

UNIVERSIDADE FEDERAL DE MINAS GERAIS

**CLIMATE CHANGE SCENARIO: EFFECTS ON AGRICULTURAL
PRODUCTIVITY AND ECONOMIC IMPACTS IN THE BRAZILIAN
STATE OF MINAS GERAIS**

DEBORAH LOPES FERREIRA

Belo Horizonte - MG

July 2024

DEBORAH LOPES FERREIRA

**CLIMATE CHANGE SCENARIO: EFFECTS ON AGRICULTURAL PRODUCTIVITY
AND ECONOMIC IMPACTS IN THE BRAZILIAN STATE OF MINAS GERAIS**

Thesis defended **MSc in Economics** at the **Universidade Federal De Minas Gerais**, as a partial requirement for obtaining the title of **Master in Economics**.

Advisor:

PhD in Economics: Aline Magalhães.

Co-Advisor:

PhD in Economics: Tarik Tanure.

Co-Advisor:

PhD in Economics: Edson Paulo Domingues

Belo Horizonte - MG

July 2024

Ficha Catalográfica

F383c Ferreira, Deborah Lopes.
2024 Climate change scenario [manuscrito]: effects on agricultural
 productivity and economic impacts in the Brazilian State of Minas Gerais
 / Deborah Lopes Ferreira. – 2024.
 1v.: il.

 Orientadora: Aline Souza Magalhães.
 Coorientador: Tarik Marques do Prado.
 Dissertação (mestrado) - Universidade Federal de Minas Gerais, Centro
 de Desenvolvimento e Planejamento Regional.
 Inclui bibliografia.

 1. Mudanças climáticas - Teses. 2. Agricultura – Aspectos
 econômicos - Teses. 3. Economia – Teses. I. Magalhães, Aline Souza.
 II. Tanure, T. III. Universidade Federal de Minas Gerais. Centro de
 Desenvolvimento e Planejamento Regional. IV. Título.

CDD: 338.1

Elaborada pela Biblioteca da FACE/UFMG – 174/2024
Fabiana Pereira dos Santos - CRB6 2530



UNIVERSIDADE FEDERAL DE MINAS GERAIS
FACULDADE DE CIÊNCIAS ECONÔMICAS
CENTRO DE DESENVOLVIMENTO E PLANEJAMENTO REGIONAL
PROGRAMA DE PÓS-GRADUAÇÃO EM ECONOMIA

FOLHA DE APROVAÇÃO

CLIMATE CHANGE SCENARIO: EFFECTS ON AGRICULTURAL PRODUCTIVITY AND ECONOMIC REGIONAL IMPACTS IN THE BRAZILIAN STATE OF MINAS GERAIS

DEBORAH LOPES FERREIRA

Dissertação de Mestrado defendida e aprovada, no dia 12 de julho de 2024, pela Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em Economia da Universidade Federal de Minas Gerais constituída pelos seguintes professores:

Belo Horizonte, 12 de julho de 2024.

Profa. Aline Souza Magalhães (Orientadora) (CEDEPLAR/FACE/UFMG)

Prof. Edson Paulo Domingues (Coorientador) (CEDEPLAR/FACE/UFMG)

Prof. Tarik Marques do Prado Tanure (Coorientador) (PPGE-IERI/UFU)

Profa. Clara Zanon Brenck (CEDEPLAR/FACE/UFMG)

Prof. Rafael Faria de Abreu Campos – (UFV)



Documento assinado eletronicamente por **Tarik Marques do Prado Tanure, Usuário Externo**, em 16/07/2024, às 12:04, conforme horário oficial de Brasília, com fundamento no art. 5º do [Decreto nº 10.543, de 13 de novembro de 2020](#).



Documento assinado eletronicamente por **Aline Souza Magalhaes, Professora do Magistério Superior**, em 16/07/2024, às 16:02, conforme horário oficial de Brasília, com fundamento no art. 5º do [Decreto nº 10.543, de 13 de novembro de 2020](#).



Documento assinado eletronicamente por **Clara Zanon Brenck, Professora do Magistério Superior**, em 16/07/2024, às 16:50, conforme horário oficial de Brasília, com fundamento no art. 5º do [Decreto nº 10.543, de 13 de novembro de 2020](#).



Documento assinado eletronicamente por **Edson Paulo Domingues, Professor do Magistério Superior**, em 16/07/2024, às 17:12, conforme horário oficial de Brasília, com fundamento no art. 5º do [Decreto nº 10.543, de 13 de novembro de 2020](#).



Documento assinado eletronicamente por **Rafael Faria de Abreu Campos, Usuário Externo**, em 17/07/2024, às 11:45, conforme horário oficial de Brasília, com fundamento no art. 5º do [Decreto nº 10.543, de 13 de novembro de 2020](#).



A autenticidade deste documento pode ser conferida no site https://sei.ufmg.br/sei/controlador_externo.php?acao=documento_conferir&id_orgao_acesso_externo=0, informando o código verificador **3381782** e o código CRC **DC98341B**.

AGRADECIMENTOS

Agradeço a todos que contribuíram para a realização desta dissertação. À minha orientadora, Profa. Dra. Aline Magalhães, e aos meus coorientadores, Tarik Tanure e Edson Paulo Domingues, que foram fundamentais nesse processo. Obrigada pelos direcionamentos, confiança e paciência.

Agradeço também à minha família, que foi a minha maior apoiadora nesta jornada desafiadora.

Por fim, agradeço à CAPES pelo financiamento desta pesquisa.

ABSTRACT

This study investigates the future economic impacts of climate change in Minas Gerais, Brazil, using an econometric model and a Regional Computable General Equilibrium (CGE) model. Initially, the econometric model estimates variations in agricultural productivity due to climate factors for seven crops, based on regional climate scenarios from the Eta-CPTEC climate model. The scenarios considered are RCP 8.5 and RCP 4.5 from the 6th IPCC report. These estimates serve as productivity shocks in the CGE model, specifically IMAGEM-MG, developed from the Brazilian IMAGEM-B model and following the Australian TERM Model framework for disaggregated regional and sectoral analyses. The results reveal a distinct spatial pattern, with climatic effects on Minas Gerais's economy varying significantly across regions. Generally, GDP and other key indicators would undergo reductions under both climate scenarios. Regions heavily dependent on agriculture, like Patos de Minas, would face the most significant deviations, while areas like Pouso Alegre, with less agricultural dependence and favorable conditions for crops like coffee, would experience the least reductions. Notably, the poorest regions are not necessarily the most affected by GDP reduction. Regions in the north and northeast of Minas, where agricultural activity is predominantly composed of small-scale farmers, may be severely impacted, exacerbating regional disparities. While most crops show productivity reductions, some regions would experience gains in specific crops, like sugarcane in Uberaba and Uberlândia and oranges in Barbacena. However, these gains do not offset the overall decline in economic activity compared to a scenario without climate change, likely due to spill-over effects on sectors dependent on agriculture.

Keywords: climate change; agriculture; Minas Gerais; computable general equilibrium model.

RESUMO

Este estudo investiga os impactos econômicos futuros das mudanças climáticas em Minas Gerais, Brasil, utilizando um modelo econométrico e um modelo de Equilíbrio Geral Computável (EGC) Regional. Inicialmente, o modelo econométrico estima variações na produtividade agrícola devido a fatores climáticos para sete culturas, com base em cenários climáticos regionais do modelo Eta-CPTEC. Os cenários considerados são RCP 8.5 e RCP 4.5 do 6º relatório do IPCC. Essas estimativas servem como choques de produtividade no modelo EGC, especificamente IMAGEM-MG, desenvolvido a partir do modelo brasileiro IMAGEM-B e seguindo o framework do modelo australiano TERM para análises regionais e setoriais desagregadas. Os resultados revelam um padrão espacial distinto, com efeitos climáticos na economia de Minas Gerais variando significativamente entre regiões. Em geral, o PIB e outros indicadores-chave apresentariam reduções sob ambos os cenários climáticos. Regiões fortemente dependentes da agricultura, como Patos de Minas, enfrentariam as maiores variações, enquanto áreas como Pouso Alegre, com menos dependência agrícola e condições favoráveis para culturas como café, experimentariam as menores reduções. Notavelmente, as regiões mais pobres não necessariamente seriam as mais afetadas pela redução do PIB. Regiões no norte e nordeste de Minas, onde a atividade agrícola é predominantemente composta por pequenos agricultores, podem ser impactadas, exacerbando disparidades regionais. Enquanto a maioria das culturas experimentariam reduções na produtividade, algumas regiões ganhariam em cultivos específicos, como cana-de-açúcar em Uberaba e Uberlândia e laranjas em Barbacena. No entanto, esses ganhos não compensariam o declínio geral na atividade econômica em comparação com um cenário sem mudanças climáticas, provavelmente devido a efeitos de transbordamento em setores dependentes da agricultura.

Keywords: mudanças climáticas; agricultura; Minas Gerais; equilíbrio geral computável.

LIST OF FIGURES

Figure 3.1 – Regions of Minas Gerais	40
Figure 3.2 – Projected Temperature (RCP 4.5)	46
Figure 3.3 – Projected Precipitation (RCP 4.5)	47
Figure 3.4 – Projected Temperature (RCP 8.5)	48
Figure 3.5 – Projected Precipitation (RCP 8.5)	48
Figure 3.6 – IMAGEM-MG Flows Database	52
Figure 3.7 – IMAGEM-MG Production Structure	55
Figure 3.8 – IMAGEM-MG Sourcing Mechanisms	56
Figure 3.9 – IMAGEM-MG Investments and Capital Stock	58
Figure 3.10–Regionalization Procedure	61
Figure 3.11–Composition of the GDP in the regions of Minas Gerais	64
Figure 4.1 – Maize Output: Cumulative % Change (RCP 4.5)	81
Figure 4.2 – Maize Output: Cumulative % Change (RCP 8.5)	82
Figure 4.3 – Sugarcane Output: Cumulative % Change (RCP 4.5)	83
Figure 4.4 – Sugarcane Output: Cumulative % Change (RCP 8.5)	83
Figure 4.5 – Soybeans Output: Cumulative % Change (RCP 4.5)	84
Figure 4.6 – Soybeans Output: Cumulative % Change (RCP 8.5)	85
Figure 4.7 – Coffee Beans Output: Cumulative % Change (RCP 4.5)	86
Figure 4.8 – Coffee Beans Output: Cumulative % Change (RCP 8.5)	86
Figure 4.9 – Temporary Crops Output: Cumulative % Change (RCP 4.5)	87
Figure 4.10–Temporary Crops Output: Cumulative % Change (RCP 8.5)	87
Figure 4.11–Permanent Crops Output: Cumulative % Change (RCP 4.5)	88
Figure 4.12–Permanent Crops Output: Cumulative % Change (RCP 8.5)	89
Figure 4.13–Orange Output: Cumulative % Change (RCP 4.5)	89
Figure 4.14–Orange Output: Cumulative % Change (RCP 8.5)	90
Figure 4.15–Real GDP (RCP 4.5) - Cumulative Deviation % from Baseline Scenario	91
Figure 4.16–Real GDP (RCP 8.5) - Cumulative Deviation % from Baseline Scenario	91
Figure A.1 – Residual Distribution	106

LIST OF TABLES

Table 3.1 – Variables and Data Source	41
Table 3.2 – Crop Yield in Minas Gerais	43
Table 3.3 – Descriptive Statistics of Rural Property Aspects	44
Table 3.4 – Sectoral Disaggregation of the IMAGEM-MG Model	50
Table 3.5 – Main sets of the IMAGEM-MG model	51
Table 3.6 – IMAGEM-MG Data Source	60
Table 3.7 – Share of Economic Activities in the GDP of Minas Gerais	62
Table 3.8 – Share of Regions in the Gross Value Added by Sector (%)	63
Table 3.9 – Share of Agricultural Sector Production by Regions in Minas Gerais (%)	67
Table 4.1 – Regression Results	69
Table 4.2 – Regression Results: Agricultural Productivity by Crop Type	71
Table 4.3 – Effects of Climate Change on Agricultural Productivity (RCP 4.5 scenario)	72
Table 4.4 – Effects of Climate Change on Agricultural Productivity (RCP 8.5 scenario)	73
Table 4.5 – Climate Change Effects on Crop Productivity (RCP 4.5)	75
Table 4.6 – Climate Change Effects on Crop Productivity (RCP 8.5)	76
Table 4.7 – GDP Growth in the Baseline Scenario (%)	78
Table 4.8 – Macroeconomic Results: 2050 (Cumulative Deviation %)	80
Table 4.9 – Share of Crops to Total Agricultural Output by Region (%)	80
Table 4.10–Gini Index of GDP for Minas Gerais	96
Table A.1 – Climate Change Effects on Crop Productivity: RCP 4.5	106
Table A.2 – Climate Change Effects on Crop Productivity: RCP 8.5	107
Table A.3 – Macroeconomic Results: 2080 (Cumulative Change %	107
Table A.4 – Industry Outputs: RCP 4.5 (2050) (Cumulative Change %)	108
Table A.5 – Industry Outputs: RCP 4.5 (2080) (Cumulative Change %)	109
Table A.6 – Industry Outputs: RCP 8.5 (2050) (Cumulative Change %)	110
Table A.7 – Industry Outputs: RCP 8.5 (2080) (Cumulative Change %)	111

LIST OF ABBREVIATIONS AND ACRONYMS

ANA	National Water Agency
CIF	Cost, Insurance, and Freight
CES	Constant Elasticity of Substitution
CO ₂	Carbon Dioxide
CGE	Computable General Equilibrium
CGIAR	Consultative Group on International Agricultural Research
EFS	Economic Forecasting Equilibrium System
Eta-CPTEC	Eta model developed by the Center for Weather Forecast and Climate Studies
FEAM	Fundação Estadual do Meio Ambiente
FJP	João Pinheiro Foundation Research
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IBGE	Brazilian Institute of Geography and Statistics
IMAGEM-MG	Multirregional Applied General Equilibrium Model for Minas Gerais
INPE	National Institute for Space Research
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
PAM	Municipal Agricultural Production
POF	Family Budget Survey
RAIS	Annual Report of Social Information
RCP	Representative Concentration Pathway
PIA	Industrial Production
REGIA	Inter-Regional General Equilibrium Model for the Brazilian Amazon

SECEX	Secretariat of Foreign Trade
TERM	The Enormous Regional Model
UNFCC	United Nations Framework Convention on Climate Change
WBG	World Bank Group
WHO	World Health Organization

SUMMARY

1	INTRODUCTION	16
2	LITERATURE REVIEW	19
2.0.1	Climate Change and Agriculture	19
2.0.2	The Economic and Social Impacts of Climate Change	21
3	EMPIRICAL STUDIES OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTIVITY IN BRAZIL AND MINAS GERAIS	29
3.0.1	Partial Equilibrium Analysis: Econometric Models	29
3.0.2	General Equilibrium Analysis: Computable General Equilibrium Models	32
3.1	METHODOLOGY	36
3.1.1	Econometric Model	36
3.1.2	The Agricultural Sector em Minas Gerais	42
3.1.3	The IMAGE-MG Model: Key Aspects	49
3.1.4	IMAGE-MG: Theoretical Framework	54
3.1.5	Regionalization Procedure	59
3.1.6	IMAGE-MG: Data	62
4	SIMULATIONS AND RESULTS	68
4.0.1	Results: Econometric Model	68
4.0.2	IMAGE-MG Simulations and Results	77
5	CONCLUDING REMARKS	97
	BIBLIOGRAPHY	100
	APPENDIX A –	106

1 INTRODUCTION

Human activities, primarily through the release of greenhouse gases, have unmistakably led to global warming. According to the Intergovernmental Panel on Climate Change (2023), global emissions of these gases have persistently risen, with varying historical and current contributions stemming from unsustainable energy practices, land use and its changes, lifestyles, consumption and production patterns across different regions, countries, and among individuals. Human-induced climate change is already influencing numerous weather and climate extremes worldwide, resulting in widespread adverse effects and associated losses and damages to both nature and people. Communities that have historically contributed the least to current climate change are disproportionately suffering its impacts.

In this context, Brazil, the fifth largest country in the world and home to six unique biomes, emerges as a vital ecosystem due to its biodiversity and its role in regulating the global climate. The impacts of global climate change and local practices on the Amazon and Cerrado biomes are particularly concerning, as these biomes provide essential ecosystem services to Brazil, the South American region, and the world. Brazil is uniquely positioned to benefit from climate action, with several competitive advantages, notably a relatively low-carbon energy supply and significant additional renewable energy potential. Its greenhouse gas emissions (GHG) are primarily driven by land use change and agriculture, rather than energy, creating specific opportunities and different costs compared to other countries (Cicowiez et al., 2022).

By the end of the century, average temperatures in Brazil are projected to rise by 1.7°C to 5.3°C from the 1986–2005 average, depending on global GHG emissions. Brazil is vulnerable to climate change impacts, which present a significant threat to the country's economic growth as well as its continued social development. Extreme temperatures, rising seas, as well as the complex challenges of different regions across the country experiencing significant water scarcity and heavy rainfall place significant pressure on vulnerable groups, urban infrastructure, the economy and the country's unique ecosystems (Brazil, 2020).

The country's economy is driven primarily by agriculture, industry and services. Brazil is the largest net-exporter of agricultural commodities, with the agri-business sector contributing approximately 20% of the country's GDP and over 30% of all domestic employment. Brazil is one of the world's leading exporters of soybeans, beef and coffee. Imports are dominated by agricultural and industrial machinery, electrical equipment, oil, and automotive parts from other countries, particularly China and the United States (Souza-Rodrigues, 2019).

Like all countries, the impacts of climate change on agricultural production in Brazil will vary in magnitude and location. Due to the country's continental dimensions, agricultural productivity is expected to decrease in lower latitudes and increase in higher latitudes. Consequently,

the North and Northeast regions will be the most affected, the Center-West and Southeast regions will experience moderate impacts, and the South region will largely benefit from global warming, leading to a shift in the geography of agricultural production in the country. This new agricultural configuration could exacerbate regional disparities, as the less developed regions will be the most affected (Tanure, 2020).

Projections for 2030 indicate a decline in crop productivity for rice, coffee, beans, maize, soybeans, and wheat, with cassava and sugarcane expected to increase compared to the baseline scenario (Martins; Assad, 2007). Assad et. al (2008) also highlight that rising temperatures could reduce areas suitable for soybean cultivation by 41% by 2070, while sugarcane areas might expand by up to 118%. In a more optimistic scenario, soybeans, maize, and cotton could face area reductions, with coffee cultivation shifting southward. Sugarcane and cassava, particularly sugarcane, would show potential for expansion.

However, most studies addressing the impact of climate change on agriculture in Brazil focus on the country's major regions, with few examining how these effects vary within individual states. Minas Gerais plays a significant role in the international projection of Brazilian agriculture, boasting the most diversified agricultural portfolio in the country. In 2022, according to the João Pinheiro Research Foundation, the agribusiness GDP reached R\$205 billion, representing 22% of the state's total GDP and approximately 9% of the total production in Brazil. It is the largest coffee producer in Brazil and also has a prominent share in the country's main crops: maize, soybeans, and sugarcane.

Furthermore, Minas Gerais is known for its climatic and geographical diversity. The state's geographical features include mountains, plateaus, and valleys, leading to a range of climate types such as tropical, tropical highland, and semi-arid. This diversity supports various ecosystems, from the Cerrado and Atlantic Forest to the Caatinga, each influencing local agriculture. This heterogeneity results in a variety of landscapes, climates, and ecosystems that significantly impact the lives of its inhabitants and the economic activities across its 13 regions. Moreover, there is great heterogeneity in the spatial distribution of agricultural establishments, with both small and large producers contributing to the state's agricultural output.

This diversity enables the identification of precise vulnerabilities and resilience strategies tailored to various crops and agricultural techniques. Thus, the aim of this study is to assess how climate change affects agricultural productivity and to analyze the consequent sectoral and regional economic impacts, focusing specifically on the Brazilian state of Minas Gerais. Such comprehension is crucial for formulating adaptive measures to safeguard food security, enhance resource efficiency, and sustain the livelihoods of both small and large-scale producers in the region. Therefore, the heterogeneity of Minas Gerais provides invaluable insights into the broader ramifications of climate change on agriculture.

In pursuit of this goal, we will generate estimates of production variation for the most

prominent crops in Minas Gerais. These estimates will rely on IPCC global warming scenarios provided by INPE, covering two distinct periods: 2021-2050 and 2051-2080. Subsequently, these estimates will serve as inputs in a Computable General Equilibrium (CGE) model, meticulously calibrated for the state's 13 regions, featuring comprehensive agricultural sector disaggregation. This model will enable the simulation of both direct and indirect repercussions stemming from alterations in agricultural productivity across Minas Gerais's economic sectors and regions.

