because of its substantial participation in both food and agroindustrial markets. We acknowledge that this classification involves some degree of simplification, since crops such as cocoa, coffee, sugarcane, cassava, and rice may participate in different markets and value chains. Therefore, the categories should be interpreted as analytical groupings rather than mutually exclusive descriptions of crop utilization.

The sensitivity analysis focused on maize because of its substantial cultivated area and its particularly important role in both food and commodity supply chains. Although alternative classifications of other crops could influence the estimated magnitude of the differences between groups, their effects were not independently evaluated in the present analysis.

Table 2. Classification of agricultural crops according to their primary functional group used in the analysis.

Crop Group	Crops Included	No. of Crops
Commodity crops	Cocoa, Coffee, Oil palm, Sorghum, Soybean, Sugarcane	6
Mixed-use crop	Maize	1
Other food crops	Annatto, Apple, Avocado, Açaí, Banana, Cashew, Guava, Lemon/Lime, Orange, Passion fruit, Pineapple, Watermelon	12
Staple food crops	Beans, Cassava, Potato, Rice	4
Total	—	23

The selection of 23 crops was intended to represent major agricultural activities associated with food production and commodity-oriented supply chains in Brazil, rather than to provide an exhaustive inventory of all cultivated crops. Consequently, the findings refer specifically to the crops included in the analysis and their respective functional classifications. The relative shares reported for commodity and staple food crops were calculated using the combined cultivated area of these two groups and should not be interpreted as percentages of the total cultivated area of all agricultural crops in Brazil.

Note: Crops were classified according to their predominant role in Brazilian agricultural production and food systems. Crops classified as commodities include those predominantly associated with commercial, agroindustrial, and commodity-oriented value chains. Staple food crops are those that play a significant role in domestic food supply, while other food crops include additional crops intended primarily for human consumption. Corn was classified separately as a mixed-use crop due to its simultaneous importance for human food, animal feed, and agroindustrial commodity chains. Alternative classifications of corn were evaluated using sensitivity analyses.

2.4. Statistical Analysis

The relations between agricultural land dynamics and climate variability were evaluated for the period from 1995 to 2025, taking into account Brazil's five macroregions. The agricultural variables used in the analyses were the area planted with crops classified as commodities, the area devoted to staple food crops, and the relative share of commodities in the combined area of staple food crops and commodities. The climate variables considered were the annual air temperature anomaly, the percentage anomaly of annual precipitation, and the normalized precipitation anomaly. Alternatives for corn were evaluated using sensitivity analyses.

The integrated dataset was organized as a region–year panel, allowing for the assessment of both general temporal patterns and their spatial heterogeneity. Initially, Pearson correlation coefficients (r) were calculated between each agricultural variable and the climate variables. Since the agricultural area and temperature time series exhibit long-term temporal trends, the correlations were assessed using three complementary configurations: (i) raw time series; (ii) detrended time series; and (iii) first annual differences.

In the trend-removal procedure, a linear regression as a function of year was fitted separately for each region and variable, and the resulting residuals were used in subsequent

analyses. For the first differences, the variations between consecutive years were calculated according to Equation (2).

$$\Delta X_t = X_t - X_{t-1} \quad (2)$$

This allows us to assess the association between interannual climate changes and annual changes in the composition of agricultural land, reducing the influence of common long-term trends. We also examined time-lagged relationships between climatic conditions and agricultural responses. For this purpose, the climatic variables were shifted by up to three years (*lags* of 1, 2, and 3 years), in addition to the contemporaneous relationship (*lag* 0), and correlated with annual changes in the agricultural variables. This approach was used to investigate whether climatic variations observed in previous years were statistically associated with subsequent changes in the composition of the cultivated area. The lagged relationships were interpreted as temporal associations and not as evidence of causality.

To account for multiple statistical comparisons in the lagged correlation analysis, the Benjamini–Hochberg [37] false discovery rate (FDR) procedure was applied to the complete family of 36 correlation tests, comprising three agricultural indicators, three climatic variables, and four temporal lags (0–3 years). Statistical significance was evaluated using FDR-adjusted p-values at a threshold of 0.05. This procedure was adopted to reduce the expected proportion of false discoveries among statistically significant findings arising from multiple exploratory comparisons.

Additionally, panel regression models with fixed effects for region and year were estimated to control for persistent structural differences among the macroregions and temporal factors common to Brazil. The models alternately used the area under commodities, the area under staple food crops, and the share of commodities as dependent variables, while temperature anomalies and standardized precipitation anomalies were used as explanatory variables.

A second specification was estimated using first differences of the agricultural and climatic variables, allowing us to test whether interannual changes in climate were associated with annual changes in agricultural land use, independent of long-term trends. To investigate the spatial heterogeneity of these relationships, linear regressions on first differences were also estimated separately for each of the five macroregions. In this analysis, the slope, Pearson's correlation coefficient, standard error, and p-value were estimated for the relationships between annual changes in agricultural variables and annual changes in temperature and precipitation anomalies.

Given the stronger association observed in the Northeast, an additional sensitivity analysis was conducted specifically for this macroregion. We estimated first-difference linear regressions relating annual changes in commodity share to annual changes in temperature anomalies, initially considering temperature as the sole predictor and subsequently including changes in standardized precipitation anomalies. To assess sensitivity to serial dependence, heteroskedasticity-consistent HC3 standard errors and heteroskedasticity and autocorrelation-consistent (HAC) Newey–West standard errors with maximum lags of 1, 2, 3, and 5 years were applied [38,39]. The analysis included 30 annual observations corresponding to the first differences of the 1995–2025 series. These alternative specifications were used to assess the stability of the estimated association rather than to establish causality.

Close attention was given to the relationship between the annual variation in temperature anomalies and the variation in the share of commodities, allowing for a comparison of the magnitude and direction of the responses across the North, Northeast, Midwest, Southeast, and South. The set of statistical procedures implemented in the script explicitly includes correlations, first differences, panel models, and regional regressions. The robustness of the agricultural classification was further examined through a sensitivity analysis specific to corn, given its multifunctional role in Brazilian agriculture. Three scenarios

were compared: S1, in which corn is maintained as a mixed-use crop; S2, in which corn is included in the commodity group; and S3, in which corn is included among staple food crops. For each scenario, the relative shares of commodities and staple food crops and their changes between 1995 and 2025 were recalculated, both at the national and regional levels.

This analysis made it possible to determine the extent to which the magnitude of the observed transition depended on the classification assigned to corn, without changing the classification of the other crops. Statistical significance was assessed at the 5% level ($p < 0.05$), with $p < 0.01$ and $p < 0.001$ additionally reported to distinguish lower p-value thresholds. The analyses were performed in Python 3.14.7, primarily using the pandas and NumPy libraries for data manipulation, SciPy for correlations and linear regressions, and statsmodels for panel regression models. The statistical relationships were interpreted as associations and were not used to infer causality between climate variability and changes in agricultural structure.

Time-series trends in annual mean temperature were estimated separately for the five Brazilian macroregions, covering the period from 1995 to 2025 (n = 31 years per region). To this end, simple linear regression was performed using the ordinary least squares (OLS) method, with the year as the independent variable and the annual mean temperature as the dependent variable [40]. The regression slopes were multiplied by ten to express the warming rates in °C per decade^{-1}. The statistical significance of the trends was assessed using a two-tailed t-test on the regression slope, with a significance level of 5% ($p < 0.05$). In addition, 95% confidence intervals were estimated for the trend coefficients.

To assess the sensitivity of regional temperature trends to potential temporal autocorrelation, linear trends estimated by ordinary least squares (OLS) were additionally evaluated using heteroskedasticity and autocorrelation-consistent (HAC) Newey–West standard errors with maximum lags of 1, 2, 3, and 5 years. Durbin–Watson statistics were calculated from the OLS residuals to examine potential first-order serial dependence. A three-year bandwidth was adopted as the reference specification, while the remaining bandwidths were used for sensitivity analysis.

Additionally, two complementary panel regression specifications were estimated to examine the associations between climate variability and agricultural indicators. The first specification incorporated region and year fixed effects to account for time-invariant differences among macroregions and temporal factors common to all regions. The model was expressed as follows (Equation (3)) [41]:

$$Y_{r,t} = \alpha_r + \lambda_t + \beta_1 T_{r,t} + \beta_2 P_{r,t} + \varepsilon_{r,t} \quad (3)$$

where $Y_{r,t}$ represents the agricultural indicator for macroregion (r) in year (t), alternately defined as commodity cultivated area (million hectares), staple food cultivated area (million hectares), or commodity share (%). $T_{r,t}$ represents the annual air temperature anomaly (°C), and $P_{r,t}$ represents the standardized annual precipitation anomaly. The terms α_r and λ_t denote region and year fixed effects, respectively, while β_1 and β_2 are the estimated regression coefficients and $\varepsilon_{r,t}$ is the error term.

The second specification used first annual differences to examine whether interannual changes in climatic conditions were associated with changes in agricultural indicators, thereby reducing the influence of persistent temporal trends. The first-difference model was expressed as follows (Equation (4)):

$$\Delta Y_{r,t} = \lambda_t + \beta_1 \Delta T_{r,t} + \beta_2 \Delta P_{r,t} + \mathcal{U}_{r,t} \quad (4)$$

where Δ denotes the difference between consecutive annual observations, λ_t represents year fixed effects, and $u_{r,t}$ is the error term. The first-difference specification included 150 region–year observations, compared with 155 observations in the fixed-effects model.

