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ARTICLE

Regional impacts of climate change on agricultural productivity: evidence on large-scale and family farming in Brazil

Os impactos regionais das mudanças climáticas sobre a produtividade agrícola familiar e patronal no Brasil

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Abstract: This paper projects and analyzes the regional impacts of climate change on the agricultural productivity of family farming and large-scale agriculture in Brazil between 2021 and 2050, using the RCP 4.5 and RCP 8.5 scenarios. The methodology adopted consists of a cross-sectional estimation of a production function in which agricultural productivity is determined by climatic, geographic, and productive factors. The study contributes to the literature by disaggregating agricultural production into family farming and large-scale agriculture, indicating the magnitude and direction of impacts by crops and regions in Brazil, a country with a great territorial dimension and relevant and heterogeneous agricultural production. The results indicate that the agricultural productivity of family farming is more sensitive and therefore this type of producer could be more vulnerable to the phenomenon. On average, the effects will be negative in the North/Northeast regions and for cassava, maize, beans, and soybeans, with possible impacts on deforestation and on food supply. Productivity gains are expected in the southern region and for the cultivation of sugar cane and soybeans. Deterioration of food security of the vulnerable farmers and regional disparities may increase in Brazil.

Keywords: climate change impacts, agricultural productivity, family farming, food security.

Resumo: O artigo analisa os impactos regionais das mudanças climáticas sobre a produtividade agrícola por cultivo da agricultura familiar e patronal no Brasil, utilizando os cenários RCP 4.5 e RCP 8.5 (IPCC, 2014), entre os anos de 2021 e 2050. A estratégia metodológica consiste na estimação em *cross section* de uma função de produção em que os resultados em termos de produtividade agrícola são determinados por fatores climáticos, geográficos e produtivos. O estudo contribui para a literatura, ao desagregar a produção agrícola em familiar e patronal, indicando a magnitude e a direção dos impactos, por cultivo e por Unidade da Federação no Brasil, pais de grande dimensão territorial e relevante e heterogênea produção agrícola. Os resultados indicaram que a agricultura familiar apresentaria maior sensibilidade, e portanto, maior vulnerabilidade ao fenômeno. Em média, os efeitos seriam negativos nas regiões Norte/Nordeste e para mandioca, milho, feijão e soja, com possíveis impactos no desmatamento e na oferta de alimentos. Esperam-se ganhos de produtividade na região Sul e para o cultivo de cana-de-açúcar e soja. A deterioração da segurança alimentar dos agricultores vulneráveis e as disparidades regionais poderiam aumentar no Brasil.

Palavras-chave: mudanças climáticas, produtividade agrícola, agricultura familiar, segurança alimentar.

1. Introduction

The analysis of the impacts of climate change (CC) is complex. The phenomenon affects a variety of aspects, which permeates ecosystem, biological, economic, and social dimensions, involves gradual transformations along an extensive time horizon, causes negative externalities, and widen uncertainties. Agriculture, in this context, presents itself as a vulnerable sector, mainly due to the high sensitivity of agricultural productivity to climatic variables, such as temperature and precipitation.

Brazil, in turn, plays a prominent role in the international agricultural scenario, being one of the largest producers and exporters of soybeans, maize, coffee, sugar, ethanol, and meat (Food and Agriculture Organization of the United Nations, 2020). Its large territorial extension is home to the fifth-largest cultivated area on the planet, approximately 66 million ha (Brasil, 2017; Miranda, 2018). The country has also shown continuous increases in agricultural productivity in the last decades, which have contributed to its outstanding performance in the international food industry (Gasques et al., 2010; Rada & Valdes, 2012; Santos et al., 2016). Its agriculture, although competitive, is quite heterogeneous in terms of crops, productivity, and producers, with large-scale agriculture linked to the production of commodities for foreign markets and family farming sectors linked to food production for the domestic market and subsistence.

The CC scenarios projected for Brazil by the PBMC (Painel Brasileiro de Mudanças Climáticas, 2014) indicate a temperature increase of between 1 °C and 5.5 °C and oscillation of +5% to -50% in precipitation levels by the end of the 21st century as well as an increase in the probability of the occurrence of extreme events. These projections corroborate the evidence that agriculture may be one of the activities that is most affected by the phenomenon. In these circumstances, according to FAO (Food and Agriculture Organization of the United Nations, 2005), the food supply and food security may be compromised and a new geography of agricultural production could be configured (Assad & Pinto, 2008). Therefore, understanding the magnitude and direction of the impacts of CC by type of culture, producer, and region is relevant not only due to its local impacts on the food security and economy in Brazil but also because of its indirect effects on the international food market.

Studies on the impacts of CC on agricultural productivity adopt three different methodological approaches: Ricardian, agronomic, and agroecological zoning models. Global studies tend to focus on commodity analysis, especially grains and cereals, indicating production reduction at low latitudes and an increase at high latitudes, with net losses in wheat and cereal production (Mendelsohn & Schlesinger, 1999; Cline, 2007; Rosenzweig et al., 2014).

Regional studies have broadened the analyzed crops. Agronomic studies focusing on Europe, such as Supit et al. (2012), Balkovič et al. (2014), Graß et al. (2015), Valverde et al. (2015), Vanuytrecht et al. (2016) and Georgopoulou et al. (2017) have indicated that the productivity of maize, wheat, and cereals, especially in the Southern region, may decline by up to 40%, with negative impacts extending to tomato, pepper, and olive cultivation. The impacts would be positive to moderate for the potato crop yield, with better performance on the northern, western, and Atlantic coasts of Europe, and for tobacco in Greece. Studies that targeted sub-Saharan Africa, such as Edame et al. (2011) indicated average yield changes in 2050 of -17% (wheat), -5% (maize), -15% (sorghum), and -10% (millet). In South Asia the productivity decrease would reach -16% (maize) and -11% (sorghum), with aggregate agricultural productivity in Africa and Asia, decreasing by up to 20% according to Knox et al. (2012).

Regarding Latin America, Fernandes et al. (2012), using an agroecological zoning model, projected heterogeneous negative impacts on the agricultural productivity of grain and cereal crops. Mexico, Brazil, and Colombia would be the most affected in the productivity of wheat.

Soybeans would lose up to 30% of productivity depending on the region, including Brazil, with Argentina being less affected. Maize would show a decline in productivity throughout Latin America, with Brazil, Ecuador, Mexico, and the Caribbean being the most affected. Rice productivity could increase throughout the region, except in Brazil, Mexico, and the Caribbean.

Regarding Brazil, studies have also focused on commodities and crops of economic relevance. There are no comparative studies of effects between the types of farmers. Sanghi et al. (1997) found that the states of the Midwest region would be the most negatively affected and that the Southern region could benefit from CC. Assad & Pinto (2008) projected the effects of CC (scenario A2) on soil aptitude for cotton, rice, coffee, sugarcane, beans, sunflowers, cassava, maize, and soybeans between 2020 and 2070 through an agroecological zoning model. The results indicated a reduction in the suitable areas for all crops except for sugarcane. The study emphasized that CC may potentiate food insecurity in Brazil. Ferreira Filho & Moraes (2014) incorporated the effects on agricultural aptitude found by Assad & Pinto (2008) into a general equilibrium model to assess the economic impacts of CC, estimating that despite the overall economic effects being small, significant losses would occur in less developed regions.

Likewise through an agroecological zoning model, the project "*Brasil 40*" estimated CC impacts on agricultural suitability for cotton, rice, sugarcane, beans, maize, soybean, sorghum, and wheat (Brasil, 2015). The results with the RCP 4.5 scenario, used also by Santos et al. (2022) to estimate the economic impacts, indicate negative effects for the crops analyzed, except sugarcane in São Paulo and in the southern region and maize in Piauí state. In the RCP 8.5 scenario, soybean could be benefited in Santa Catarina and Rio Grande do Sul states and the Northeast region. Féres et al. (2009), Assunção & Chein (2016) and DePaula (2018) reinforced the heterogeneity of projected impacts on agricultural productivity, with the northern regions being negatively impacted.

The comparative analysis of the impacts of CC on agriculture considering the size of the property or the type of producer is very scarce. In this line, Reidsma et al. (2010) found that, in Greece, Spain, and Germany, smaller farms showed lower sensitivity to temperature. However, in Italy, France, Belgium, the Netherlands, Luxembourg, the United Kingdom, and Scandinavia, a smaller size was associated with greater temperature sensitivity. In another approach, De Salvo et al. (2013) analyzed the sensitivity of agricultural income to the climate in the Italian Alps region, via the Ricardian model, noting that, although CC would negatively affect the revenue, the size of the property or the type of producer would not influence the result. Troost & Berger (2015) used agent-based models (ABMs) to explore adaptation to CC in southwestern Germany. The authors indicated that the farm´s size could reduce the sensitivity of agricultural income to CC, suggesting that economies of scale in the adoption of technologies that are less vulnerable to the climate could favor larger-scale producers.

The literature on impacts of CC on agriculture, such as those presented briefly above, have focused on certain types of crops, mostly soy, maize, wheat, and coffee, and those linked to large producers, notably crops of greater economic relevance. There is a gap in the specialized literature represented by the comparative impacts on different types of producers. In this sense, the objective of this work is to estimate the effects of CC on the agricultural productivity of crops produced by large-scale and family farming. To this end, projections of variation in agricultural production for both types of producers will be elaborated through the cross-sectional estimation of a production function in which the results in terms of agricultural productivity are determined by geographical, productive, and climatic factors, based on the global warming scenarios, between 2021 and 2050.