This thesis is organized into three chapters, in addition to this introduction and the concluding remarks. Chapter 1 will explore the relationship between climate change and agriculture, along with an empirical review of key studies in this field. In Chapter 2, estimates will be developed for the agricultural productivity of the main crops in Minas Gerais, aligning with the climate change scenarios proposed by the IPCC and INPE. These estimates will be incorporated into the productivity shock used by the CGE model. Chapter 3 will elucidate the theoretical framework and operational structure of the model tailored for the 13 regions of Minas Gerais, known as IMAGEM-MG. Chapter 4 will delineate the simulations and analysis of the outcomes concerning the impacts of climate change on agricultural productivity and its sectoral and regional economic ramifications. The final section comprises the concluding remarks.

2 LITERATURE REVIEW

2.0.1 Climate Change and Agriculture

According to the latest assessment from the IPCC (2023), as global warming advances, the magnitude of changes in extreme weather events grows more pronounced. It is anticipated that persistent global warming will exacerbate the global water cycle, amplifying its fluctuations, affecting global monsoon patterns, and contributing to more frequent occurrences of extremely wet and dry weather events and seasons. At 1.5°C of global warming, there are projections indicating that heavy precipitation and flooding events will intensify and occur more frequently across most regions in Africa, Asia, North America, and Europe. When the temperature rises to 2°C or higher, these trends are expected to extend to additional regions or become even more substantial. Moreover, more frequent and severe agricultural and ecological droughts are projected to affect Europe, Africa, as well as North, Central, and South America.

In most developing countries, the agricultural sector serves as the primary source of livelihood and employment for the majority of the population, making a significant contribution to the National Gross Domestic Product (GDP). Consequently, any declines in agricultural output resulting from impending climate change could pose a substantial threat to food security and further deteriorate the living conditions of rural communities in poverty.

Due to its inherent dependence on natural resources, agricultural production is vulnerable to uncertainties stemming from climate fluctuations, including extreme events like floods and droughts. For instance, alterations in temperature and precipitation can prove advantageous for certain crops in specific regions, particularly those previously constrained by cold or inadequate rainfall. Conversely, these changes can be detrimental to other crops in different areas characterized by hot and arid conditions. These newly emerging hot climates will have detrimental effects on land utilization by altering crop productivity, irrigation requirements, and land management practices. They will also lead to a decline in vegetation productivity in numerous regions globally, counteracting any potential advantages to land utilization and land cover resulting from higher atmospheric CO₂ levels (Cramer et al, 2019).

According to the World Bank (2008), there are five main factors through which climate change affects agriculture systems: changes in precipitation, temperature, carbon dioxide (CO₂) fertilization, climate variability, and surface water runoff. Shifts in temperature and rainfall patterns play a major role in the distribution of agro-ecological zones. Temperature and soil moisture are pivotal factors that govern the duration of the growing season and exert control over a crop's growth and water needs. Generally, elevated temperatures tend to reduce the frost period, thereby encouraging cultivation in regions with cooler climates that were previously marginal for crop production. Nevertheless, in arid and semi-arid regions, higher temperatures can lead to

a shorter crop cycle and decreased crop yields (IPCC, 2007).

Rosenzweig and Hillel (1998) outline that, in middle and higher latitudes, elevated temperatures will extend the growing seasons and push the boundaries of crop-producing regions further towards the poles. This is expected to bring advantages to countries in these regions. However, the benefits of an extended growing season may be moderated by less fertile soils in higher latitudes. It remains uncertain to what extent soil quality will pose a significant constraint, given the numerous other influential factors, such as changes in precipitation, fertilizer use, irrigation availability, and so on. In contrast, in lower latitudes, it is anticipated that higher temperatures will have detrimental effects on growing conditions, particularly in areas where temperatures are already close to or at the optimal level for crop growth to begin with.

Precipitation is a key element in determining the availability of freshwater and the moisture content in the soil, both of which are essential factors for crop development. Increased precipitation or effective irrigation can narrow the yield difference between rainfed and irrigated farming. However, it's important to note that excessive precipitation, leading to flooding, can also have detrimental effects on crop yield, causing them to be submerged in water (Calzadilla et al., 2013). On the other hand, a decrease in precipitation is expected to heighten the utilization of aquifers for agricultural purposes and add more pressure on other surface and groundwater sources, which are used for non-agricultural purposes. Simultaneously, an elevation in potential evapotranspiration is likely to exacerbate drought conditions, particularly in semi-arid tropical and subtropical regions (Rosenthal, 2003).

These alterations in precipitation patterns can wield substantial influence on both irrigation practices and water supply systems. As the demand for water undergoes changes, climate change is also expected to have an adverse effect on water supply. In some regions, a significant portion of the surface runoff utilized for irrigation originates from the melting of snow and ice in mountainous regions. These sources may be particularly vulnerable to warmer and drier conditions (IPCC, 2014). Hayoe et al (2004) examined the overarching patterns concerning agriculture in California, the leading state in agricultural production in the United States, which heavily relies on snowpack from the Sierra Nevada for irrigation purposes. This assessment suggested that the increasing climate-induced demand would probably coincide with a notable decline in snowpack and a shift towards earlier runoff. Such changes would bear serious consequences for agricultural production.

Regarding carbon dioxide concentrations, Aydinalp and Cresser (2008) highlight that they are expected to result in, to a certain extent, favorable outcomes for agriculture. They enhance the rate of photosynthesis and improve water use efficiency, primarily benefiting plants such as potatoes, wheat, rice and soybeans. Although the positive impact of carbon dioxide enrichment is less pronounced, it still holds true for plants like maize, millet, and sorghum, as well as sugarcane. Nevertheless, even though elevated atmospheric CO₂ concentrations can enhance crop water

use efficiency and photosynthesis rates by reducing evapotranspiration (Darwin, 2001), the overall outcome may be mitigated by the expense incurred due to pest and weed infestations (Rosenzweig; Hillel, 1998). Studies show that such pests, including aphids (Newman, 2003) exhibit a favorable response to higher CO₂ levels. Besides that, most agricultural diseases have greater potential to reach severe levels under warmer and more humid conditions (Parry, 1990).

2.0.2 The Economic and Social Impacts of Climate Change

As stated, climate change can have a profound impact on agriculture, influencing crops, livestock, the value of farmland, household well-being, and food security. Research indicates that its consequences for agriculture can be intricate and multifaceted. The challenge of food production and food security in the context of global warming becomes particularly prominent. This is because the world's population continues to grow significantly, leading to an increased demand for food production. Meanwhile, climate change is expected to have potential repercussions on both the quantity and quality of food produced. According to the Consultative Group on International Agricultural Research (2016) estimates, food demand is expected to increase significantly, potentially by 60% to 70% over the next four decades. Meeting this demand will be a formidable task, especially in an environment where droughts and fluctuations in precipitation levels are anticipated to negatively impact production (Tilman et al., 2011; Alexandratos, N; Bruinsma, J. 2012; CGIAR, 2016).

It was estimated that global crop yields would decline by approximately 1% per decade due to climate change, consistent with previous assessment reports (Porter et al., 2014; Porter et al., 2014). Further research supports the notion that climate change will have a disproportionate impact on crop yields across different regions, with most areas expected to experience more negative than positive effects.

According to the National Research Council estimates (2012), a moderate temperature increase combined with elevated CO₂ levels and shifts in precipitation patterns will likely lead to increased crop yields in regions with moderate to high latitudes. However, in arid regions and areas with lower latitudes, production is expected to decrease. Additionally, the study suggests that for every 1°C rise in global temperature, there is an anticipation, for instance, of a 5% to 15% reduction in maize production in the United States and Africa, as well as wheat production in India. Furthermore, some positive effects have been observed for rice and wheat in Eastern Asia, as well as for wheat in Northern Europe. Conversely, the impacts have predominantly been negative in regions such as Sub-Saharan Africa, South America, the Caribbean, Southern Asia, Western Europe, and Southern Europe.

The climate factors influencing long-term yield trends also differ across regions. For instance, in Western Africa, a 1°C warming above pre-industrial climate levels has resulted in increased heat and rainfall extremes, leading to yield reductions of 10%-20% for millet and 5%-

15% for sorghum (Sultan et al., 2019). In Australia, decreased rainfall and rising temperatures have lowered the potential yield of wheat by 27%, contributing to the limited yield growth observed between 1990 and 2015 (Hochman et al., 2017). Southern Europe has experienced negative impacts on the yields of nearly all major crops due to climate warming, resulting in recent yield stagnation (Moore and Lobell, 2015; Agnolucci and De Lipsis, 2020; Brás et al., 2021).

Variability in crop production is significantly influenced by climate fluctuations, as evidenced by various studies (Ray et al., 2015; Iizumi and Ramankutty, 2016; Frieler et al., 2017). Weather-related patterns affecting yield variability tend to be more pronounced in highly productive regions compared to less productive areas. In these less productive regions, additional factors such as pests, diseases, and poor soil fertility also contribute to yield limitations. Nevertheless, it is important to note that yield variability in less productive regions has significant and adverse impacts on local food availability and people's livelihoods (Frieler et al., 2017).

South America stands out as an exceptionally diverse region, characterized by rich cultural and biological diversity. In recent decades, numerous countries within the region have enjoyed prolonged economic growth, resulting in significant strides towards poverty reduction. However, the region remains marked by considerable social inequality, including the highest levels of land ownership disparity. A substantial portion of the population still lives below the poverty line, with disparities evident between rural and urban areas, as well as across dimensions like gender and race. These vulnerable groups are particularly susceptible to the impacts of climate change and frequent natural extreme events that affect the region (IPCC, 2022).

Land use changes, particularly driven by deforestation, hold significant importance, primarily attributed to agricultural production for export purposes, which constitutes one of the primary income sources for the area. Moreover, the land faces additional pressures stemming from illegal activities, pollution, and human-induced fires. These transformations exacerbate the effects of climate change and position the region as a pivotal player in the future of global economics and food production (Salazar et al., 2015). Moreover, South America boasts the world's largest tropical forest and encompasses other crucial biomes with high biodiversity. There is potential for continued agricultural expansion and development, but this may come at the cost of substantially reducing the natural biome areas.

Being the largest nation in South America, Brazil confronts substantial exposure to the risks associated with climate change, thereby presenting a notable threat to its economic advancement and continual social development. From extreme temperatures to rising sea levels, coupled with the intricate challenges of varying regional water scarcity and intense rainfall, the nation confronts mounting pressure on vulnerable communities, urban infrastructure, and its diverse ecosystems. Additionally, the dominance of Brazil's agricultural sector in its economy brings forth intertwined demands and economic priorities, intricately linked with environmental preservation and the

imperatives of climate change adaptation and mitigation (Souza-Rodrigues, [2019](#)).

Agriculture remains a cornerstone of the Brazilian economy, witnessing a more than twofold increase in total output since the 1990s. By 2016, the sector employed over 18 million individuals and contributed over one-fifth to the nation's GDP. Despite being the world's largest net exporter of agricultural commodities, a significant portion of Brazil's farmers—85%—operate as part of small family farms. The Brazilian livestock sector contributes to 14% of global beef production. With vast agricultural and grazing lands occupying 33.4% of its total land area, Brazil plays a significant role in global agricultural output and stands as a major exporter of various agricultural products including soybeans, maize, coffee, beef, sugarcane, and rice. Additionally, due to its extensive coastline, the fishing industry holds importance for both the economy and food security (IBGE, [2017](#)).

The significant loss of forests and degradation of the environment in the nation are primarily attributed to agricultural activities. As of 2022, the Agriculture, Forest, and Land-Use sectors accounted for 75% of the country's greenhouse gas emissions, while the energy sector contributed 18%. Mato Grosso, Pará, and Minas Gerais are the states with the highest emissions. In Mato Grosso and Pará, the forest and land-use change sector is the leading emitter, while agriculture tops the emissions in Minas Gerais (SEEG, [2022](#)).

Consequently, Brazil faces significant susceptibility to climate variability and change, both in the short and long term, notably affecting vital sectors such as water, agriculture, forestry, energy, and health. Although technological advancements have largely fueled the increase in agricultural productivity, shifts in rainfall patterns and escalating temperatures pose significant challenges to both the sustained prosperity of the agricultural sector and Brazil's food security (Brazil, [2020](#)).

Recent modeling suggests that average temperatures and the frequency of dry days are projected to rise, particularly in central Brazil. This implies an anticipated decrease in pasture and grain productivity by 2050, along with alterations in the regions best suited for livestock and agricultural activities. There are projections for an increase in rainfall variability, particularly during the rainy season across various Brazilian biomes (Marengo et al., [2011](#)). This entails decreased averages in the North and Northeast regions and increased averages in the South region (Marengo et al., [2017](#)). Said changes may have a negative impact on the production systems since only 5% of agricultural areas in Brazil are irrigated (Assad et al., [2018](#)).

For instance, it is estimated that a temperature increase of 4°C in the Amazon could lead to a reduction in rainfall occurrences by 40% to 45% (Brazil, [2020](#)). Consequently, regions reliant on rainfed and subsistence farming will be particularly affected, as these systems depend heavily on rainfall to meet the water needs of crops. Moreover, the frequency and duration of prolonged droughts are on the rise, affecting vulnerable areas like the Semi-Arid region, where water availability is already a challenge. These droughts not only impact food production but

also affect water usage by the local population. Moreover, regions with significant agricultural potential, such as the Cerrado biome, which is responsible for a substantial portion of grain production in Brazil, are also being affected by such changing climate patterns (Rossato et al., 2017).

Giannini et al. (2017) emphasize that climate-related risks, including land availability constraints, drive agricultural intensification, exacerbating deforestation, soil erosion, and degradation. This intensification, coupled with deforestation, could lead to the potential loss of 11 million hectares of agricultural land by the 2030s, further impacting agricultural production. Additionally, climate change is projected to reduce pollinator presence in low GDP municipalities, with implications for crop productivity and crop-pollinator relationships. These multiple impacts could worsen agricultural income in economically vulnerable municipalities, exacerbating their socioeconomic difficulties.

According to Gateau (2018), soybean and cotton crops are anticipated to experience moderate effects from climate changes, while maize and wheat yields are expected to decline significantly. The agricultural sector faces the threat of an increase in extreme events, with heightened frequency and intensity of flooding and drought due to robust El Niño occurrences. Key specialty crops like coffee and cocoa are likely to be influenced by elevated temperatures and shifting rainfall patterns, given their sensitivity to drought and reliance on specific precipitation patterns. Sugarcane, heavily dependent on ample water supply, may see improved production zones in southern Brazil due to increased rainfall (Marin et. al, 2013).

Projections for 2030 indicate a decline in crop productivity for rice, coffee, beans, maize, soybeans, and wheat, with cassava expected to increase compared to the baseline scenario (Martins & Assad, 2007). Assad et al. (2008) similarly emphasize adverse effects on crops, except for sugarcane and partially cassava. Rising temperatures may reduce areas suitable for soybean cultivation by 41% by 2070, while sugarcane could expand by up to 118%. Additionally, in a more optimistic scenario, soybeans, maize, and cotton face potential area reductions, with coffee shifting southward. Sugarcane and cassava show potential for expansion, especially sugarcane.

The livestock industry in Brazil is also highly susceptible to the adverse effects of rising temperatures. Heat stress is expected to negatively impact various aspects of Brazil's crops and livestock, notably affecting milk production and reproduction in dairy cows (Brazil, 2020). By 2050, the domestic supply of milk is anticipated to decrease by 18.8%, while that of eggs is expected to decrease by 3.4%. The domestic supply of beef is projected to decrease by 7.0%, resulting in a total of 11.9 million tons in 2030, compared to 12.8 million tons without climate change. This remains above the domestic demand of 10.3 million tons (Assad et.al, 2013). Moreover, Brazil's thriving fishing sector is at heightened risk due to increasing ocean temperatures and shifts in ocean currents. Overfishing and rising sea temperatures could lead to

a potential decrease of up to 50% in maximum fish catch potential (Brazil, [2020](#)).

Given the influence of climate change, it is crucial to mitigate food loss and waste across all stages from cultivation to consumption. This imperative arises not solely from the disposal of vital items crucial for human survival and well-being but also due to the squandering of energy, soil, and the generation of greenhouse gas emissions associated with unused food, leading to economic losses throughout the production chain. In Brazil, significant food losses occur during storage and transportation, particularly for perishable items like vegetables and fruits (Costa et al., [2015](#)). Overall, there is an anticipated increase in losses throughout the agricultural production chain, which will have repercussions on the heightened production costs and subsequent rise in food prices, which will likely lead to shifts in consumption patterns among families—especially those with lower purchasing power—and impact producers' earnings (Blum, [2001](#)).

Another potential consequence of climate change is water availability. According to the World Bank Climate's Profile Report ([2021](#)), Brazil has faced increasing water crises, particularly in the central and northern regions since 2012. Factors contributing to heightened water scarcity locally include excessive groundwater pumping, particularly for irrigation purposes, extensive deforestation, unregulated urban expansion, and the discharge of wastewater into rivers and water bodies. Furthermore, the extensive deforestation and forest fires in the Amazon are disrupting the country's precipitation patterns. These crises have led to critical conditions in northeastern rivers due to limited rainfall and high evapotranspiration. In the southeast, growing water demand driven by population growth, urbanization, and pollution exacerbates the situation. Metropolitan areas are especially affected by supply uncertainty, while in the south, water stress arises from heavy demand for rice irrigation (Mercure et. al., [2019](#)).

The utilization of irrigation is projected to encompass 10 million hectares by 2030. This trend has already exhibited significant expansion in recent decades, surging from 1.5 million hectares in 1980 to 7 million hectares in 2015 (ANA, [2021](#)). The expansion of grain production in the Cerrado region is primarily responsible for the augmented irrigated area in the country. Martins et al. ([2019](#)) demonstrated that the decline in maize productivity in Northeast Brazil was less pronounced with the implementation of irrigation compared to the productivity losses observed in rainfed cultivation. In this way, enhanced water efficiency achieved through better water management practices and reduced pollution can protect the sector and alleviate water stress experienced by industry operators and communities (Barbosa et. al, [2016](#)).

Increasing temperatures and shifting precipitation trends in Brazil are projected to affect both the nation's energy demand and its capacity for supply, notably in the hydroelectric sector. The Brazilian Water Balance Index underscores a decline in hydroelectric production potential in the northern and central watershed areas of the country. The anticipated decline in rainfall and alterations in seasonal precipitation patterns are expected to diminish the potential for hydropower generation and increase the risk of revenue loss from overbuilt hydro facilities,

which might experience under-supply. Moreover, elevated evaporation rates from current water storage infrastructures will raise production expenses, leading to heightened costs for consumers. Rising temperatures and shifting rainfall patterns could also modify the seasonal energy demand, potentially elevating demand during peak periods and projecting an overall increase in net electricity usage (Brazil, 2020).

Another possible repercussion for the energy sector concerns bioenergy. Brazil ranks as the second-largest producer of ethanol and biodiesel globally. Its significant production serves as vehicular fuel and contributes to generating bioelectricity for the National Interconnected System (SIN), utilizing surplus sugarcane bagasse from distilleries (USDA, 2018; Goldemberg; Coelho; Guardabassi, 2008; Horta Nogueira et al., 2013).

As stated in a report released by the United Nations Framework Convention on Climate Change (2020), approximately 84% of active biodiesel plants in Brazil are located in the Cerrado and Atlantic Forest regions, potentially encountering substantial challenges regarding input supplies for biofuel production. Concerning ethanol, the majority of current production facilities, approximately 76%, are located in areas that could be affected by diminishing suitable land for sugarcane cultivation. To address this, a suggested strategy involves reallocating 35% of low-risk sugarcane cultivation areas to high-risk (primarily) and medium-risk zones, necessitating irrigation techniques. However, expanding crops to new areas may affect plant productivity, increase irrigation demands, and heighten vulnerability or create impacts on other sectors.

This scenario poses a challenge to increasing sustainable bioenergy in the Brazilian energy grid to approximately 18% by 2030 (Brazil, 2020). Additionally, considering that bioelectricity generation peaks during the harvest, coinciding with drought and reduced hydroelectric generation, both hydroelectricity and bioelectricity outputs would decline simultaneously during this period.

Several studies have also underscored the potential repercussions of climate change on public health. In Brazil, the population faces a significant burden of climate-sensitive diseases, exacerbated by rising temperatures. These warmer conditions often provide a more conducive environment for the spread of vector-borne, water-borne, and other infectious diseases. The increased frequency of heavy rainfall and extreme weather events is expected to worsen sanitation challenges and the prevalence of water-borne diseases like cholera, particularly in flood-prone areas. Mosquito-borne diseases such as malaria and dengue are prevalent in regions like the Amazon, northern, and central-western Brazil. As climate patterns shift, there is a concern that malaria zones may expand across the country (Filho et al., 2018).

