Revista Brasileira de Estudos Regionais e Urbanos (RBERU)
Vol. 07, n. 2, pp. 19-33, 2013
http://www.revistaaber.org.br

REGIONAL ECONOMIC IMPACTS OF CLIMATE ANOMALIES IN BRAZIL

Eduardo Amaral Haddad
Department of Economics at the University of Sao Paulo, Brazil
E-mail: ehadda@usp.br

Alexandre Alves Porsse
Department of Economics at the Federal University of Parana, Brazil
E-mail: porsse@gmail.com

Paula Carvalho Pereda
Department of Economics at the University of Sao Paulo, Brazil
E-mail: paulapereda@gmail.com

RESUMO: A variabilidade climática é uma das principais causas ambientais de perdas para o sector agrícola, mas a maioria das abordagens metodológicas aplicadas para estimar o custo econômico desses eventos extremos geralmente capturam apenas ao impacto econômico direto na atividade agrícola. Neste trabalho, desenvolvemos uma abordagem metodológica na qual um modelo físico é integrado com um modelo CGE inter-regional a fim de permitir avaliar o impacto econômico sistêmico de anomalias climáticas. A análise é realizada para a economia brasileira considerando as anomalias climáticas observadas em 2005. O impacto sistêmico é mensurado levando-se em conta tanto as ligações indiretas do setor agrícola com outros setores no sistema econômico como também a interdependência regional entre os estados brasileiros associados decorrente dos fluxos comerciais. Os resultados mostram que os custos econômicos das anomalias climáticas são significativamente subestimados se apenas os efeitos de equilíbrio parcial são contabilizados. Estimamos que cada perda de R$ 1,00 na produção agrícola, causada pelas anomalias climáticas de 2005, implicaram em perdas adicionais de R$ 3,25 na economia como um todo. Observamos também que as ligações intersetoriais e inter-regionais, bem como os efeitos dos preços, são canais importantes para propagar os efeitos econômicos de anomalias climáticas localizadas em determinada região sobre o restante do Brasil.

Palavras-chave: Anomalias climáticas; Impactos sistêmicos; Agricultura; modelos EGC.

Classificação JEL: C68; Q10; Q51; Q54.

ABSTRACT: Climate variability is one of the main environmental causes of losses to the agricultural sector but most of the methodological tools applied to estimated the economic cost of such extreme events usually account for only to the direct impact on agricultural activity. In this paper we develop an methodological approach were a physical model is integrated with an interregional CGE model in order to allow evaluating the systemic economic impact of climate anomalies. The analysis is carried out for the Brazilian economy considering the climate anomalies observed in 2005. This systemic impact is evaluated taking into account both the indirect linkages of the agricultural sector with other sectors in the economic system and the regional interdependence among Brazilian states associated with the trade flows. The results show that the economic costs of climate anomalies can be significantly underestimated if only partial equilibrium effects are accounted for. For the whole country, the loss of BRL 1.00 in the agricultural production caused by climate anomalies such as those occurred in 2005 implied additional losses of BRL 3.25 in the economy as a whole. It was also observed that intersectoral and interregional linkages as well as price effects are important channels for spreading the economic effects of located climate anomalies on other regions of the country.

Keywords: Climate anomalies; Systemic impacts; Agriculture; CGE analysis.

JEL Code: C68; Q10; Q51; Q54.

1. Introduction

While longer term changes in climate have the potential to modify agricultural land use patterns (*e.g.* Evenson and Alves, 1998; Gurgel *et al.*, 2007; Matthews *et al.*, 2007; Ronnenberger *et al.*, 2009), short-term climate conditions directly affect crop yields and farmers' earnings (*e.g.* Moore and Negri, 1992; Mendelsohn *et al.*, 1994; Mendelsohn *et al.*, 2004; Sands and Edmonds, 2005; Dêschenes and Greenstone, 2007). Agriculture losses in the recent past are often associated not only to climate variability but also to weather-related extreme events, such as droughts and floods (DING *et al.*, 2010).

Climate change is expected to modify the frequency, intensity and duration of extreme events in many regions (CHRISTENSEN *et al.*, 2007). In South America, significant changes in rainfall extremes and dry spells are projected, including increased intensity of extreme precipitation events in western Amazonia and significant changes in the frequency of consecutive dry days in northeast Brazil and eastern Amazonia (Marengo *et al.*, 2009). As pointed out by Sena *et al.* (2012) in a study on extreme events in the Amazonia, modifications in precipitation patterns could be expected in the region, as changes in temperature can lead to several modifications of the environment, amongst them, alteration in the global hydrologic cycle, provoking impact on water resources at the regional level. In such scenarios, Brazilian agriculture would be expected to face higher risk of crop failure due to climate variability.

Climate variability is one of the main environmental causes of losses to the agricultural sector. In general, the direct effects of climate on agriculture are mainly related to lower crop yields or failure due to drought, frost, hail, severe storms, and floods; loss of livestock in harsh winter conditions and frosts; and other losses due to short-term extreme weather events. Some of these effects of climate on agriculture have already been studied in Latin American countries (MAGALHAES, 1996; BOYD and IBARRARÁN, 2008). However, there are not many studies exploring the systemic economic costs of the impacts of climate anomalies on the agriculture sector within a country.[1] This broad territorial view is essential in a context of an integrated approach of production value chain – the agribusiness.[2]

Existing studies usually focus on the direct (partial equilibrium) effects of climate variables on different types of crops located within the geographical limits of the study areas. However, backward and forward linkages affect, to different extents, local demand by the various economic agents. Especially for the agribusiness complex, spatial and sectoral linkages play an important role. In any given region, firms exchange goods and services with each other; this phenomenon is usually captured in input-output tables [Hewings, 1999; p. 2]. With this formulation in place, it is possible to trace the consequences on other sectors of the economy of an expansion or contraction in any one sector or set of sectors. However, regional economies are, by their very nature, open and subject to the economic vicissitudes of demand and supply interactions in other parts of the country and other parts of the world. Hence, in parallel to the economic linkages between sectors within a region, there is a parallel set of linkages between regions. The growth or decline of one region's economy will have potential impacts on the economies of other regions; the nature and extent of this impact will depend on the degree of exchange between the two regions – as well as exchange with other regions. Thus, there is a need to address these issues in a general equilibrium context including price effects.