The study differs and, therefore, contributes to the literature by showing that the agricultural productivity of family farming and large-scale agriculture respond differently to the impacts of CC. The results, by indicating the direction and magnitude of the impacts in terms of agricultural productivity change and considering the specificities of family farming and large-scale agriculture, could complement the information available, assisting in the planning and definition of adaptive policies. Thus, the study estimates the pure effect of CC on agricultural productivity based on the most recent projections, indicating the magnitude of productivity required, via technical progress, to mitigate the negative effects of CC.

2. Theoretical and Empirical Approach

The paper uses a theoretical structure that links land use to production functions, common in agronomic models, to approximate the methodological structure of Ricardian models. This section, presents the theoretical framework that shows the process of land allocation of agricultural producers, following the methodological strategy find in Assunção & Chein (2016) and Miyajima (2018). The model will guide the econometric analysis stage of this study.

Suppose that an agricultural economy has M municipalities and, in each municipality $m \in M$, a representative farmer allocates land L_m between K different crops. The production P_{mk} of crop $k \in K$ in municipality $m \in M$ depends on the amount of land L_{mk} and inputs X_{mk} allocated to this crop and on a vector with geographical and climatic characteristics GC_m:

$$P_{mk}\left(GC_m\right) = \gamma_{mk} f^k\left(L_{mk}, X_{mk} \mid GC_m\right) \tag{1}$$

γ_{mk} is an individual productivity vector and $f_L^k > 0$ $f_X^k > 0$, $f_{LL}^k \leq 0$, and $f_{XX}^k \leq 0$. Consider w_m as the unit price of inputs. The problem of the representative farmer can be divided into two stages. In the first, he or she chooses the amount of inputs to maximize the profit obtained in the production of cultivation k in municipality m for each value of L_{mk}, considering the costs from gross revenue. The value function of this problem is defined as:

$$V_{mk}\left(L_{mk} \mid GC_m\right) = \max_{X_{mk}}[\gamma_{mk} f^k (L_{mk}, X_{mk} | GC_m) - w_m x_{mk}] \tag{2}$$

In the second stage, the representative farmer chooses the land use that maximizes the aggregate return subject to the restriction of available land:

$$\max_{\{Lmk\}} \Pi_m(GC_m) = \sum_k V_{mk} \ (L_{mk} \mid GC_m), \text{ subject to} \sum_k L_{mk} = L_m \tag{3}$$

The first-order conditions of problem (3) are given by:

$$V'_{mk}\left(L_{mk} \mid GC_m\right) \geq V'_{mk}\left(L_{mk} \mid GC_m\right), \ \forall k,\ k' > 0 \in K \tag{4}$$

Equation 4 will be valid as equality whenever $L^*_{mk} > 0$ and will be valid as strict inequality whenever $L^*_{mk} = 0$. The balance of the model is given by the following equality:

$$\sum_k L^*_{mk}(GC_m) = L_m \tag{5}$$

Equations 4 and 5 implicitly define the optimal allocation of land, allowing us to understand how climate change, present in GC_m, affects farmers' choices and agricultural productivity. Suppose that the vector with the climatic characteristics' changes from GC_m to GC'_m, heterogeneously affecting the marginal value of the different agricultural activities. This implies that the allocation of land L^*_{mk} (GC'_m) will be different from the initial allocation of land L^*_{mk} (GC_m) since farmers reallocate their crop to the most profitable type due to climate change. There are two effects of climate change in GC_m, the first on agricultural productivity and the second on land use change due to the change in productivity. In this way, the model captures farmers' adjustment to climate change in terms of land use allocation.

By defining a productivity vector (capital, labor, and its productive configuration) by cultivation $\gamma_m = (\gamma_{m1}, \gamma_{m2}, \ldots, \gamma_{mk})$, solving the system defined in the Equations 4 and 5, and using the production function defined in Equation 1, we can express the agricultural productivity of each crop in equilibrium as a function of the model parameters:

$$Y^*_{mk}(GC_m) = \frac{P^*_{mk}(GC_m)}{L^*_{mk}(GC_m)} = Y_k(w_m, {}_m\ GC_m) \qquad (6)$$

The agricultural productivity for each crop (i.e., individual agricultural productivity) is determined by the ratio between the value of production and the crop area, in hectares. The crops in an aggregate form (i.e., aggregate agricultural productivity) in equilibrium, are defined by (7):

$$Y^*_m(GC_m) = \frac{P^*_m(GC_m)}{L^*_m(GC_m)} = Y_m(w_m, {}_m\ GC_m) \qquad (7)$$

The value of production, as a common denominator, reflects the price of each crop in its respective unit, whether bag, ton, kilo etc. Thus, allowing the aggregate calculation of productivity. Equations 6 and 7 are the basis of the empirical exercise carried out in the next section, allowing the estimation of how individual and aggregate agricultural productivity reacts to climatic factors.

3. Methodology

3.1 Econometric Specification and Estimation

The econometric model, based on Assunção & Chein (2016), Georgopoulou et al. (2017), and Miyajima (2018), used to estimate the sensitivity of agricultural productivity to the effects of CC of cultivation *k* in municipality *m*, is determined from Equation 6. Suppose that there is perfect mobility of productive factors between the municipalities of the sample. This hypothesis implies that the price of the factors is the same in all municipalities ($w = w_m$, $\forall$ m) and that we can estimate the model without factor price data. The functional form for the relationship between climatic factors and productivity is given by:

$$Y_{mk} = Y(w, \gamma_m, GC_m) = exp[\theta(GC_m) + y_m + \epsilon_m] \qquad (8)$$

ϵ_m is an idiosyncratic term of error. Rewriting (8), we have:

$$lnY_m = \gamma_m + \theta(GC_m) + \epsilon_m \qquad (9)$$

The approximation of the characteristics of the municipalities γ_m, without the use of panel data, is carried out using the observable characteristics X_m. In this way, we have the following equations for aggregate (10) and individual (11) cultivation:

$$lnY_m = \theta\left(GC_m\right) + \beta' X_m + \epsilon_m \tag{10}$$

$$lnY_{mk} = \theta_k\left(GC_m\right) + \beta'_k X_m + \epsilon_{mk} \tag{11}$$

As climate shocks that affect the k crop also correlate with shocks that affect the k' crop, there is covariance (ε_{mk}, ε_{mk}') in the system of equations presented. Thus, the SUR[1] (Seemingly Unrelated Regression) method is recommended to estimate productivity; however, since GC_m and X_m are equal for all crops, the regressors are the same, so this method would be equivalent to the estimation following the ordinary least square (OLS) method.

After estimating the model represented in (10) and (11), the mean temperature and precipitation variables GC_m are replaced, in the same model, with their GC'_m projections, referring to the RCP 4.5 and RCP 8.5 scenarios, and the other control variables remain. Then, the predicted value of ln Y_m is calculated[2].

$$lnY_m = \theta\left(GC'_m\right) + \beta' X_m + \epsilon_m \tag{12}$$

The variation[3] in aggregate agricultural productivity caused by the change in climate variables is given by the difference determined by:

$$\Delta\, lnY_m = \left[\theta\left(GC_m\right) + \beta X_m\right] - \left[\theta\left(GC'_m\right) + \beta X_m\right] \tag{13}$$

Thus, Y_{m0} is the agricultural productivity when $GC_m = GC_{m0}$, and Y_{m1} is the agricultural productivity when $GC_m = GC_{m1}$. The impact of climate change is given by $\Delta Y^* = Y^*_{m1} - Y^*_{m0}$.

The estimation is performed with the addition of a quadratic polynomial of temperature and precipitation to capture the nonlinearity of these variables since increases in temperature and precipitation can contribute to increased productivity at first, but the marginal increase can harm productivity (Féres et al., 2009; Mendelsohn et al., 1994). The quarterly averages of temperature and precipitation are considered to capture the specific effects of climatic seasonality on the agricultural productivity of each crop, and the aggregated agricultural productivity is weighted by the square root of the planted area of each municipality (Schlenker et al., 2006).

The incorporation of new productive technologies, as an adaptive strategy of farmers, is an important aspect to consider in studies involving the impacts of climate change. The estimated model does not incorporate technological progress. Therefore, it may present overestimated results of the variation in agricultural productivity. Thus, the results should be understood as the pure effect of climate on productivity, also evidencing the magnitude of technological progress necessary to mitigate the effects (Assunção & Chein, 2016).

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1 The SUR method was proposed by Zellner (1962) to estimate a set of apparently uncorrelated regressions, such as the equations that determine the productivity of each crop. The method is used when some of the explanatory variables differ between equations but the error terms are correlated. For the SUR method, see Beasley (2008).

2 The predicted value for individual cultivation is given by ln $Y_{mk} = \theta_k(GC'_m) + \beta_k' X_m + \epsilon_{mk}$

3 The variation in individual agricultural productivity is given by Δ ln $Y_{mk} = [\theta_k(GC_m) + \beta_k X_m] - [\theta_k(GC'_m) + \beta_k X_m]$

3.2 Database

The database used to access the municipal agricultural productivity, by cultivation, was extracted from the National Agricultural Census (Instituto Brasileiro de Geografia e Estatística, 2006[4]). Twenty-one crops were selected: rice, wheat and cereals, maize grain, cotton in fiber, sugarcane, soybean grain, cassava, tobacco leaf, tomatoes, potatoes, onions, peanuts, pineapples, bananas, beans, cashew nuts, grapes for juice or wine, oranges, coffee grain, and other permanent and temporary crops. The crops are disaggregated into production from family farming and production from large-scale agriculture.