According to the World Health Organization (2015), under high emissions scenarios, the elderly are projected to face a substantial increase in heat-related deaths, soaring to approximately 72 deaths per 100,000 by the 2080s, compared to the current rate of 1 death per 100,000 annually. Moreover, the expansion of malaria's range is anticipated to place approximately 168 million

additional people at risk of contracting the disease by the 2070s. Furthermore, labor productivity is forecasted to decrease significantly in Brazil. With a projected 4-degree Celsius rise in global mean temperature, approximately 12% of annual daily work hours for labor-intensive tasks—such as agricultural, construction, and certain industrial work—are expected to be lost (Kjellstrom et al., 2016).

Projections indicating reduced agricultural productivity will adversely affect Brazil's food security, nutrition, and malnutrition rates. Additionally, challenges persist regarding water accessibility and quality in many communities, with expectations of further decline due to flooding, agricultural runoff, and contamination from mining activities. Furthermore, extreme events are anticipated to exacerbate risks, potentially limiting access to healthcare in highly vulnerable areas and communities (Massuda et. al., 2018).

Considering the information presented, it is crucial to acknowledge that diverse vulnerabilities related to climate change are present in each region. These vulnerabilities are shaped by factors like production models and scales, the availability of technical assistance services, access to information (especially for family production units and traditional communities), and the extent of environmental degradation and ecosystem fragmentation.

Minas Gerais plays a significant role in the international projection of Brazilian agriculture, boasting the most diversified agricultural portfolio in the country. In 2022, according to the João Pinheiro Research Foundation, the agribusiness GDP reached R\$205 billion, representing 22% of the state's total GDP and approximately 9% of the total production in Brazil. The state leads the nation in the production of milk and coffee. Between 2010 and 2021, it held the second position nationally in the average production of sugarcane and cattle. During the same period, Minas Gerais produced 52.3% of the country's coffee, equivalent to 16.8% of the global average.

In national production, the state also holds substantial shares in the cultivation of maize, soybeans, potatoes, garlic, pineapples, tomatoes, and bananas, as well as in the populations of poultry, horses, and pigs, and in the production of chicken eggs. It should be taken into account that the configuration of agricultural production in Minas Gerais encompasses a wide variety of rural properties, ranging from small establishments of family farming to large estates of commercial agriculture.

Furthermore, the state exhibits a highly heterogeneous productive, geographical, and climatic structure. Aggregate results for the state, found in other studies, can obscure regional variabilities. Therefore, it is crucial to examine the territory in a more disaggregated manner. This approach considers the importance of agriculture in each region, the interdependencies with other sectors, and the varying levels of economic development. By accounting for the presence of both subsistence and large-scale commercial farming, regional disparities, infrastructure, and environmental conditions, the study provides a nuanced understanding of climate change impacts. This comprehensive analysis informs more effective policy-making, promoting tailored

adaptation strategies and sustainable development across the state.

3 EMPIRICAL STUDIES OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTIVITY IN BRAZIL AND MINAS GERAIS

Climate change stems from the release of greenhouse gasses associated with diverse economic activities, including energy production, industrial processes, transportation, and land management. Similar to many environmental issues, human-induced climate change fundamentally represents an externality. Those accountable for emitting greenhouse gasses contribute to climate change, thereby imposing costs on both the current world and future generations. However, they typically do not directly bear the full consequences of these costs through market mechanisms or other means.

Climate change possesses unique characteristics that collectively present specific challenges to the conventional economic theory of externalities: it represents the most extensive and significant market failure witnessed to date. Consequently, economic analysis must adopt a global perspective, consider long-term horizons, prioritize the economics of risk and uncertainty, and explore the potential for significant, non-marginal changes. In attempting to estimate the economic impacts of this climate phenomenon, economists have employed and developed various alternative methodologies (Stern, 2007).

Studies on the economic and social impacts of climate change are concentrated in two methodological approaches: i) partial equilibrium and ii) general equilibrium. The first approach refers to econometric studies, based on statistical techniques that use a series of past information to make inferences about aspects related to economic phenomena. The second approach utilizes general equilibrium models to examine direct and indirect effects of a phenomenon on an economy.

The combined use of these methodologies is also common in the literature concerning impacts on agriculture, where the estimated results in terms of changes in land use or alterations in areas suitable for cultivation are used as inputs in general equilibrium models.

3.0.1 Partial Equilibrium Analysis: Econometric Models

Within the applications of econometric models, there are two main streams in the literature studying the economic impact of climate change on agriculture: the production function approach and the Ricardian approach. The production function approach, specifies the production function of certain types of crops as a function of changes in climate variables such as temperature, precipitation, and levels of carbon dioxide to calculate the variation in production levels due to climate factors. Its advantage lies in estimating the effects of climate change without bias, as it isolates and holds constant other non-climate factors in the analysis (Feres et al., 2009; Assunção; Chein, 2016). However, according to Mendelson et al. (1994), this method tends to

overestimate the impacts of damage due to the lack of consideration of adaptive behavior by farmers in response to the new economic situation and/or climate conditions.

The Ricardian approach, on the other hand, considers variations in agricultural land prices in specific geographical areas due to climate change, rather than analyzing the productivity of specific crops. In this model, the market exhibits perfect competition, and farmers are profit maximizers. Thus, climate change prompts the allocation of land for more profitable cultivation, and the model can incorporate the adaptive effects of both the economy and climate. Therefore, according to the author, this approach has the advantage of measuring both the direct impacts of global warming through the profitability of different crops and the indirect impacts caused by crop substitution.

On the other hand, one of the drawbacks of this approach is that i) it does not consider transaction costs, which are an important factor in the producer's adaptive decision-making, ii) are static, iii) do not account for the possibility of irrigation, a fundamental variable for mitigating the effects of changes in precipitation levels, iv) do not account for the effect of price changes due to alterations in the volume produced, and v) do not present the direction or mechanisms by which producers adapt to climate change (Kurukulasuriya et al., 2013; Sanghi; Mendelsohn, 2008; Assunção; Chein, 2016).

Studies analyzing the economic effects of climate change on Brazilian agriculture predominantly utilizes either the production function approach or an intermediate approach that integrates land productivity value into crop production functions. Sanghi et al. (1997) conducted a pioneering study on the effects of climate change on Brazilian agriculture, employing the production function methodology. The study analyzed variations in temperature and precipitation and their implications for land use and agricultural productivity. The findings suggested that states in the Midwest region would face the most adverse impacts of climate change, whereas the Southern region might experience potential benefits.

Evenson and Alves (2001) extended a Ricardian land productivity model to analyze the impacts of climate change on land productivity and land use allocation among agriculture, pasture, and forest. Additionally, they combine climate change-induced shocks with technological shocks stemming from intensified research and development (R&D) activities. The results showed an increase in the share of cultivated lands largely at the expense of natural pastures. The share of cultivated lands increases from 29% to 31.4%. Enhanced agricultural technology mitigates the climate effects on pastures. This technology benefits pastures and counters the climate-induced conversion of natural forest areas into natural pasture areas. Additionally, neither the effects of climate change nor technological change favor forestry.

Similar to the aforementioned study, Feres et. al (2009) aims to assess the impact of climate change on land use patterns in Brazilian agricultural establishments, utilizing an econometric model to estimate changes in land allocation between agricultural area, livestock farming, and

forest cover. The implemented climate shocks correspond to the emission scenarios A2 (more pessimistic, estimating a temperature increase between 2°C and 5.4°C by 2100) and B2 (more optimistic, predicting a temperature rise between 1.4°C and 3.8°C by 2100), as defined by the IPCC report (AR4), over three periods. The results indicate a significant substitution of forested areas for pastureland. In a more optimistic scenario, forested areas are predicted to decrease by 15.4% and pastureland to increase by 6.5%.

Masseti et. al (2013) employ a Ricardian model to assess how climate change impacts Brazilian agriculture during two time frames: 2046-2065 and 2080-2099. Using historical data from agricultural censuses conducted in 1975, 1985, 1995, and 2006, along with two Ricardian model specifications—a pooled model and a two-stage model—they estimate the marginal effects of temperature increase and rainfall variation (increases in the South, Southeast, and Midwest; decreases in the North and Northeast). The marginal effects prove particularly detrimental to the North and Northeast regions, while the effects in other regions remain ambiguous.

De Paula's (2020) study stands out for examining the effects of climate change on the Brazilian agricultural sector in distributive terms. To achieve this, the econometric strategy employed involves estimating a Ricardian model for different quantiles of agricultural productivity, allowing analysis of how the magnitude of impacts varies according to the efficiency levels of agricultural establishments. Considering a 1°C temperature increase, the results indicated heterogeneous impacts: a substantial reduction of 34% in the land value of properties in the Northern region and a more moderate decrease of 5% in the Southern region. In distributive terms, the reduction in agricultural yields in the lowest quantile of productivity considered is 80%, resulting in a doubling of agricultural productivity inequality between percentiles 1 and 99. Furthermore, the increase in productivity inequality induced by rising temperatures is more pronounced with higher average temperatures in the region.

Bragança (2015) assessed the impact of climate change on Brazilian agriculture by analyzing the sensitivity of agricultural productivity to temperature and precipitation variations. Using data from the 2006 Agricultural Census and climate models from INPE, simulations were conducted under the IPCC's RCP 8.5 scenario. The study's model allowed for an evaluation of climate change effects on both crop productivity and land allocation. Results showed a projected 30% decline in Brazilian agricultural productivity between 2041 and 2070, followed by a further 47% decrease from 2071 to 2099. While changes in land use may partly mitigate impacts in the earlier period, they are expected to worsen negative effects thereafter. Geographically, adverse effects are widespread across federative units, except for certain states in the South and Southeast regions. In Minas Gerais, agricultural productivity is forecasted to remain relatively stable in the first period but decline by 28% between 2071 and 2099.

Assunção and Chein (2016) conducted a cross-sectional estimation of the sensitivity of Brazilian agricultural productivity to climate change. Agricultural productivity data were derived

from the average values reported by the Municipal Agricultural Production (PAM) surveys from 1997 to 2006. Additionally, soil variables were added as controls. The results suggested a 18% reduction in Brazilian agricultural productivity for the period from 2030 to 2049. Regionally, the results for federative units varied from -37% in Rondônia to +1% in Santa Catarina. In Minas Gerais, the impacts would be close to the national average: a reduction of 16.6%.

In summary, econometric model applications in the Brazilian context provide insights into the climatic effects on land use conversion and variations in average agricultural productivity. To estimate the impacts of climate change on agricultural productivity, the present study adopts the methodological strategy mentioned above, based on Bragança (2015) and Assunção and Chein (2016), which links land use to production functions.

A key contribution of this thesis is its estimation of the regional impacts on Minas Gerais, which has a highly heterogeneous productive, geographical, and climatic structure. Aggregate results for the state, found in other studies, can obscure regional variabilities. Therefore, it is crucial to examine the territory in a more disaggregated manner, both in sectoral terms to better understand the direct and indirect effects of variations in agricultural productivity due to climate change, and in regional terms, considering that different areas have different levels of economic development, as well as the presence of subsistence farming and large-scale agriculture. This approach provides a more nuanced understanding, informing policymakers and stakeholders engaged in climate resilience and sustainable development initiatives, thereby enhancing the region's capacity to effectively manage and mitigate the impacts of climate change.

3.0.2 General Equilibrium Analysis: Computable General Equilibrium Models

Since the late 1980s, Computable General Equilibrium (CGE) modeling has been widely acknowledged as a suitable method for numerical analyses of climate change policies. This recognition is due to CGE's robust theoretical foundations and extensive empirical data, making it particularly valuable for analyzing climate change scenarios beyond past experiences. CGE's integration of resource constraints and price-responsive behavior is pivotal to its effectiveness. Its comprehensive analysis of various industries, occupations, regions, and household types enables the identification of winners and losers resulting from policy changes and economic shocks. By projecting the impacts of climate change scenarios across all sectors of the economy, CGE models facilitate informed public debate and provide an evidence base for compensating groups likely to be adversely affected by policies aimed at mitigating catastrophic climate change (Madden et al., 2020).

Domingues et al. (2008) was among the early studies to project the impact of climate change on an inter-regional CGE model in Brazil, the TERM-BR Model (The Enormous Regional Model), specifically focusing on the Northeast region. In this study, estimates of the implications for land availability for agriculture were used as proxies for the effects of climate change, based

on scenarios provided by the IPCC. The calculated shocks pertained to variations in land supply for the aggregated agricultural sector. Simulation results indicated negative impacts on GDP (-13.1%) and employment (-5.95%) in the Northeast. These economic losses were particularly pronounced in the poorest states. Thus, the need for mitigation policies and emission control is emphasized to prevent potential increases in migratory flows to less affected regions, thereby putting pressure on urban infrastructure services in metropolitan areas.

Haddad et al. (2010) evaluated the impacts of climate change under scenarios A2 and B2 from the IPCC on the Brazilian economy in macroeconomic, regional, and sectoral terms, using an integrated CGE model, the EFES (Economic Forecasting Equilibrium System). The results show that the industry would face a decline in its GDP under both scenarios in the period 2008-2055, while the service sector presents consistent gains in its share of the national GDP. As for the regional results, in both scenarios, there is a noticeable spatial deconcentration of economic activity, particularly shifting away from São Paulo and Rio de Janeiro. Additionally, there is an interiorization of growth, with a relatively greater decline in metropolitan positions in scenario A2. The Federal District experiences a relative loss of position due to the reduction in the "size" of the Government in scenario A2. Furthermore, there is a strengthening of the role of medium-sized centers.

Faria (2012) developed a CGE model with detailed land use specifications for Brazil and assessed the economic impacts of climate change in the country. The shocks implemented were calculated using the sensitivity of land use change types estimated econometrically, taking into account the IPCC's A2 and B2 climate scenarios. Under the A2 scenario, the results indicated a cumulative reduction in the national real GDP of -0.02% in 2039, -0.05% in 2069, and -0.11% in 2099. For scenario B2, the projections suggest a contraction of -0.02% in 2039, -0.04% in 2069, and -0.07% in 2099. In terms of sectors, the greatest losses would occur in agricultural activities, particularly for wheat, grains, coffee, and soybeans. On the other hand, sugarcane and cotton would experience gains.

Ferreira-Filho and Moraes (2013), in an analysis of the impacts of climate change on agriculture, also find that in both climate scenarios (A2 and B2), the Northeast region of Brazil would be the most affected by climate change, with a reduction in GDP (-6.13%) and employment (-2.95%), while the Southeast region would experience gains (+0.36% and +0.55%, respectively). Regarding changes in land use, the study indicates that coffee would be one of the most affected crops in all Brazilian regions, except in the Southeast, which would see an expansion of this cultivation (+24%) under a more pessimistic climate scenario. Additionally, the authors project a reduction in land use for forests by 2070, especially in the North (-19.9%), Northeast (-45%), Southeast (-46.1%), and Midwest (-20.8%) regions.

Carvalho and Domingues (2016) utilize the REGIA model (Interregional General Equilibrium Model for the Brazilian Amazon) to simulate economic growth and resulting deforestation

in 30 regions of the Amazon from 2006 to 2030. This model incorporates land use dynamics, including conversion between natural forest, planted forest, agriculture, and pasture. The study identifies regions within the arc of deforestation (Mato Grosso, Pará, and Rondônia) as experiencing the greatest GDP growth, particularly in soybean and cattle production areas. Despite projected economic growth and increased production in these sectors, total deforestation over 19 years (2012 to 2030) is expected to be lower compared to the previous 15 years (19 million hectares vs. 24 million hectares). This suggests that economic growth may not substantially exacerbate deforestation due to the low productivity of agricultural activities in the region.

Souza (2018) measured the economic impacts of climate change on Brazilian regions through changes in agricultural productivity of crops such as soybeans, sugarcane, maize, beans, coffee, and oranges, establishing a regional vulnerability indicator to these impacts. The analyzed climate scenarios are the RCP 2.6 and RCP 8.6 from the IPCC, spanning from 2020 to 2100. The results indicate variations in agricultural losses ranging from 9.7% to 55.6% by 2100, with impacts on GDP estimated at -0.05% in the optimistic scenario and -0.26% in the pessimistic scenario. São Paulo, Paraná, and Minas Gerais would be the most affected states in terms of losses.

Stocco et al. (2018) analyzed the effects of partially closing the livestock yield gap in Brazil to mitigate deforestation and emissions. They focus on the top 10% most productive municipalities in livestock production, calculating average productivity and estimating achievable regional productivity. Using yield gap estimates, they simulate the economy-wide impacts of gap reduction with the TERM-BR model. A key finding is that reducing the yield gap would lead to decreased production of certain commodities like soybeans. However, it would also allow for a 23.5% increase in beef cattle production by 2030, accompanied by a 4.24 Mha reduction in pasture area. This represents a 1.5% annual increase in livestock production above the baseline trend. The pasture area would be reallocated to agriculture, milk livestock, and forest preservation, resulting in both economic and environmental benefits.

Tanure (2020) analyzes the future impacts of climate change on agricultural productivity of crops in Brazil and its potential economic effects using an econometric and a CGE model for the periods of 2021-2050 and 2051-2080 under RCP 4.5 and RCP 8.5 climate scenarios. The CGE model, called AGRO-BR, features a regional configuration composed of the 27 Federation Units and 42 agricultural sectors, disaggregated into small-scale and large-scale farmers. The results obtained indicate that the agricultural productivity of family farmers is more sensitive to climate change. Crops such as cassava, maize, and beans, typical of family farming, would, on average, be impacted by productivity loss. Conversely, sugarcane and soybean plantations would experience productivity gains in the main producing regions. In terms of economic impacts, the North and Northeast regions would be negatively affected, while the Midwest and Southeast would experience moderate impacts. On the other hand, the South region would mostly benefit

from these changes.

3.1 METHODOLOGY

The projections regarding changes in agricultural productivity due to climate change serve as the starting point for examining the impact of this phenomenon on Minas Gerais' economy. Agriculture emerges as a sector vulnerable to the impacts of climate change, given its dependence and sensitivity to climate variables. The diversity in Minas Gerais agricultural production, both in terms of regions, productive structure and crops, combined with the heterogeneous nature of the effects of climate change in space, adds complexity to the analysis and underscores the importance of the topic. In this context, the purpose of this study is to estimate changes in agricultural productivity for a specific set of crops in Minas Gerais aiming to determine which crops and regions within the state will be affected by variations in climate patterns.

3.1.1 Econometric Model

3.1.1.1 Theoretical Framework

This section, drawing from Bragança (2015) and Assunção and Chein (2016), introduces the theoretical framework that informs the land allocation process for agricultural producers. The model presented will direct the econometric analysis phase of this study.

Consider an agricultural economy with M municipalities, where each municipality $m \in M$, a representative farmer allocates land L_m among 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 that crop and a vector with geographic and climate characteristics GC_m :

$$P_{mk}(GC_m) = \gamma_{mk} f^k(L_{mk}, X_{mk} | GC_m) \quad (1)$$

Here, γ_{mk} is a vector representing individual productivity, and $f_L^k > 0$, $f_X^k > 0$, $f_{LL}^k \leq 0$, and $f_{XX}^k \leq 0$.

Considering w_m as the unit price of inputs, the problem of the representative farmer can be divided into two stages. In the first stage, the farmer selects the quantity of inputs to maximize the profit obtained in the production of crop k in municipality m for each value of L_{mk} . The value function for this problem is defined as:

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

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

$$\max_{\{L_{mk}\}} \Pi_m(GC_m) = \sum_k V_{mk}(L_{mk} | GC_m), \quad st. \quad \sum_k L_{mk} = L_m \quad (3)$$

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

$$V'_{mk}(L_{mk}|GC_m) \geq V'_{mk'}(L_{mk'}|GC_m), \quad \forall k, k' > 0 \in K \quad (4)$$

Equation (4) holds as equality whenever $L_{mk}^* > 0$ and holds as strict inequality whenever $L_{mk}^* = 0$. Thus, the equilibrium of the model is expressed by the following equality:

$$\sum_k L_{mk}^*(GC_m) = L_m \quad (5)$$

Through equations (4) and (5), the optimal land allocation is implicitly defined. The change in the climate vector GC_m to GC'_m (climate change scenario) would impact the agricultural productivity of different crops, leading to the optimal redistribution of initial land $L_{mk}^*(GC_m)$ to $L_{mk}^*(GC'_m)$. This is because farmers reallocate activities from lower relative profitability to those with higher relative profitability, aiming to maximize their profits.