There is an extent literature dealing with the systemic effects of climate change on agriculture in the context of computable general equilibrium (CGE) models.[3] Modeling strategies attempt to either include more details in the agriculture sectors within CGE model structures (*e.g.* modeling of

[1] The pioneering study by Horridge *et al.* (2005) may be regarded as a milestone in the field.

[2] While the agriculture share in Brazilian GDP was 7.5% in 1999, the contribution of agribusiness, which takes into account the entire value chain related to agriculture, was 26.6% of national GDP. This picture varies by region: for instance, the figures for the South were 12.8% (share of agriculture in regional GDP) and 41.4% (share of agribusiness in regional GDP), and for the Southeast region 4.7% and 21.2%, respectively (FURTUOSO and GUILHOTO, 2003).

[3] CGE models are based on systems of disaggregated data, consistent and comprehensive, that capture the existing interdependence within the economy (flow of income).

land use and land classes) or to integrate stand-alone models of agriculture land use with CGE models, usually through soft links using semi-iterative approaches (PALATNIK and ROSON, 2012). Most of such CGE applications are global in nature, providing economic impacts only at the level of world regions or countries. The detailed spatially disaggregated information on land characteristics that may be present in the land use models is lost in aggregation procedures to run the global CGE models, providing few insights on the differential impacts within national borders.

Within this context, the objective of this study is to analyze the susceptibility of agricultural outputs to climate variations and the extent to which it propagates to the economic system as a whole. For this analysis, the definition for climate variability is related to a short-term approach (climate anomaly). We use a methodological framework in which physical and economic models are integrated for assessing the economic wider impacts of observed climate anomalies in 2005 in Brazil.[4] As the agriculture sector has important forward linkages in the Brazilian economic structure, and specific location patterns, those climate anomalies, even if spatially concentrated, may have implied in important economic losses for the whole country with distinct regional impacts. While physical models of agriculture productivity can provide estimates of the direct impact of climate variability on the quantum of agriculture production, spatial general equilibrium models can take into account the systemic impact of climate anomalies considering the linkages of the agriculture sector with other sectors of the economy and the locational impacts that emerge.

The remaining of the paper is structured as follows. In the next section, we discuss the methodological approach and present the estimates of the direct effects of climate anomalies derived from a physical agronomic model. The next two sections provide an onverview of the integrated approach to derive the economy-wide impacts of the 2005 climate anomalies, followed by the presentation of the results and a discussion.

2. Direct Effects: Methodology and Results

In this study, we first analyze how the production of different cultures is affected by climate variables by using a profit function approach (LAU, 1978; JEHLE and RENY, 2000; MAS-COLELL *et al*., 2006). This approach allows the measurement of the crop production variation (direct effects), which will be used as the physical measure of output change. It is assumed that farmers allocate inputs (i.e. land, labor, fertilizers and energy) for the production of temporary crops and permanent crops. Allocation decision is based on a profit maximization problem in competitive markets. Climate variables are considered as exogenous fixed inputs to the profit function. Information on both long-term climate (seasonal pattern) and short-term climate variability (specific anomaly in the year) is introduced. Moreover, other fixed factors such as soil type, investments and farmer education are also considered. Appendix A provides more details on the approach.

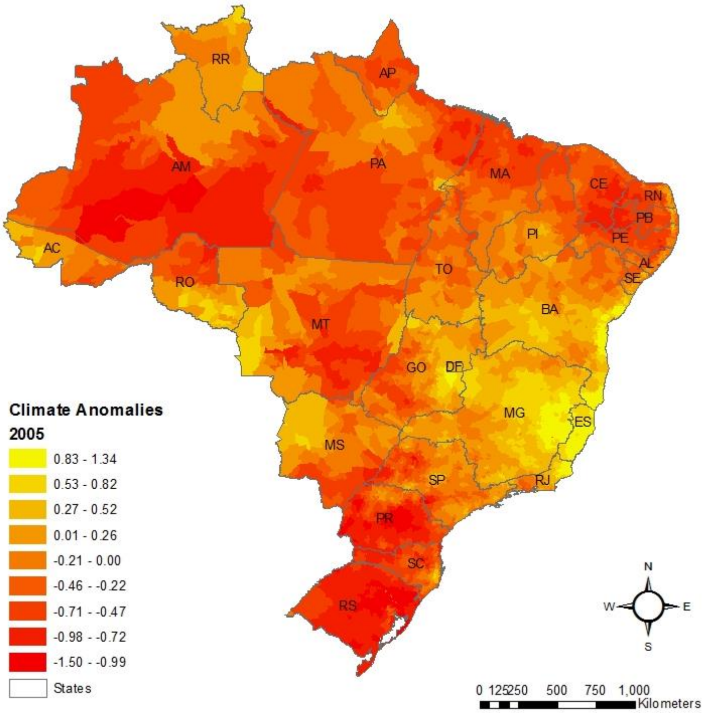
Cross-section data were used as empirical support in this study. The unit of analysis was the Brazilian municipalities. The agricultural data were obtained from the Brazilian Agricultural Census of 2006, produced by the Brazilian Institute of Geography and Statistics (IBGE).[5] The climate data were obtained from different sources: historical temperature information was obtained from the National Meteorology Institute (INMET); historical rainfall data was collected from CPC

[4] In 2005, several Brazilian regions experienced expressive declines in precipitation compared to the historic averages. A symbolic case about extreme precipitation event in Amazonian Basin is the drought occurred in that year (SENA *et al.*, 2012), which hit more severely the southwest of Amazonia and the state of Pará. In the same year, Brazil's northeast Sertão, encompassing the states of Ceará, Rio Grande do Norte, Paraíba and Pernambuco, and the south of the country also faced droughts during the main harvest season.

[5] The Brazilian Institute of Geography and Statistics (IBGE) conducts the Brazilian Agricultural Census every 10 years with the objective of updating population estimates and information about the economic activities carried out in the country by members of society and the agricultural companies. The last one employed technological refinements, mainly related to the introduction of new concepts to encompass the transformations that occurred in agricultural activities and in the countryside since the previous census.

Morphing/NOAA.[6] Climate anomaly was defined as the difference between the observed values and the long-term averages (for rainfall) divided by the respective standard deviations over the period. Figure 1 presents the spatial pattern of climate anomalies among Brazilian municipalities for 2005. Comparing to the historic average, it can be observed an expressive reduction in precipitations, mainly in some areas of North, Northeast and South of Brazil.