Productive factors are used as control variables in the estimation as they determine the agricultural productivity along with the climatic variables. The selected variables follow the studies by Féres et al. (2009) and Miyajima (2018) and represent the main productive factors determining agricultural productivity, extracted from the National Agricultural Census (Instituto Brasileiro de Geografia e Estatística, 2006). The following variables are used: i) the natural logarithm of the machinery, equipment, and tractor values present on the properties per hectare; ii) the natural logarithm of the number of workers per hectare; iii) the area of improvements, represented by areas with buildings, improvements, or paths; iv) the natural logarithm of the value of facilities in the properties; v) the natural logarithm of the irrigated area in hectares; vi) the participation of owners in cooperatives; vii) the participation of owners in associations; and viii) geographic variables, by municipality, referring to altitude, latitude, and longitude, extracted from Instituto de Pesquisa Econômica Aplicada (2019).

Categorical variables by soil type are usually included in studies using agronomic and Ricardian models; however, they are not included in this study due to the alterations resulting from CC and being passive in correction or adaptation (Clair & Lynch, 2010; Falloon et al., 2007; Kardol et al., 2010). Assunção & Chein (2016) estimated a similar model, incorporating soil types as a control, and verified that geographic variables are more relevant to marginal climate effects than a *dummy* by soil type. Thus, this study uses geographical variables, altitude, latitude, and longitude.

The historic climatic data of temperature and precipitation are from the *Terrestrial Air Temperature and Precipitation Database* described by Matsuura & Willmott (2012). The time frame selected for the construction of the base model comprises a period of 34 years, between 1971 and 2005, thus respecting the minimum 30-year standard established by the World Meteorological Organization (2017) for climate change analyses. Semi-annual averages of temperature and precipitation for each municipality of the sample in the period 1971-2005 were then elaborated and used to minimally capture the seasonality of the crop cycle. The municipal climate data consists of the average of the climate data of the four grids around the centroid of the municipality. This average is weighted by the distance from the centroid to each grid. The projected temperature and precipitation data refer to the RCP 4.5 and RCP 8.5 scenarios from the IPCC (Intergovernmental Panel on Climate Change, 2014), considering the period between 2021 and 2050. The climatic projections for Brazil were developed by INPE (Chou et al., 2014) based on the climatological normal of 1971/2005 and carried out through the regional climate model Eta-CPTEC.

The RCP 4.5 scenario represents a more optimistic path for the performance of global GHG emissions, with an average global warming projection of 1.8 ºC in 2100 compared with the average temperature between 1986 and 2005. The RCP 8.5 scenario represents a pessimistic

[4] The model estimated with the base climate scenario uses the climatological normal period calculated between 1971 and 2005. Therefore, the 2006 census data was used, not the 2017 census, as data from the 2017 census already incorporate the effects of climate change, verified between 2006 and 2017.

global temperature evolution, with a likely warming estimate of 3.7 ºC in 2100 (Intergovernmental Panel on Climate Change, 2014). Thus, it is possible to define a range of results, given a scenario that includes mitigating policies, in which the increase in the global average temperature would be below 2 ºC, and another pessimistic scenario with a relevant increase in temperature. It is worth noting that, according to the latest reports, the recent path of emissions has approached the projections of the most pessimistic scenario (Schwalm et al., 2020).

The model considers a sample of 5364 municipalities in estimating the climatic impacts on the aggregate agricultural productivity originating from family farming and 5327 considering large-scale agriculture. Municipalities that do not present land use and climatic data were removed from the samples. The descriptive statistics of the control variables used in the study are available in Appendix A.

4. Results

The objective of the empirical analysis is to verify the effects of climate change on family farming and large-scale agriculture productivity in Brazil, under the hypothesis that their respective productive structures are relevant to determine the sensitivity of agricultural productivity to climatic effects. Initially, we estimate Equation 10 considering the sample with data on family farming and large-scale agriculture pooled. In the pooled estimation, a binary variable, by type of producer, was created to verify the effect of "family farming" on agricultural productivity. Variables of interaction between the dummy and the climatic variables are included in the estimation. This exercise indicated that the dummy "family farming" contributes negatively to average productivity. The terms of interaction with *low temperature*, *high precipitation*, and *low precipitation* indicates greater sensitivity of the productivity of family farming to the effects of climate change. That is, the marginal effect of climate variables on the productivity of family farming is more pronounced.

The results in terms of greater sensitivity of the family farmers to climate change may be due to the lower use of productive technology, whether in the form of inputs, such as fertilization, use of pesticides, soil correction, or technical assistance, compared to large-scale agriculture. In this way, the production of family farming is more dependent on climatic factors, while the production of large-scale agriculture, being more controlled, is less dependent. These results provide evidence of different climatic effects on family farming and large-scale agriculture and the need to discriminate between the samples.

In the second empirical exercise, we estimate the effect of climate change on agricultural productivity among the types of farmers separately. The results provide us with an insight into the way in which the effects of climate change on agricultural productivity vary between regions and agricultural types. An initial base model, with historical climatic data, referring to the period from 1971 to 2005, is estimated for each type of producer. Then, the climatic variables are changed according to the RPC 4.5 and RCP 8.5 scenarios, maintaining the estimated coefficients and other control variables, and the result is verified in terms of agricultural productivity variation.

4.1 Family Farming Results

The aggregate agricultural productivity is estimated in the base model, with historical climatic data, in three stages to verify the performance in terms of the signal and significance of the coefficients related to temperature and precipitation, as the control variables are inserted.

Table 1 presents the productivity estimation results for crops in aggregate form. Table A1 in the Appendix A presents the descriptive statistics of the family farming analysis.

Table 1 - Effects on family farming agricultural productivity in the base model (1971/2005)

Control Variables	Dependent Variable: log (Aggregate Agricultural Productivity)		
	Step (3)	Step (2)	Step (1)
High Temperature	-3.088***	-3.363***	-3.376***
(Average Spring and Summer)	(0.382)	(0.465)	(0.484)
Low Temperature	1.427***	1.519***	1.520***
(Average Autumn and Winter)	(0.127)	(0.142)	(0.142)
Squared High Temperature	0.060***	0.066***	0.066***
(Average Spring and Summer)	(0.008)	(0.010)	(0.010)
Squared Low Temperature	-0.029***	-0.031***	-0.031***
(Average Autumn and Winter)	(0.003)	(0.003)	(0.003)
High Precipitation	0.013***	0.014***	0.014***
(Average Spring and Summer)	(0.002)	(0.002)	(0.002)
Low Precipitation	0.005***	0.003	0.002
(Average Autumn and Winter)	(0.002)	(0.002)	(0.002)
Squared High Precipitation	-0.000***	-0.000***	-0.000***
(Average Spring and Summer)	(0.000)	(0.000)	(0.000)
Squared Low Precipitation	0.000	0.000	0.000
(Average Autumn and Winter)	(0.000)	(0.000)	(0.000)
Geographical Characteristics	Yes	Yes	Yes
Primary Factors	Yes	Yes	No
Social Capital	Yes	No	No
Other	Yes	No	No
Observations	5128	5358	5358
Adjusted R-Square	0.432	0.390	0.389

Source: Own elaboration based on the results of the econometric model.
Note: Robust standard error to heteroscedasticity in parentheses. p-value <0.01, ** p-value <0.05, *p-value <0.10.

As shown in Table 1, the signs and significance levels of the climatic variables were maintained between steps 1 to 3, as other control variables were included in the estimation. In step 1, in addition to the climatic variables, the estimation was performed with geographic variables of latitude, longitude, and altitude. In step 2, variables related to capital and labor were incorporated. Step 3 incorporated all control variables, including irrigation and social relationships.

In the estimation with all the control variables (step 3) the results suggest that an increase of 1 ºC in the average temperature considering spring and summer, would cause a reduction of 3.08% in the average productivity (given in R$/Ha) of the aggregated crops in Brazil. During autumn and winter, there would be a productivity increase of 1.42%. An increase of 1 ºC in the squared temperature in the high (low) season would contribute 0.06% (-0.02%) of productivity variation. A reduction of 1 mm in the average precipitation level between spring and summer implies a reduction in the aggregate agricultural productivity of 0.01%, during autumn and winter the loss of productivity would be 0.005%. It is noteworthy that these results reflect the average variations for the country and that, given the large territorial dimension of Brazil and the heterogeneity of its agricultural production, these effects can vary considerably in the regions. The Northeast region of the country, historically the most affected by adverse weather conditions typical of a semi-arid climate, tends to suffer more intense effects.

Table 2 presents the results of the impacts of climate change on the aggregate agricultural productivity of family farmers in the Brazilian federation units (FUs). The results are spatially heterogeneous and are obtained by replacing the historical temperature and precipitation variables in the base model with the variables projected in the climatic scenarios.