To derive the equation capturing the effects of climate factors on agricultural productivity, we consider the vector of individual productivity $\gamma_m = (\gamma_{m1}, \gamma_{m2}, \dots, \gamma_{mk})$. By solving the system of equations (4) and (5) with the agricultural production function from equation (1), it is possible to obtain the productivity function for each crop at equilibrium. The resulting function is expressed solely with model parameters and takes the following form:

$$\gamma_{mk}^*(GC_m) = \frac{P_{mk}^*(GC_m)}{L_{mk}^*(GC_m)} = Y_k(w_m, \gamma_m, GC_m) \quad (6)$$

Therefore, equation (6) enables the estimation of the impacts of climate factors on the productivity of the k crop in the m municipality. From equation (6), we can define agricultural productivity as:

$$Y_m(GC_m) = \frac{P_m^*(GC_m)}{L_m} = Y(w_m, \gamma_m, GC_m) \quad (7)$$

Equations (6) and (7), which define agricultural productivity, form the basis of the empirical exercise conducted in the next section. These equations enable the estimation of how agricultural productivity responds to climate factors.

3.1.1.2 Econometric Specification

The econometric model employed to assess how agricultural productivity responds to climate change impacts for crop k in municipality m is determined from equation (6). Assume perfect mobility of productive factors across the sample municipalities. This assumption implies that the factor prices are the same in all municipalities ($w = w_m, \forall m$), allowing us to estimate the model without factor price data. The functional form for the relationship between climate factors and productivity is given by:

$$Y_m = Y(w, \gamma_m, GC_m) = \exp[\theta(GC_m) + \gamma_m + \varepsilon_m] \quad (8)$$

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

$$\ln Y_{m_k} = \gamma_m + \theta_k(GC_m) + \varepsilon_{m_k} \quad (9)$$

To enable the estimation of the above equation in the absence of panel data, the function is approximated to municipal characteristics γ_m using observable features X_m . Thus, we obtain the following equation for the relationship between agricultural productivity of crop k and climate factors:

$$\ln Y_{m_k} = \theta_k(GC_m) + \beta'_k X_m + \varepsilon_{m_k} \quad (10)$$

The system of equations above exhibits a covariance ($\text{cov}(\varepsilon_{m_k}, \varepsilon_{m'_k}) \neq 0$), as shocks affecting crop k are likely to be correlated with shocks affecting another crop k' . In this case, the Seemingly Unrelated Regression (SUR) method should be employed to recover sensitivity. However, since GC_m and X_m are the same for all crops, this method is equivalent to Ordinary Least Squares (OLS) estimation.

After estimating the agricultural productivity of crop k in municipality m using the equation defined in (10), the same equation is then estimated with the temperature and precipitation variables replaced by their projections GC'_m . The change in agricultural productivity due to climate change is expressed by the following expression:

$$\Delta E(\ln Y_{mk}) = [\theta_k(\hat{GC}_m) + \beta'_k X_m] - [\theta_k(GC_m) + \beta'_k X_m] \quad (11)$$

The future climate scenarios considered in the simulations are RCP 8.5 and RCP 4.5 for the periods 2021-2050 and 2051-2080. RCP 8.5 represents the most pessimistic outlook, foreseeing a global average temperature rise of approximately 4°C by the end of the 21st century. Conversely, RCP 4.5 stands as the more optimistic scenario, anticipating a global warming of around 2°C (IPCC, 2023).

To account for the seasonality of climate impacts on agricultural productivity, considering that each crop demonstrates varying productivity levels throughout the year, climate data were computed as semi-annual averages. This involved calculating averages for January to June, representing the spring and summer period, and July to December, representing the fall and winter period. The estimation also involves incorporating a quadratic polynomial of temperature and precipitation to account for the non-linearity of these variables. This is because initial increases in temperature and precipitation may enhance productivity, but the marginal increase (interpreted as an excess of temperature or precipitation) can adversely affect productivity (Mendelsohn et al., 1994; Feres et al., 2009).

Moreover, for estimating aggregate productivity, each observation was weighted by the square root of the total area dedicated to crops in each municipality. This choice is justified

because, according to Sanghi and Mendelsohn (2008), larger municipalities tend to have more agricultural establishments and fewer measurement errors, hence deserving more weight. While observations related to smaller municipalities exhibit higher variance, the inclusion of these weights mitigates the heteroskedasticity in the dataset. Going further, to fully address the heteroskedasticity, Huber-White estimators were employed.

Regarding the productivity estimates of individual crops, they are weighted by the share or percentage of the cultivation area of crop k in relation to the total cultivation area of municipality m . It can be expressed as:

$$S_{mk} = \frac{\text{Cultivated area by crop } k \text{ in } m}{\text{Cultivated area in } m}$$

It is important to highlight that the model does not take into account technological progress, which is a crucial adaptive factor in the face of climate change. In this context, the results should be interpreted as the impacts of climate change on agricultural productivity, taking into account existing technological standards. Alternatively, the results may suggest the need for technical improvements to ensure that future agricultural productivity remains at current levels (Assunção; Chein, 2016).

3.1.1.3 Database

The main data source used is the 2017 Census of Agriculture from IBGE. From this database, agricultural production and agricultural establishment area indicators were constructed for $k \in K$ crops and $m \in M$ municipalities in Brazil.

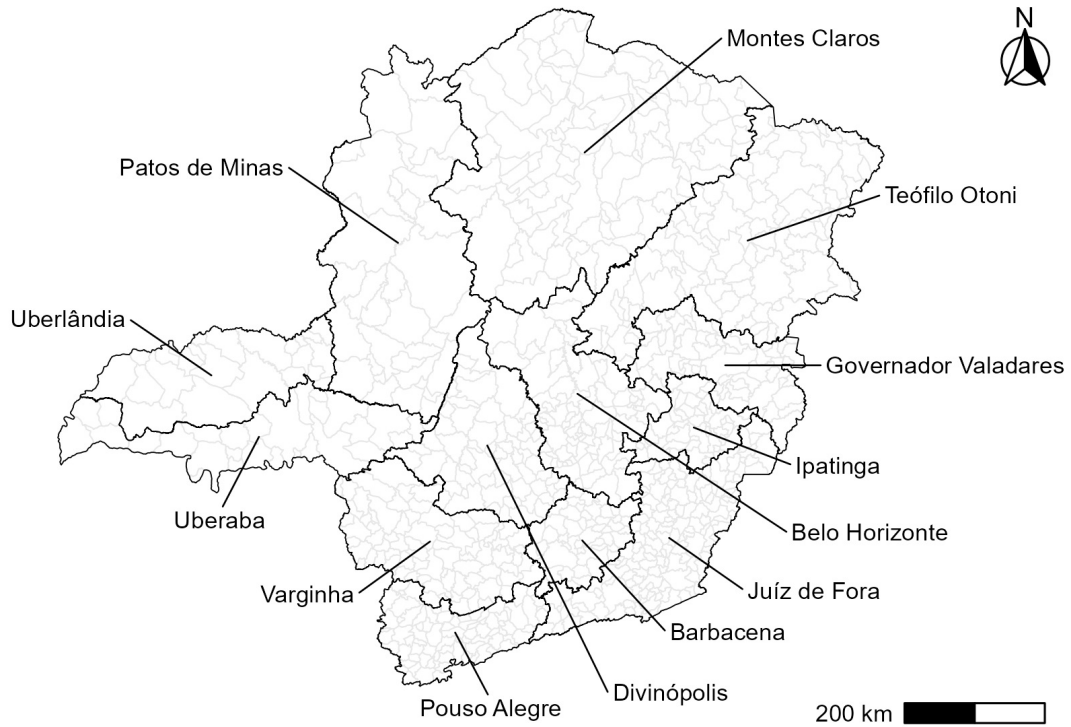
The chosen agricultural crops in this study comprise seven varieties: coffee, orange, soybeans, maize, sugarcane, as well as temporary and permanent crops. Temporary crops are those planted and harvested within the same agricultural year, encompassing pineapple, garlic, potato, onion, beans, cassava, melon, tomato, rice and wheat in this study. In contrast, permanent crops are planted once and do not necessitate replanting for multiple years. This category in our study includes grape, banana, apple, papaya, passion fruit, mango, peach, and coconut.

The choice of these crops is based on two reasons: they are major crops in the Brazilian state of Minas Gerais in terms of production value, and they align with the categorization of agricultural sectors in the CGE model, constructed according to the input-output matrix of Brazil. The primary goal of estimating agricultural productivity is to provide input to the regional CGE model to simulate the scenario of climate change through a decrease (or increase) in agricultural productivity in Minas Gerais.

The estimations for agricultural productivity were conducted with observations at the county-level and the results were aggregated according to the 13 Regions of Minas Gerais, namely: Barbacena, Belo Horizonte, Divinópolis, Governador Valadares, Ipatinga, Juiz de Fora,

Montes Claros, Patos de Minas, Pouso Alegre, Teófilo Otoni, Uberlândia, Uberaba, Varginha – see Figure 3.1:

Figure 3.1 – Regions of Minas Gerais



Source: Elaborated by the author.

The productivity of each crop k is defined as the production value divided by the area of land used for crop k , given as follows:

$$Y_{mk} = \frac{\text{Production Value of } k \text{ in } m}{\text{Area of crop } k \text{ in } m}$$

The total agricultural productivity is given by:

$$Y_m = \frac{\sum_k \text{Production Value of } k \text{ in } m}{\text{Cultivated area in } m}$$

In addition to information related to agricultural production, the variables used as controls in the empirical analysis also originate from the 2017 Census of Agriculture. Table 3.1 provides an overview of the variables used in the analysis and their respective sources.

Table 3.1 – Variables and Data Source

Variable	Description	Source
Agricultural Productivity	Output (R\$)/ Area	IBGE
Temperature	Monthly Average (°C)	INPE
Precipitation	Monthly Average (°mm)	INPE
Altitude/Latitude/Longitude	-	INPE
Machinery	Number of Machines / Area	IBGE
Log (Workers)	Number of Workers	IBGE
Farm Expenditure	Expenditure (R\$) / Area	IBGE
Log (Irrigated Land)	Area (in hectares)	IBGE
% Fertilizer Usage	Proportion of establishments using fertilizer	IBGE
% Membership	Proportion of establishments associated with cooperatives	IBGE
% Higher Education	Proportion of establishments owned by individuals with a college education	IBGE
% Pesticide Usage	Proportion of establishments using pesticide	IBGE

Source: Compiled by the author.

Regarding climate data, cumulative precipitation (mm) and average temperature (°C) variables were used for both observed (baseline) climate data and climate projections. For the estimation of the baseline model, monthly averages of temperature and precipitation were calculated for the period between 1971 and 2005 from the INPE (National Institute for Space Research) database, adhering to the minimum thirty-year interval, known as the climatological normal.

For simulations of climate scenarios, temperature and precipitation projections from INPE were utilized. They consist of monthly projections for the periods 2006-2040, 2040-2070, and 2071-2099, calculated using the regional climate model Eta-CPTEC from INPE and provided at a spatial resolution of 20 km x 20 km. The scenarios considered in these projections are RCP 8.5 and RCP 4.5 from IPCC.

Regarding the model configuration, the decision was made to conduct the estimation considering all municipalities in Brazil, even though the projections are focused solely on Minas Gerais. This choice is supported by several reasons. Firstly, this approach is a conventional practice in the literature, where the model is initially estimated for the entire country and later used to project results for each federative unit (Tanure, 2020). The use of state-level data, due to the lower volume of information, may compromise the accuracy of the estimation. Therefore, the coefficients of the climate variables in the model adjusted for the entire Brazil are statistically more robust, benefiting from a larger number of observations and greater variability in climate conditions.

Moreover, the state of Minas Gerais partially mirrors the diverse climate conditions and crop variations present across the nation. Consequently, the ultimate database utilized for model estimation encompasses 4,467 observations. Municipalities lacking accessible climate data were omitted from the sample, as were those with agricultural variables registering zero or inhibited values. Consequently, the samples for specific crop estimates have fewer observations since, owing to diverse climate conditions, not all municipalities cultivate every type of crop. The following section will present a comprehensive overview of the agricultural sector in Minas Gerais.

3.1.2 The Agricultural Sector em Minas Gerais

Brazil's participation in agricultural and livestock activities ranks among the highest in the global market. Minas Gerais plays a significant role in the international projection of Brazilian agriculture, boasting the most diversified agricultural portfolio in the country. In 2022, according to the João Pinheiro Research Foundation, the agribusiness GDP reached R\$205 billion, representing 22% of the state's total GDP and approximately 9% of the total production in Brazil. The state leads the nation in the production of milk and coffee. Between 2010 and 2021, it held the second position nationally in the average production of sugarcane and cattle. During the same period, Minas Gerais produced 52.3% of the country's coffee, equivalent to 16.8% of the global average. In national production, the state also holds substantial shares in the cultivation of potatoes, garlic, pineapples, tomatoes, and bananas, as well as in the populations of poultry, horses, and pigs, and in the production of chicken eggs.

It should be taken into account that the configuration of agricultural production in Minas Gerais, as well as in Brazil, encompasses a wide variety of rural properties, ranging from small establishments of family farming to large estates of commercial agriculture. Additionally, the state reflects the rich agrobiodiversity and regional heterogeneity of crops found throughout Brazil. In this context, and considering that the results of the econometric exercise are disaggregated by agricultural crop and regions within the state, it is crucial to characterize the composition of crops and the production structure in each of these regions (IBGE, 2017).

Table 3.2 presents the total value of crop production for each of the regions in Minas Gerais, along with their main crops. Considering the entire set of regions, the average value produced was R\$2.315 billion in 2017. The regions of Varginha, Uberaba, Patos de Minas and Uberlândia stand out as the largest producers in the state. Among these regions, the primary crop in Patos de Minas and Uberlândia is soybeans, while the most important cultivation in Uberaba is sugarcane, which accounts for 55% of the total production in the region. Meanwhile, the majority of Varginha's agricultural production centers around coffee, representing over 74% of the output in the region. Pouso Alegre, Juiz de Fora and Ipatinga are also major coffee producers within the state.

Table 3.2 – Crop Yield in Minas Gerais

Regions	Crop Yield (in thousands R\$)	Major Crop (%)	Second Major Crop (%)	Third Major Crop (%)
Belo Horizonte	270,441	Sugarcane (32%)	Maize (24%)	Banana (23%)
Montes Claros	1,049,675	Banana (34%)	Sugarcane (18%)	Maize (14%)
Teófilo Otoni	382,260	Coffee (32%)	Sugarcane (22%)	Cassava (16%)
Governador Valadares	191,789	Sugarcane (27%)	Coffee (24%)	Maize (20%)
Ipatinga	428,062	Coffee (79%)	Sugarcane (8%)	Maize (4%)
Juiz de Fora	1,977,985	Coffee (80%)	Maize (8%)	Sugarcane (7%)
Barbacena	516,193	Maize (51%)	Beans (20%)	Soybeans (11%)
Varginha	6,156,330	Coffee (74%)	Maize (11%)	Soybeans (7%)
Pouso Alegre	1,362,083	Coffee (62%)	Maize (17%)	Potato (10%)
Uberaba	6,125,811	Sugarcane (55%)	Soybeans (18%)	Maize (10%)
Uberlândia	3,292,609	Soybeans (33%)	Sugarcane (20%)	Coffee (15%)
Patos de Minas	5,783,065	Soybeans (34%)	Coffee (24%)	Maize (21%)
Divinópolis	1,275,589	Sugarcane (33%)	Maize (28%)	Coffee (20%)

Source: Compiled by the author based on IBGE (2017).

Table 3.3 below presents the descriptive statistics of variables related to the characteristics of rural properties in each region. These variables, utilized as controls in the econometric estimation, unveil that the western and northwestern portions of Minas Gerais, where the regions of Uberaba, Uberlândia, and Patos de Minas are located, concentrate the largest agricultural establishments on average. Despite the low proportion of irrigated land across the state, the aforementioned regions, along with Pouso Alegre, distinguish themselves through the more prevalent adoption of irrigation methods. Regarding fertilizer usage, more than half of the establishments in all regions utilize it. In terms of pesticide usage, special attention is warranted for Varginha and Pouso Alegre, where approximately 67% and 40% of establishments in the respective regions use pesticides. On the other hand, Teófilo Otoni stands out as the region with the lowest pesticide usage, with only 6% of establishments employing it. Regarding membership, which pertains to agricultural establishments associated with cooperatives, we observe that the proportion is relatively high in all regions. However, concerning technical assistance, which is one of the services provided by cooperatives, the proportion of establishments receiving assistance is significantly lower than those associated, especially in the regions of Montes Claros, Teófilo Otoni, and Governador Valadares.

Additionally, it is worth mentioning that a significant majority of establishments are

overseen by owners with limited educational attainment. Among the regions, Uberaba (18%), Uberlândia (18%), Varginha (12%), and Divinópolis (12%) stand out for having the highest proportion of farmers with a higher education degree, whereas Montes Claros (4%), Teófilo Otoni (5%), and Ipatinga (5%) have the lowest percentages.

Table 3.3 – Descriptive Statistics of Rural Property Aspects

Region	Average Area	Irrigated Land	Expenditure	Pesticide Usage	Fertilizer Usage	Membership	Higher Education	Technical Assistance
Belo Horizonte	77.28	2%	735.62	12%	61%	23%	12%	28%
Montes Claros	71.96	2%	332.89	23%	36%	67%	4%	16%
Teófilo Otoni	64.01	1%	333.22	6%	42%	48%	5%	11%
Governador Valadares	63.42	1%	583.02	11%	47%	33%	6%	14%
Ipatinga	32.99	2%	1,091.39	28%	69%	33%	5%	16%
Juiz de Fora	29.64	1%	1,184.29	27%	73%	34%	7%	27%
Barbacena	30.84	1%	1,534.08	23%	72%	27%	7%	20%
Varginha	38.66	2%	2,666.29	67%	81%	49%	12%	55%
Pouso Alegre	25.56	8%	1,762.69	40%	62%	17%	8%	32%
Uberaba	157.63	6%	2,493.77	31%	51%	43%	18%	45%
Uberlândia	136.78	4%	1,778.19	33%	49%	39%	18%	41%
Patos de Minas	141.44	5%	1,221.59	30%	50%	38%	9%	27%
Divinópolis	68.84	2%	1,540.58	19%	58%	39%	12%	27%

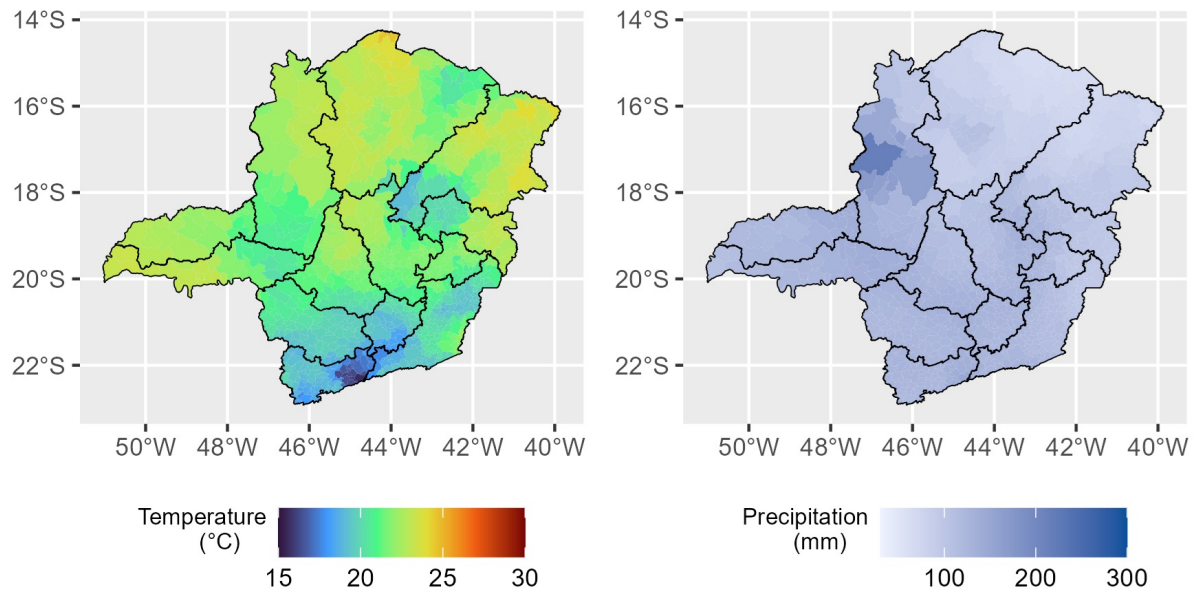
Source: Compiled by the author based on IBGE (2017).

3.1.2.1 Climate Scenarios

In this section, we provide a contrast between the average monthly temperature and precipitation from 1971 to 2005 and their projections for the years 2050 and 2080, considering the RCP 4.5 and 8.5 scenarios in Minas Gerais, sourced from INPE's database.