Figure 1 - Climate (Rainfall) Anomalies: Brazilian Municipalities, 2005



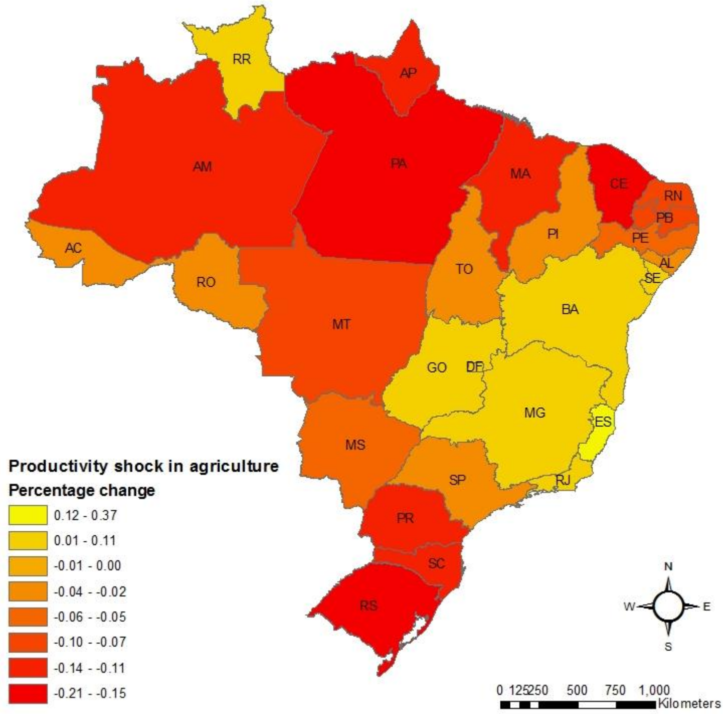
Source: Elaborated by the authors.

The profit model was estimated to predict the physical impact of climate anomalies for permanent and temporary crops in 2005. The total direct impact on the agriculture sector in each Brazilian state was then calculated using Laspeyres indices whose weights were given by the shares of both permanent and temporary crops outputs for each municipality that were further aggregated to obtain a measure of the physical change in agriculture production at the state level.[7]

Such results were translated into productivity shocks changing the production functions of the agriculture sector in each state (Figure 2).[8] As expected, the spatial distribution of these shocks is correlated to the climate anomalies showed in Figure 1, that is, the higher the reduction in precipitation the higher the negative impact on agriculture productivity. The states located mainly in the North (Amazonas, Para and Amapa) and South (Parana, Santa Catarina and Rio Grande do Sul) were the most affected by the climate anomalies in 2005. Noteworthy is that there are also states with gains in productivity associated with more favorable climate conditions which one are located mainly in the Southeast (Minas Gerais, Rio de Janeiro and Espirito Santo). These productivity shocks only account for the direct impact of climate anomalies. As the agriculture sector provides inputs for many other sectors in the economy, it is naturally expected that the effects of climate anomalies will spread to the whole economic system. The strategy adopted to calculate the wider economic impacts follows.

[6] Rainfall data were calculated from CMORPH (CPC Morphing technique) for the production of global precipitation estimates (JOYCE *et al.*, 2004).
[7] Appendix B shows the estimated coefficients of the profit model. It is worth mentioning that these coefficients were estimated using data for 2006, but climate anomalies were structurally estimated using rainfall data for 2005.
[8] As the CGE model is calibrated based upon an interstate input-output system, this bottom-up spatial aggregation procedure was necessary to define the linkages between the physical and the economic models.

Figure 2 - Productivity Changes in the Agriculture Sector due to Climate (Rainfall) Anomalies: Brazilian States, 2005



Source: Elaborated by the authors.

3. Wider Economic Impacts: Methodological Approach

An interstate computable general equilibrium (CGE) model was used to simulate the systemic impacts of changes in agricultural yields by state due to climate variation. The departure point is the B-MARIA model, developed by Haddad (1999). The B-MARIA model – and its extensions – has been widely used for assessing regional impacts of economic policies in Brazil. Since the publication of the reference text, various studies have been undertaken using, as the basic analytical tool, variations of the original model.[9]

The theoretical structure of the B-MARIA model is well documented.[10] The model recognizes the economies of 27 Brazilian regions. Results are based on a bottom-up approach – i.e. national results are obtained from the aggregation of regional results. The model identifies 56 production/investment sectors in each region producing 110 commodities, one representative household in each region, regional governments and one Federal government, and a single foreign area that trades with each domestic region, through a network of ports of exit and ports of entry. Three local primary factors are used in the production process, according to regional endowments (land, capital and labor). The model is structurally calibrated for 2005-2007; a rather complete data set is available for that period.