Table 2 - Simulated effects of climate change on family farming agricultural output per hectare (2050)

Region	Federation Unit (FU)	RCP 4.5				RCP 8.5			
		Mean	Sd	95% confidence interval		Mean	Sd	95% confidence interval	
North	Acre (AC)	-17.7%	0.07	-20.7%	-14.7%	-20.9%	0.08	-24.4%	-17.4%
	Amapá (AP)	-83.5%	0.05	-86.4%	-80.6%	-83.1%	0.04	-85.7%	-80.5%
	Amazonas (AM)	-16.4%	0.25	-23.6%	-9.1%	-16.4%	0.23	-23.3%	-9.5%
	Pará (PA)	-46.2%	0.23	-50.1%	-42.3%	-43.6%	0.27	-48.2%	-39.0%
	Rondônia (RO)	-20.3%	0.05	-21.7%	-18.9%	-22.2%	0.06	-23.9%	-20.5%
	Roraima (RR)	-53.6%	0.10	-59.1%	-48.1%	-51.7%	0.10	-57.5%	-45.8%
	Tocantins (TO)	-21.8%	0.16	-24.7%	-18.9%	-16.4%	0.18	-19.8%	-13.0%
Northeast	Alagoas (AL)	-46.8%	0.09	-48.8%	-44.8%	-49.4%	0.09	-51.3%	-47.5%
	Bahia (BA)	-49.5%	0.10	-50.5%	-48.5%	-51.5%	0.08	-52.3%	-50.6%
	Ceará (CE)	-5.4%	0.30	-9.7%	-1.1%	-19.8%	0.27	-23.7%	-15.8%
	Maranhão (MA)	-19.0%	0.30	-23.2%	-14.9%	-22.5%	0.28	-26.4%	-18.7%
	Paraíba (PB)	-39.6%	0.10	-40.9%	-38.3%	-46.5%	0.08	-47.5%	-45.4%
	Pernambuco (PE)	-42.3%	0.10	-43.7%	-40.8%	-47.6%	0.07	-48.5%	-46.6%
	Piauí (PI)	-7.5%	0.28	-11.3%	-3.7%	-17.3%	0.27	-21.0%	-13.7%
	Rio Grande do Norte (RN)	-24.1%	0.17	-26.8%	-21.4%	-34.9%	0.14	-37.2%	-32.6%
	Sergipe (SE)	-52.8%	0.14	-56.2%	-49.4%	-53.2%	0.12	-56.1%	-50.3%
Southeast	Espírito Santo (ES)	-13.7%	0.60	-27.4%	0.0%	-12.7%	0.54	-25.0%	-0.4%
	Minas Gerais (MG)	-26.2%	0.21	-27.7%	-24.8%	-26.0%	0.25	-27.7%	-24.3%
	Rio de Janeiro (RJ)	48.8%	0.70	34.1%	63.6%	34.0%	0.56	22.0%	46.0%
	São Paulo (SP)	66.9%	0.48	63.1%	70.8%	104.7%	0.77	98.4%	111.0%
Midwest	Goiás (GO)	-30.8%	0.18	-33.3%	-28.2%	-26.7%	0.24	-30.1%	-23.3%
	Mato Grosso (MT)	-4.3%	0.28	-9.3%	0.6%	5.2%	0.37	-1.3%	11.7%
	Mato Grosso do Sul (MS)	121.2%	0.71	104.8%	137.7%	232.4%	1.09	207.2%	257.6%
South	Paraná (PR)	144.1%	0.99	134.2%	154.0%	210.5%	1.71	193.4%	227.6%
	Rio Grande do Sul (RS)	87.5%	0.74	80.8%	94.3%	126.8%	1.05	117.2%	136.3%
	Santa Catarina (SC)	121.5%	0.72	112.9%	130.1%	154.6%	0.91	143.7%	165.6%

Source: Author´s elaboration

In the RCP 4.5 scenario, it is verified that the North and Northeast region, located at lower latitudes, would be the most negatively affected. MG and ES in the Southeast region are also negatively affected. In relation to the FUs that benefit from an agricultural productivity gain, we highlight SP, RJ, MS, PR, RS and SC. RCP 8.5 would increase the deterioration of the productivity situation, especially in the Northeast region while other regions would experience negative impacts of a slightly lower magnitude. The South region, in addition to SP and MS, would present a more intense increase in productivity levels. Tables 3 and 4 present the projected results for the analyzed[5] crops.

[5] Crops that show productivity increments above 100% had their results replaced by their average positive variation.

Table 3 - Effect of Climate Change on Family Farming Productivity (RCP 4.5) (2021-2050)

FU / Sector	Banana	Coffee	Cashew Nuts	Orange	Grape	Others. Perm.	Pineapple	Herbaceous Cotton	Peanut	Rice and Cereals	Potato	Sugarcane	Onion	Beans	Tobacco	Cassava	Maize	Soybeans	Tomato	Wheat	Others. Temp.
AC	-42%	-18%	-	-23%	-	-31%	-2%	-6%	10%	4%	92%	18%	-	-13%	-26%	-22%	-13%	-	-	-	-25%
AP	7%	-	-	30%*	-	-57%	14%	-	-	64%	-	8%	-	-56%	-	-73%	-72%	-	-	-	-59%
AM	-23%	11%	-	47%	-	-31%	14%	-	23%	8%	97%	-19%	-	-11%	-56%	-26%	-22%	-	-	-	24%
PA	-14%	-38%	-47%	3-*	-	-53%	10%	-74%	19%	14%	22%	7%	-14%	4%	42%	-55%	-23%	-23%	33%	-	-14%
RO	-54%	-9%	-	31%	-	-41%	1%	-	37%	7%	92%	14%	73%	-3%	-	-43%	-14%	-42%	-43%	-	-10%
RR	11%*	-59%	-	30%*	-	-69%	-66%	-	-76%	42%	-	22%	-	9%	-	-54%	-	-	27%*	-	43%
TO	-18%	-	-42%	-74%	-	89%	-7%	-	75%	2%	55%*	-47%	-	30%	-	-53%	-8%	-24%	-	-	40%*
AL	2-	-44%	-12%	-21%	-	-56%	5%	-71%	-18%	1%	-42%	34%	-	-28%	-49%	-29%	-37%	-	13%	-	-22%
BA	2%	-46%	-37%	-79%	-70%	-22%	22%	-77%	40%	17%	-39%	-17%	-41%	-33%	-29%	-29%	-41%	-27%	41%	-	9%
EC	-3%	-35%	1%	-58%	-	-28%	6%	13%	18%	2%	-8%	1%	23%	-1%	-25%	27%	-8%	-	4%	-	-15%
MA	1%	-46%	68%	11%	-	9%	-2%	-	22%	7%	-	-6%	-	-4%	-	-	-13%	-33%	-	-	36%
PB	-14%	-35%	-27%	-77%	-68%	-32%	3%	-34%	8%	-4%	-2%	18%	45%*	-20%	-53%	-20%	-30%	-	6%	-	-1%
PE	-3%	-34%	-37%	-76%	-50%	-14%	22%	-78%	45%	5%	-23%	35%	-7%	-27%	-44%	-31%	-36%	-8%	27%	-	-11%
PI	28%	-	30%	46%	-	63%	20%	-55%	63%	3%	-	-20%	-	10%	-28%	-8%	-9%	-36%	-5%	-	63%
RN	2%	-23%	-15%	-71%	-	-56%	2%	49%	13%	-9%	-	24%	45%*	-13%	-47%	-16%	-22%	11%	-4%	-96%	-26%
IF	23%	-	36%	-61%	-	-52%	-4%	-	-24%	-	-49%	26%	-1%	-31%	-53%	-33%	-45%	-	66%	-	-33%
ES	-36%	-28%	-	-46%	-57%	-14%	-32%	-	47%	15%	-42%	7%	-56%	-35%	-	21%	-45%	-	24%	-	-28%
MG	-26%	-18%	-	-16%	-48%	4%	5%	-51%	98%	19%	3%	-7%	-47%	-30%	-16%	-29%	-30%	-40%	-5%	-	9%
RJ	-44%	-27%	-	16%	-	2%	-32%	-	-	18%	-31%	11%	-43%	-38%	-	20%	-29%	-	-12%	-	-38%
SP	-58%	68%	-	-55%	100%	32%*	-59%	3%	69%	7%	52%	-46%	-39%	4%	66%*	-25%	19%	-11%	-47%	43%*	40%*
GO	6%	-21%	-	-3%	-	25%	77%	-	96%	8%	55%*	-22%	81%	11%	-11%	-47%	-19%	-40%	-68%	-	95%
MT	-62%	8%	-53%	-11%	-	-	-25%	-20%	50%	1%	55%*	-43%	-	19%	-	-55%	3%	-46%	-27%	-	40%*
MS	-79%	45%*	-	-9-	-	32%*	-55%	-40%	48%*	6%	55%*	-74%	-36%	13%*	-	-63%	29%	2%	-55%	43%*	40%*
PR	-70%	45%*	-2%	-54%	16%	32%*	13%	44%	48%*	4%	36%	-52%	-1%	-10%	100%	-26%	19%	1%	-35%	43%*	40%*
RS	-57%	93%	-	-17%	-55%	57%	15%*	-	86%	-4%	58%	-38%	-9%	6%	38%	16%	17%	5%	-39%	43%*	40%*
SC	-75%	45%*	-	-37%	-11%	41%	15%*	-	96%	-9%	41%	-29%	2%	-14%	83%	46%	6%	4%	-41%	43%*	40%*

Source: Own elaboration based on the results of the econometric model.
Note: * Average positive variation.