To assess the sensitivity of statistical inference to temporal and cross-sectional dependence, Driscoll–Kraay standard errors were estimated using a Bartlett kernel and bandwidths of 1, 3, and 5 years. The regression coefficients were retained across covariance specifications, allowing the sensitivity of their statistical significance to be evaluated. Residual serial dependence was examined using the Durbin–Watson statistic separately for each macroregion. Given the limited number of cross-sectional units (five macroregions), these procedures were interpreted as sensitivity analyses rather than definitive corrections for all sources of statistical dependence.

To investigate geographical heterogeneity, additional linear regressions using first annual differences were estimated separately for each macroregion. The estimated slopes, Pearson correlation coefficients, standard errors, and p-values were used to compare the magnitude, direction, and statistical significance of the associations between interannual changes in agricultural indicators and climatic variables. All regression results were interpreted as statistical associations rather than evidence of causal relationships.

To further assess the sensitivity of the panel regression results to temporal and cross-sectional dependence, we re-estimated statistical inference using Driscoll–Kraay standard errors with a Bartlett kernel and bandwidths of 1, 3, and 5 years. These specifications retained the original regression coefficients and fixed-effects structures, allowing us to evaluate whether statistical significance was sensitive to the covariance estimator. Residual serial dependence was also examined using the Durbin–Watson statistic separately for each macroregion. Given the limited number of spatial units (five macroregions), these analyses were interpreted as sensitivity checks rather than definitive corrections for all sources of statistical dependence. All regression results were interpreted as associations, without assuming causal relationships between climate variability and agricultural changes.

3. Results

3.1. Structural Shift from Staple Foods to Commodities

The temporal evolution of cultivated areas reveals a profound restructuring of Brazilian agriculture between 1995 and 2025 (Figure 2). Crops classified as commodities showed the most pronounced expansion, rising from approximately 19 million hectares at the beginning of the time series to more than 62 million hectares in 2025—a growth of more than three times the initial area. Conversely, staple food crops showed a progressive decline, with the cultivated area decreasing from about 12 million to approximately 6 million hectares over the period.

Corn, considered separately as a dual-purpose crop, also expanded, particularly beginning in the 2010s, with continuous growth, reaching more than 22 million hectares by the end of the time series. Meanwhile, other food crops remained relatively stable and accounted for a comparatively small portion of the analyzed area. Taken together, these trends reveal a significant shift in the composition of cultivated areas in Brazil, marked by the growing predominance of crops linked to commodity chains, alongside a decline in areas devoted to staple food crops.

An analysis of the relative share of different crop groups underscores the magnitude of the transformation observed in Brazilian agriculture between 1995 and 2025 (Figure 3). The share of commodities in the total area analyzed increased from approximately 41% in 1995 to about 67% in 2025, becoming progressively dominant in the composition of cultivated land. In contrast, staple food crops followed a virtually continuous downward trend, falling from about 25% to just over 6% during the same period.

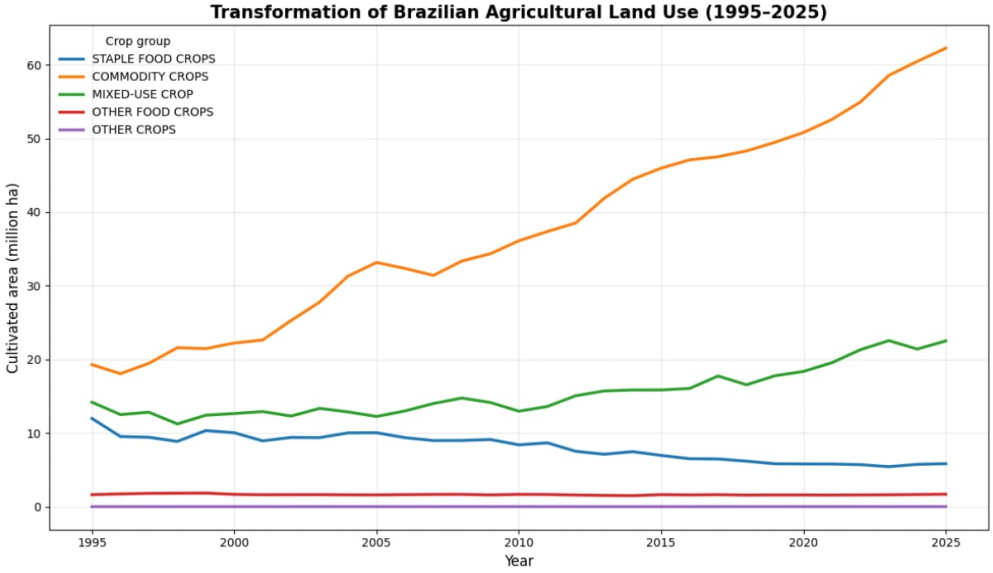

Figure 2. Temporal evolution of the cultivated area for different groups of agricultural crops in Brazil between 1995 and 2025. Crops were grouped into commodities, staple food crops, mixed-use crops (represented by corn), other food crops, and other crops. The figures correspond to the annual sum of the cultivated areas reported for crops belonging to each group, expressed in millions of hectares. The time series highlight long-term changes in the composition of Brazilian agriculture during the period analyzed.

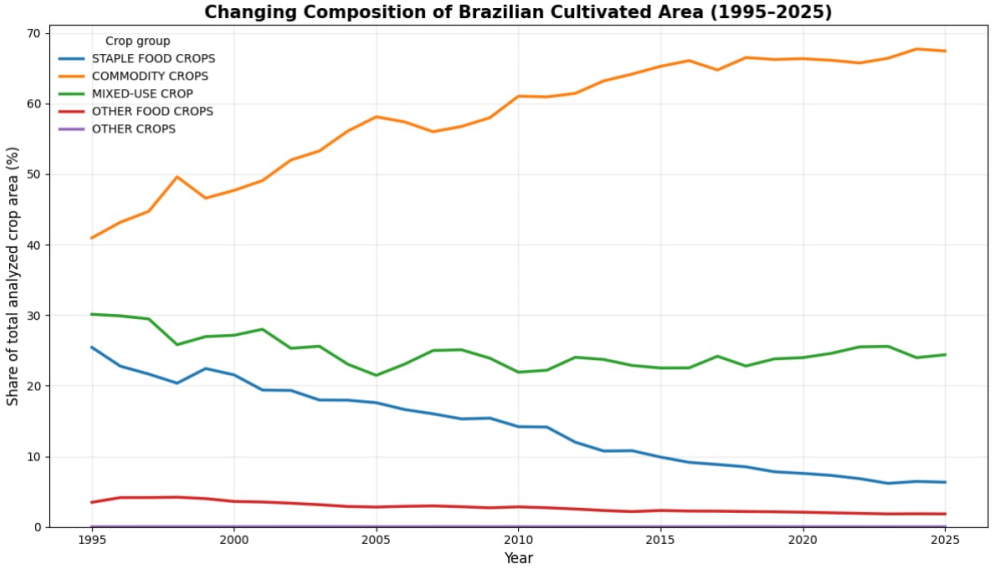

Figure 3. Changes in the relative composition of cultivated land in Brazil between 1995 and 2025, expressed as the percentage share of each crop group in the total area of the crops analyzed. The time series represent commodities, staple food crops, mixed-use crops (represented by corn), other food crops, and other crops. The share of each group was calculated annually as the ratio of its cultivated area to the total area of the crops included in the study, multiplied by 100.

Corn, classified as a dual-purpose crop, accounted for approximately 30% of the analyzed area at the beginning of the time series and, despite interannual fluctuations, has stabilized at around 22–25% in recent decades. The other food crops also lost relative share, albeit to a lesser extent, while the "other crops" group remained negligible. These results show that the expansion of commodities did not occur only in absolute terms but also substantially altered the relative structure of the analyzed agricultural area, increasing

its share while simultaneously reducing the relative weight of crops directly associated with staple foods.

A direct comparison between commodities and staple food crops highlights even more clearly the structural shift in the composition of Brazil's cultivated area over the three decades analyzed (Figure 4). In 1995, commodities already accounted for approximately 62% of the combined area of these two groups, while staple food crops accounted for about 38%. This difference widened almost continuously over the course of the time series, reaching, in 2025, approximately 91% for commodities and 9% for staple food crops.

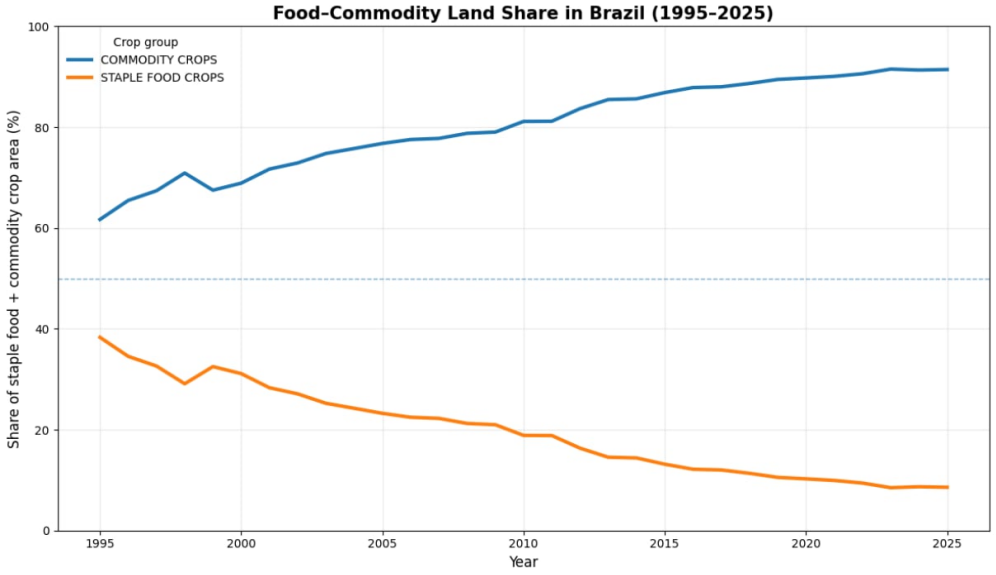

Figure 4. Trends in the relative share of crops classified as commodities and staple food crops in the combined cultivated area of these two groups in Brazil, from 1995 to 2025. For each year, the share was calculated relative to the sum of the areas cultivated with commodities and staple food crops, such that the two together total 100%. The horizontal dashed line at 50% represents the condition of equal share between the two groups.