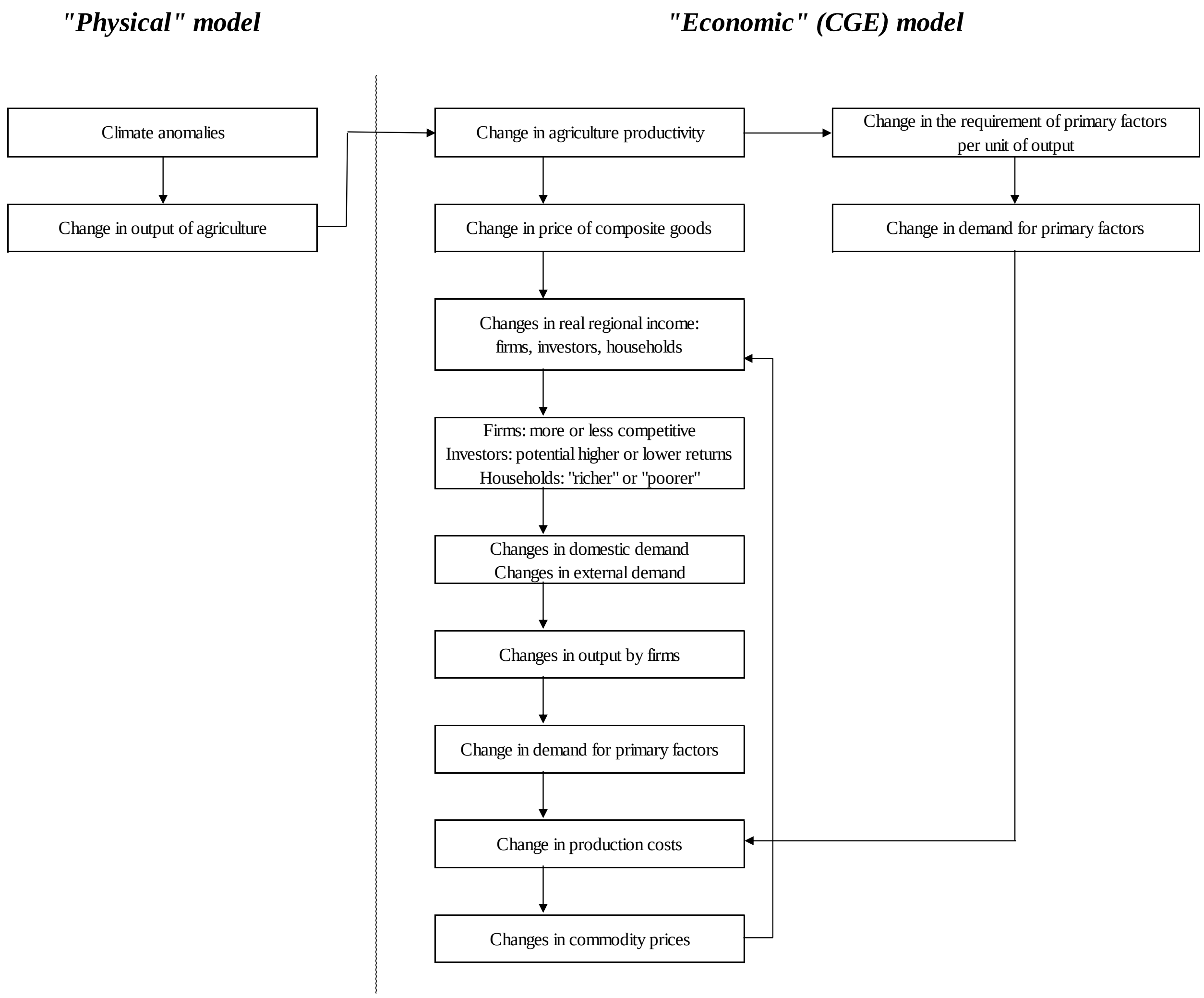
The B-MARIA framework includes explicitly some important elements from an interregional system, needed to better understand macro spatial phenomena, namely: interregional flows of goods and services, transportation costs based on origin-destination pairs, interregional movement of primary factors, regionalization of the transactions of the public sector, and regional labor markets segmentation. We have also introduced the possibility of (external) non-constant returns in the production process, following Haddad (2004). This extension is essential to adequately represent one of the functioning mechanisms of a spatial economy.

[9] Critical reviews of the model can be found in the Journal of Regional Science (POLENSKE, 2002), Economic Systems Research (SIRIWARDANA, 2001) and in Papers in Regional Science (AZZONI, 2001).

[10] See Haddad (1999), and Haddad and Hewings (2005).

In order to capture the effects of climate anomalies on agriculture productivity, the simulations were carried out under a standard short run closure. Capital stocks were held fixed, as well as regional population and labor supply, regional wage differentials, and national real wage. Regional employment is driven by the assumptions on wage rates, which indirectly determine regional unemployment rates. On the demand side, investment expenditures are fixed exogenously – firms cannot re-evaluate their investment decisions in the short run. Household consumption follows household disposable income, and real government consumption, at both regional and federal levels, is fixed. It is assumed that the public sector keeps its expenditure level through running short-term deficits (surpluses). Finally, preferences and technology variables are exogenous allowing for exogenous changes in the production functions of the state agriculture sectors, consistent with projection of the profit function estimates. Typical results must be understood in a comparative-static sense; in other words, they show the percentage change in the endogenous variables that would have been observed in the benchmark year had the climate anomalies occurred in the benchmark database.

Figure 3 - The Integrated Framework



Source: Elaborated by the authors.

The strategy for sequentially modeling integration is summarized in Figure 3. At the first stage, the partial equilibrium model was used to project the physical change in the production of the agriculture sector (permanent and temporary crops) conditioned by the climate anomalies observed in 2005. At the second stage, such physical changes in the state agricultural output were translated as technological productivity shocks into the CGE model. The productivity shocks are modeled as technical change in the requirements for primary factors used in the production function. For instance, if the climate anomalies implied in a 10% reduction in the agriculture output, it was assumed that the primary factors requirements of the agricultural sector would increase also by 10% in order to achieve the same current production. As a consequence, productivity decreases in the agricultural sector, causing increases in the composite prices and decreases in the real income of economic agents. The main channels of propagation of the general equilibrium effects of climate anomalies through the economic system consist in supply constraints from the agricultural sector to other sectors, as well changes in prices of composite goods and primary factors, affecting firms' competitiveness and household welfare.

4. Simulation Results

What if climate in 2005 had followed historical trends in Brazil? What would be the difference in terms of value added (GRP/GDP) for the country and its regions? Results of the CGE simulations with the software GEMPCAK were computed via a 1-2-4 Euler procedure with extrapolation (HARRISON and PEARSON, 1996), under a short-run closure (exogenous capital stocks). In what follows, we focus our analysis on the national, sectoral and regional activity effects.

Table 1 shows the results for the macroeconomic effects of the 2005 climate anomalies generated by the CGE simulation. It can be seen that it is expected climate variability to have lowered the national GDP by 0.163%, and employment by 0.403%. Despite the localized occurrence of droughts within specific regional limits, they reduce output growth beyond the affected territories. They also contribute to a decline in welfare of national residents (lower real household consumption), a reduction in tax revenue[11], and a decrease in the country's competitiveness in international markets, as verified by the worsening of the international balance of trade (stronger decline of exports).