Figure 3.2 depicts the climate conditions of the baseline scenario utilized in the econometric model adopted for this study. We notice a heterogeneous pattern in the spatial distribution of temperature and precipitation across Minas Gerais. The regions with the highest average temperatures are predominantly situated in the north and northeast, whereas the lowest temperatures are observed in the southeast and south. Regarding precipitation, a more uniform distribution is evident, with emphasis on the Patos de Minas region, which records higher precipitation levels. The minimum observed temperature among the municipalities, from 1971 to 2005, was 15.6°C, while the maximum value was 24.6°C. As for precipitation, the minimum observed was 63 mm, and the maximum was 215 mm.

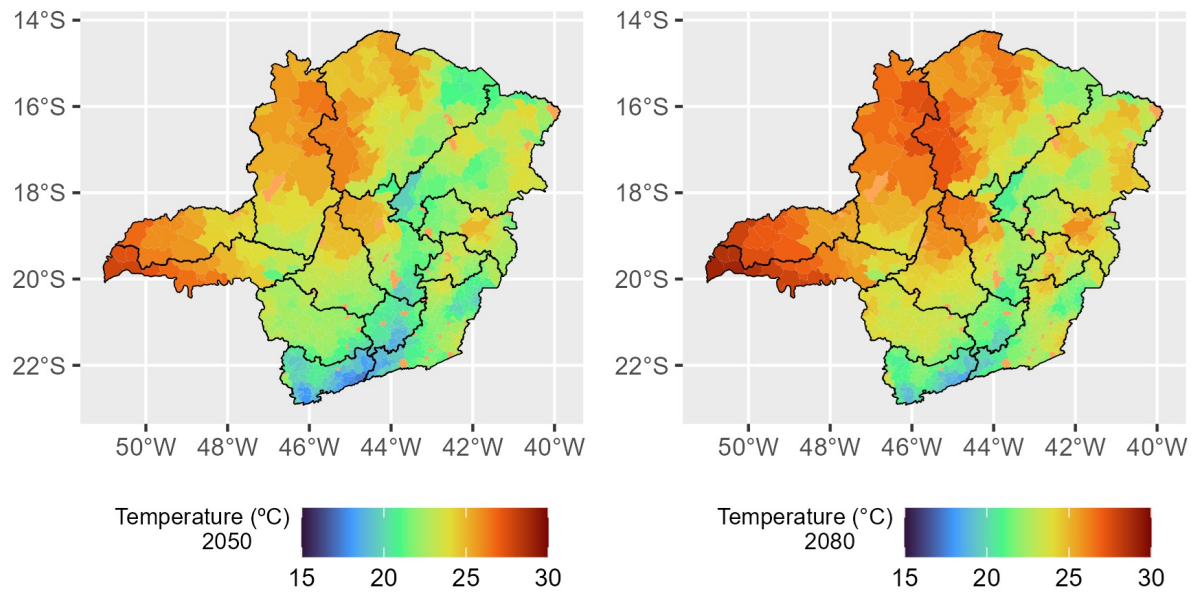
Figure 3.2 - Temperature and Precipitation (1971-2005)



Source: Elaborated by the author.

Figure 3.3 presents projections of average temperature changes relative to the baseline scenario (1971-2005) for the years 2050 and 2080, under the RCP 4.5 scenario. The projections suggest an increase of 2°C to 3°C in average temperature for Minas Gerais in 2050, with a more pronounced effect in the northwest and west, particularly in the regions of Patos de Minas, Uberlândia, and Uberaba. The projected minimum average temperature for this period is 17.3°C and the maximum is 27.8°C. In 2080, the temperature increase intensifies, especially in the extreme west of the state. The projected minimum average temperature for this period is 18.4°C and the maximum is 28.9°C.

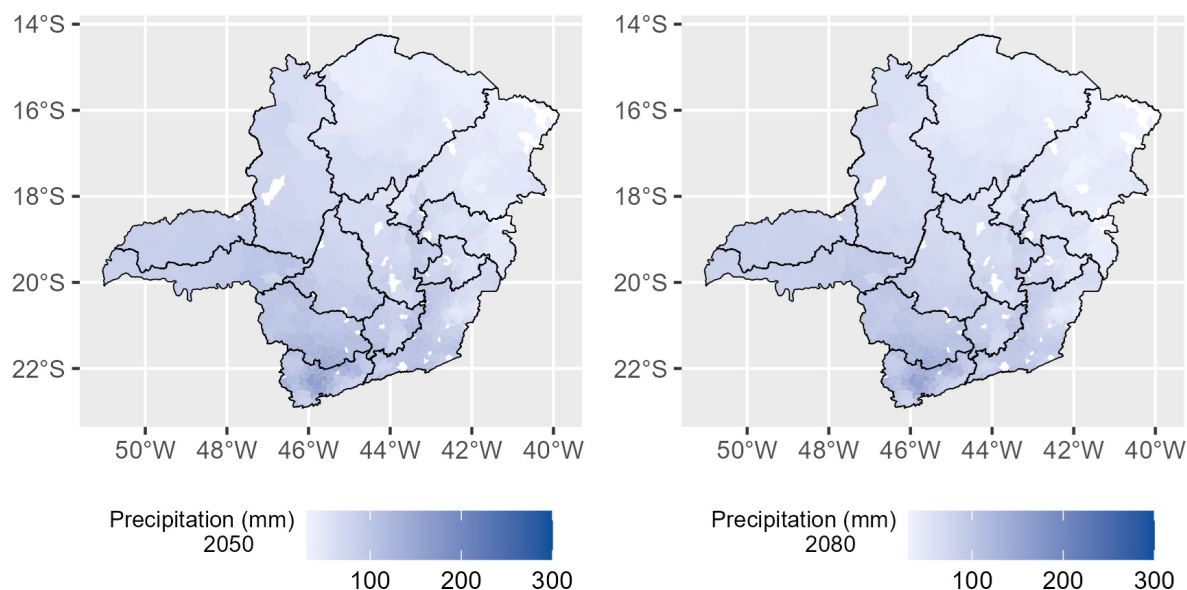
Figure 3.2 – Projected Temperature (RCP 4.5)



Source: Elaborated by the author.

Similarly, Figure 3.4 depicted below showcases forecasts detailing alterations in average precipitation volume compared to the baseline scenario for identical periods and under the same climate conditions. Projections for both timeframes indicate a reduction of 45mm to 60mm in monthly average precipitation, with the northern and northeastern regions, historically characterized by warmer climates, witnessing the most substantial decline. The anticipated lowest average precipitation for 2050 is 22mm, while the highest is projected to be 163mm. By 2080, this decline intensifies, with a projected minimum of 18mm and a maximum of 155mm. Overall, most areas of Minas Gerais would face losses in cumulative precipitation, worsening over time.

Figure 3.3 – Projected Precipitation (RCP 4.5)



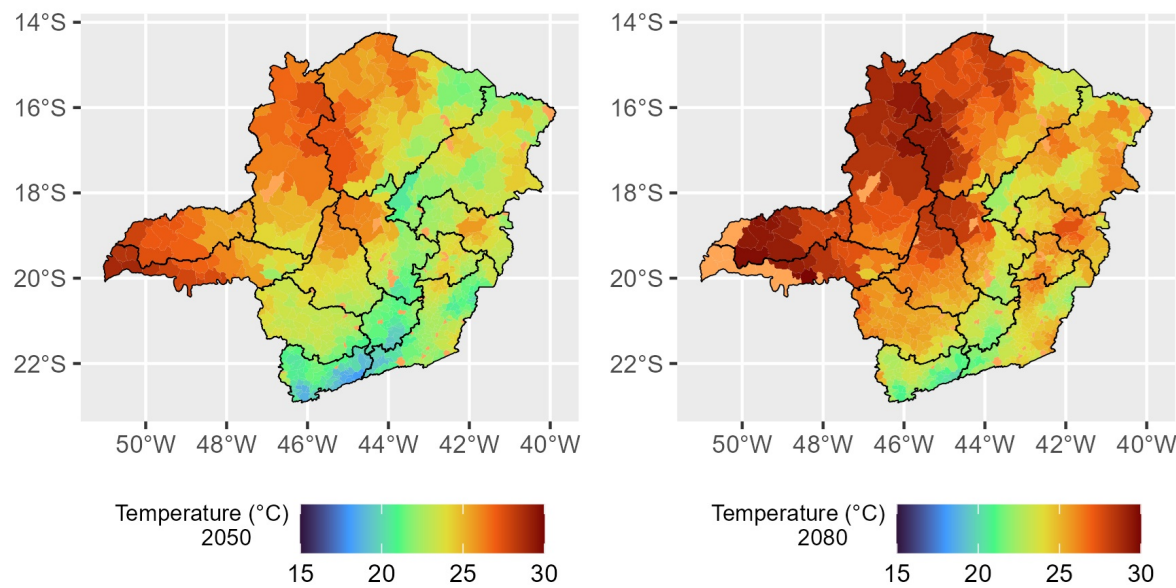
Source: Elaborated by the author.

As Figure 3.5 and Figure 3.6 below are presented in a manner consistent with the two preceding figures, but now under the RCP 8.5 scenario, Figure 3.5 indicates a more pronounced rise in average temperature, especially in the year 2080. The areas most significantly impacted by this increase in average temperature would include Uberlândia, Uberaba, Patos de Minas, and the southwest portion of Montes Claros. Conversely, regions situated in the south, notably Varginha and Pouso Alegre, which have historically been cooler, would undergo a significant increase in average temperatures. The projected minimum average temperature for 2080 is 20°C and the maximum is 31.2°C.

Regarding Figure 3.6, in general, the majority of regions within Minas Gerais would experience a significant decline in average monthly precipitation under RCP 8.5 scenario, and this effect would worsen over time. The most affected regions would be Montes Claros, Teófilo Otoni and Governador Valadares. The projected minimum average monthly precipitation for 2080 is 13mm and the maximum is 138mm.

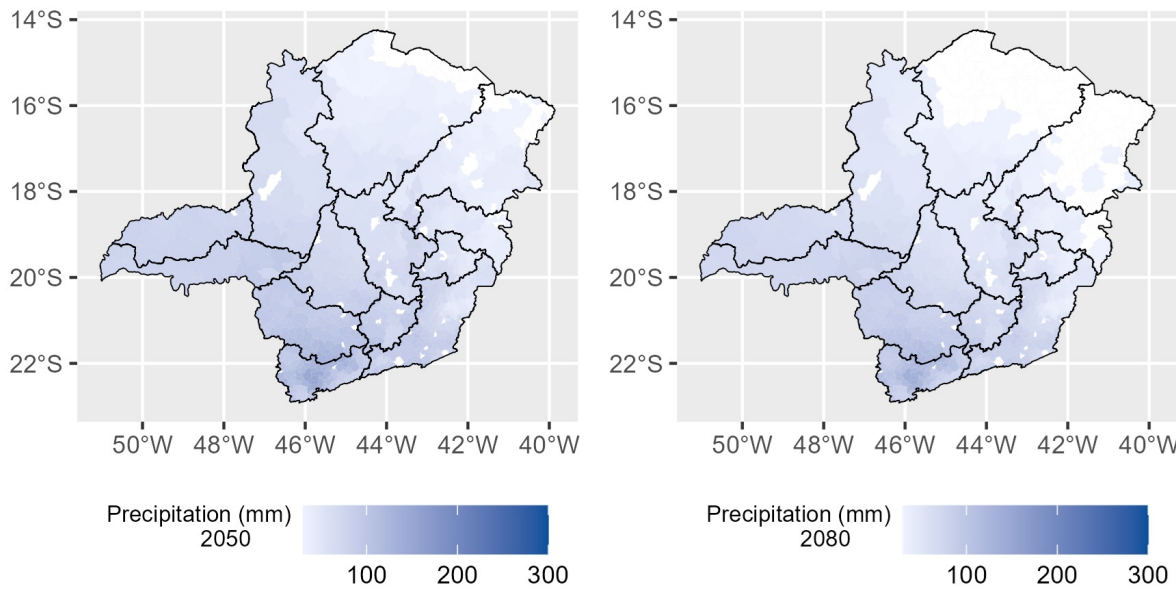
Considering the aforementioned points, it is evident that climate change can affect regions heterogeneously. Furthermore, considering that different regions specialize in various agricultural crops, it is imperative to thoroughly investigate the impacts of climate change on agricultural productivity. This examination should consider the heterogeneity among regions in order to formulate effective solutions.

Figure 3.4 – Projected Temperature (RCP 8.5)



Source: Elaborated by the author.

Figure 3.5 – Projected Precipitation (RCP 8.5)



Source: Elaborated by the author.

3.1.3 The IMAGEM-MG Model: Key Aspects

The variations in agricultural productivity estimated by the econometric model are incorporated into the Computable General Equilibrium (CGE) model named IMAGEM-MG, focusing on analyzing the direct and indirect impacts of climate change on the economy of Minas Gerais. CGE models comprise systems of equations aimed at describing the economy in equilibrium, capturing the behavior of economic agents and interactions among sectors. This methodology is employed to analyze and project the effects of climate change on regional economic dynamics. In addition to being influenced by climate factors, regional economic variables are also affected by conjunctural and structural factors, and this intricate chain of interrelations is considered in CGE models. This chapter provides detailed specifications related to the functioning of the IMAGEM-MG model, its theoretical structure and database description.

This study employs IMAGEM-MG, the *Integrated Multirregional Applied General Equilibrium Model for Minas Gerais*, a regional model for Minas Gerais developed from IMAGEM-B, the *Integrated Multirregional Applied General Equilibrium Model for Brazil*. The aforementioned models follow the theoretical framework of the Australian *bottom-up* model TERM, *The Enormous Regional Model*, developed with the aim of providing disaggregated analyses from both regional and sectoral perspectives. It proves to be valuable for assessing regional impacts of shocks that may have spatially heterogeneous effects. In its initial application, it was employed to evaluate the regional effects of the drought disaster that occurred in Australia in the years 2002 and 2003 (Horridge; Madden; Wittwer, 2005).

The Johansen-type general equilibrium model utilized in this research is characterized by a set of linearized equations in which variables are expressed in terms of growth rates or elasticities. This model follows a general equilibrium approach, employing linear specifications for demand and supply functions. Its main advantage lies in flexibility, equation formulation, and the ability to incorporate sectoral and behavioral changes in a detailed manner (Dixon; Jorgenson, 2012).

The main objective of this thesis is to investigate the economic impacts resulting from climate change on agriculture in Minas Gerais. Thus, variations in the productivity of agricultural sectors calculated through the econometric model developed in this study will be used as shocks in the general equilibrium model to estimate their impacts on GDP, consumption, investment, imports, exports and employment.

In this manner, we have chosen a regionalization approach with a clearly defined demarcation of the regions within Minas Gerais, along with their respective municipalities. This approach allows for the consideration of spatial heterogeneity. Consequently, IMAGEM-MG encompasses 14 regions, including 13 regions within Minas Gerais: Barbacena, Belo Horizonte, Divinópolis, Governador Valadares, Ipatinga, Juiz de Fora, Montes Claros, Patos de Minas, Pouso Alegre, Teófilo Otoni, Uberlândia, Uberaba, Varginha, and the remaining area of Brazil. This regionalization stands as a significant methodological contribution, particularly due to the

scarcity of CGE models designed to assess the economic impacts of climate change with such a high level of regional detail for Minas Gerais.

The detailed disaggregation of the model's database focused on agricultural sectors, which are directly associated with and affected by climate variations. In this context, the IMAGEM-MG structure encompasses 30 sectors. Among them, 9 are specifically dedicated to agricultural commodities, 1 to livestock activities, and 20 include those that could be directly or indirectly affected by changes in agricultural productivity. This influence might occur through trade, regional production reallocation, or other transmission pathways, as outlined in Table 3.4.

Table 3.4 – Sectoral Disaggregation of the IMAGEM-MG Model

Nº	Sector	Nº	Sector
1.	Rice, Wheat & Cereals	16.	Biofuels
2.	Maize	17.	Inorganic Chemical Products
3.	Cotton	18.	Manure & Fertilizers
4.	Sugarcane	19.	Agrochemicals
5.	Soybeans	20.	Electronics
6.	Temporary Crops	21.	Other Industries
7.	Orange	22.	Electricity
8.	Coffee beans	23.	Water & Sewage
9.	Permanent Crops	24.	Construction
10.	Livestock	25.	Trade
11.	Forestry	26.	Freight Transport
12.	Fishing	27.	Services
13.	Oil, Gas & Mining	28.	Information & Communication
14.	Food and Beverages	29.	Public Sector
15.	Manufacturing	30.	Private Sector

Source: Compiled by the author.

Moreover, Table 3.5 presents the relevant sets for the operation of IMAGEM-MG, forming the input-output structure of the model. The indices (s, c, m, i, d, etc.) denote the dimensions of the matrices and correspond to their respective sets. The sets COM and IND have the same dimension because, in the model, each sector (IND) produces only one product (COM). The sets DST, ORG, and PRD are also equal, representing the 14 regions of the model, differing only in the context in which they are used.

Table 3.5 – Main sets of the IMAGEM-MG model

Index	Set Name	Description	Size
s	SRC	Origin (dom, imp)	2
c	COM	Commodities	30
m	MAR	Margin commodities (trade, transport)	2
i	IND	Industries	30
d	DST	Regions of use (destination)	14
r	ORG	Regions of origin	14
p	PRD	Regions of margin production	14
f	FINDEM	Final demanders (HOU, INV, GOV, EXP)	4
u	USER	Users = IND + FINDEM	34

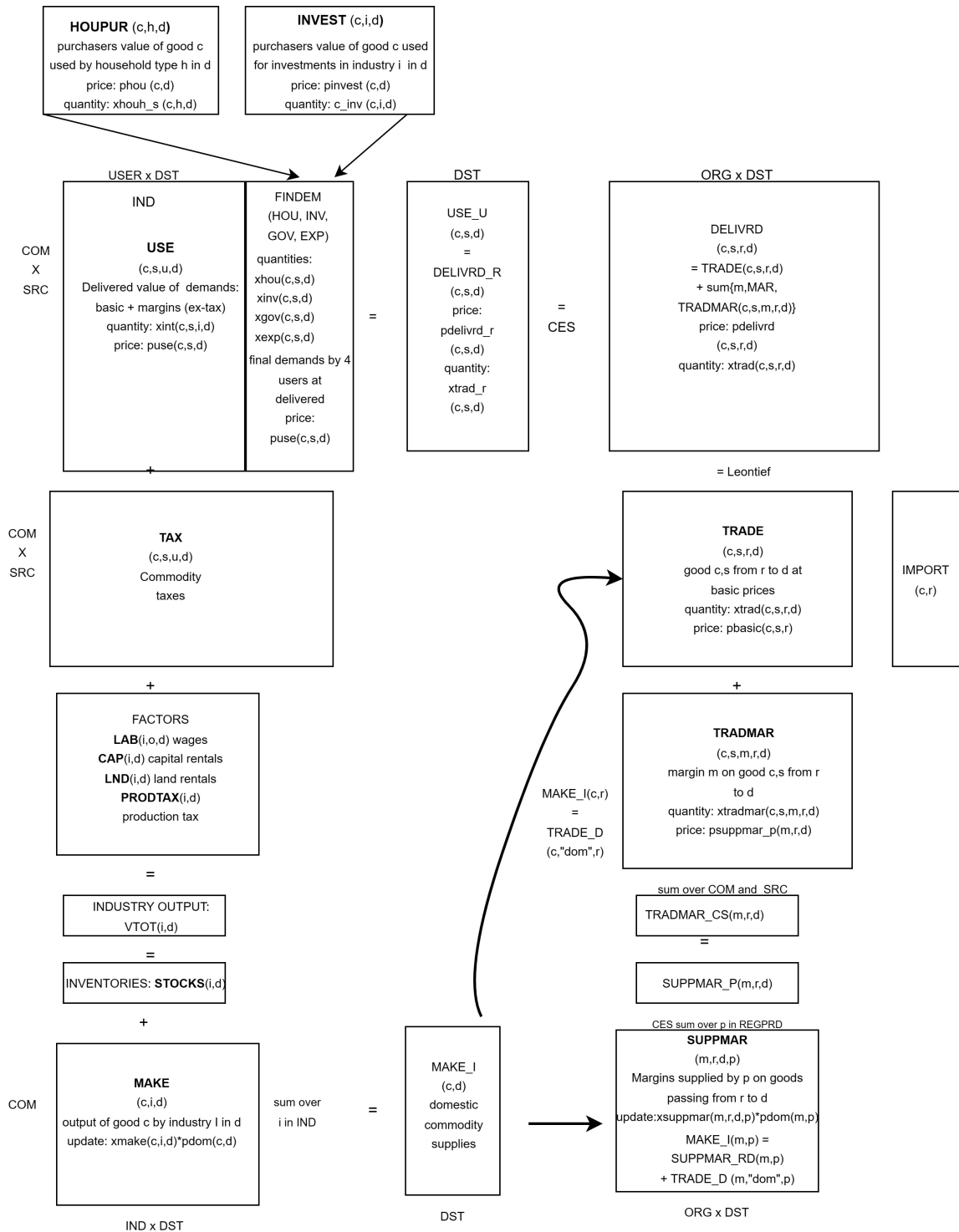
Source: Compiled by the author based on Horridge (2012).