Although there are minor year-to-year fluctuations—especially in the late 1990s—the long-term trend is unmistakable, with an increase of about 30 percentage points in the share of commodities and a proportional decrease in that of staple food crops. Considering only the area occupied by these two groups, the results reveal a growing concentration of cultivated land in crops geared toward commodity supply chains, alongside a relative decline in the share of staple food crops from 1995 to 2025.

The sensitivity analysis of corn classification confirms that the trend of relative expansion of commodities remains robust regardless of the classification framework adopted for this crop (Figure 5). Since the area under cultivation for corn is significant in Brazil, its full inclusion in either of the two groups could artificially alter the magnitude of the relative shares of commodities and staple food crops and, consequently, influence the interpretation of the observed shift. For this reason, this sensitivity analysis was conducted, in which corn was alternately treated as a dual-purpose crop (S1), a commodity (S2), and a staple food crop (S3). This approach allows us to assess whether the main trend identified depends on the methodological decision regarding the classification of corn.

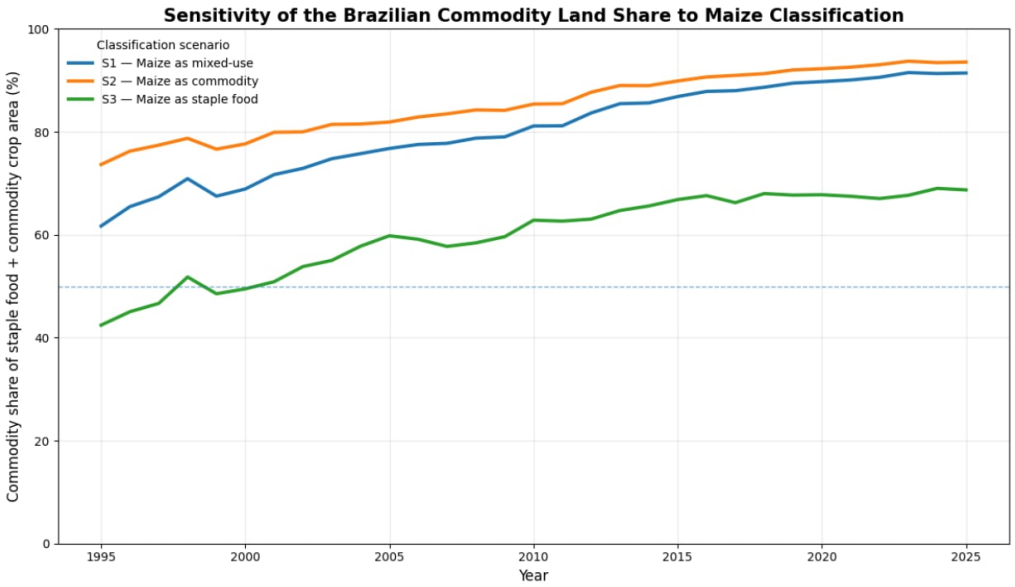

Figure 5. Sensitivity analysis of the share of commodities in Brazil's cultivated area based on different classifications of corn, between 1995 and 2025. Three scenarios were considered: S1, in which corn is classified as a mixed-use crop; S2, in which corn is included in the commodity group; and S3, in which corn is included in the staple food crops group. In each scenario, the share of commodities was calculated relative to the combined area of commodities and staple food crops, taking into account the respective classification of corn. The horizontal dashed line at 50% represents the condition of equal share between commodities and staple food crops.

In the main scenario (S1), in which corn was considered a dual-purpose crop, the share of commodities increased from 61.6% in 1995 to 91.4% in 2025, corresponding to an increase of 29.73 percentage points. When corn was included in the commodities category (S2), this share rose from 73.6% to 93.5% (+19.91 percentage points).

Even under the most conservative scenario for the share of commodities (S3)—in which corn was classified entirely as a staple food crop—an increase was observed from 42.4% to 68.7% (+26.28 percentage points). The last scenario shows that staple food crops accounted for a larger share than commodities at the beginning of the time series, but this relationship reversed by the late 1990s and widened progressively in the following decades. Therefore, although the classification of corn substantially alters the absolute magnitude of each group's share, it does not change the main trend observed: the consistent increase in the share of commodities in Brazil's cultivated area between 1995 and 2025.

This additional analysis is necessary because corn plays a functionally ambiguous role within the Brazilian agri-food system. Unlike other crops that are predominantly associated with commodities or directly with human consumption, corn is simultaneously part of different production chains, being used for human consumption, animal feed, and industrial processing.

3.2. Regional Climate Trajectories

The trends in annual temperature anomalies reveal a consistent shift in the thermal regime across Brazil's five macroregions over the analyzed period (Figure 6). During the first half of the time series, especially between the mid-1990s and the early 2000s, negative or near-zero anomalies predominated, although interspersed with occasional warmer years. Starting in the 2010s, there was a greater frequency and magnitude of positive anomalies, a pattern particularly evident after 2014 and common to all five regions.

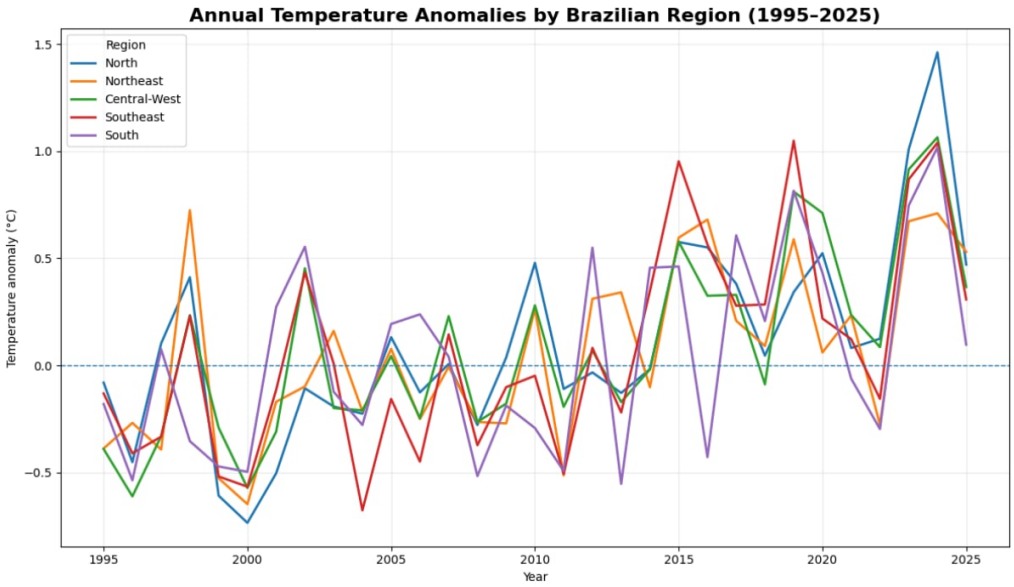

Figure 6. Trends in annual air temperature anomalies in Brazil's five macroregions—North, Northeast, Central-West, Southeast, and South—between 1995 and 2025. The anomalies, expressed in °C, were calculated separately for each region relative to the respective average temperature for the 1995–2025 reference period. Positive values indicate warmer years, and negative values indicate colder years relative to the regional reference average. The horizontal dashed line represents a zero anomaly.

In recent years, positive anomalies have simultaneously become elevated across much of Brazil, particularly in 2023–2024, when all macroregions experienced conditions substantially warmer than their respective reference averages. The North Region exhibits the highest positive anomaly in the series, close to 1.5 °C in 2024, while the Midwest, Southeast, and South also reach values close to or exceeding 1.0 °C. Despite interannual and regional differences, the progressive predominance of positive anomalies toward the end of the series indicates a general trend of warming across Brazil's five macroregions between 1995 and 2025.

Unlike temperature, annual precipitation anomalies exhibit high interannual variability and strong heterogeneity among Brazil's macroregions (Figure 7). In the first half of the series, wetter and drier years alternated, with significant positive episodes, such as those observed in the South in the late 1990s and in the Northeast and Southeast in 2009. Starting in the 2010s, however, negative anomalies of greater magnitude became more frequent, although interspersed with regional episodes of above-average precipitation. This pattern is particularly evident in the Northeast, which experienced deficits exceeding 30% in some years, as well as in the Southeast, Midwest, and South, where there were successive episodes with anomalies below −20%.

In the final years of the series, especially between 2022 and 2025, negative anomalies predominate in most regions, although there are significant differences in their magnitude. In 2025, all five macroregions show precipitation below their respective reference averages. Therefore, unlike the progressive trend observed for temperature, precipitation is characterized mainly by strong temporal and regional variability, associated with the recurrence of more pronounced precipitation deficits in the recent portion of the series.