Table 4 - Effect of Climate Change on Family Farming Productivity (RCP 8.5) (2021-2050)

FU / Sector	Banana	Coffee	Cashew Nuts	Orange	Grape	Others. Perm.	Pineapple	Herbaceous Cotton	Peanut	Rice and Cereals	Potato	Sugarcane	Onion	Beans	Tobacco	Cassava	Maize	Soybeans	Tomato	Wheat	Others. Temp.
AC	-51%	-16%	-	-49%	-	-26%	-9%	10%	23%	-1%	69%*	19%	-	-8%	-5%	-29%	-9%	-	-	-	1%
AP	3%	-	-	39%	-	-43%	2%	-	-	61%	-	-3%	-	-51%	-	-76%	-70%	-	-	-	-38%
AM	-28%	21%	-	27%	-	-21%	19%	-	34%	4%	69%*	-17%	-	2%	-36%	-30%	-17%	-	-	-	46%
PA	-20%	-24%	-63%	23%*	-	-26%	-10%	-73%	43%	16%	67%	-13%	-22%	15%	-22%	-63%	-22%	-27%	25%	-	49%
RO	-61%	-2%	-	-15%	-	-31%	-11%	-	57%	2%	69%*	7%	88%	7%	-	-52%	-8%	-51%	-39%	-	53%
RR	70%	-57%	-	23%*	-	-76%	-73%	-	-78%	29%	-	44%	-	21%	-	-56%	16%	-	54%*	-	44%*
TO	-42%	-	-51%	-83%	-	54%*	-40%	-	56%*	6%	69%*	-56%	-	49%	-	-65%	-4%	-36%	-	-	44%*
AL	-31%	-48%	-32%	-67%	-	-61%	-10%	-87%	2%	8%	-62%	61%	-	-48%	-16%	-27%	-46%	-	88%	-	-58%
BA	-48%	-46%	-54%	-88%	51%*	-37%	8%	-92%	75%	22%	-58%	-3%	-76%	-51%	19%	-31%	-50%	-44%	54%*	-	-32%
EC	-7%	-44%	-37%	-73%	-	-9%	17%	-51%	50%	11%	-23%	2%	-57%	-19%	44%	19%	-22%	-	65%	-	-27%
MA	-6%	-48%	-44%	-28%	-	72%	-1%	-	58%	14%	-	-25%	-	-3%	-	-20%	-20%	-48%	-	-	44%*
PB	-38%	-49%	-33%	-85%	51%*	-30%	-3%	-76%	35%	5%	-37%	33%	-25%	-41%	-20%	-16%	-41%	-	76%	-	-33%
PE	-40%	-39%	-48%	-88%	51%*	-25%	10%	-92%	92%	10%	-47%	50%	-63%	-47%	-19%	-32%	-47%	-33%	54%*	-	-43%
PI	-4%	-	16%	3%	-	54%*	-3%	-83%	56%*	11%	-	-34%	-	-4%	19%	-22%	-18%	-50%	58%	-	98%
RN	-18%	-36%	-24%	-87%	-	-50%	-3%	-38%	47%	-	-	36%	-5%	-33%	-11%	-14%	-33%	-13%	63%	11%	-46%
IF	-33%	-	-1%	-77%	-	-60%	-12%	-	-6%	7%	-68%	55%	-61%	-50%	-17%	-31%	-51%	-	54%*	-	-64%
ES	-71%	-34%	-	-68%	70%	-33%	-38%	-	96%	26%	-49%	28%	-75%	-49%	-	4%	-53%	-	60%	-	-55%
MG	-48%	-19%	-	-27%	-28%	9%	-16%	-83%	56%*	27%	-4%	-2%	-68%	-45%	7%	-35%	-35%	-50%	46%	-	17%
RJ	-68%	-34%	-	-36%	-	-13%	-37%	-	-	29%	-38%	29%	-69%	-52%	-	1%	-42%	-	5%	-	-62%
SP	-76%	22%*	-	-73%	51%*	54%*	-74%	-21%	56%*	13%	94%	-59%	-50%	5%	41%*	-40%	22%	-15%	-53%	11%*	44%*
GO	-26%	-16%	-	-42%	-	58%	57%	-	56%*	10%	69%*	-31%	12%	-	35%	-57%	-18%	-48%	-65%	-	44%*
MT	-72%	23%	-65%	-24%	-	66%	-44%	-11%	71%	-1%	69%*	-54%	-	39%	-	-65%	16%	-54%	-22%	-	44%*
MS	-89%	22%*	-	-96%	-	54%*	-72%	-48%	56%*	1%	69%*	-82%	-40%	16%*	-	-73%	55%	10%	-61%	11%*	44%*
PR	-82%	22%*	-18%	-70%	31%	54%*	-5%	14%	56%*	7%	45%	-63%	-13%	-12%	95%	-43%	22%	3%	-42%	11%*	44%*
RS	-79%	22%*	-	-29%	-58%	73%	91%	-	98%	-	84%	-47%	-23%	7%	42%	-	17%	9%	-49%	11%*	44%*
SC	-89%	22%*	-	-46%	-18%	45%	91%	-	56%*	-3%	55%	-34%	-7%	-18%	66%	25%	1%	3%	-51%	11%*	44%*

Source: Own elaboration based on the results of the econometric model.
Note: * Average positive variation.

The production of family farming has a greater participation in the national production of cassava, tobacco, onions, pineapples, cashew nuts, and grapes and relevant participation in banana and coffee crops (Instituto Brasileiro de Geografia e Estatística, 2017). In individual terms, cassava, coffee, maize, bananas, and beans would be, on average, negatively affected in most Brazilian states. In relation to coffee, there is a possible displacement of production toward the south, since the main producers, MG and ES, which concentrate about 85% of production, would present a reduction in productivity, while productivity would rise in the states of SP, PR, MS, and PR.

The productivity of cashew nuts would be negatively affected in the Northeast region, which concentrates 99% of the national production; however, in the state of Ceará, the largest producer, the impacts could be slightly positive in RCP 4.5. Tomatoes, in relevant producing regions such SP and GO, could be negatively affected in both scenarios, with possible positive impacts in the main producing region, BA. The cultivation of pineapples is dispersed across the country and would present positive performance in RCP 4.5. Negative impacts could occur in RCP 8.5 in the North, Southeast, and part of the Northeast regions. The productivity of onion cultivation could be negatively affected in the South, the main producing region, and the negative impacts could be accentuated in the RCP 8.5 scenario. Commercial crops such maize, cotton, rice, and soybean, would be negatively impacted with productivity decrease, especially in the Legal Amazon region. The main losses are concentrated in PA and MT.

The crops of tobacco, peanuts, grapes, and other temporary tillage crops would benefit from increased productivity. In regional terms, the FUs located in the South-Central region of the country (SC, PR, RS, SP, and GO), in addition to the states of MA, PI, and CE, located in the Northeast, would be positively affected.

4.2 Large-Scale Agriculture Results

The productivity of large-scale agriculture is estimated following the same procedure as for family farming. Table 5 presents the estimated results of the base model, with historical climatic data. Table A2 in the Appendix A presents the descriptive statistics of the large-scale agriculture analysis.

Table 5 - Effects on large-scale agricultural productivity in the base model (1971/2005)

Control Variables	Dependent Variable: log (Aggregate Agricultural Productivity)		
	Step (3)	Step (2)	Step (1)
High Temperature	-2.269***	-2.206***	-2.294***
(Average Spring and Summer)	(0.338)	(0.338)	(0.343)
Low Temperature	0.837***	0.907***	0.984***
(Average Autumn and Winter)	(0.149)	(0.135)	(0.131)
Squared High Temperature	0.0463***	0.0448***	0.0466***
(Average Spring and Summer)	(0.00699)	(0.00700)	(0.00713)
Squared Low Temperature	-0.0206***	-0.0220***	-0.0239***
(Average Autumn and Winter)	(0.00310)	(0.00284)	(0.00280)
High Precipitation	0.0115***	0.0109***	0.0118***
(Average Spring and Summer)	(0.00240)	(0.00243)	(0.00240)
Low Precipitation	-0.00673**	-0.00876***	-0.00774***
(Average Autumn and Winter)	(0.00273)	(0.00268)	(0.00276)
Squared High Precipitation	-0.0000229***	-0.0000209***	-0.0000235***
(Average Spring and Summer)	(0.00000560)	(0.00000564)	(0.00000562)
Squared Low Precipitation	0.0000233**	0.0000320***	0.0000283**
(Average Autumn and Winter)	(0.0000110)	(0.0000108)	(0.0000111)
Geographical Characteristics	Yes	Yes	Yes
Primary Factors	Yes	Yes	No
Social Capital	Yes	No	No
Other	Yes	No	No
Observations	5119	5324	5324
Adjusted R-Square	0.293	0.266	0.261

Source: Own elaboration based on the results of the econometric model.
Note: Robust standard error the heteroscedasticity in parentheses. p-value <0.01, ** p-value <0.05, *p-value <0.10.

As shown in Table 5, the signs and significance levels of the climatic variables were maintained between steps 1 to 3, as other control variables were included in the estimation. In step 3, the coefficients of the climatic variables indicate that an increase in temperature during the warmer period (spring and summer) would negatively affect the aggregate agricultural productivity, while an increase in the temperature in the autumn and winter would contribute to increase productivity. Regarding precipitation, the analysis verifies that the average productivity rises with increases in precipitation levels in the spring and summer seasons and reduces with an increase in the volume of precipitation in the autumn and winter seasons. Table 6 presents the simulated effects, for the year 2050, of climate change on large-scale agricultural production per hectare.