The IMAGEM-MG model database adheres to the structure outlined in Figure 3.6, based on Horridge (2012). The rectangles signify flow matrices. Bold matrices represent the primary ones, and the remaining matrices can be derived from these two. In Figure 3.6, matrices illustrate flow values using three methods:

1. Basic price, aligning with production prices for domestically produced goods or CIF prices for imports (inclusive of costs, insurance, and freight);
2. Selling price, derived by adding margins to the basic price;
3. Purchase price, obtained by summing the selling price and taxes.

This distinction in values enables the model to capture the impact of transportation margins based on flow and production region. Each region in the model incorporates four final demand categories: the representative household (HOU); capital formation (INV); government demand (GOV), spanning federal, state, and municipal levels; and export demand (EXP).

Figure 3.6 – IMAGEM-MG Flows Database



Source: Elaborated by the author based on Horridge (2012).

The matrices on the left side of the diagram resemble, for each region, a single-region input-output database. Taking the USE matrix as an example in the upper-left corner, it displays the value of demand for each good (represented by 'c' in COM), whether domestic or imported (indicated by 's' in SRC), in each destination region (DST) for each user (USER), covering both

the sectors (IND) and the 4 final demanders (households, investments, government, and exports). As an example, the elements of the USE matrix may be configured as follows:

1. $USE(c, s, u, d) = USE(\text{"Maize"}, \text{"Dom"}, \text{"Food and Beverages"}, \text{"Varginha"})$: Usage of maize, domestically produced, by the food and beverages industry in the region of Varginha.
2. $USE(c, s, u, d) = USE(\text{"Coffee"}, \text{"Imp"}, \text{"HOU"}, \text{"Juiz de Fora"})$: Coffee, imported, demanded by households in Juiz de Fora.

The two matrices (USE and TAX), combined with the matrices of primary factor costs and production taxes, constitute the production costs (or product value) for each regional industry. From an accounting perspective, the product value of each regional industry is also equivalent to the sum of inventories with the value of production for each product in each industry and region (MAKE matrix). Although the production of different goods by different sectors is possible, in the model under consideration, we assume that each sector produces only one good. Thus, the MAKE matrix becomes square and diagonal in each region. The byproduct of the MAKE matrix, called MAKE_I, represents the total production of each product in each destination region. This entire structure resembles conventional input-output databases for each region.

The remaining structure represents the mechanism of regional supply. The regional origin of goods is provided by the TRADE matrix, which represents the flow of trade between regions for each of the 127 goods in the model, in both domestic and imported origins. The diagonal of this matrix shows the value of local use that is offered locally. In the case of imported products, the regional origin is the entry port into the country. The IMPORT matrix relates to the total imports for each port, simply aggregating the import portion of the TRADE matrix. The TRADMAR matrix presents the value of the margin necessary for the realization of trade flows for each element of the TRADE matrix, but without any inference on where the margin flow is produced. The sum of the TRADE and TRADMAR matrices gives rise to the "delivery" price of all product flows (DELIVRD).

The origin of the margins is presented in the SUPPMAR matrix without distinction between products or their origin, whether domestic or imported. This implies that the total use of margins for marketing or transporting any product from one region to another follows the same proportion. The sum of regional margins forms the SUPPMAR_P matrix, which has the same value as TRADMAR_CS, derived from the TRADMAR matrix through the margins of domestic and imported products. In this structure, TRADMAR_CS is an aggregation of SUPPMAR using a Constant Elasticity of Substitution (CES) function. Consequently, the margins for a specific product on a particular route are established according to the price of that margin in various regions.

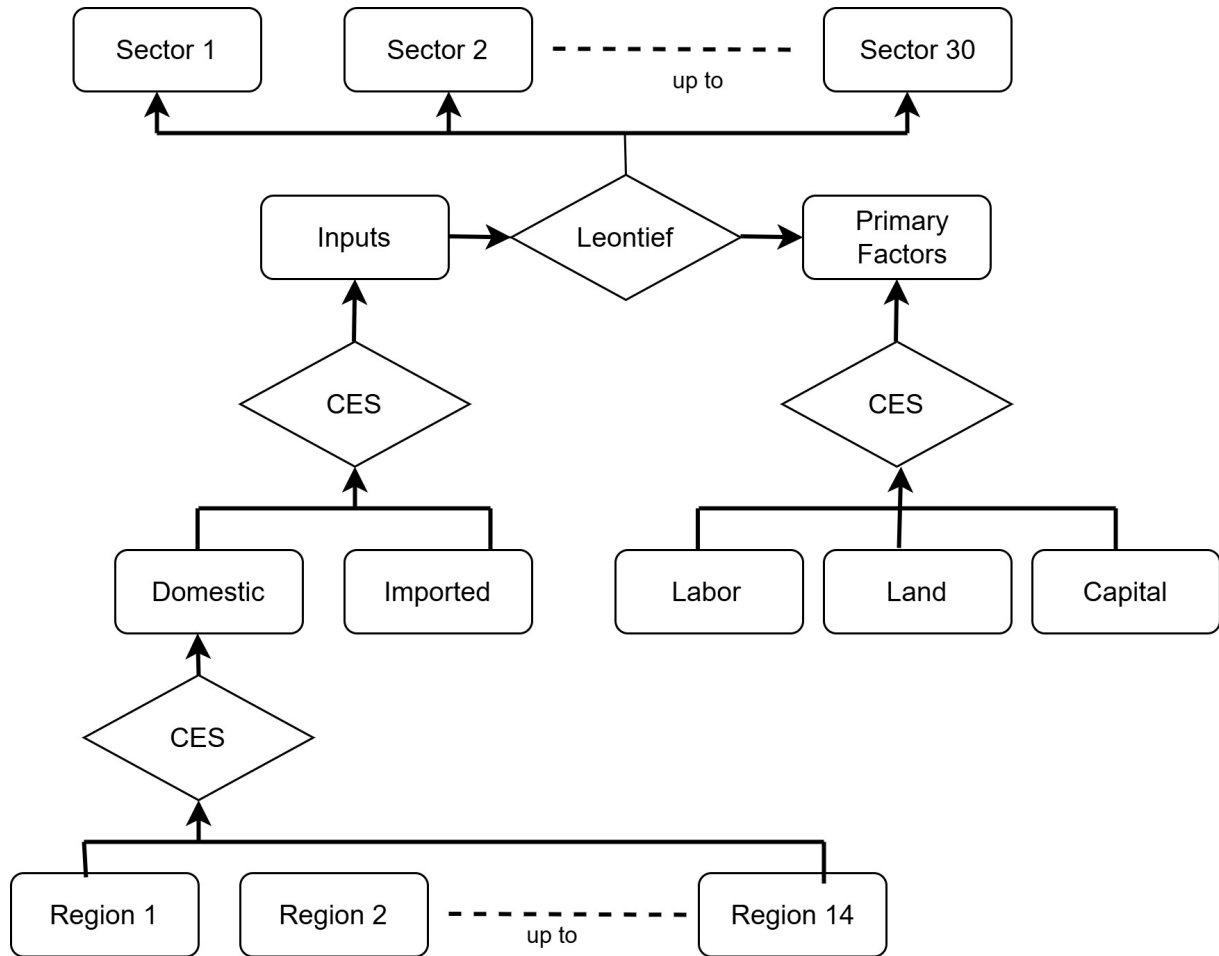
In the model, all users of a specific good in a region have the same origin mix, adopting the Armington substitution, where the $DELIVRD_R$ matrix is a CES composition of the $DELIVRD$ matrix. The existence of equilibrium depends on the sum of USE (USE_U) being equal to the sum of $DELIVRD$ ($DELIVRD_R$). The compatibility between the supply and demand for domestic goods occurs between the $MAKE_I$ matrix and the $TRADE$ and $SUPPMAR$ matrices. For products that are not margins, the domestic elements in the $TRADEM$ matrix are added to the corresponding elements in the $MAKE_I$ matrix of commodity supply. In the case of margin goods, the margin requirements from the $SUPPMAR_RD$ matrix are considered, along with the direct demand presented in the $TRADE_D$ matrix. Investments are allocated according to the industry of destination or point of entry for imports in the $INVEST$ matrix.

3.1.4 IMAGEM-MG: Theoretical Framework

3.1.4.1 Sectoral Production

The structure of the sectoral production technology (Figure 3.7) illustrates the scheme of combining primary factors and intermediate inputs for production in each sector. The sectoral production technology is determined by the fixed combination of primary factors (capital, labor, and land) and intermediate inputs, following a constant proportion (Leontief function). The demand for intermediate inputs occurs between domestic and international origins, defined by a CES function. In the case of domestic origin, the demand is disaggregated among different national regions (13 mesorregions of Minas Gerais and the rest of Brazil) through a CES function. At this stage, the assumption of imperfect substitution is considered in the allocation between domestic and international intermediate inputs, as well as between inputs from different national regions, following the Armington hypothesis (1969). Additionally, sectoral production assumes the minimization of production costs subject to a technology of constant returns to scale. The use of constant returns to scale is more common to avoid certain potential methodological issues.

Figure 3.7 – IMAGEM-MG Production Structure

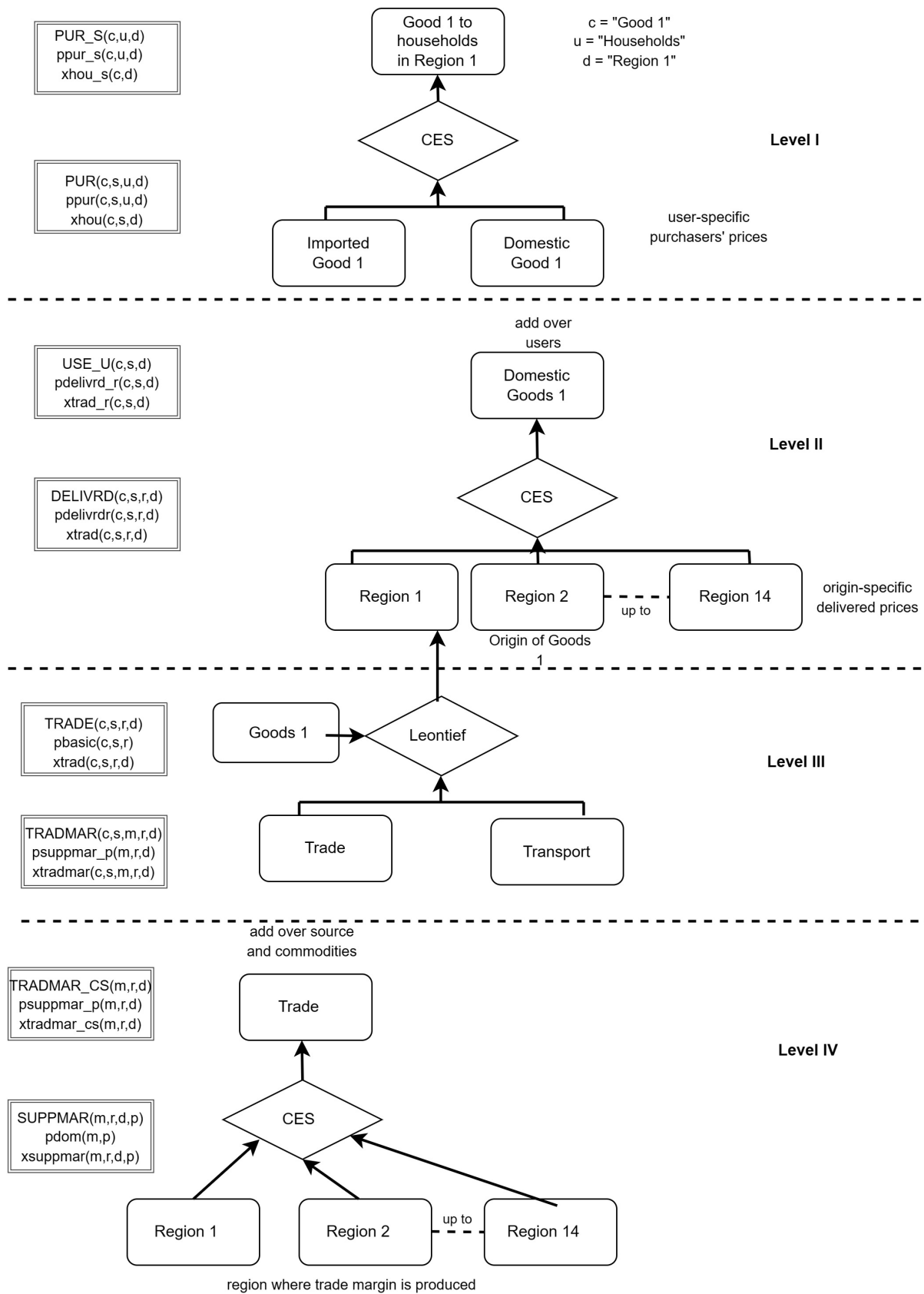


Source: Elaborated by the author based on Horridge (2012).

3.1.4.2 Regional Demand/Households

The specification of consumption in the IMAGEM-MG model is accomplished through the relationship between prices and expenditures, taking into account conditions for maximizing utility. This happens by considering various substitution options throughout the process, thus forming the mechanism that constitutes demand, as illustrated in Figure 3.8.

Figure 3.8 – IMAGEM-MG Sourcing Mechanisms



Source: Elaborated by the author based on Horridge (2012) and Campos (2021).

While Figure 3.8 depicts the demand for a single good or product - Good 1 - from a single user - Households (hou) - in a single region - Region 1 -, the same diagram would be applicable to other commodities, users, and regions. Households decide whether to consume Good 1, which can originate from two distinct sources: domestic or imported (from another country). This choice follows a CES function, as evidenced in Level I of Figure 4. Demands are related to specific purchase values per user (these values are presented in the PUR matrix, defined as the sum of the USE and TAX matrices). The elasticity of substitution between the domestic and imported composite is specific to each commodity but common for each user and destination or usage region, although differentiated estimates can be used.

At Level II, the demands for domestic Good 1 in a particular region are aggregated (for all users) to determine the total value (USE_U). The use matrix (USE_U) is valued at *delivered* prices, which include basic and margin values but exclude taxes for specific use. The origin system of domestic products (USE_U) among regions is also determined through a CES function, which controls this allocation. In other words, regions with a decrease in the relative cost of production increase their *market* share in the destination region of the product. The DELIVRD matrix shows how this composite is formed from the originating regions. According to Sessa (2019), the substitution mechanism is based on delivered prices, which include trade and transportation margins. Therefore, even if production prices are fixed, changes in transportation costs affect regional *market* share.

The composition of basic values and trade and transportation margins for Good 1 among regions is depicted at Level III. This structure follows a Leontief function, indicating that the share of each component in the final price is fixed. Thus, the assumption of substitution between trade and transportation margins is eliminated. The contribution of each margin to the delivered price is a combination of origin, destination, commodity, and source.

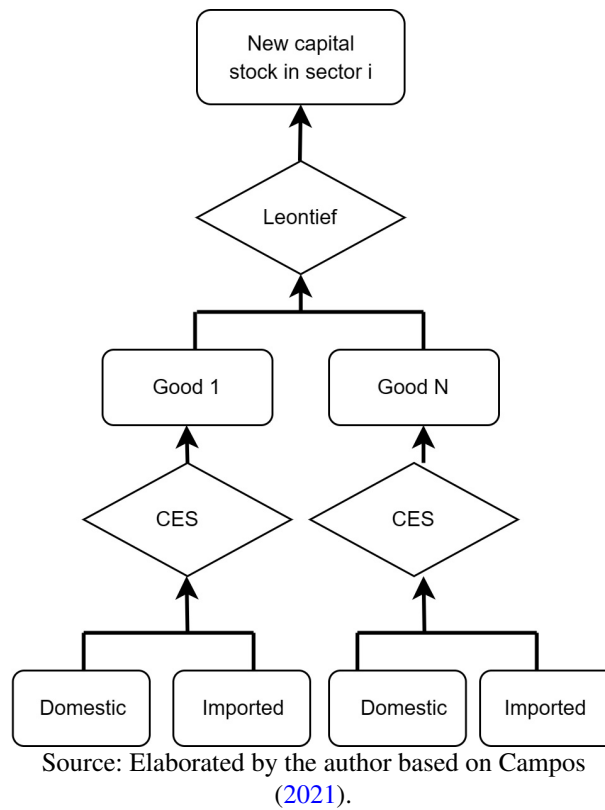
At Level IV, after aggregating trade margins for all sources (domestic and imported) and all commodities, the origins of transportation margins among the various regions of the model are established. These margins are evenly distributed between origin and destination, with some degree of substitution among margin suppliers, regulated by elasticity, which can capture the capacity of transporters to relocate their storage depots along routes. Regarding trade margins, the majority is produced in the destination region (use), and therefore, the scope for substitution should be smaller, with an elasticity calibrated close to zero (Magalhães, 2011). This substitution decision is made at the aggregate level, under the implicit assumption that a region's participation in providing margins for the trade of goods between two regions is the same, regardless of the commodity being transported. The same mechanism for the origin of flows is applied to imported goods, but tracing their origin to the entry port and not to the region of origin (which is the external market).

3.1.4.3 Investment and Capital Stock

Through a cost minimization process subject to a hierarchical technology structure, investors select the inputs used in the capital creation process. These inputs represent a category of final demand responsible for producing new units of capital (gross fixed capital formation).

Capital goods are produced using both domestic and imported inputs, similar to the production technology shown in the Figure below. In the first node, a CES function is employed in combining goods from domestic and imported sources. In the second node, an aggregate of the set of composed intermediate inputs is formed by a fixed proportion combination (Leontief), determining the level of production for the sector's capital. No primary factor is used directly as an input in the capital formation process (Horridge, 2012).

Figure 3.9 – IMAGEM-MG Investments and Capital Stock



3.1.4.4 Labor Market

The IMAGEM-MG Model considers national employment as exogenous, without incorporating a temporal adjustment system for the labor market. In other words, since the main disaggregated regions in the model have a limited share in the national labor market, total employment in Brazil is considered exogenous. A simplified theory of the labor market is adopted to streamline the computational process of the model.

As in Horridge (2012), the regional labor market is endogenous and operates in two ways:

1. Real (or nominal) fixed wages and employment determined by demand in the labor market. This is the default configuration for short-term analysis, where all wages are indexed to the consumer price index in the region or a national price index.
2. Exogenous national employment, with wages adjusting endogenously to balance the regional labor market. The value of national employment is determined by historical demographic characteristics. This is the default configuration for long-term analysis, where the labor market responds endogenously to the average wage, with fixed sectoral and regional wage differentials. This allows for the simulation of intersectoral and regional labor mobility.

3.1.4.5 Market Equilibrium, Margin Demand, and Purchase Prices

The model operates using market equilibrium equations for all locally consumed goods, both domestic and imported. Purchase prices for each usage group (producers, investors, households, exporters, and government) are the sum of basic values, taxes (direct and indirect) on sales, and margins. Sales taxes are treated as *ad-valorem* rates on basic flows. There is market equilibrium for all goods, both domestic and imported, as well as in the factor market (capital and labor) in each region. Margins' demands (transport and trade) are proportional to the flows of goods to which the margins are connected. Purchase prices for each usage group in each region (producers, investors, households, exporters, and government) are the sum of basic values, taxes (direct and indirect) on sales, and margins (trade and transport) (Magalhães, 2011).

3.1.5 Regionalization Procedure

The process of regionalization is one of the most crucial steps in the development of regional CGE models and requires significant time and dedication to construct the database. The IMAGEM-MG is constructed and regionalized based on the national model IMAGEM-B (*Integrated Multirregional Applied General Equilibrium Model for Brazil*) (Domingues *et.al*, 2010), which, in turn, incorporates elements from the specifications of the MONASH and ORANI models (Dixon and Rimmer, 1998; Dixon et al, 1982). The regionalization process in this research follows the procedures utilized in Simonato (2017) and Tanure (2020).

The IMAGEM-MG is configured for the year 2015, following the sectoral and product classification of the input-output matrix from IBGE, comprising 127 sectors/goods. It includes five components of final demand (household consumption, government consumption, investment, exports, and stocks), two primary factor elements (capital and labor), two margin sectors (trade and transportation), imports by product for each of the 127 sectors. The regionalization process is conducted using data from the national model and data on macroeconomic indicators such as GDP, investment, household consumption, government expenditures, imports and exports, as detailed in Table 3.6.