Analysis of linear trends confirms that the warming observed over the time series occurred in all Brazilian macroregions, albeit to varying degrees (Figure 8). The highest rates were recorded in the North and Central-West regions, both close to 0.34 °C per decade, followed by the Southeast, with approximately 0.32 °C per decade. The Northeast showed warming of about 0.26 °C per decade, while the lowest rate was observed in the South, at approximately 0.23 °C per decade. Considering the 31 years analyzed, these rates represent

a significant and spatially widespread regional warming trend, corroborating the increase in the frequency of positive anomalies observed in Figure 6.

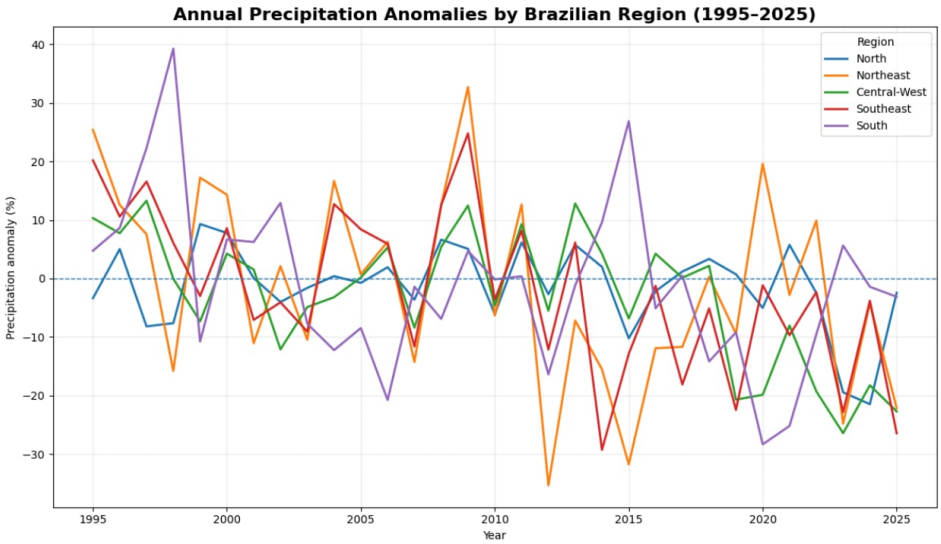

Figure 7. Trends in annual precipitation anomalies across Brazil's five macroregions—North, Northeast, Central-West, Southeast, and South—between 1995 and 2025. The anomalies are expressed as percentages (%) and calculated separately for each region relative to its respective average annual precipitation for the 1995–2025 reference period. Positive values indicate years with precipitation above the regional reference average, while negative values represent drier years. The horizontal dashed line indicates an anomaly of zero, corresponding to the average precipitation for each macroregion's reference period.

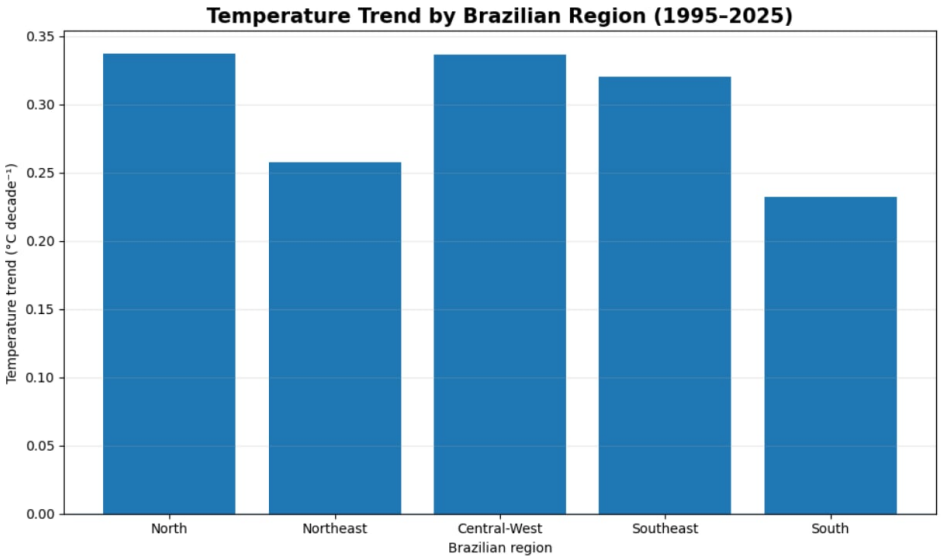

Figure 8. Linear trends in annual mean temperature across Brazil's five macroregions between 1995 and 2025. The trends were estimated individually for the North, Northeast, Central-West, Southeast, and South regions and expressed in °C per decade^{-1} ($p < 0.01$ in all regions). All regions showed positive temperature trends during the analyzed period, with magnitudes of approximately 0.34 °C per decade^{-1} in the North, 0.26 °C per decade^{-1} in the Northeast, 0.34 °C per decade^{-1} in the Central-West, 0.32 °C per decade^{-1} in the Southeast, and 0.23 °C per decade^{-1} in the South.

The statistical significance of the regional warming trends was further examined using HAC Newey–West standard errors to account for potential temporal autocorrelation. All five macroregions maintained statistically significant positive temperature trends across

the alternative bandwidths of 1, 2, 3, and 5 years ($p < 0.01$ in all specifications). Using a three-year bandwidth, the estimated warming rates were 0.337 °C decade^{-1} in the North, 0.258 °C decade^{-1} in the Northeast, 0.337 °C decade^{-1} in the Central-West, 0.320 °C decade^{-1} in the Southeast, and 0.232 °C decade^{-1} in the South ($p < 0.001$ for all regions). Durbin–Watson statistics ranged from 1.607 to 2.371. These findings indicate that the statistical significance of the observed warming trends was maintained across the alternative HAC covariance specifications.

Another noteworthy finding is that the highest rates of warming occurred in the North and Central-West, regions that also experienced strong expansion of commodity-oriented agriculture throughout the study period. This spatial and temporal coincidence is a relevant factor for subsequent analyses of the associations between climate change and changes in the composition of agricultural land, though it does not, in and of itself, imply a causal relationship between the two processes.

The regional climate trajectories occurred alongside substantial differences in agricultural crop composition and distribution across Brazil's five macroregions. According to the agricultural area data, the North experienced a marked expansion of soybean cultivation, from approximately 0.025 million hectares in 1995 to 3.63 million hectares in 2025, while maize increased from 0.61 to 1.81 million hectares. In the Northeast, soybean area expanded from 0.57 to 4.53 million hectares, whereas bean cultivation declined from 2.79 to 1.16 million hectares. The Central-West exhibited the largest soybean area in 2025, reaching 22.26 million hectares compared with 4.55 million hectares in 1995. Maize cultivation also increased substantially in this region, from 1.85 to 11.95 million hectares.

Distinct agricultural patterns were observed in the Southeast and South. In the Southeast, sugarcane area increased from 2.73 to 6.72 million hectares, while coffee remained an important permanent crop, increasing from 1.57 to 1.73 million hectares. In the South, soybean cultivation expanded from 5.42 to 13.47 million hectares, whereas maize area declined from 5.65 to 4.10 million hectares. These results indicate substantial regional heterogeneity in the composition and spatial distribution of cultivated areas over the study period. When considered alongside the temperature and precipitation trajectories presented in Figures 6–8, these agricultural changes provide additional context for understanding the regional dimensions of land-use transformation. However, the temporal concurrence of agricultural expansion and climate variability does not establish a causal relationship between these processes.

3.3. Climate Associations with Agricultural Restructuring

A joint analysis of agricultural and temperature time series shows that the shift in the composition of cultivated land occurred simultaneously with a gradual change in temperature conditions in Brazil (Figure 9). Over the period 1995–2025, the share of commodities increased from approximately 62% to more than 90% of the total area considered in this comparison, while the share of staple food crops followed the opposite trend, decreasing from about 38% to less than 10%.

At the same time, temperature anomalies shifted from a predominance of negative or near-zero values in the early decades to more frequent and intense positive values beginning in the mid-2010s, reaching their highest levels in the final years of the time series. The temporal overlap thus shows that the growing predominance of commodities occurred during a period also characterized by progressive warming, suggesting a temporal covariation between the transformation of the agricultural structure and thermal conditions. However, a combined visualization of the time series does not allow for the establishment of a causal relationship between these processes, making it necessary to apply statistical

analyses that control for their shared temporal trends and assess whether the associations persist after these trends are removed.