Table 6 - Simulated effects of climate change on large-scale agricultural output per hectare (2050)

Region	Federation Unit (FU)	RCP 4.5				RCP 8.5			
		Mean	Sd	95% confidence interval		Mean	Sd	95% confidence interval	
North	Acre (AC)	-14.1%	0.02	-15.1%	-13.0%	-12.8%	0.03	-13.9%	-11.6%
	Amapá (AP)	-65.3%	0.08	-70.3%	-60.3%	-65.1%	0.06	-69.3%	-61.0%
	Amazonas (AM)	-15.4%	0.24	-22.9%	-7.9%	-13.1%	0.22	-20.1%	-6.1%
	Pará (PA)	-28.5%	0.18	-31.5%	-25.4%	-27.8%	0.23	-31.8%	-23.9%
	Rondônia (RO)	-14.2%	0.10	-16.9%	-11.5%	-10.1%	0.12	-13.4%	-6.8%
	Roraima (RR)	-54.8%	0.12	-61.6%	-48.0%	-50.4%	0.17	-59.6%	-41.2%
	Tocantins (TO)	5.5%	0.14	3.0%	8.0%	4.2%	0.18	0.9%	7.5%
Northeast	Alagoas (AL)	-14.6%	0.17	-18.0%	-11.1%	-36.1%	0.12	-38.5%	-33.8%
	Bahia (BA)	-35.0%	0.06	-35.6%	-34.4%	-47.4%	0.04	-47.8%	-47.0%
	Ceará (CE)	4.3%	0.21	1.2%	7.4%	-18.8%	0.18	-21.4%	-16.3%
	Maranhão (MA)	-10.0%	0.11	-11.6%	-8.4%	-21.1%	0.11	-22.7%	-19.6%
	Paraíba (PB)	-4.8%	0.10	-6.1%	-3.4%	-27.7%	0.08	-28.8%	-26.7%
	Pernambuco (PE)	-26.8%	0.13	-28.7%	-24.9%	-41.6%	0.11	-43.1%	-40.0%
	Piauí (PI)	-12.6%	0.17	-15.0%	-10.3%	-27.5%	0.14	-29.4%	-25.5%
	Rio Grande do Norte (RN)	-7.2%	0.15	-9.6%	-4.9%	-30.2%	0.10	-31.8%	-28.7%
	Sergipe (SE)	-27.0%	0.10	-29.4%	-24.6%	-40.8%	0.07	-42.4%	-39.1%
Southeast	Espírito Santo (ES)	-12.9%	0.24	-18.2%	-7.6%	-30.6%	0.17	-34.3%	-26.8%
	Minas Gerais (MG)	-21.1%	0.18	-22.3%	-19.9%	-24.2%	0.24	-25.9%	-22.6%
	Rio de Janeiro (RJ)	22.3%	0.30	15.7%	28.8%	-1.6%	0.23	-6.5%	3.2%
	São Paulo (SP)	26.6%	0.31	24.1%	29.1%	48.0%	0.50	44.0%	52.0%
Midwest	Goiás (GO)	-15.9%	0.15	-18.1%	-13.8%	-9.3%	0.23	-12.5%	-6.1%
	Mato Grosso (MT)	-3.2%	0.19	-6.4%	0.0%	7.6%	0.27	3.0%	12.3%
	Mato Grosso do Sul (MS)	77.1%	0.46	66.8%	87.4%	151.6%	0.74	135.0%	168.3%
South	Paraná (PR)	49.2%	0.52	44.0%	54.3%	76.9%	0.89	67.9%	85.8%
	Rio Grande do Sul (RS)	33.5%	0.26	31.2%	35.9%	49.7%	0.41	46.0%	53.4%
	Santa Catarina (SC)	24.5%	0.32	20.6%	28.3%	26.6%	0.36	22.3%	30.9%

Source: Author´s elaboration

The results suggest that most of the FUs would be negatively affected. The states in the North and Northeast regions, would show a decrease in productivity, while the states in the Southern region, together with the states of SP, MS, and TO, would benefit from the average agricultural productivity gain. The region with the highest productivity decrease in RCP 4.5 would be Amapá, with a reduction of 65.3%, followed by Roraima (-54.8%), Bahia (-35%), Pará (-28.5%), and Sergipe (-27%). Among the states with a productivity gain, it is notable that, although the Southern region concentrates the positive effects, the most benefited in terms of agricultural productivity is MS, with an increase of 77% in RCP 4.5. The negative variations in productivity are intensified in RCP 8.5 for the units in the Northeast, MG, ES, and RJ. Tables 7 and 8 present the results by individual crops.

Table 7 - Effect of Climate Change on Large-scale Agriculture Productivity (RCP 4.5) (2021-2050)

FU / Sector	Banana	Coffee	Cashew Nuts	Orange	Grape	Others. Perm.	Pineapple	Herbaceous Cotton	Peanut	Rice and Cereals	Potato	Sugarcane	Onion	Beans	Tobacco	Cassava	Maize	Soybeans	Tomato	Wheat	Others. Temp.
AC	-61%	-9%	-	-71%	-	19%	1%	-	4%	3%	-	2%	-	-23%	-1%	-46%	-10%	-	-	-	7%
AP	-	-	-	-68%	-	-24%	34%*	-	-	-10%	-	-	-	-	-	-75%	-64%	-	-	-	32%*
AM	-37%	12%	-	50%*	-	-10%	91%	-	-	-6%	-	-12%	-	-20%	-	-33%	-14%	-	-	-	-24%
PA	-22%	-45%	49%*	46%	-	-29%	20%	-	-13%	-11%	-44%	13%	-	-1%	-41%	-59%	-34%	-9%	-77%	-	19%
RO	-80%	-	-	-7-	-	2%	7%	-	-59%	-3%	-	8%	-	-23%	-	-61%	-28%	-1%	21%	-	10%
RR	37%*	-	-	50%*	-	-39%	-62%	-	-	-12%	-	14%	-	-21%	-	-51%	-48%	-35%	-	-	32%*
TO	-37%	-	-97%	-35%	-	30%*	-59%	-	19%	-13%	-	58%	-	-9%	-	-10%	-49%	-6%	-	-	64%
AL	37%*	-	-17%	-46%	-	-52%	66%	-63%	-34%	-10%	18%	-11%	-	-31%	-23%	-35%	-19%	-	-	-	32%*
BA	24%	-34%	-11%	-44%	-	5%	34%*	-87%	25%	18%	-89%	5%	70%	-39%	28%	-27%	-51%	-15%	-20%	-	-32%
EC	10%	-32%	49%*	50%*	-	-35%	18%	47%*	-41%	-2%	-	-7%	27%	-	93%	2%	7%	-9%	40%	-	-20%
MA	-12%	-	59%	-21%	-	46%	1%	-	12%	-3%	-	38%	-	-7%	-	14%	-29%	-9%	-	-	37%
PB	-2%	-6%	-4%	-42%	79%	-3%	61%	-40%	16%	-8%	-22%	-7%	8%	-25%	-36%	-29%	-12%	-	54%*	14%	-14%
PE	14%	-15%	-35%	-59%	-13%	12%	34%*	-85%	24%	7%	12%	2%	45%	-35%	-	-33%	-22%	-	90%	-	-20%
PI	60%	-10%	-41%	88%	-	55%	-	-62%	-11%	1%	-	-4%	-	-5%	-	21%	-30%	-12%	-28%	-	-12%
RN	28%	-	39%	-	-	-37%	34%*	1%	-	-10%	-	-9%	-34%	-14%	-35%	-31%	10%	-	68%	12%	36%
IF	88%	-	-	-35%	-	-45%	34%*	-	-42%	-6%	-18%	-13%	-	-38%	-36%	-34%	-24%	-	-	-	-9%
ES	-38%	-21%	-	43%	15%	-5%	-65%	-	38%	12%	-66%	-2%	38%*	-49%	-	4%	-38%	-	-13%	-	-23%
MG	-21%	-12%	-	-48%	44%*	52%	-63%	-28%	24%	-1%	26%	26%	-54%	-31%	-25%	-29%	-43%	-4%	-44%	84%	-19%
RJ	-48%	-33%	-	13%	-	14%	-59%	-	-	14%	-23%	-13%	-	-29%	-	-7%	-21%	-	-53%	-	-29%
SP	-59%	15%	-	-43%	44%*	30%*	-97%	94%	62%	11%	-21%	43%	-7%	-	61%*	23%	-35%	10%	-40%	5%	76%
GO	-16%	-25%	-	-57%	-	60%	77%	-39%	-8%	-2%	-9%	38%	-93%	-32%	-	-26%	-47%	-4%	-52%	75%	2%
MT	-84%	4%	-	67%	-	30%*	-63%	-31%	-41%	-10%	19%*	70%	-	-31%	-	-57%	-29%	1%	51%	-	32%*
MS	-86%	85%	-	-12%	-	30%*	-97%	-59%	54%	-26%	-	28%*	-	11%	-	35%	-63%	4%	-	43%*	32%*
PR	-82%	71%	-35%	-8%	44%*	30%*	-85%	-14%	29%*	-17%	-12%	58%	38%*	7%	61%*	47%	-39%	14%	54%*	74%	40%
RS	-47%	-	-	-15%	40%	-10%	3%	-	29%*	-4%	-20%	22%	38%*	18%	61%*	77%	-16%	12%	54%*	36%	-17%
SC	-80%	-	-	41%	-36%	-19%	-41%	-	29%*	24%	-20%	-2%	38%*	9%	61%*	-	-13%	16%	54%*	-2%	-45%

Source: Own elaboration based on the results of the econometric model.
Note: * Average positive variation.