Table 1 - Macroeconomic Impacts of Climate Anomalies (in percentage change)

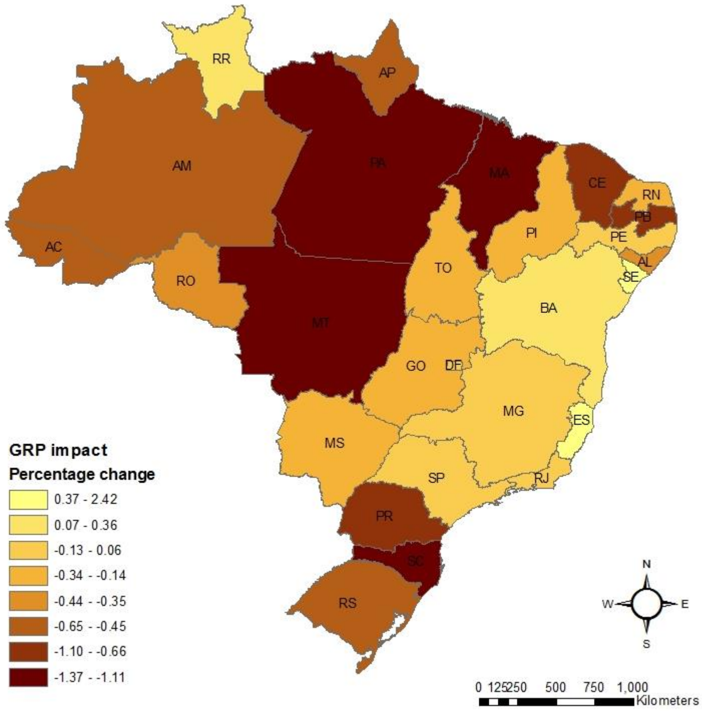
Variables	%
Real GDP	-0.163
Real household consumption	-0.163
Real investment	-
Real government consumption - Regional	-
Real government consumption - Federal	-
International export volume	-0.819
International import volume	-0.481
GDP deflator	0.705
Consumer price index	0.800
Investment price index	0.341
Government price index - Regional	0.683
Government price index - Federal	0.676
International export price index	0.412
International import price index	-
Employment	-0.403

Source: Elaborated by the authors.

[11] Our assumption regarding adjustment in the real government expenditure considers constant real expenditures adjusted by budget deficits/surpluses for both regional and federal governments.

From a spatial perspective, Figure 4 presents the impact of climate anomalies on GRP of Brazilian states. The spatial distribution of these impacts is highly correlated with the shape of climate anomalies shown in Figure 2. The biggest reductions in GRP are concentrated in some states located in the North (Pará, Amazonas and Amapá), Northeast (Maranhão, Paraíba and Ceará), Center-West (Mato Grosso) and South (Santa Catarina, Paraná and Rio Grande do Sul), especially where more severe droughts occurred in 2005.

Figure 4 - Impacts on GRP

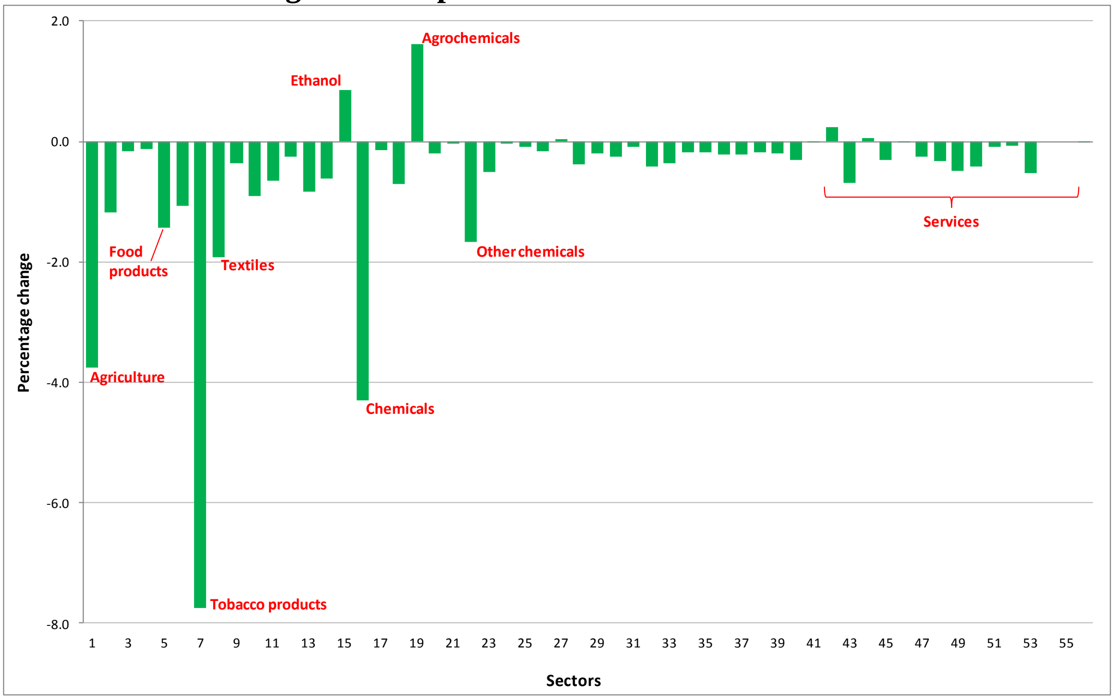


Source: Elaborated by the authors.

Such effects are determined by both the direct impacts of climate anomalies on the agricultural sector and the indirect and induced impacts on other sectors, since agricultural goods are not only used as intermediate inputs to other sectors, but also as part of the exports and household consumption. According to Figure 5, the sectors most affected (indirectly) by climate anomalies are those related to the agribusiness complex such as tobacco products, textiles and food products. Additionally, non-tradable goods such as those in the service sectors are negatively affected by climate anomalies. This negative effect is mostly due to a reduction in real income caused by the general increase in prices led by the increase in the prices of agricultural products. Such effect on prices also hampers Brazilian competitiveness in foreign markets.

To better understand the short-run regional results of the model, a thorough analysis of the structure of the economy is needed (HADDAD *et al.*, 2009). A close inspection on the benchmark data base is necessary, conducted not only on the relationships in the interregional input-output data base, but also on the other relevant structural parameters of the model. As shown in Haddad *et al.* (2002), structural coefficients derived from the SAM lead short-run results in less flexible environments (closures). As one precludes factor mobility to a great extent, understanding of disaggregated results may be achieved through econometric regressions on key structural coefficients.

Figure 5 - Impacts on Sectoral Value Added



Source: Elaborated by the authors.

How important is the existing economic structure in explaining the short-run spatial results associated with climate anomalies in Brazil? Do backward and forward linkages matter? To answer these questions, following Dixon *et al.* (1982, 2007), we regress the model results (regional activity level) against selected structural coefficients of the model and the size of the shock (direct effects). The OLS regressions are shown in Tables 2, and aim only at revealing the influence of the benchmark structure on the short-run results.