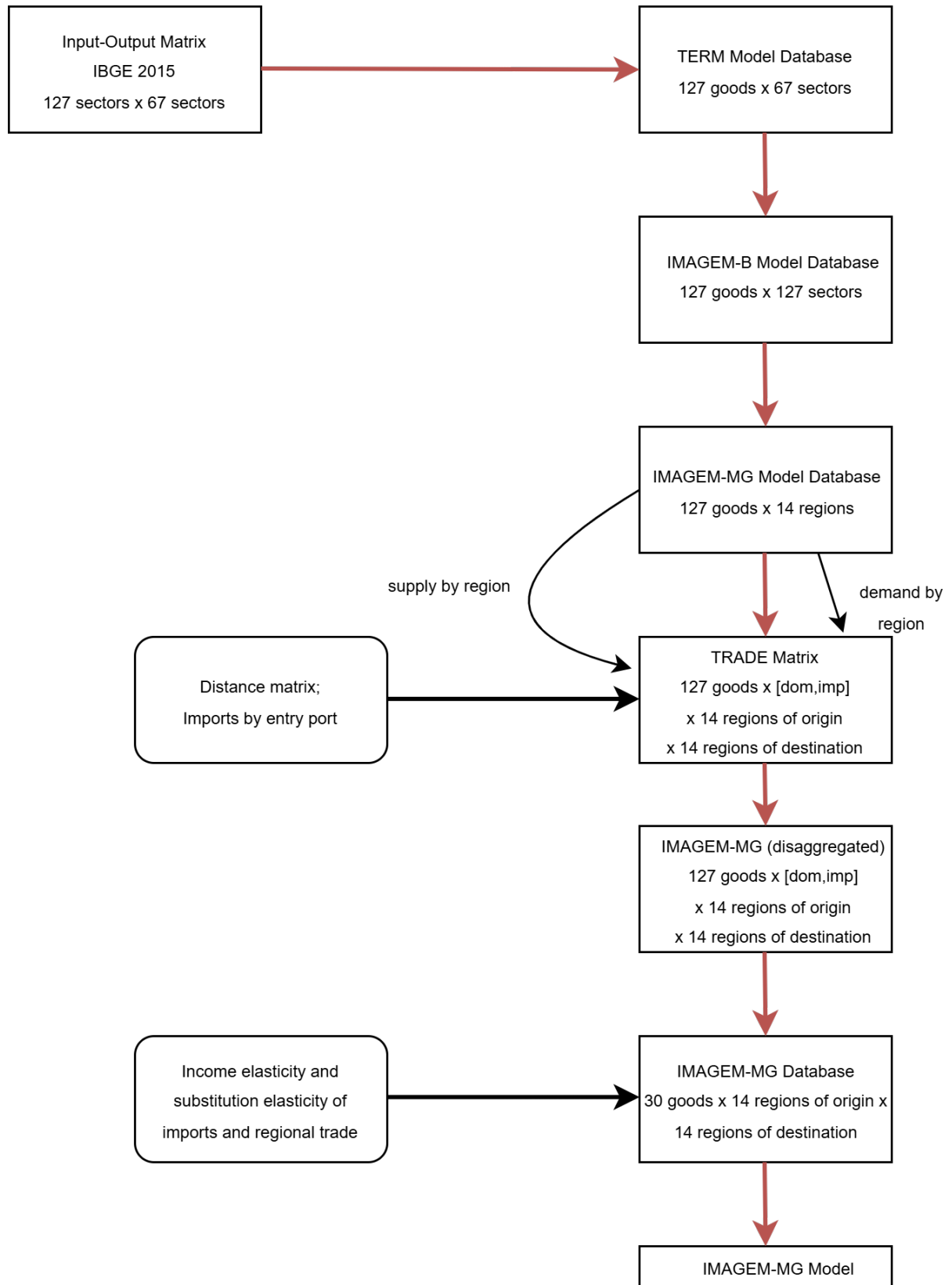
Table 3.6 – IMAGEM-MG Data Source

Description	Source
Input-Output Matrix	IBGE
Regional % of Production	IBGE, RAIS
Regional % of Investment	RAIS
Regional % of Household Consumption	POF (IBGE, 2015)
Regional % of Exports by Exit Port	SECEX
Regional % of Government Consumption	IBGE
Regional % of Inventory Variation	RAIS
Regional % of Imports by Entry Port	SECEX
Population	IBGE
Distance between Regions	Own elaboration
Import and Export Substitution Elasticity	(DOMINGUES, 2009)
Regional Trade Substitution Elasticity	(FARIA; HADDAD, 2014)
Income Elasticity	(HOFFMANN, 2010)

Source: Compiled by the author.

Figure 3.10 below shows the process of building the IMAGEM-MG model's database. Throughout the procedure, efforts are made to ensure the consistency of the database with official data from Regional Accounts, National Accounts, Input-Output Matrix, information from POF (Family Budget Survey), Secretariat of Foreign Trade (SECEX), Industrial Production (PIA), and Annual Report of Social Information for employment data (RAIS).

Figure 3.10 – Regionalization Procedure



Source: Elaborated by the author based on Horridge (2012), Simonato (2017) and Campos (2021).

3.1.6 IMAGEM-MG: Data

In this section, the goal is to perform a descriptive analysis of some indicators from the IMAGEM-MG model's database. Table 3.7 presents the share of Agriculture, Industry, and Services in the composition of GDP in Minas Gerais.

Within the agricultural sector, crop production constitutes 65% of its contribution, with notable emphasis on key crops such as soybeans (35%), temporary crops (18%), sugarcane (15%), and maize (10%), which serve as primary drivers. Additionally, livestock contributes significantly, comprising 27% of the agricultural GDP, with cattle breeding, poultry, and dairy production playing pivotal roles. Turning to the industrial sector, manufacturing and construction collectively account for over 85% of production. Despite its lower share at 6%, the extractive industry remains noteworthy, reflecting the state's abundant mineral resources. In the services sector, approximately 24% of the contribution comes from accommodation, food services, research and development, architectural and engineering services, arts, recreation, and leisure. Public administration services follow closely at 21%, with trade (wholesale and retail) also making a substantial contribution.

Table 3.7 – Share of Economic Activities in the GDP of Minas Gerais

Sector	Share
Agriculture	65%
Livestock	27%
Forestry & Fishing	7%
Extractive Industry	6%
Manufacturing Industry	70%
Electricity and waste management activities	8%
Construction	16%
Trade	18%
Transport	9%
Information and communication	6%
Financial activities	10%
Real Estate activities	12%
Other service activities	24%
Public administration and services	21%

Source: Compiled by the author.

Economic concentration is evident in a select few regions within the state, as just three of them collectively accounted for 56.5% of Minas Gerais' GDP in 2015. Belo Horizonte contributed 40.2%, Uberlândia contributed 8.2%, and Juiz de Fora contributed 8.1% to the state's GDP. The columns in Table 3.8 below present the participation of the regions in the total value produced in the state for each economic activity.

Agricultural activity is mainly concentrated in Varginha (17.8%), Uberaba (15.0%), Uberlândia (14.0%) and Patos de Minas (12.5%). Together, they accounted for 59.7% of the state's agricultural value added in 2015. On the other hand, Ipatinga, Barbacena, Governador Valadares and Teófilo Otoni together contributed less than 8%.

In the industrial sector, production is concentrated in Belo Horizonte (45.9%), Uberlândia (8.7%), and Uberaba (7.7%). Together, they accounted for 62.3% of the state's industrial value added. In contrast, Teófilo Otoni, Governador Valadares, Patos de Minas, and Varginha collectively contributed only 7.8%.

In terms of public administration, Belo Horizonte had the largest share (37.1%), followed by Juiz de Fora (9.8%) and Uberlândia (8.2%). However, the smallest shares in the sector were observed in Teófilo Otoni and Governador Valadares.

The same pattern was observed for the services sector. Only three regions accounted for 56.5% of the sector in the state: Belo Horizonte (39.6%), Juiz de Fora (9.2%), and Uberlândia (7.7%). On the other hand, Governador Valadares, Barbacena, and Teófilo Otoni represented only 8.5% of the total in the period.

Table 3.8 – Share of Regions in the Gross Value Added by Sector (%)

Region	Agriculture	Industry	Public Administration	Services
Belo Horizonte	2.60	45.91	37.06	39.63
Montes Claros	5.26	5.23	5.01	5.15
Teófilo Otoni	2.79	0.75	2.83	2.97
Governador Valadares	2.56	0.97	2.83	2.84
Ipatinga	1.36	4.44	3.39	3.28
Juiz de Fora	8.96	5.14	9.85	9.20
Barbacena	1.62	4.05	2.98	2.72
Varginha	17.79	3.62	7.06	6.43
Pouso Alegre	6.03	5.46	7.12	6.63
Uberaba	15.04	7.66	5.04	4.49
Uberlândia	13.98	8.67	8.18	7.67
Patos de Minas	12.50	2.53	2.90	3.02
Divinópolis	9.50	5.55	5.76	5.98
Total	100%	100%	100%	100%

Source: Compiled by the author based on IBGE (2015).

However, given the geographic and productive heterogeneity of Minas Gerais, a more detailed analysis of its constituent regions is necessary. Figure 3.11 depicts the sectoral production composition of the regions comprising the state.

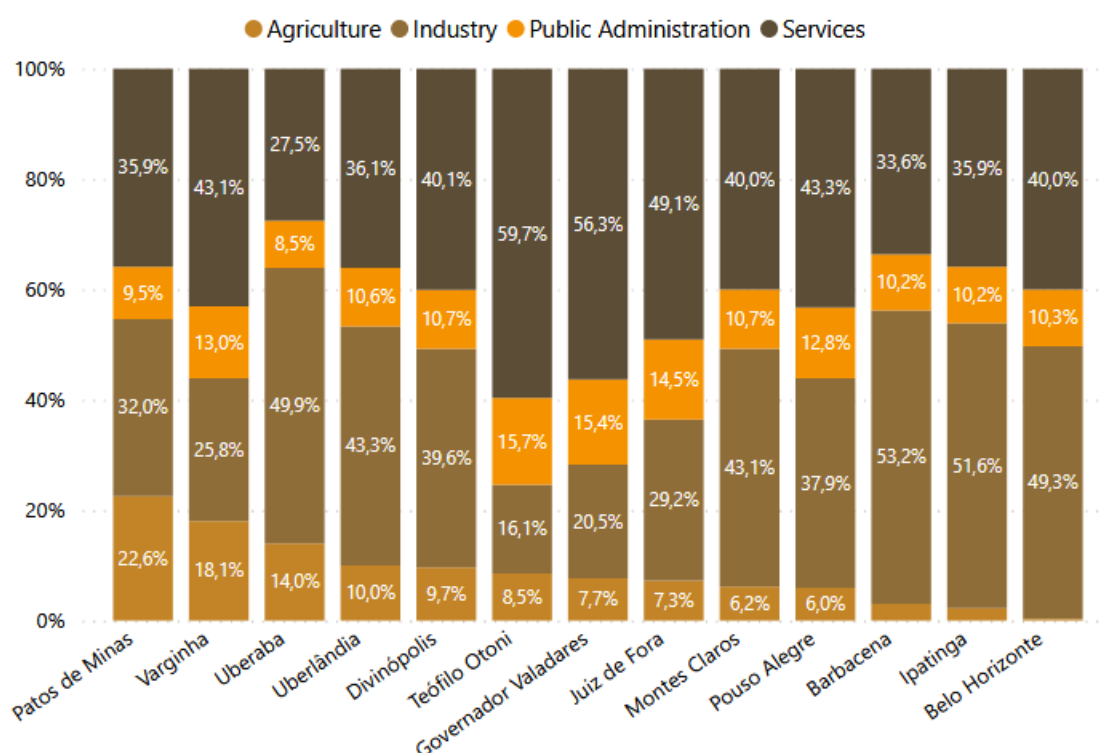
In 7 out of the 13 regions of Minas Gerais, including Patos de Minas, Varginha, Divinópolis,

Juiz de Fora, Pouso Alegre, Teófilo Otoni, and Governador Valadares, the services sector holds the largest portion of the GDP. Notably, in the latter two regions, services make up more than half of the total value generated. These services are primarily focused on activities such as financial intermediation, transportation, information and communication services, accommodation and food services, as well as scientific, technical, and administrative endeavors.

In contrast, Uberaba, Uberlândia, Montes Claros, Barbacena, Ipatinga, and Belo Horizonte have a larger share of the industrial sector. In Uberaba and Uberlândia, industrial activities are concentrated in food manufacturing, energy and natural gas production, and the manufacturing of inorganic chemical products. Barbacena and Ipatinga are known for their crude iron production and steelmaking, while Montes Claros has a strong presence in construction and electric power generation. Belo Horizonte stands out for its petroleum refining, manufacturing of non-metallic mineral products, and construction activities.

The agricultural sector holds the smallest portion of the total value produced in all regions of the state. Nonetheless, it is worth noting that its contribution is significant in Patos de Minas (22.6%), Varginha (18.1%), and Uberaba (14.0%). These regions also excel in food production, which exhibits strong intersectoral connections, with agriculture and livestock being the primary suppliers.

Figure 3.11 – Composition of the GDP in the regions of Minas Gerais



Source: Elaborated by the author based on IBGE (2015).

Considering the study's focus on analyzing the impacts of climate change on the agricultural sector, it becomes crucial to delve deeper into the distribution of production across different regions. Below, Table 3.9 provides insights into the share of the crops considered in the IMAGEM-MG model, utilized within this study, relative to the total output in Minas Gerais.

We observe that the production of rice and cereals is concentrated in three regions: Uberaba, Varginha, and Barbacena, which together account for more than 70% of the state's production. Meanwhile, maize production is concentrated in the regions of Patos de Minas, Uberlândia, and Uberaba. Together, they account for nearly 60% of the production in Minas Gerais. As raw materials, they are utilized across various industries, including food, beverages, animal feed, biofuels, and even in the manufacturing of construction materials.

Regarding cotton and other fibers, production is heavily concentrated in Patos de Minas, which alone accounts for almost 90% of the production. Fibers, in general, have a wide range of industrial uses, not only in the production of fabrics for clothing but also in the manufacturing of automotive components such as carpets and upholstery; in papermaking; and they have also been used as a basis for biofuel production (from cottonseed, for example).

The production of sugarcane and soybeans is also concentrated in Patos de Minas, Uberlândia, and Uberaba. While sugarcane production is more evenly distributed among these regions, soybean production is notably uneven. Collectively, these three regions contribute to 80% of the state's sugarcane production, with Uberaba alone accounting for over 60% of soybean production. These crops are essential not only for food production but also for their significant role in potential biofuel production. For instance, ethanol is primarily derived from sugarcane and maize. Uberaba (51.10%) and Patos de Minas (33.75%) play prominent roles in the state's biofuel production.

In terms of cultivating temporary crops, Uberlândia emerges as a prominent player (38.61%), closely followed by Divinópolis (27.63%). On the other hand, for permanent crop production, Montes Claros and Varginha take the lead, collectively contributing to over 50% of the state's total output. Notably, orange production, a permanent crop, is predominantly concentrated in the regions of Patos de Minas, Uberaba, and Uberlândia. In addition, Minas Gerais is the largest producer of coffee in Brazil, with production concentrated in Varginha (40.63%) and Juiz de Fora (15.7%).

Cattle farming is concentrated in the regions of Uberaba, Uberlândia, Patos de Minas, and Divinópolis. Together, they account for about 55% of the production in the state. On the other hand, the raising of cows and dairy production is more evenly distributed among the regions of Divinópolis (14.93%), Patos de Minas (14.47%), Uberlândia (10.76%), Juiz de Fora (10.5%), and Varginha (9.54%). Swine production is more concentrated in Juiz de Fora (35.18%) and Divinópolis (21.65%), while poultry farming and egg production are centered in Divinópolis (25.53%), Pouso Alegre (22.83%), and Montes Claros (16.84%).

As for forestry, activities are more concentrated in Montes Claros (28.54%) and Teófilo Otoni (21.59%). Meanwhile, fishing is predominant in the regions of Divinópolis (33.81%) and Varginha (25.67%).

Belo Horizonte (27.60%), Uberlândia (24.6%), and Uberaba (10%) concentrate the production of food and beverages. The latter region also plays a fundamental role in the production of manure and fertilizers (66.16%) and agrochemicals (88.13%).

Table 3.9 – Share of Agricultural Sector Production by Regions in Minas Gerais (%)

Sector&Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice&Cereals	0.37	0.93	0.25	0.64	0.11	0.24	20.64	20.93	6.28	29.45	12.52	7.30	0.35
Maize	1.06	3.49	0.92	0.95	0.37	4.14	5.17	14.51	4.10	17.19	18.07	23.47	6.55
Cotton&Fibers	0.62	10.41	0.04	0.04	0.06	0.13	0.05	0.10	0.10	0.10	0.13	88.13	0.10
Sugarcane	1.15	1.66	0.00	0.00	0.00	0.37	0.92	7.13	0.95	22.00	26.17	32.67	6.97
Soybeans	0.21	3.41	1.02	0.76	0.23	2.20	0.20	3.39	0.17	63.06	11.54	10.88	2.94
Temporary C.	14.28	1.14	0.25	0.03	0.04	0.42	0.01	6.41	0.25	9.99	38.61	0.92	27.63
Orange	0.29	8.69	2.51	1.71	0.40	4.27	4.27	8.58	7.09	19.05	11.77	28.12	3.23
Coffee Beans	0.06	0.70	0.98	0.98	2.89	15.70	0.31	40.63	9.52	3.45	11.74	7.23	5.82
Permanent C.	5.15	34.06	2.82	4.94	1.08	7.59	2.36	17.70	8.43	4.02	4.73	3.34	3.77
Cattle	4.56	8.63	6.95	6.45	1.02	5.78	1.24	6.03	3.71	20.01	14.95	10.68	10.00
Dairy	5.50	3.13	4.40	6.47	1.47	10.50	4.83	9.54	6.83	7.17	10.76	14.47	14.93
Swine	4.72	2.38	1.14	0.50	0.11	35.18	2.66	5.98	1.28	2.21	11.68	10.52	21.65
Poultry	3.28	16.84	1.31	0.61	0.19	2.29	1.34	10.26	22.83	4.31	9.45	1.75	25.53
Forestry	5.04	28.54	21.59	6.89	2.53	6.29	0.27	0.88	2.34	1.79	2.05	11.55	10.24
Fishing	4.12	0.75	0.74	1.09	0.22	6.06	0.39	25.67	9.71	2.43	11.88	3.11	33.81
Food&Beverage	27.25	1.89	2.00	2.60	1.51	6.70	2.22	4.94	4.96	10.06	24.60	5.38	5.88
Biofuels	0.05	2.40	1.76	0.03	0.05	0.07	0.00	0.1	0.01	51.10	6.77	33.75	3.81
Inorg. Chem.	65.15	2.27	0.27	0.01	5.25	1.51	2.33	9.71	2.04	0.93	2.45	0.00	8.07
Manure&Fert.	4.58	0.01	0.01	0.01	0.01	7.19	0.00	5.53	5.32	66.16	4.47	3.33	3.38
Agrochemicals	0.06	0.01	0.29	0.01	0.02	0.11	0.00	0.04	0.01	88.35	0.01	11.08	0.01

Source: Compiled by the author based on IBGE (2015).

Note*: BH - Belo Horizonte; MC - Montes Claros; TO - Teófilo Otoni; IPT - Ipatinga; JF - Juiz de Fora; BC - Barbacena; VA - Varginha; PA - Pouso Alegre; UBE - Uberaba; UBR - Uberlândia; PM - Patos de Minas; DV - Divinópolis.

4 SIMULATIONS AND RESULTS

The main purpose of the simulations in this study is to forecast and analyze the economic impacts of climate change in the state of Minas Gerais, taking into account both regional and sectoral perspectives. This section will detail the procedures employed for the simulations using the econometric and the IMAGEM-MG model, along with the resulting outcomes.

4.0.1 Results: Econometric Model

As presented in Table 4.1, the model for agriculture was estimated in four stages, where agricultural productivity was first regressed against climate and geographical variables, while other explanatory variables were gradually included. This procedure aims to assess the stability of temperature and precipitation coefficients in terms of both sign and statistical significance (Mendelsohn; Nordhaus; Shaw, 1994).

The first column indicates estimation without control variables, while the subsequent columns display estimations with the gradual addition of controls. In the second column, controls for geographic characteristics such as altitude, latitude, and longitude were added. In the third column, primary factors like capital and labor were included as controls. In the fourth column, controls for the social capital of agricultural producers were incorporated.

The results indicate that the climate variables remain statistically significant with the gradual inclusion of explanatory variables, providing a certain stability to the model. The coefficients of the model suggest that the effect of spring and summer temperature on agricultural productivity is not linear and may depend on the magnitude of the temperature. Initially, an increase in temperature may have a negative effect on agricultural productivity, but as the temperature rises, this effect may become less negative or even positive. For winter and autumn temperatures, the relationship is reversed.