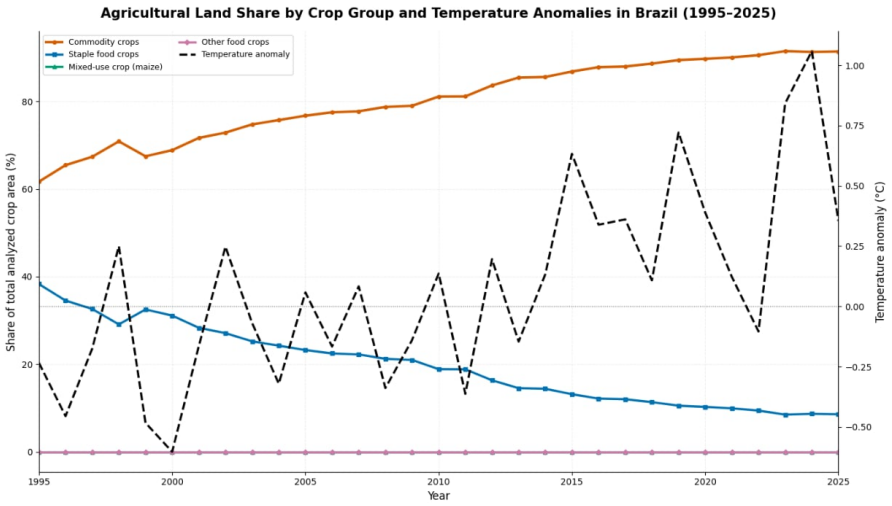

Figure 9. Combined evolution of the relative share of different crop groups in the analyzed agricultural area and of annual temperature anomalies in Brazil between 1995 and 2025. The agricultural time series represent the percentage share of commodities, staple food crops, corn as a mixed-use crop, and other food crops in the total area of crops considered in the study. Temperature anomalies (black dashed line; secondary axis), expressed in °C, were calculated relative to the 1995–2025 reference period.

The results of the statistical analysis confirm that the apparent association between changes in agricultural structure and climatic conditions depends on the time scale and the treatment applied to the data series (Figure 10). In the original data series, the share of commodities showed a positive correlation with temperature anomalies ($r \approx 0.30$; $p < 0.001$) and negative correlations with both the percentage precipitation anomaly and the standardized precipitation anomaly ($r \approx -0.21$; $p < 0.01$).

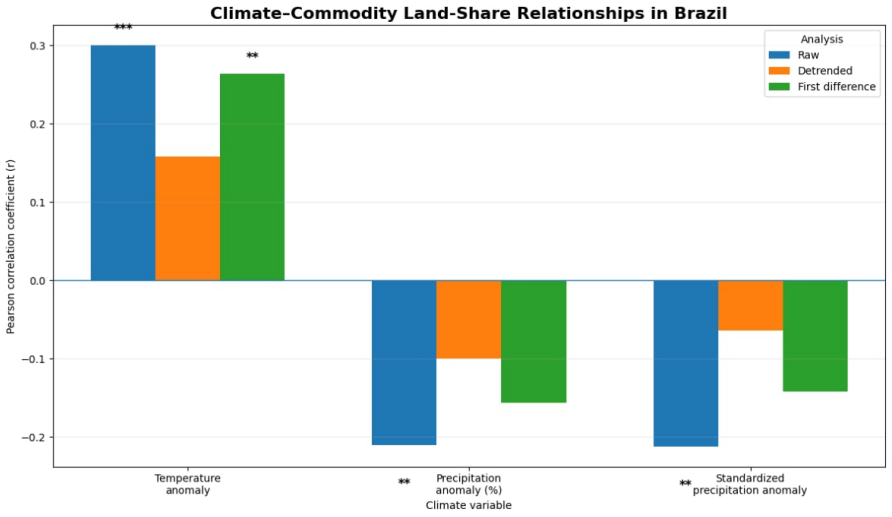

Figure 10. Relationships between the share of commodities in agricultural land and climate anomalies in Brazil between 1995 and 2025. The bars represent Pearson's correlation coefficients (r) between the relative share of commodities and temperature anomalies, percentage precipitation anomalies, and standardized precipitation anomalies, considering three approaches: raw series, detrended series, and annual first differences. Positive values of r indicate direct associations, and negative values indicate inverse associations. Asterisks indicate the statistical significance of the correlations: ** $p < 0.01$; *** $p < 0.001$.

The removal of linear trends substantially reduced the magnitude of these relationships, indicating that a significant portion of the correlations observed in the original time series stems from long-term trends shared between agricultural and climatic variables. However, the relationship with temperature reemerged in the first differences, with a positive correlation of approximately $r = 0.26$ ($p < 0.01$), showing that year-over-year increases in temperature anomalies were associated with year-over-year increases in the relative share of commodities. For precipitation, the associations remained negative, though weaker and statistically insignificant after trend removal and in the first differences.

Together, these results indicate a more consistent statistical association with temperature than with precipitation, although they do not allow us to attribute causality to climate in the transformation of Brazil's agricultural structure.

Analysis of time-lagged relationships revealed that the associations between temperature anomalies and annual agricultural changes varied across the temporal lags examined (Figure 11). After applying the Benjamini–Hochberg FDR correction to 36 lagged correlation tests, only two of the eight initially significant associations remained statistically significant. Both involved temperature anomalies with a one-year lag: commodity share was negatively correlated with the preceding year's temperature anomaly ($r = -0.278$; FDR-adjusted $p = 0.021$), whereas staple food cultivated area showed a positive correlation ($r = 0.243$; FDR-adjusted $p = 0.049$). No associations involving precipitation remained statistically significant after adjustment. The previously observed negative correlation between staple food area and temperature at a three-year lag ($r = -0.184$) was no longer significant (FDR-adjusted $p = 0.131$). These findings indicate that most nominally significant lagged associations were sensitive to multiple-testing correction and should be interpreted as exploratory rather than as evidence of delayed causal effects.

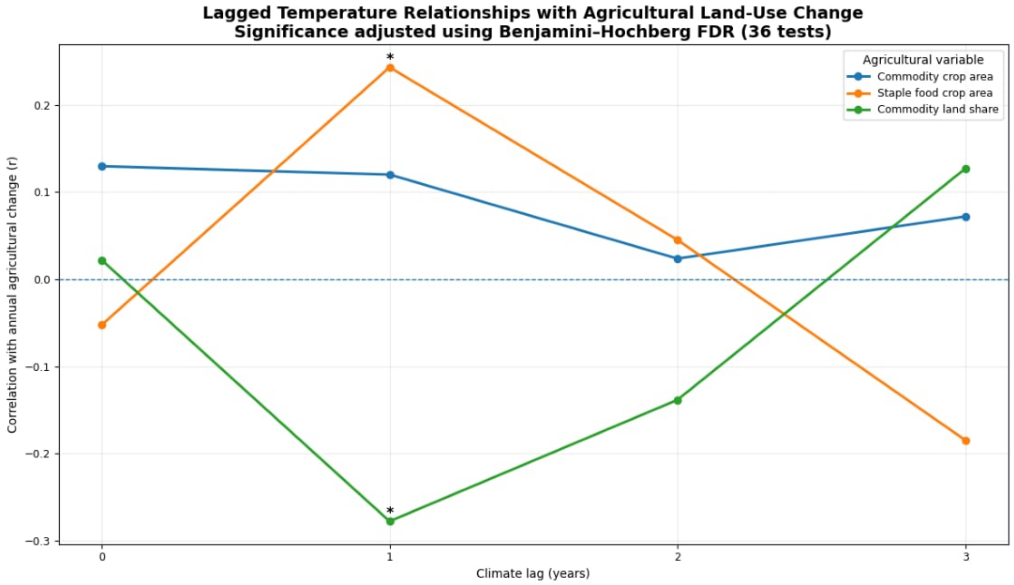

Figure 11. Lagged relationships between annual temperature anomalies and interannual changes in commodity crop area, staple food crop area, and commodity share across Brazil's five macroregions (1995–2025). Pearson correlation coefficients (r) were calculated for contemporaneous temperature anomalies (lag 0) and anomalies preceding agricultural changes by one, two, or three years. Asterisks indicate statistically significant associations after Benjamini–Hochberg false discovery rate correction across 36 lagged correlation tests (*FDR-adjusted $p < 0.05$). These associations should not be interpreted as evidence of causality.

The alternating magnitude and direction of the coefficients demonstrate that the phase-shifted relationships do not follow a simple or monotonic temporal response. These results

should be interpreted as evidence of a temporal structure in the associations, rather than as an indication of delayed causal effects of temperature on agricultural land use. Regional disaggregation also showed that the relationship between interannual temperature variations and changes in commodity shares was highly heterogeneous across Brazil (Figure 12). The estimated coefficients were positive in the North (+0.97 percentage points $°C^{-1}$), Northeast (+3.20 percentage points $°C^{-1}$), Central-West (+0.86 percentage points $°C^{-1}$), and South (+0.08 percentage points $°C^{-1}$), while the Southeast showed a slightly negative coefficient (−0.09 percentage points $°C^{-1}$).