According to the results for regional activity level, structural indicators explain 82 percent of the variation across states in the CGE model results. Explanations for specific regional results should consider structural and parametric aspects of the data base. Regions that present higher decreases in their output tend to face stronger initial impacts due to inadequate climate conditions; they also tend to have an overall higher share of agribusiness in their sectoral structure, suffering from the effects in the production value chain. Also, regions that face stronger negative effects tend to concentrate their sales to foreign consumers. Finally, a higher labor share in the regional value added seems to benefit economic performance in the short-run, as employment adjustment turns out to be more flexible. Thus, the extent to which climate anomalies affect short term regional economic growth is conditioned by the structural characteristics of each regional productive system, mainly the degree of specialization in agriculture and agribusiness activities and their backward and forward linkages into the integrated interregional economic system.

Table 2 - Structural Analysis of Short-run Activity Level Results

Dependent Variable: ACT_SR

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-2.27925	0.68300	-3.33712	0.00300
AGR_SH	-0.94169	0.47047	-2.00160	0.05780
LSH	4.24702	1.31617	3.22680	0.00390
SHOCK	-0.02354	0.01081	-2.17696	0.04050
SHOCK*SAL4	-0.15878	0.05860	-2.70955	0.01280
R-squared	0.81668			

Source: Elaborated by the authors.

Note: ACT_SR = percentage change in regional activity level; AGR_SH = share of agribusiness in regional productive structure; LSH = share of labor payments in regional value added; SHOCK = initial productivity change in the agriculture sector; SHOCK*SAL4 = interaction between initial productivity change in the agriculture sector and export share in total sales.

The evaluation of the importance of these structural characteristics for propagating climate shocks over the territory can be achieved by computing and comparing the direct economic costs to the total economic impact of climate shocks in terms of changes in the level of sectoral production. The direct impact, or damage, can be obtained through the changes in agricultural production caused by the productivity shock, while the total impact is calculated by taking into account the general equilibrium effects on the activity level of all sectors of the state economies.

Table 3 - Total Costs of Climate Anomalies (BRL millions 2011)

	Direct damage	*Total impact*	*Total impact-damage ratio*
North	***-921***	***-2103***	***2.28***
RO	-31	-105	3.36
AC	-18	-36	1.98
AM	-80	-393	4.88
RR	6	4	0.65
PA	-757	-1519	2.01
AP	-18	-23	1.26
TO	-22	-32	1.47
Northeast	***-437***	***-713***	***1.63***
MA	-233	-145	0.62
PI	-19	-38	2.01
CE	-326	-778	2.39
RN	-115	-198	1.72
PB	-176	104	-0.59
PE	-399	-626	1.57
AL	-109	-141	1.29
SE	9	65	7.07
BA	930	1045	1.12
Southeast	***3178***	***-6029***	***-1.90***
MG	1568	938	0.60
ES	2162	1719	0.79
RJ	127	-1725	-13.54
SP	-680	-6961	10.24
South	***-6453***	***-14032***	***2.17***
PR	-2948	-4379	1.49
SC	-804	-1017	1.26
RS	-2701	-8636	3.20
Center-West	***-1303***	***-2336***	***1.79***
MS	-208	-430	2.07
MT	-1179	-1592	1.35
GO	93	-192	-2.07
DF	-9	-122	14.14
BRAZIL	***-5936***	***-25212***	***4.25***

Source: Elaborated by the authors.

Table 3 shows these economic costs calculated in terms of monetary changes in the sectoral production, in BRL 2011 values, and the total impact-damage ratio which represents the multiplier effect associated with each specific economic system. For the whole country, the loss of BRL 1.00 in the agricultural production caused by climate anomalies implied additional losses of BRL 3.25 in the economy as a whole. Considering the macro-regions with negative direct and indirect impacts, the North and South presented indirect economic costs relatively higher than the Center-West and Northeast. For the Southeast, the total impact was also negative despite the fact that this macro-region presented positive direct effects due to more favorable climate conditions to the agriculture production in 2005; this can be explained by the indirect and induced negative impacts on Sao Paulo and Rio de Janeiro. This result is heavily influenced by the structure of backward and forward linkages in the Brazilian interregional productive structure, in which these states play a central role, leading to strong interdependence between the core and the more peripheral regions in the North, Northeast and Center-West. The reduction in the demand originated in the more affected states causes a decrease in the demand for goods produced in the more economically developed states in the center-south of the country.

5. Conclusion

The frequency of extreme climate events have increased recently as observed by the Intergovernmental Panel on Climate Change (IPCC). This raises the importance to evaluate the potential damage caused by extreme climate events. This paper focuses on climate variability as environmental causes of losses to the agricultural sector as well to the entire economic system. Considering the climate variability observed in Brazil for 2005, this paper used an interregional CGE approach integrated to a physical production model estimated for agriculture to evaluate the systemic economic impact of climate anomalies in Brazil.

The results show that the economic costs of climate anomalies can be significantly underestimated if only partial equilibrium effects (direct impact/damage) are accounted for. Thus, a general equilibrium approach can provide a better understanding on the systemic impact of climate anomalies, contributing to formulate more consistent public policies in order to mitigate the potential impact of extreme climate events. Moreover, our results suggest that intersectoral and interregional linkages as well as price effects are important channels for spreading the economic effects of climate changes on the whole country.

References

Azzoni, C. R. Book Review: Regional Inequality and Structural Changes – Lessons from the Brazilian Experience. *Papers in Regional Science*, v. 83, n. 2, 2001.

Boyd, R.; Ibarrarán, M. E. Extreme Climate Events and Adaptation: An Exploratory Analysis of Drought in Mexico. *Environment and Development Economics*, v. 14, n. 3, 2008.

Christensen, J. H.; Hewitson, B.; Busuioc, A.; Chen, A.; Gao, X.; Held, I.; Jones, R.; Kolli, R. K.; Kwon, W-T.; Laprise, R.; Magaña Rueda, V.; Mearns, L.; Menéndez, C. G.; Räisänen, J.; Rinke, A.; Sarr, A.; Whetton P. Regional Climate Projections. In: *Climate Change 2007*: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L (eds)]. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA, 2007.