Table 8 - Effect of Climate Change on Large-scale Agriculture Productivity (RCP 8.5) (2021-2050)

FU / Sector	Banana	Coffee	Cashew Nuts	Orange	Grape	Others. Perm.	Pineapple	Herbaceous Cotton	Peanut	Rice and Cereals	Potato	Sugarcane	Onion	Beans	Tobacco	Cassava	Maize	Soybeans	Tomato	Wheat	Others. Temp.
AC	-70%	-1%	-	-86%	-	58%	-22%	-	13%	-1%	-	14%	-	-24%	46%*	-51%	-16%	-	-	-	32%
AP	-	-	-	-78%	-	1%	44%*	-	-	-12%	-	-	-	-	-	-75%	-69%	-	-	-	33%*
AM	-42%	26%	-	48%	-	5%	31%	-	-	-10%	-	-2%	-	-19%	-	-37%	-22%	-	-	-	-6%
PA	-33%	-37%	-16%	6%	-	10%	-38%	-	-24%	-9%	-70%	36%	-	-16%	-70%	-60%	-50%	-8%	-78%	-	19%
RO	-85%	10%	-	-86%	-	44%	-27%	-	-58%	-8%	-	25%	-	-24%	-	-65%	-36%	-	30%	-	48%
RR	17%*	-	-	41%*	-	-25%	-72%	-	-	-20%	-	22%	-	-14%	-	-58%	-47%	-35%	-	-	33%*
TO	-66%	-	-99%	-56%	-	24%*	-87%	-	4%	-12%	-	92%	-	-18%	-	-25%	-63%	-5%	-	-	33%*
AL	27%	-	62%*	-53%	-	-36%	34%	-55%	-32%	7%	54%	-12%	-	-49%	2%	-54%	-25%	-	-	-	29%
BA	-48%	-38%	62%*	-58%	-	23%	72%	-89%	23%	30%	-87%	1%	53%*	-55%	91%	-54%	-57%	-16%	-18%	-	-41%
EC	-1%	-41%	-20%	48%	-	-9%	-3%	88%*	-23%	14%	-	-2%	66%	-22%	46%*	-11%	-21%	-10%	-9%	-	-35%
MA	-33%	-	-46%	-34%	-	24%*	-49%	-	16%	6%	-	61%	-	-19%	-	-	-49%	-10%	-	-	58%
PB	-35%	-23%	70%	-58%	-78%	22%	17%	-66%	23%	9%	-15%	-8%	82%	-45%	37%	-43%	-32%	-	56%*	81%	-31%
PE	-33%	-19%	50%	-62%	-92%	42%	86%	-84%	42%	23%	9%	-1%	53%*	-53%	-	-51%	-36%	-	77%	-	-35%
PI	6%	-18%	-26%	80%	-	24%*	-	-81%	-10%	10%	-	13%	-	-25%	-	5%	-50%	-14%	-62%	-	-8%
RN	-4%	-	65%	-	-	-18%	58%	-27%	-	5%	-	-9%	-8%	-35%	37%	-43%	-14%	-	8%	81%	-11%
IF	-17%	-	-	-53%	-	-35%	44%*	-	-42%	14%	32%	-18%	-	-53%	-16%	-55%	-28%	-	-	-	-29%
ES	-77%	-30%	-	69%	-77%	6%	-68%	-	37%	25%	-62%	-9%	53%*	-61%	-	-42%	-46%	-	-17%	-	-42%
MG	-54%	-13%	-	-62%	93%	24%*	-83%	-55%	31%*	5%	22%	45%	-44%	-45%	18%	-49%	-54%	-4%	-53%	52%*	-9%
RJ	-77%	-37%	-	4%	-	27%	-59%	-	-	28%	-26%	-19%	-	-47%	-	-45%	-34%	-	-58%	-	-46%
SP	-84%	27%	-	-51%	68%*	24%*	-99%	88%	67%	20%	-39%	73%	12%	-10%	46%*	16%	-48%	11%	-48%	31%	33%*
GO	-49%	-24%	-	-75%	-	24%*	11%	-72%	-2%	-1%	-16%	67%	-92%	-41%	-	-42%	-57%	-3%	-58%	52%*	40%
MT	-91%	18%	-	17%	-	24%*	-81%	-71%	-43%	-13%	29%*	45%*	-	-32%	-	-62%	-40%	3%	85%	-	33%*
MS	-93%	33%*	-	-22%	-	24%*	-99%	-83%	52%	-37%	-	45%*	-	22%	-	29%	-69%	8%	-	52%*	33%*
PR	-90%	86%	-43%	-6%	68%*	24%*	-89%	-51%	31%*	-26%	-15%	91%	53%*	-2%	46%*	42%	-51%	15%	82%	52%*	33%*
RS	-79%	-	-	13%	97%	-4%	-33%	-	31%*	-8%	-27%	31%	53%*	14%	46%*	65%	-27%	13%	56%*	56%	6%
SC	-93%	-	-	83%	13%	-18%	-59%	-	31%*	31%	-20%	-4%	53%*	-1%	89%	-29%	-24%	17%	56%*	10%	-45%

Source: Own elaboration based on the results of the econometric model.
Note: * Average positive variation.

In terms of individual crops, the negative impacts are concentrated in maize, cotton, beans, coffee, oranges, potatoes, and bananas. Maize would be the most negatively affected crop, with reduced productivity in all regions and scenarios, followed by the cultivation of beans, which would benefit only in the Southern region in RCP 4.5. Santos et al. (2022) using an agroecological zoning model, also indicated that maize would be negatively affected in RCP 4.5 scenario, in most regions, although in RCP 8.5, the impacts would be positive. In relation to coffee, there is the same pattern as for family farming production, with regions in the south becoming more conducive to cultivation. The state of MT, the main national cotton producer, would also be negatively affected, with a sharp drop in RCP 8.5.

The productivity of potatoes would be negatively affected in regions with relevant production, such as SP and the South region, however, the impacts would be positive in MG, the largest national producer. In relation to banana cultivation, it is verified that only the Northeast region would benefit from productivity increases in RCP 4.5 scenario, while, in RCP 8.5, the deterioration of productivity would be accentuated in the country, including in the Northeast. The productivity of orange cultivation in the state of São Paulo, which concentrates about 80% of national production, would have a negative impact in both scenarios, as also pointed out by Maçorano (2017).

The positive highlights would be the increase in the productivity of sugarcane in the main producer regions such as SP, MT, MS e PR, as also indicated by Assad & Pinto (2008) and Assad et al. (2016). The productivity of grape cultivation in the states of SP, PR, and RS and wheat in the states of MS, PR, and RS, typical of regions with a mild climate, would also present an increase. Soybean production would benefit in MT, MS, and the South region; however, in the other regions, including Matopiba,[6] the current frontier of soybean production expansion in Brazil, the impacts would be negative. Zilli et al. (2020) and Santos et al. (2022) evaluated that in the RCP 4.5 scenario the impacts on soybean production in the Matopiba region would also be negative, evidencing that studies with different methodologies indicate results in line with the one presented here.

5. Discussion

Our results, using a measure of partial productivity, at the Brazil level, indicated that the productivity of family farming is lower than the productivity of large-scale agriculture. The lower productivity of family members is due to their productive configuration, linked to lower levels of physical capital, inputs and human capital, compared to large-scale agriculture. The first one focused on the domestic market, with a predominance of family labor, and the other, producer of commodities, also linked to the foreign market and with a predominance of hired labor, the latter even concentrating productivity gains, especially from the 1980s onwards, according to Gasques et al. (2014).

These findings may seem contradictory considering the debate on the TFP and area relationship, whose literature indicates that there is an inverse relationship between area and TFP (Rasmussen, 2010; Fuglie, 2008; Headey et al., 2010; Helfand & Taylor, 2021). However, when dealing with family farming, this observation must be made with reservations, since the classification of large-scale and family farming uses fiscal modules, and its classification is delimited differently between regions of Brazil. Family farming, by definition, comprises an area of up to 4 fiscal modules. The fiscal modules start at 5 hectares in the South of the country,

[6] The region that represents the frontier of the expansion of soybean, other grain, and fiber production, formed by the states of Maranhão (MA), Tocantins (TO), Piauí (PI), and Bahia (BA) (Empresa Brasileira de Pesquisa Agropecuária, 2020).

reaching 110 hectares in the North region (Landau et al., 2012). Therefore, a property of family farming in the North region occupies a considerably larger area than that of the South region, and yet, large-scale agriculture in the South could have an area smaller than one of family farming in the North.

Helfand et al. (2014), comparatively evaluated the productivity of family farming and large-scale agriculture in the South and Northeast of Brazil, controlling the analysis by the size of the property, and found that family farmers had lower productivity in relation to large-scale producers, in both the South and Northeast, indicating that the advantage of large-scale agriculture in terms of land productivity appears to be the result of more intensive use of purchased inputs and capital, as well as higher levels of human capital. This finding corroborates our results. Thus, the lower use of inputs, capital, and technology makes productivity more dependent on other factors such as climate, and therefore, more sensitive to climate change.

There is heterogeneity of impacts on producers and regions, with greater negative effects in the North and Northeast regions, as also pointed out by Araújo et al. (2014), Assad & Pinto (2008), Ferreira Filho & Moraes (2014), Assad et al. (2016), and Fernandes et al. (2012). These regions are home to 59% of Brazilian family farmers. The South region, which benefits from average productivity gains, concentrates only 21% of family farmers. The projected impacts could contribute to an increase in Brazil's regional disparities to the extent that they would affect less developed regions negatively and developed regions positively, further expanding the productivity differential among family farmers, as pointed out by De Paula (2018).

Family farming located in negatively affected regions is characterized by low productive dynamism, with a large part of production linked to subsistence. Such producers account for only 21% of the national production of family farming. On the other end, family farmers located in the benefited South region, are responsible for 57% of the national family farming production. The states of PR and RS stand out, with only 13% of producers but responsible for 40% of the national family farming production (Instituto Brasileiro de Geografia e Estatística, 2017).

Crops relevant to family farming, especially in the North region in terms of subsistence, such as cassava, beans, bananas, maize, and others of permanent agriculture, will suffer significant productivity losses, with intensified effects in the pessimistic scenario. This result contributes to the increase in the vulnerability of these producers since the reduction in productivity would imply the reduction of production, with possible repercussions on the subsistence and income of the producers.