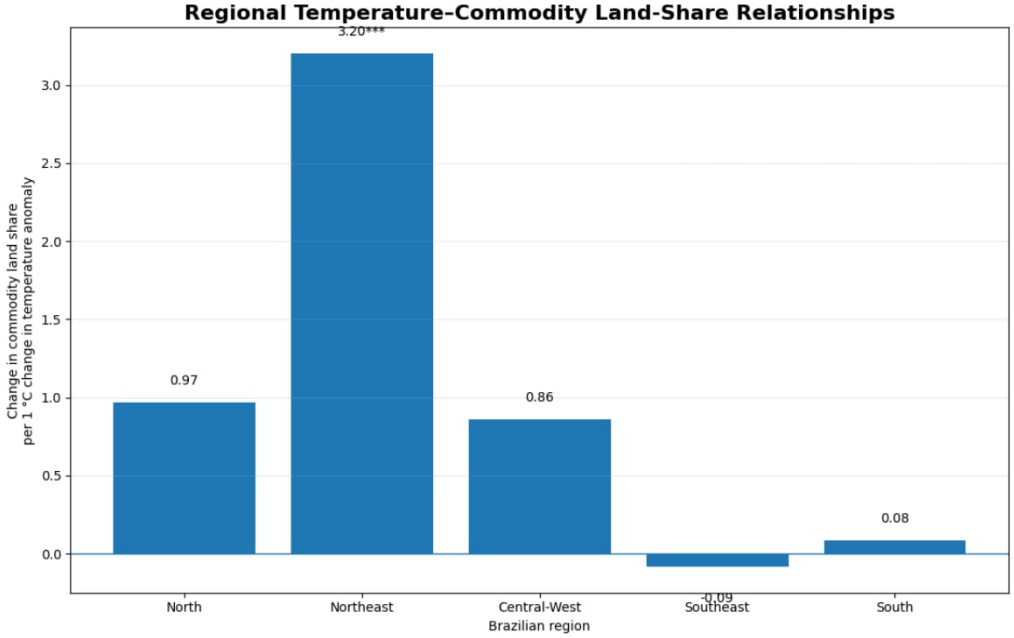

Figure 12. Regional relation between year-over-year changes in temperature anomalies and changes in the share of commodities in the agricultural area of Brazil's five macroregions, from 1995 to 2025. The bars represent the slopes obtained from linear regressions on first differences, expressed as the change in the share of commodities, in percentage points, associated with a 1 °C change in temperature anomaly. The estimated values were 0.97 percentage points $°C^{-1}$ for the North, 3.20 for the Northeast, 0.86 for the Central-West, −0.09 for the Southeast, and 0.08 for the South. Asterisks indicate statistical significance (*** $p < 0.001$).

However, only the Northeast showed a statistically significant association ($p < 0.001$), with a magnitude substantially greater than that observed in the other regions. This result demonstrates that the national association between global warming and the growing share of commodities does not represent a spatially uniform response: it is strongly influenced by regional dynamics and, in particular, by the response observed in the Northeast. The lack of statistical significance in the other macroregions—despite some positive coefficients—reinforces the need to consider territorial heterogeneity when interpreting the relationship between climate change and the transformation of Brazil's agricultural production structure.

Additional sensitivity analyses confirmed that the stronger association observed in the Northeast was consistent across alternative regression specifications. In the temperature-only first-difference model, the estimated coefficient was 3.203 percentage points per °C ($R^2 = 0.594$; n = 30). After including annual changes in standardized precipitation anomalies, the temperature coefficient remained virtually unchanged at 3.208 percentage points per °C ($R^2 = 0.594$). Statistical significance was maintained when using HC3 standard errors and HAC Newey–West standard errors with maximum lags of 1, 2, 3, and 5 years ($p < 0.001$ in all specifications). These findings indicate that the association identified for

the Northeast was not sensitive to the alternative covariance estimators or to the inclusion of precipitation changes. Nevertheless, the results refer to the macroregion as an aggregate geographical unit and do not establish that the same relationship occurs uniformly across its constituent states or climatic subregions.

Figure 13 complements the previous analyses by directly showing the relationship between year-over-year changes in temperature and the composition of agricultural land, thereby reducing the influence of long-term trends present in the original time series. When considering Brazil's five macroregions collectively, a positive and statistically significant association was observed between the annual variation in temperature anomalies and the annual variation in the share of commodities in the cultivated area ($r = 0.26$; $p = 0.001$).

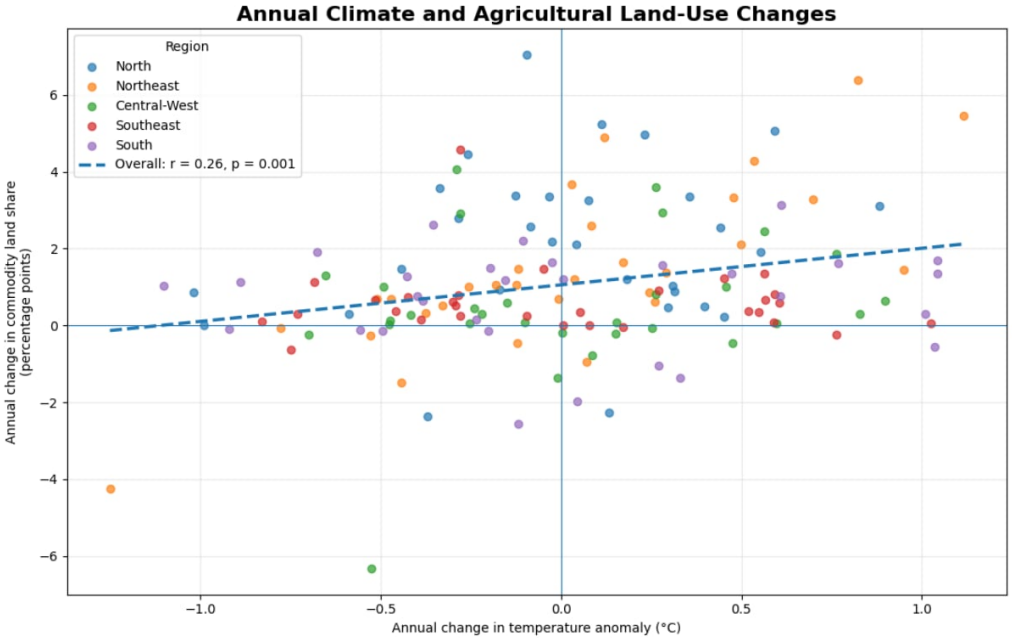

Figure 13. Association between year-over-year changes in temperature anomalies and annual changes in the share of commodities in the agricultural area of Brazil's five macroregions, from 1995 to 2025. Each point represents a region–year observation in first differences, with colors corresponding to the North, Northeast, Central-West, Southeast, and South regions. The dashed line represents the linear trend when all observations are considered together. A positive and statistically significant association was observed between the two variables ($r = 0.26$; $p = 0.001$). The horizontal and vertical lines indicate no annual change in the share of commodities and in the temperature anomaly, respectively.

Therefore, years characterized by an increase in the temperature anomaly compared to the previous year tended, on average, to coincide with increases in the relative share of commodities. However, the wide dispersion of observations and the uneven distribution of data points across regions highlight considerable spatial and interannual heterogeneity in this relationship. This pattern is consistent with the regionalized results presented earlier, in which the magnitude of the association varied substantially among the macroregions. Although the aggregate relationship is statistically significant, temperature explains only a limited portion of the annual variability observed in the composition of the cultivated area, indicating that Brazil's agricultural transformation results from a complex dynamic in which climatic conditions coexist with other factors not directly assessed in this analysis.

Additional panel regression analyses provided a more qualified interpretation of the relationships between climate variability and agricultural composition (Table 3). In models incorporating region and year fixed effects, neither temperature nor precipitation anomalies were significantly associated with commodity cultivated area, staple food cultivated area,

or commodity share ($p > 0.05$). For commodity share, the estimated temperature coefficient was 3.463 percentage points per °C (SE = 3.476; $p = 0.321$). Similarly, the first-difference model did not identify a statistically significant association between annual changes in temperature anomalies and commodity share (β = 0.677 percentage points per °C; SE = 0.447; $p = 0.132$).

Table 3. Panel regression estimates of associations between climatic anomalies and agricultural indicators across Brazilian macroregions (1995–2025).

Model/Dependent Variable	Predictor	β	SE	*p*
Two-way fixed effects (N = 155)				
Commodity area	Temperature	−0.283	0.613	0.645
	Precipitation	−0.401	0.255	0.119
Staple food area	Temperature	−0.012	0.108	0.914
	Precipitation	−0.014	0.038	0.725
Commodity share	Temperature	+3.463	3.476	0.321
	Precipitation	+1.047	1.275	0.413
First differences (N = 150)				
Commodity area	ΔTemperature	−0.188	0.058	0.0016
	ΔPrecipitation	−0.002	0.024	0.947
Staple food area	ΔTemperature	−0.131	0.074	0.078
	ΔPrecipitation	+0.002	0.012	0.859
Commodity share	ΔTemperature	+0.677	0.447	0.132
	ΔPrecipitation	−0.060	0.142	0.675

Note: β = estimated regression coefficient; SE = Driscoll–Kraay standard error (Bartlett kernel, bandwidth = 3 years). Commodity and staple food areas are expressed in million hectares; commodity share is expressed in percentage points. Temperature is expressed in °C and precipitation as a standardized anomaly. Statistical significance is evaluated at $p < 0.05$. The first-difference models use annual changes in agricultural and climatic variables.

In contrast, the first-difference model indicated a negative association between annual changes in temperature anomalies and commodity cultivated area (β = −0.188 million ha per °C; SE = 0.058; $p = 0.0016$). However, this relationship was not statistically significant in the two-way fixed-effects model estimated in levels ($p = 0.645$). The association between temperature changes and staple food cultivated area was also not statistically significant at the 5% level ($p = 0.078$), while precipitation coefficients remained nonsignificant across all specifications. These differences indicate that the estimated climate–agriculture relationships depend on the agricultural indicator and model specification. Consequently, the results do not support attributing the observed long-term restructuring of Brazilian agriculture primarily to climate variability.

4. Discussion

4.1. Agricultural Land Use Transformation and Food Security

The results of this study reveal a significant structural transformation in the composition of Brazilian agriculture between 1995 and 2025, characterized by the continuous expansion of crops linked to commodity chains and the simultaneous decline in the relative importance of staple food crops. More than just an increase in cultivated land area, the results show a shift in the functional composition of agricultural production: while the area devoted to

commodities increased from approximately 19 to more than 60 million hectares, the area devoted to staple food crops followed a downward trajectory.