Dêschenes, O.; Greenstone, M. The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather. *American Economic Review*, v. 97, n. 1, 2007.

Ding, Y.; Hayes, M. J.; Widhalm, M. Measuring Economic Impacts of Drought: a Review and Discussion. *Papers in Natural Resources*, Paper 196, 2010.

Dixon, P. B.; Parmenter, B. R.; Sutton, J.; Vincent, D. P. *ORANI: A Multisectoral Model of the Australian Economy*. Amsterdam: North-Holland, 1982.

Dixon, P. B.; Rimmer, M. T.; Tsigas, M. Regionalizing Results from a Detailed CGE Model: Macro, Industry and State Effects in the US of Removing Major Tariffs and Quotas. *Papers in Regional Science*, v. 86, 2007.

Evenson, R. E.; Alves, D. C. Technology, Climate Change, Productivity and Land Use in Brazilian Agriculture. *Planejamento e Políticas Públicas*, v. 18, 1998.

Furtuoso, M. C. O.; Guilhoto, J. J. M. Estimativa e Mensuração do Produto Interno Bruto do Agronegócio da Economia Brasileira, 1994 a 2000. *Revista de Economia e Sociologia Rural*, Brasília, v. 41, n. 4, p. 803-827, 2003.

Gurgel, A. C.; Reilly, J. M.; Paltsev, S. Potential Land Use Implications of a Global Biofuels Industry. *Journal of Agricultural & Food Industrial Organization*, v. 5, 2007.

Haddad, E. A. *Regional Inequality and Structural Changes*: Lessons from the Brazilian Experience. Aldershot: Ashgate, 1999.

Haddad, E. A. *Retornos crescentes, custos de transporte e crescimento regional*. Tese (Livre Docência) – Faculdade de Economia e Administração, Universidade de São Paulo, São Paulo, 2004.

Haddad, E. A.; Bonet, J.; Hewings, G. J. D.; Perobelli, F. S. Spatial Aspects of Trade Liberalization in Colombia: A General Equilibrium Approach. *Papers in Regional Science*, v. 88, 2009.

Haddad, E. A.; Hewings, G. J. D.; Peter, M. Input-Output Systems in Regional and Interregional CGE Modeling. In: G. J. D. Hewings, M. Sonis and D. Boyce. (Eds.). *Trade, Networks and Hierarchies*, Berlin: Springer-Verlag, 2002.

Haddad, E. A.; Hewings, G. J. D. Market Imperfections in a Spatial Economy: Some Experimental Results. *The Quarterly Review of Economics and Finance*, v. 45, p. 476-496, 2005.

Harrison, W. J.; Pearson, K. R. Computing Solutions for Large General Equilibrium Models Using GEMPACK. *Computational Economics*, v. 9, p. 83-127, 1996.

Horridge, M.; Madden, J.; Wittwer, G. The Impact of the 2002-2003 Drought in Australia. *Journal of Policy Modeling*, v. 27, 2005.

Huffman, W.; Evenson, R. E. Supply and Demand Functions for Multiproduct U.S. Cash Grain Farms: Biases Caused by Research and Other Policies. *American Journal of Agricultural Economics*, v. 71, n. 3, p. 761-773, 1989.

Hewings, G. J. D. *Economic Forecasting for Business Strategic Decision-Making in Minas Gerais*. Unpublished Technical Note, Belo Horizonte: AERI, 1999.

Jehle, G. A.; Reny, P. J. Advanced Microeconomic Theory. Addison Wesley, 2nd Edition, 2000.

Joyce, R. J.; Janowiak, J. E.; Arkin, P. A.; Xie, P. CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution. *J. Hydromet*, 5, 487-503, 2004.

Lau, L. J. Application of Profit Functions. In: M. Fuss and D. Mcfadden (eds.). *Production Economics*: Dual Application to Theory and Applications, North Holland, Amsterdam, 1978.

Magalhaes, A. R. Adapting to Climatic Variations in Developing Regions: A Planning Framework. In: J. B. Smith, N. Bhatti, G. V. Menzhulin, R. Benioff, M. Campos, B. Jallow, F. Rijsberman, M. I. Budyko and R. K. Dixon (Eds.), Adapting to Climate Change: An International Perspective, Springer, pp. 44-54, 1996.

Marengo, J.; Jones, R.; Alves, L. M.; Valverde, M. C. Future Change of Temperature and Precipitation Extremes in South America as Derived from the PRECIS Regional Climate Modeling System. *International Journal of Climatology*, v. 29, n. 15, 2009.

Mas-Colell, A.; Whinston, M.; Green, J. *Microeconomic Theory*, Oxford: Oxford University Press, 2006.

Matthews, R. B.; Gilbert, N. G.; Roach, A.; Polhill, J. G.; Gotts, N. M. Agent-based Land-use Models : A Review of Applications. *Landscape Ecology*, v. 22, n. 10, 2007.

Mendelsohn, R. W.; Nordhaus, W.; Shaw, D. The Impact of Global Warming on Agriculture: a Ricardian Analysis. *American Economic Review*, v. 84, n. 4, 1994.

Mendelsohn, R. W.; Nordhaus, W.; Shaw, D. The Impact of Climate Variation on US Agriculture. In: R. Mendelsohn and J. E. Neumann (Eds.), *The Impact of Climate Change on the United States Economy*, Cambridge: Cambridge University Press, 2004.

Moore, M. R.; Negri, D. H. A Multicorp Production Model of Irrigated Agriculture Applied to Water Allocation Policy of the Bureau of Reclamation. *Journal of Agricultural and Resource Economics*, v. 17, n. 1, 1992.

Palatnik, R. R.; Roson, R. Climate Change and Agriculture in Computable General Equilibrium Models: Alternative Modeling Strategies and Data Needs. *Climatic Change*, 112 (3-4). pp. 1085-1100, 2012.

Polenske, K. R. Book Review: Regional Inequality and Structural Changes – Lessons from the Brazilian Experience. *Journal of Regional Science*, v. 42, n. 2, 2002.

Ronnenberger, K.; Berrittella, M.; Bosello, F.; Tol, R. S. KLUM@GTAP: Introducing Biophysical Aspects of Land-use Decisions into a Computable General Equilibrium Model a Coupling Experiment. *Environmental Modeling and Assessment*, v. 14, n. 2, 2009.