Food security can be compromised to the extent that the loss of productivity can lead to reduced production, resulting in smaller amounts of food produced and consumed on the property and in smaller amounts of food destined for the market, resulting in lower income. Income instability, according to Hoffmann (2014), has a relevant contribution in determining food security in Brazil. Lower income, in addition to implying in lower food consumption, it represents an increase in the consumption of foods of low nutritional quality, notably cheaper. Also, the supply of food in remote regions, with a low level of infrastructure and sanitation, has considerable relevance for the food security of these populations.

Commercial crops related to deforestation, such maize, cotton, rice, and soybean, would be negatively impacted with productivity decrease, especially in the Legal Amazon region. The main losses are concentrated in PA and MT, states with the largest share of deforestation in the region. It is reiterated that such crops, although characteristic of large-scale agriculture, are not restricted to these producers and, therefore, such results may imply greater pressure for deforestation, even on the part of family farmers if producers decide to compensate for loss of productivity by expanding the cultivated area. Soybean cultivation plays an important role on deforestation, pushing pasture areas over natural forest (Barona et al., 2010). Although the restriction of soy production in illegal areas is well guaranteed by the soy moratorium, the decrease in productivity may still affect deforestation, to a lesser extent compared to pre-moratorium rates, as the harvest continues to expand in the region (Gibbs et al., 2015; Kastens et al., 2017).

Regarding large-scale agriculture, the effects would be, on average, negative in regions that have a higher number of establishments but are less technology intensive and have a smaller market share. Regions with more productive properties would benefit from productivity increases. North and Northeast regions concentrate 50% of large-scale properties in Brazil but are responsible only for 13% of large-scale production, while the states in the Southern region, together with the states of SP, MS, and TO, accounts for 47% of the national large-scale agricultural production (Instituto Brasileiro de Geografia e Estatística, 2017). These effects could widen the inequality between producers in the south-central and northern parts of the country.

The results, as well as those obtained for family farming, could point to an increase in pressure for deforestation in the region of the Legal Amazon due to the reduction in average productivity, mainly in the states of PA, AM and MT, states that make up the so-called deforestation belt. In the RCP 8.5 scenario, increased productivity in MT could ease this pressure, if we consider that productivity increases imply a reduction in the need for new productive land. This strategy is supported by public policies such as the ABC Plan (Brasil, 2012) and the Sustainable Rural Project (Newton et al., 2016). However, this relationship is not very clear. Villoria (2019) assesses that in some regions this relationship is inverse, with productivity gains leading to increased deforestation, especially when it comes to commodities. A result also pointed out by Hertel (2012), who highlights that the land supply and the price elasticity of commodities can play a more predominant role in the expansion of land use than the increase in productivity.

Among all the crops analyzed, large-scale agriculture stands out with greater participation in the national production of rice, wheat and cereals, maize, cotton, sugarcane, soybeans, beans, potatoes, oranges, and other temporary and permanent tillage crops. The negative impacts in maize, cotton, beans, coffee, oranges, and potatoes could generate supply and price instability in the country, with possible effects on the international market, since Brazil ranks among the largest exporters and producers of maize, coffee, orange juice, cotton, and beans, the latter focused on domestic consumption (Food and Agriculture Organization of the United Nations, 2020). These projections are in line with Assad & Pinto (2008), Fernandes et al. (2012), Assad et al. (2016) and Santos et al. (2022), studies carried out with another methodology, but which indicate the same direction of impacts.

The change in agricultural productivity in coffee cultivation indicates a movement of increased productivity in regions south of the main producing regions, currently MG and ES. Same pattern for family farmers. This phenomenon was also projected by Assad & Pinto (2008), indicating that the states of SP and PR could become important coffee-producing regions in the future. The productivity of sugarcane, the main source of ethanol production, would benefit in the main producing region, SP, and in the adjacent states of the central-south part of the country, with potential positive economic effects, given the trend to use fuels from renewable energy, as also indicated by Assad & Pinto (2008), Assad et al. (2016), Zilli et al. (2020) and Santos et al. (2022).

In general terms, the results of the impacts of CC on agricultural productivity achieved in this study pointed out negative impacts on crops relevant to food security in the North and Northeast regions; positive performance for sugarcane production; and an increase in the average agricultural productivity in the south-central regions of Brazil. It also indicates a possible increase in inequality between the productivity of farmers located in the central-south region and that of farmers located in the north-northeast region of the country. It is noteworthy that our results contribute to the literature by estimating impacts for a broader set of crops, mainly pointing to the direction and magnitude of climatic effects by type of producer, indicating, notably, the greater vulnerability of family farmers to climate change.

6. Conclusion

This study analyzed the effects of climate change on agricultural productivity by cultivation and by type of producer in the Brazilian federation units. We show that the effects are different between producers. The composition of its productive structures, regarding the use of inputs, capital, labor, and technology, differentiates agricultural sensitivity. On average, it can be concluded that family farming is more sensitive since it presents more intense variations in productivity due to the lower use of productive factors. Their productivity would tend to respond more to climatic factors, which would translate into greater vulnerability to climate change.

The negative impacts would be concentrated in the North and Northeast regions of Brazil, regions where the projections indicate a more significant increase in temperature and reduction of precipitation and which concentrate a large portion of family farmers whose production is focused on subsistence. The Midwest and Southeast regions, which, together with the Southern region, account for much of the Brazilian agricultural production, would experience moderate impacts. The Southern region would benefit mostly from productivity gains in both scenarios and for both types of producers.

The estimates show that the changes in agricultural productivity are heterogeneous in terms of magnitude, region, and cultivation. Regarding family farming, the crops of cassava, coffee, maize, bananas, beans, and oranges would be negatively affected in most regions, with implications for food security, especially in the North and Northeast regions. Positive impacts would be verified in the crops of tobacco leaf, peanuts, grapes, and wheat and other crops of temporary tillage. Regarding large-scale agriculture, maize, cotton, beans, oranges, and coffee crops would be negatively affected and sugarcane, grape, and wheat crops would be positively affected. The impacts on soybeans would be moderate, with positive impacts on SP, MS, and the South region and negative impacts on MATOPIBA. The results also point to a possible increase in pressure for deforestation in the Legal Amazon region, due to the average reduction in agricultural productivity.

Furthermore, although the study performed a cross-sectional analysis, disregarding the adaptive capacity of farmers, it contributes to the literature by estimating the pure effect of the climate on agricultural productivity in a comparative way between types of producers, evidencing the magnitude of the productive/technological advance required, by type of producer, crop, and region, to mitigate the impacts of climate change. Nevertheless, the next research efforts will focus on the analysis of the effects of CC on agricultural productivity quantiles since, despite the breakdown into family farming and large-scale agriculture, both profiles still present great heterogeneity.

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APPENDIX A - Descriptive Statistics

Table A1 - Descriptive Statistics of Climate and Family Farming Control Variables

Variable	Number of observations	Average	Standard Deviation	Min.	Max.
Temperature (monthly)	5364	22,23	3,38	13,82	29,02
Precipitation (monthly)	5364	114,74	42,2	32,68	292,77
Spring/Summer Temperature	5364	23,86	2,46	16,49	29,57
Autumn/Winter Temperature	5364	20,61	4,37	11,16	28,48
Spring/Summer Precipitation	5364	134,33	57,12	31,78	386,78
Autumn/Winter Precipitation	5364	95,15	49,2	9	281,15
Altitude	5364	413,44	269,7	0	1495,63
Latitude	5364	-16,26	9,41	-33,51	3,88
Longitude	5364	-46,58	7,06	-72,91	-34,81
Machinery and Equipment (R$/Ha)	5364	6.364*	11.700*	12	184.000*
Labour	5364	0,08	0,31	0	320
Associated with class entities	5364	0,15	1,58	0	1830,7
Associated with cooperatives	5364	0,04	0,13	0	59,74
Improvements (area)	5364	397,61	639,01	0	10851
Facilities (R$/Ha)	5364	11.400*	16.400*	15	203.000*
Irrigated Area	5364	287,22	860,34	0	13969,15

Source: Own elaboration based on Matsuura & Willmott (2012), IBGE (Instituto Brasileiro de Geografia e Estatística, 2006) and Instituto de Pesquisa Econômica Aplicada (2019).
Note: *Amounts in thousands Reais (R$)

Table A2 - Descriptive Statistics of Climate and Large-scale Agriculture Control Variables

Variable	Number of observations	Average	Standard Deviation	Min.	Max.
Temperature (monthly)	5327	22,01	2,47	13,83	29,03
Precipitation (monthly)	5327	128,27	25,31	32,68	292,78
Spring/Summer Temperature	5327	23,67	1,78	16,50	29,57
Autumn/Winter Temperature	5327	20,35	3,29	11,16	28,48
Spring/Summer Precipitation	5327	179,53	55,19	31,78	386,79
Autumn/Winter Precipitation	5327	77,00	44,26	9,01	302,70
Altitude	5327	507,30	246,89	0,00	1495,64
Latitude	5327	-19,07	6,43	-33,69	4,48
Longitude	5327	-50,33	5,27	-72,92	-34,81
Machinery and Equipment (R$/Ha)	5327	16.400*	36.600*	52	654.000*
Labour	5327	0,01	0,04	0	12,2
Associated with cooperatives	5327	0,13	0,47	0	145,85
Associated with class entities	5327	0,14	0,90	0	174,37
Improvements (area)	5327	794,11	1603,33	0	66.740
Facilities (R$/Ha)	5327	20.200*	38.800*	2	48.600*
Irrigated Area	5327	4897,5	9175,9	0	69.843

Source: Own elaboration based on Matsuura and Willmott (2012), IBGE (Instituto Brasileiro de Geografia e Estatística, 2006) and Instituto de Pesquisa Econômica Aplicada (2019).
Note: * Amounts in thousands Reais (R$)