Consequently, the share of commodities in the group comprising commodities and staple food crops rose from about 62% to over 90%. This pattern is consistent with independent evidence of the strong expansion of cash crops in Brazil and South America. Studies [42] demonstrated that the area planted with soybeans in South America more than doubled between 2000 and 2019 and that Brazil accounted for a substantial portion of this expansion, including particularly rapid growth in the Amazon and the Cerrado. There is a notable increase in the areas devoted to commodity crops, even amid rising climate anomalies (drought and heat), likely due to the use of techniques such as irrigation, since family-based farming generally lacks sufficient resources for this. Studies on the Midwest also show that Brazil's agricultural expansion has combined an increase in cultivated area, productivity gains, and the replacement of previous land uses—especially pastures—with soybeans and corn [43].

This interpretation, however, requires an important distinction. The data used in this study represent cultivated or harvested areas reported for different crops and, therefore, do not demonstrate that every hectare added to commodity production directly corresponds to the removal of a hectare previously used for food production. Second-crop systems, crop rotation, intensification, and the use of previously cleared pastures make Brazil's land-use dynamics substantially more complex [44].

This caveat is important for soybeans and corn, whose integration into double-cropping systems has become a defining feature of Brazilian agriculture. The literature shows that a considerable portion of the recent expansion of soybean cultivation occurred on land previously used for pasture, while intensification has made it possible to increase production on land that had already been converted [42]. Therefore, the results of this study are best interpreted as a reorganization of the composition of cultivated agricultural land rather than as direct evidence of physical land conversion between food crops and commodities. Nevertheless, the magnitude and persistence of this change have important implications for the debate on food security. The decline in the share of crops such as rice, beans, cassava, and potatoes occurs simultaneously with the growing specialization of agriculture in supply chains that are highly integrated with national and international markets [45].

A recent systematic review on changes in agricultural land use and food security highlights that shifts in the availability and use of agricultural land can affect different dimensions of food security and that economic, environmental, and social factors interact in determining these changes [19]. In the Brazilian context, therefore, high agricultural production capacity and a prominent position in international food trade do not necessarily imply the maintenance of the same crop diversity within the domestic production structure.

The results of this study do not allow for direct inferences regarding effects on prices, consumption, or food availability, but they clearly demonstrate that the territorial base of the crops analyzed has become progressively more commodity-oriented. An important limitation of this analysis is that changes in cultivated area do not necessarily correspond to equivalent changes in agricultural production. Reductions in the area allocated to staple food crops may be accompanied by improvements in crop yields resulting from technological advances, improved management, irrigation, or other forms of agricultural intensification.

Consequently, the observed contraction in the cultivated area of staple food crops cannot, by itself, be interpreted as a reduction in the quantity of food produced or as evidence of declining food security. The indicators examined here describe changes in the composition and geographical distribution of cultivated areas, rather than production volumes, agricultural productivity, food prices, or household access to food. The implications for

food security should therefore be understood as potential concerns related to agricultural specialization and crop diversification, rather than as directly measured outcomes.

This process takes on greater significance when interpreted from the perspective of the agricultural bioeconomy. The bioeconomy is not limited to food production; it encompasses biomass flows destined for human consumption, animal feed, energy, biofuels, industrial processing, and global markets [46].

The expansion of soybeans, sugarcane, corn, and other cash crops may, in this sense, lead to increased biomass production capacity and economic integration, but the sustainability of this trajectory depends on its compatibility with agricultural diversification, food security, environmental conservation, and climate resilience. A recent study focused on Brazil's Northern Region also identified a shift from crops traditionally associated with food production to products with higher commercial value and argued that a sustainable bioeconomy requires productive diversification, technological innovation, and climate adaptation policies [2]. The results of this study broaden this debate both spatially and temporally by showing that the change is not restricted to the Amazon but constitutes a national phenomenon, albeit with varying intensities across the macroregions.

The sensitivity analysis involving corn reinforces the clarity of this conclusion. Corn's functional role in the Brazilian agri-food system is inherently ambiguous, since the crop is used simultaneously for human consumption, animal feed, and agro-industrial supply chains [47]. Even when corn was classified entirely as a staple food crop, the share of commodities showed significant growth over the period analyzed. When incorporated into the commodities category, the predominance of this group became even greater. Therefore, the general trend toward commoditization does not result from an arbitrary choice of how to classify corn.

4.2. Agricultural Intensification and Environmental Sustainability

This issue is important in Brazil, where the expansion of soybean–second-crop corn systems is a fundamental component of agricultural intensification. Studies about changes in the Cerrado show that land conversion and agricultural intensification have even altered the climatic conditions to which corn is exposed, highlighting the close interaction between agricultural expansion, intensification, and the regional environment [48]. The observed agricultural transformation also cannot be separated from the environmental consequences of commodity expansion.

Studies have already shown that much of the recent expansion of soybean cultivation has occurred on previously converted pastures, but they have also identified direct conversion of natural vegetation, especially along the agricultural frontiers of the Cerrado [42]. This demonstrates that intensification and horizontal expansion can occur simultaneously. Governance policies for production chains can significantly alter this relationship: studies [49] showed that the Soy Moratorium reduced deforestation associated with areas suitable for soy in the Amazon and prevented thousands of square kilometers of forest loss, although its effectiveness depended on its interaction with public monitoring and territorial governance instruments.

The distinction between territorial expansion and production intensification is also relevant in this context for interpreting the resilience of agricultural systems. The sustainability implications of these transformations must also be interpreted within the scope of the indicators examined. The expansion of commodity cultivated area, the declining relative importance of staple food crops, and the regional differences in these trajectories provide evidence of changes in agricultural specialization and crop composition. However, these indicators do not directly measure resource-use efficiency, biodiversity conservation, greenhouse gas emissions, economic returns, or social outcomes. Likewise, the observed

associations with temperature and precipitation describe the climatic context of agricultural restructuring but do not quantify the environmental performance or resilience of individual production systems. Therefore, the results contribute to the discussion of bioeconomy sustainability by identifying changes in the agricultural production structure that warrant further investigation, rather than by establishing whether these changes are environmentally or socially sustainable.

Evidence from the Cerrado shows that climate changes associated with deforestation may jeopardize the successive cultivation of soybeans and corn [50]. However, studies on crop rotation diversification and conservation agriculture indicate potential benefits for soil quality, production stability, and resilience to global warming, although the magnitude of these benefits depends on management and environmental conditions [15,51]. The growing share of commodities observed in this study should therefore be interpreted in conjunction with the diversity of production systems and their sustainability conditions—factors that cannot be directly quantified solely by the agricultural area and climate data series used here.

The trajectory of an agricultural bioeconomy based on commodities is not necessarily predetermined; its environmental effects depend on the location of expansion, the use of previously cleared areas, the intensification of production, and the institutions responsible for territorial governance [52].

4.3. Climate Variability and Agricultural Restructuring

The climate dimension adds another layer to this transformation. All macroregions showed a positive temperature trend between 1995 and 2025, ranging approximately between 0.23 and 0.34 °C per decade^{-1}, while precipitation anomalies exhibited high interannual and regional variability. This warming is significant because much of Brazilian agriculture depends on precipitation and is concentrated in regions where temperature, the duration of the rainy season, and water availability determine the viability of intensive farming systems. Studies [25] demonstrated that abnormally hot and dry conditions reduce yields and limit expansion and intensification along the Amazon–Cerrado frontier, estimating that a substantial portion of agricultural areas has already shifted outside its optimal climate zone.

Similarly, modeling studies indicate that climate changes associated with vegetation removal may reduce corn productivity in the Cerrado [48] and that changes in precipitation associated with deforestation may simultaneously compromise soybean and corn yields [53]. Given this context, the positive correlation observed between commodity share and temperature anomalies in the original time series ($r \approx 0.30$) should not be interpreted as evidence that global warming caused the expansion of commodity production.

The temperature and the share of these crops have both shown upward trends over the three decades, so a correlation between non-stationary time series may partially reflect shared temporal trends. The reduction in the coefficient after trend removal confirms this need for caution. Although a positive association was observed in the bivariate first-difference analysis, this relationship was not statistically significant in the additional multivariate panel specifications, indicating that its interpretation depends on the statistical approach adopted.

An extensive review of statistical studies on climate and agriculture shows that agricultural responses to temperature and precipitation exhibit significant spatial heterogeneity and are confounded by technology, management, and other non-climatic factors [54]. The results regarding precipitation reinforce this cautious interpretation. The negative correlations found in the original time series weakened after detrending and differencing, indicating less temporal robustness than the association observed with temperature. The

literature also shows that the effects of precipitation are more spatially heterogeneous and dependent on crop type, phenological stage, and the intra-annual distribution of rainfall than the effects of average temperature [54]; for the Amazon–Cerrado frontier, for example, it is not only the annual total, but also the predictability of the rainy season and the combined occurrence of heat and water deficit that are key determinants of production [25].

The use of aggregate annual precipitation in this study therefore most likely captures only part of the hydrological influence on agricultural decisions. Lag analyses also suggest that there is no simple, monotonic climatic response. The alternating signs of correlations across different lags indicate that changes in agricultural area may reflect economic and productive processes with distinct response times, in addition to statistical variability itself. Decisions regarding the allocation of cultivated areas result from the interaction between environmental conditions and multiple economic and institutional factors, including prices, access to credit, infrastructure, transportation costs, and characteristics of production chains [55].