Sands, R. D.; Edmonds J. A. Climate Change Impacts for the Conterminous USA: An Integrated Assessment – Part 7 – Economic Analysis of Field Crops and Land Use with Climate Change. *Climate Change*, v. 69, 2005.

Sena, J. A.; De Deus, L. A. B.; Freitas, M. A. V.; Costa, L. Extreme Events of Droughts and Floods in Amazonia: 2005 and 2009. *Water Resources Management*, 2012.

Siriwardana, M. Book Review: Regional Inequality and Structural Changes – Lessons from the Brazilian Experience. *Economic Systems Research*, v. 13, n. 1, 2001.

Appendix A. Profit Function Approach

In order to measure the short- and long-terms impacts of climate change on agricultural production, an econometric model was specified and estimated in accordance with the microeconomics production theory. By specifying a profit function, it was possible to obtain the optimal input-output allocation for each type of crop or farm product.

Based on the partial equilibrium approach postulated by microeconomic theory, it is assumed that producers allocate their *k* inputs for 2 types of production: temporary crops; and permanent crops. The total output plus the total input represent the *m* products considered in the analysis. The producers decide how to allocate their inputs by solving a profit maximization problem in a competitive market. Thus, prices are considered as taken/exogenous. Besides the historical input and output prices, $p = (p_1,...,p_m)'$, each producer faces a vector of *h* exogenous climate variables, $z = (z_1,...,z_h)'$, which affects the production and the farmers' profits. Other variables, such as soil type; farmer's schooling (Huffman and Evenson, 1989)[12] and other *r* fixed factors, represented by $X = (X_1, ..., X_r)'$, also significantly affect the production decision (q).

The farmer's optimization problem can be described as follow:

$$\underset{q_1,q_2,...,q_m}{Max}\left(\sum_{i=1}^{m}\Pi_i(p,z,X,q)\right) \quad i=1,...,m \tag{A.1}$$

The first-order condition is:

$$\frac{\partial \Pi_i}{\partial q_i} = 0, \quad i = 1,...,m \tag{A.2}$$

Solving equation (A.2) leads to the optimal allocation for the supply outputs and demand (q_i), which depend on prices, climate, environmental variables, investments and other factors.

$$q_i^*(p_i, z, X), \quad i = 1,...,m \tag{A.3}$$

The chosen functional form for estimating the supply equations is the log-linear function. The *m* equations, obtained from deriving the profit equations in respect to the *s* outputs and *k* inputs, are described below.

$$\ln(q_i^*) = \beta_0^i + \sum_{f=1}^{m}\beta_{1f}^i p_f + \beta_{2.1}^i z_{mean} + \beta_{2.2*}^i z_{\text{var}} + \beta_3^i X + \varepsilon_i, \quad i = 1,...,m \tag{A.4}$$

The climate variables of the model (vector *z*) are represented by temperature and precipitation measures. For both variables, we considered:

- z_{mean}: The 15-year average of historical data, to compute the 2006 current climate pattern in each municipality[13]. The mean was calculated for the seasons, giving the long-term seasonal mean.

- z_{var}: The 2006 anomalies in temperature and precipitation by municipality and season. Anomaly is defined as the difference between the observed value in 2006 and the long-term average mentioned above.

where $z_{mean,j} = (z_{mean,j}^{Temp}, z_{mean,j}^{Rain})$; $z_{\text{var},j} = (z_{annom,j}^{Temp}, z_{annom,j}^{Rain})$ for each *j* season, and βs are the vectors of parameters to be estimated.

[12] An increase in the level of farmer education, all else equal, increases the use of more advanced techniques. Thus, better education can spur the spread of technical change.

[13] Fifteen years were used due to lack of historical information. The municipality is the local political division in Brazil and is similar to a county, except there is a single mayor and municipal council.

Table B.1 summarizes the results of the supply equations estimated for the permanent and temporary crops. These results indicate that the summer and spring seasons are the most sensitive seasons when it comes to the drought risks. During those seasons, the coefficients estimated suggest that production might be more affected to negative deviations from the normal rain conditions.

Table B.1 -Production model for the permanent and temporary crops

Variables	**(1) Permanent Crops Model**	**(2) Temporary Crops Model**
price_maize	-0.640***	-1.302***
price_soybean	-0.124	0.336
price_ot_temp	-0.00174***	-0.00410***
price_coffe	0.000184	-0.00156
price_ot_perm	-0.00321**	0.000550
price_milk	1.088***	0.0982
price_cattle	0.333	-0.0323
price_wood	0.0128**	0.00322
price_ot_for	0.00375	-0.00375**
price_land	0.0174	0.00172
price_labor	0.0101	0.0246***
price_fuel	-0.0527	-0.312**
price_fert	0.0932***	0.0370*
rdi_stock_2006	0.000181***	0.000318***
degr_tot_areas	0.920	-2.233
agri_tot_areas	0.143	2.071***
tam_medio	-0.00489***	-0.000129
AMAZON	2.165***	3.277***
CAATINGA	1.390***	2.104**
CERRADO	0.970***	3.030***
MATA_ATL	1.969***	2.705***
PANTANAL	0.468	1.929*
alfab_temp	-0.377	-1.536***
ensfun_inc_temp	0.338	-1.070***
ensfun_comp_temp	1.178**	0.360
ensmed_comp_temp	0.298	0.113
enssup_temp	2.974***	4.089***
temp_fall_mean	0.449***	-0.157
temp_winter_mean	0.0824	-0.400***
temp_spring_mean	0.0135	0.523***
temp_summer_mean	-0.585***	0.0246
temp_fall_var	0.221*	0.000933
temp_winter_var	0.00636	0.476***
temp_spring_var	-0.812***	-0.312**
temp_summer_var	-0.0216	0.520***
rain_summer_mean	-0.000872	-0.00480***
rain_fall_mean	0.00259	-0.00157
rain_winter_mean	-0.00363*	0.00196
rain_spring_mean	-0.00793***	-0.00471***
rain_summer_diff	**0.00474*** **	**0.00259** **
rain_fall_diff	**-0.00527*** **	**-0.00745*** **
rain_winter_diff	**-0.000522**	**-0.0146*** **
rain_spring_diff	**0.00576*** **	**0.00545*** **
Constant	5.067***	5.753***
Observations	**4,770**	**5,361**
R-squared	**17%**	**32%**

Source: Elaborated by the authors.

Note: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.