Studies based on the perceptions of Brazilian farmers confirm that land-use decisions result from the interaction between climatic, commercial, and socioeconomic factors, with significant variation among farmers and regions [56]. Similarly, an analysis conducted in the Brazilian portion of the La Plata Basin found no evidence that climate, on its own, was primarily responsible for historical changes in agricultural land use, highlighting other socioeconomic factors [57].

The additional panel analyses reinforce the distinction between long-term changes in agricultural composition and their potential climatic determinants. Although the bivariate correlation between annual temperature changes and commodity share was statistically significant, its magnitude was relatively small ($r = 0.26$), and the association was not statistically significant in the panel specifications with fixed effects or first differences after accounting for temporal and cross-sectional dependence.

Moreover, the contrasting results obtained for absolute commodity area indicate that climatic associations are sensitive to the agricultural indicator and temporal specification considered. Agricultural prices, international demand, technological innovation, productivity gains, infrastructure, and public policies may also contribute to these transformations. Since these factors were not directly included in the models, their individual contributions cannot be quantified, and the observed associations should not be interpreted as causal effects.

4.4. Regional Heterogeneity and Agricultural Resilience

This reinforces the point that the *lags* identified here should be understood as exploratory patterns of covariation, rather than as estimates of delayed climate effects. Regional heterogeneity is, in this sense, one of the most important findings of this study. Although the North, Northeast, and Central-West regions show positive coefficients between annual temperature changes and the share of commodities, only the Northeast region exhibited a statistically significant association of high magnitude (+3.20 percentage points $°C^{-1}$). The Southeast and South regions showed relationships close to zero. This contrast demonstrates that the national correlation does not represent a homogeneous agricultural response to warming, reinforcing regional differences in production structure, technological availability, infrastructure, and adaptive capacity—such as the greater economic investment and technological development in Brazil's South and Southeast regions compared to the North, Northeast, and Central-West regions.

The literature on Brazilian agricultural frontiers also emphasizes strong spatial differentiation: changes in the Midwest are associated with the replacement of pastures, intensification, and the expansion of soybean cultivation [43], while the MATOPIBA region

exhibits distinct processes of soybean expansion, land-use pressure, and socioeconomic reorganization [58]. Therefore, adaptation policies and bioeconomy strategies are unlikely to be effective if designed based on a uniform national climate response. The results also reveal an apparent paradox in Brazil's agricultural bioeconomy: the expansion of commodity value chains demonstrates an extraordinary capacity for innovation, intensification, and integration into global markets, yet it occurs simultaneously with the relative decline of staple food crops and within a territory increasingly subject to climate warming. This does not mean that commodities and food security are necessarily incompatible.

The stronger association identified in the Northeast remained statistically significant across alternative regression specifications, including models controlling for precipitation changes and accounting for serial dependence through HAC standard errors. Nevertheless, this result should be interpreted in light of the substantial geographical diversity within the Northeast, which encompasses humid coastal areas, semiarid environments, and agricultural frontiers with different production systems. The use of macroregional averages may conceal contrasting relationships among individual states and climatic subregions. Consequently, the stability of the regional coefficient across statistical specifications does not necessarily imply spatial homogeneity within the Northeast. Analyses at the state or municipal level, integrating more detailed agricultural and climatic information, would be necessary to determine whether the observed association persists across finer geographical scales.

The generalizability of these findings is constrained by the selection of agricultural crops and the spatial aggregation adopted in this study. Although the analysis covers all five Brazilian macroregions, the 23 selected crops do not represent the entirety of national agricultural production, and the observed changes in cultivated area should not be extrapolated to crops excluded from the analysis. Furthermore, macroregional averages may conceal substantial differences in agricultural practices, technological development, climatic conditions, and production systems among states and municipalities. These limitations are especially relevant when interpreting the associations between climate variability and agricultural restructuring.

While the results document broad changes in the composition of cultivated areas and identify differences among macroregions, the estimated climate–agriculture relationships were sensitive to statistical specification and agricultural indicator. Therefore, these associations should not be interpreted as uniform responses across Brazilian agricultural systems or as evidence of causal effects. Analyses at finer geographical scales, incorporating additional crops and socioeconomic variables, would be necessary to assess the extent to which these relationships persist under different agricultural and environmental conditions.

4.5. Outlook: Market Demand, Agricultural Exports, and the Future of the Brazilian Bioeconomy

The expansion of commodity-oriented agriculture in Brazil must also be understood in the context of increasing domestic and international demand for agricultural products. Over recent decades, the integration of Brazilian agriculture into global supply chains has created economic incentives for the expansion and specialization of commercial crops, particularly soybean, maize, sugarcane, and other products associated with food, animal feed, energy, and industrial markets. International trade opportunities, agricultural prices, exchange rate conditions, transportation infrastructure, access to credit, and technological development can influence decisions regarding crop selection and the allocation of cultivated areas. These factors may help explain why commodity-oriented production has expanded considerably across Brazilian agricultural regions, although their relative contributions were not directly quantified in this study.

The scale of Brazilian agricultural exports also provides an important context for interpreting the observed transformation. Large international markets for agricultural commodities can encourage production systems characterized by specialization, economies of scale, and integration into commercial supply chains. In regions where agricultural infrastructure and market access have improved, these conditions may favor the expansion of export-oriented crops. Nevertheless, the relationship between export demand and cultivated area is not necessarily uniform across crops or regions, since domestic consumption, agricultural productivity, land availability, production costs, and public policies also influence agricultural development.

From the perspective of the bioeconomy, the expansion of commercial crops presents both opportunities and challenges. Increased agricultural production can strengthen economic activity, generate biomass for different industrial applications, and support the development of agricultural value chains. However, an agricultural bioeconomy centered predominantly on commodity production may also raise concerns regarding productive specialization, the relative importance of staple food crops, environmental pressures, and vulnerability to market fluctuations. The findings of this study indicate that the expansion of commodity-oriented cultivated areas occurred alongside a substantial reduction in the area allocated to staple food crops, highlighting the importance of considering agricultural diversification and domestic food supply when evaluating long-term sustainability.

Future research should integrate agricultural land-use data with commodity prices, export volumes, international demand indicators, agricultural credit, and transportation infrastructure to assess the relative contribution of economic and institutional factors to the observed changes. Combining these variables with regional climate information would also help distinguish the influence of market conditions from that of climatic variability on agricultural land-use decisions. Such analyses could provide a more comprehensive understanding of the mechanisms underlying agricultural transformation in Brazil.

The main challenge for the coming decades will therefore be to reconcile the economic opportunities associated with international agricultural markets with food security, ecosystem conservation, and climate resilience. Policies supporting technological innovation, sustainable intensification, productive diversification, and the use of previously converted agricultural land may contribute to this objective. The development of a sustainable Brazilian bioeconomy will depend not only on increasing agricultural production and export competitiveness but also on maintaining diversified and climate-resilient production systems capable of meeting domestic and international demands.

5. Conclusions

This study demonstrated that Brazilian agriculture went through a significant structural transformation between 1995 and 2025, characterized by an expansion in the area planted with commodities and by an absolute and relative reduction in staple food crops. As a result, commodities came to account for more than 90% of the combined area allocated to the two groups by the end of the period analyzed. The sensitivity analysis showed that this trend remains evident regardless of the functional classification assigned to corn, confirming that the observed pattern is not the result of a specific decision regarding crop grouping.

All five Brazilian macroregions exhibited warming trends between 1995 and 2025, while precipitation showed greater spatial and interannual variability. Although the bivariate first-difference analysis identified a positive association between annual temperature changes and commodity share, this relationship was not statistically significant in the additional panel specifications incorporating region and year fixed effects or first differences. Regional analyses nevertheless revealed substantial heterogeneity, with the Northeast exhibiting a positive association that remained statistically significant across alternative covariance

estimators and after controlling for precipitation changes. These findings indicate that the relationships between climate variability and agricultural composition depend on geographical context and statistical specification and do not establish a causal influence of climate variability on agricultural restructuring.

From the perspective of the agricultural bioeconomy, the results document a long-term shift in the composition of cultivated areas toward commodity-oriented crops, accompanied by a declining relative share of staple food crops and substantial regional differences. These findings provide evidence of increasing agricultural specialization but do not establish corresponding changes in food production, agricultural productivity, or food security. In particular, reductions in cultivated area may coexist with productivity gains, and the present analysis does not quantify production volumes or yields. Similarly, although the observed transformations are relevant to discussions of agricultural diversification and sustainability, the indicators analyzed do not directly assess environmental, economic, or social sustainability outcomes. Future studies integrating cultivated area, production volumes, crop yields, resource-use efficiency, and socioeconomic indicators would allow a more comprehensive assessment of the implications of agricultural restructuring for food security and the sustainability of Brazil's bioeconomy.

The expansion of agricultural value chains integrated with the food, animal feed, energy, and raw materials markets constitutes an important component of the Brazilian bioeconomy, but its long-term sustainability will depend on the ability to balance economic competitiveness with productive diversification, food security, ecosystem conservation, and climate adaptation. The trajectory observed over the past three decades therefore suggests that the future of Brazil's agricultural bioeconomy will depend not only on how much the country will be able to produce, but also on which crops will form the basis of its production, where that production will happen, and how resilient it will be in the face of a progressively warmer climate.

These conclusions are limited to the selected crops and the macroregional scale adopted in this study. Although the results characterize broad changes in the composition of cultivated areas across Brazil, they should not be generalized to all agricultural crops or to individual states and municipalities. Likewise, the observed associations between climate variability and agricultural restructuring vary according to region, agricultural indicator, and statistical specification, and should not be interpreted as causal or spatially uniform relationships.

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