Furthermore, it is observed that an increase in precipitation during spring and summer has a positive but non-linear effect on agricultural productivity. As precipitation increases, the effect may become less positive or even negative. Regarding the behavior of the variable in winter and autumn, the relationship is reversed: initially, an increase in rainfall levels during these seasons reduces agricultural productivity, and this effect may become less negative or even positive as precipitation increases.

The variables related to capital and labor included in the model show varying degrees of significance. With the exception of membership (the number of agricultural establishments associated with cooperatives), all other factors increase agricultural productivity. For example, the use of machinery, fertilizers, and pesticides, the number of workers, and the education level of the establishment owners.

Table 4.1 – Regression Results

Dependent Variable: Log (Agricultural Productivity)				
Variables	Model 1	Model 2	Model 3	Model 4
Temperature (Spring/Summer)	-1.766*** (0.163)	-2.357*** (0.157)	-2.351*** (0.158)	-2.134*** (0.154)
Temperature (Fall/Winter)	1.039*** (0.088)	1.233*** (0.084)	1.235*** (0.086)	0.940*** (0.083)
<i>Temperature</i> ² (Spring/Summer)	0.034*** (0.004)	0.045*** (0.003)	0.045*** (0.003)	0.042*** (0.003)
<i>Temperature</i> ² (Fall/Winter)	-0.023*** (0.002)	-0.025*** (0.002)	-0.024*** (0.002)	-0.019*** (0.002)
Precipitation (Spring/Summer)	0.011*** (0.002)	0.008*** (0.001)	0.008*** (0.001)	0.010*** (0.001)
Precipitation (Fall/Winter)	-0.009*** (0.001)	-0.013*** (0.001)	-0.013*** (0.001)	-0.013*** (0.001)
<i>Precipitation</i> ² (Spring/Summer)	-0.000*** (0.000)	-0.000*** (0.000)	-0.000*** (0.000)	-0.000*** (0.000)
<i>Precipitation</i> ² (Fall/Winter)	0.000*** (0.000)	0.000*** (0.000)	0.000*** (0.000)	0.000*** (0.000)
Altitude	- (-)	-0.000*** (0.000)	-0.000*** (0.000)	-0.000*** (0.000)
Latitude	- (-)	-0.043*** (0.004)	-0.043*** (0.004)	-0.028*** (0.004)
Longitude	- (-)	0.016*** (0.003)	0.016*** (0.003)	0.012*** (0.004)
Machinery / Area	- (-)	- (-)	2.113*** (0.572)	1.374** (0.658)
Log (Workers)	- (-)	- (-)	0.053*** (0.011)	0.004 (0.012)
Expenditures (R\$) / Area	- (-)	- (-)	0.015*** (0.004)	0.010*** (0.003)
Log (Irrigated Land)	- (-)	- (-)	- (-)	0.045*** (0.004)
% Fertilizer Usage	- (-)	- (-)	- (-)	5.078*** (0.495)
% Membership	- (-)	- (-)	- (-)	-0.248*** (0.043)
% Higher Education	- (-)	- (-)	- (-)	0.652*** (0.133)
% Pesticide Usage	- (-)	- (-)	- (-)	0.063 (0.048)
Observations	4,629	4,629	4,629	4,467
R-squared	0.236	0.302	0.316	0.370

Source: Compiled by the author based on the results of the econometric model.

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Note*: The residual distribution can be seen in Figure A1, Appendix A.

Table 4.2 presents the results of the baseline model estimation for agricultural productivity across different crop types. The productivity of selected crops shows varied responses to climate variables. For instance, higher temperatures during spring and summer seasons can slightly increase productivity for crops like coffee and maize, but decrease it for permanent crops and sugarcane. Conversely, increased temperatures during autumn and winter could reduce coffee and maize productivity while enhancing productivity for temporary crops and soybeans. Additionally, higher rainfall during summer and spring may lead to improved productivity for coffee, maize, and temporary crops and higher precipitation during autumn and winter could reduce maize productivity.

Table 4.2 – Regression Results: Agricultural Productivity by Crop Type

Dependent Variable: Log (Agricultural Productivity by crop <i>k</i>)								
Variables	Agriculture	Coffee	Orange	Permanent Crops	Soybeans	Maize	Sugarcane	Temporary Crops
Temperature (Spring/Summer)	-2.134*** (0.154)	2.497*** (0.924)	1.888 (1.227)	-3.150** (1.536)	0.0118 (0.077)	0.766*** (0.172)	-1.380** (0.661)	-1.310** (0.624)
Temperature (Fall/Winter)	0.940*** (0.084)	-1.923*** (0.525)	-0.901 (0.962)	2.378** (0.951)	0.111** (0.045)	-0.732*** (0.110)	0.190 (0.353)	0.851*** (0.326)
<i>Temperature</i> ² (Spring/Summer)	0.042*** (0.004)	-0.053** (0.021)	-0.045* (0.026)	0.064* (0.033)	-0.002 (0.002)	-0.019*** (0.004)	0.030** (0.014)	0.021 (0.014)
<i>Temperature</i> ² (Fall/Winter)	-0.019*** (0.002)	0.047*** (0.013)	0.026 (0.023)	-0.052** (0.022)	-0.002* (0.001)	0.019*** (0.003)	-0.006 (0.008)	-0.011 (0.007)
Precipitation (Spring/Summer)	0.010*** (0.001)	0.026*** (0.006)	0.008 (0.009)	-0.009 (0.006)	-0.001 (0.001)	0.013*** (0.001)	0.004 (0.003)	0.009*** (0.003)
Precipitation (Fall/Winter)	-0.013*** (0.001)	0.012 (0.008)	-0.001 (0.006)	0.004 (0.004)	0.002* (0.002)	-0.008*** (0.002)	-0.004 (0.003)	0.003 (0.002)
<i>Precipitation</i> ² (Spring/Summer)	-0.000*** (0.000)	-0.000*** (0.000)	-0.000 (0.000)	0.000*** (0.000)	0.000 (0.000)	-0.000*** (0.000)	-0.000 (0.000)	-0.000*** (0.000)
<i>Precipitation</i> ² (Fall/Winter)	0.000*** (0.000)	-0.000 (0.000)	-0.000 (0.000)	0.000 (0.000)	-0.000 (0.000)	0.000*** (0.000)	0.000 (0.000)	0.000* (0.000)
Observations	4,467	798	783	2,034	1,213	3,712	1,860	3,892
R-Squared	0.370	0.525	0.736	0.482	0.491	0.625	0.280	0.561

Source: Compiled by the author based on the results of the econometric model.

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Note: The model incorporated the explanatory variables, but they were omitted from the table.

In summary of the projected productivity shocks, Tables 4.3 and 4.4 present the results of simulations from the econometric model by regions of Minas Gerais under RCP 4.5 and RCP 8.5 scenarios. It is important to emphasize that these values should be interpreted as the impact of climate change on average agricultural productivity, considering only the effects of temperature and precipitation changes, given the technological conditions of the baseline scenario. Under the RCP 4.5 scenario, the findings indicate that a majority of the regions are expected to witness a decline in agricultural productivity. Among them, Barbacena, Juiz de Fora, Pouso Alegre and Varginha are projected to be the most adversely affected, while Uberaba and Uberlândia are anticipated to experience increases in productivity.

Table 4.3 – Effects of Climate Change on Agricultural Productivity (RCP 4.5 scenario)

Region	2050		2080	
	Mean	Std.	Mean	Std.
Barbacena	-29%	0.043	-41%	0.038
Belo Horizonte	-14%	0.059	-16%	0.129
Divinópolis	-17%	0.069	-16%	0.122
Governador Valadares	-8%	0.122	-18%	0.106
Ipatinga	-16%	0.052	-26%	0.044
Juiz de Fora	-23%	0.051	-35%	0.039
Montes Claros	-12%	0.082	-8%	0.161
Patos de Minas	-7%	0.246	-12%	0.292
Pouso Alegre	-27%	0.066	-39%	0.051
Teófilo Otoni	-10%	0.133	-20%	0.122
Uberaba	5%	0.221	24%	0.406
Uberlândia	3%	0.117	15%	0.217
Varginha	-28%	0.031	-33%	0.043

Source: Compiled by the author based on the results of the econometric model.

Under the RCP 8.5 scenario, it is noticeable that Barbacena, Juiz de Fora, Pouso Alegre and Varginha remain the most affected regions, and the magnitude is close to that observed in the RCP 4.5 scenario. Special attention should be given to the projected scenario for the regions of Uberaba, Uberlândia, and Patos de Minas in 2080, as the projections indicate that the magnitude of the increase in agricultural productivity will be even greater.

Table 4.4 – Effects of Climate Change on Agricultural Productivity (RCP 8.5 scenario)

Region	2050		2080	
	Mean	Std.	Mean	Std.
Barbacena	-34%	0.039	-41%	0.046
Belo Horizonte	-20%	0.066	-5%	0.208
Divinópolis	-21%	0.076	-1%	0.176
Governador Valadares	-17%	0.126	-19%	0.084
Ipatinga	-26%	0.050	-25%	0.040
Juiz de Fora	-28%	0.060	-34%	0.039
Montes Claros	-18%	0.077	2%	0.213
Patos de Minas	-3%	0.248	-40%	0.375
Pouso Alegre	-34%	0.047	-39%	0.065
Teófilo Otoni	-14%	0.135	-18%	0.103
Uberaba	11%	0.315	85%	0.820
Uberlândia	6%	0.162	64%	0.408
Varginha	-33%	0.027	-24%	0.071

Source: Compiled by the author based on the results of the econometric model.

In light of the results presented above, it becomes imperative to analyze projections of changes in agricultural productivity by crop. This is essential because the decrease or increase in productivity in a specific region may be attributed to the adaptation of particular crops to adverse climate conditions. Given the climate and agricultural production heterogeneity, Tables 4.5 and Table 4.6 below present the projected variations in agricultural productivity for different crops under the RCP 4.5 and RCP 8.5 scenarios.

In the scenario of RCP 4.5, by the year 2050, a significant portion of the decline in agricultural productivity in Barbacena can be attributed to losses in the productivity of temporary crops (-64%), primarily comprising fruits such as grape, banana, apple, papaya, etc. Furthermore, the region is expected to undergo a notable decrease in maize productivity (-22%), which represents over half of the total agricultural production in the area. In Juiz de Fora, where more than 80% of its agricultural output relies on coffee production, a reduction in coffee productivity of approximately 53% is anticipated. Interestingly, despite coffee accounting for more than 70% of agricultural output in the region, Varginha is poised to experience a slight reduction in this crop (-10%) but a more pronounced decline in productivity for permanent crops (-53%) and sugarcane (-22%). Meanwhile, Pouso Alegre is expected to face a more substantial reduction in sugarcane productivity (-21%).

In Montes Claros, the productivity of coffee, maize, and temporary crops would undergo the largest reductions, respectively. In Governadores Valadares, the agricultural productivity loss would affect the most representative crops of the region, such as coffee (-69%), maize (-39%), and sugarcane (-34%). Similarly, in Ipatinga, where approximately 79% of agricultural

production is focused on coffee, the productivity loss is estimated at 58%. In Teófilo Otoni, where a large portion of agricultural production is centered around coffee, sugarcane, and cassava, the most significant productivity loss would occur for coffee (-66%), maize (-38%), sugarcane (-24%), and cassava (-32%), which falls under the category of temporary crops. Meanwhile, in Divinópolis, the reduction in agricultural productivity would be driven by both permanent and temporary crops as well as maize.

In regions like Uberaba and Uberlândia, the projected rise in agricultural productivity is expected to originate from an increase in sugarcane yields, with increments of 35% and 27%, respectively. This remarkable upsurge is particularly noteworthy given sugarcane's preference for warmer temperatures. On the other hand, there would be a significant reduction in orange productivity (-58%), temporary crops (-39%), and maize (-31%) in Uberaba. Meanwhile, in Uberlândia, such decrease would be more prominently observed for permanent crops (-52%), coffee (-44%), and maize (-31%).

Under the RCP 8.5 scenario, coffee is expected to face a substantial decline in productivity, particularly in regions where it constitutes the majority of agricultural output. The regions most adversely affected by this productivity loss include Governador Valadares (-75%), Ipatinga (-70%), Juiz de Fora (-67%), Patos de Minas (-50%), and Teófilo Otoni (-74%). Conversely, for Uberlândia and Uberaba, where an increase in productivity is projected, this gain would once again be driven by sugarcane, with an anticipated rise of 56% and 44%, respectively.

The aforementioned findings align with a study published by Embrapa (Brazilian Agricultural Research Corporation) in 2008, examining global warming and the evolving geography of agricultural production in Brazil. The study, considering the RCP 4.5 and RCP 8.5 scenarios for the year 2050, suggested that coffee would be among the crops most adversely affected, particularly in the states of São Paulo and Minas Gerais. In contrast, sugarcane was anticipated to experience increased productivity, particularly in the Central-West region of Brazil. However, the study emphasizes that these crops would become increasingly dependent on supplementary irrigation during drier periods.

This holds true for regions in Minas Gerais that have a historical pattern of higher temperatures, lower rainfall, and lower levels of agricultural development, such as Montes Claros, Governador Valadares, and Teófilo Otoni. Despite the considerable significance of sugarcane cultivation in these areas, fluctuations in temperature and precipitation are anticipated to result in reduced productivity in the absence of adequate irrigation.

Table 4.5 – Climate Change Effects on Crop Productivity (RCP 4.5)

RCP 4.5 (2050)							
Region	Coffee	Orange	Permanent Crops	Soybeans	Maize	Sugarcane	Temporary Crops
Barbacena	-0.15	0.18	-0.64	-0.02	-0.22	-0.27	-0.36
Belo Horizonte	-0.46	-0.06	-0.61	-0.12	-0.36	-0.22	-0.27
Divinópolis	-0.23	-0.14	-0.52	-0.11	-0.29	-0.08	-0.32
Governador Valadares	-0.69	-0.10	-0.32	-	-0.38	-0.34	-0.26
Ipatinga	-0.58	-0.10	-0.30	-	-0.35	-0.27	-0.22
Juiz de Fora	-0.53	-0.02	-0.41	-0.03	-0.27	-0.28	-0.18
Montes Claros	-0.58	-0.25	0.04	-0.12	-0.40	-0.20	-0.33
Patos de Minas	-0.41	-0.17	-0.64	-0.18	-0.30	-0.24	-0.25
Pouso Alegre	0.01	0.04	-0.14	-0.04	-0.13	-0.21	-0.12
Teófilo Otoni	-0.66	-0.11	-0.15	-	-0.38	-0.24	-0.32
Uberaba	-0.25	-0.58	-0.39	-0.19	-0.31	0.35	-0.26
Uberlândia	-0.44	-0.40	-0.52	-0.17	-0.31	0.27	-0.14
Varginha	-0.10	-0.16	-0.53	-0.09	-0.20	-0.22	-0.20

Source: Compiled by the author based on the results of the econometric model.

Table 4.6 – Climate Change Effects on Crop Productivity (RCP 8.5)

Region	RCP 8.5 (2050)						
	Coffee	Orange	Permanent Crops	Soybeans	Maize	Sugarcane	Temporary Crops
Barbacena	-0.38	0.17	-0.57	0.01	-0.33	-0.42	-0.24
Belo Horizonte	-0.62	-0.08	-0.54	-0.14	-0.42	-0.34	-0.12
Divinópolis	-0.39	-0.18	-0.50	-0.12	-0.38	-0.16	-0.23
Governador Valadares	-0.75	0.01	-0.25	-	-0.46	-0.47	-0.09
Ipatinga	-0.70	-0.08	-0.18	-	-0.46	-0.43	-0.09
Juiz de Fora	-0.68	-0.01	-0.34	0.01	-0.39	-0.43	-0.04
Montes Claros	-0.65	-0.17	-0.06	-0.12	-0.40	-0.32	-0.17
Patos de Minas	-0.50	-0.17	-0.63	-0.19	-0.33	-0.30	-0.09
Pouso Alegre	-0.11	0.05	-0.18	-0.03	-0.22	-0.33	-0.03
Teófilo Otoni	-0.74	-0.03	-0.05	-	-0.44	-0.38	-0.14
Uberaba	-0.39	-0.69	-0.37	-0.22	-0.39	0.56	-0.16
Uberlândia	-0.54	-0.49	-0.48	-0.21	-0.39	0.44	-0.02
Varginha	-0.25	-0.24	-0.51	-0.10	-0.31	-0.29	-0.10

Source: Compiled by the author based on the results of the econometric model.

4.0.2 IMAGEM-MG Simulations and Results

In this section, we will delineate the simulation strategies utilized by the IMAGEM-MG model to project and analyze the projected changes in agricultural productivity according to IPCC climate scenarios, showcasing the causal relationships between the effects of agricultural productivity changes and their impacts on sectors and regions within the Brazilian state of Minas Gerais. The simulation is based on scenarios where agriculture in the regions of Minas Gerais experiences productivity gains or losses due to the impacts of climate change, encompassing shifts in precipitation and temperature levels, spanning the periods from 2021 to 2050 and from 2051 to 2080.

4.0.2.1 Model Closure

One of the fundamental steps for simulating a CGE model is defining the closure for both the base scenario and the climate change scenario. Closure refers to the set of endogenous and exogenous variables that define the mechanism of adjustment of the economy and how shocks will be incorporated, i.e., the operationalization hypothesis of the simulations (Carvalho, 2014). The reference and policy scenarios in the IMAGEM-MG model simulations have different closures, following those outlined in Tanure (2020).

First, a simulation was conducted disregarding the effects of climate change, where the performance of the main macroeconomic variables was determined according to historical average growth rates, referred to as the baseline scenario. Two climate change scenarios are considered in the policy simulations. In the RCP 4.5 scenario, considered optimistic, the magnitude of agricultural productivity changes is on average smaller than those observed in the RCP 8.5 scenario, which, in contrast, represents a scenario of intensified effects of climate change.

The simulations begin in the year 2015 and cover a time horizon of 65 years, divided into 13 five-year periods. The periodization was established to capture the effects of climate change and therefore comprises two 30-year periods corresponding to the climatological normal: i) from 2021 to 2050 and ii) from 2051 to 2080, each divided into 6 five-year periods. Shocks in the policy scenario are implemented within these five-year periods.

In the baseline scenario from 2015 to 2020, macroeconomic variables such as real GDP, aggregate employment, household consumption, government consumption, investment, and exports are treated as exogenous. To allow for exogenous growth, variables related to capital supply, shifts in household consumption, government consumption, export quantities, and shifts in investments are endogenous and are allocated in a manner that respects the determined behavior of the aforementioned macro variables. These shift variables adjust demand (or supply) curves or quantities within those curves to accommodate exogenous growth rates of specific variables.

The closure of the policy scenario is the same for both the RCP 4.5 and RCP 8.5 scenarios. The closure configuration also implies the adoption of the following assumptions: i) endogenous capital supply among sectors and regions; ii) exogenous aggregate employment, but with mobility between regions and sectors determined by the wage differential; iii) endogenous household consumption following GDP performance; iv) exogenous government consumption; v) external trade balance is given as a share of GDP; v) national investment is endogenous and guided by the differential rates of return and capital stock.

4.0.2.2 Baseline Scenario

In the baseline scenario, the results are shaped by the regional productive structure, the model's database, and the growth rates applied to key macroeconomic variables. Each region's sectoral activities adjust to achieve growth aligned with aggregate macroeconomic goals, influencing factor allocations across sectors and regions. This approach yields heterogeneous outcomes tied to the underlying framework. Table 4.7 displays the growth rates of exogenous macroeconomic variables used in the baseline scenario simulations. These variables reflect observed growth rates in the economy from 2015 to 2020.

Table 4.7 – GDP Growth in the Baseline Scenario (%)

Region	GDP (%)
Minas Gerais	-0.56
Belo Horizonte	-1.14
Montes Claros	0.38
Teófilo Otoni	0.78
Governador Valadares	0.64
Ipatinga	-0.99
Juiz de Fora	0.14
Barbacena	-1.06
Varginha	-0.01
Pouso Alegre	-0.64
Uberaba	-0.85
Uberlândia	-0.53
Patos de Minas	0.32
Divinópolis	-0.43

Source: Compiled by the author based on the IMAGEM-MG model.

4.0.2.3 Policy Scenario: Impacts of Climate Change on Regional Economic Indicators

This section presents the economic impact of climate change specifically for Minas Gerais, based on the outlined scenarios. The figures below show cumulative percentage changes relative to the baseline scenario, which excludes the effects of climate change on agriculture. Results for other Brazilian regions are not included due to the model treating the country as a single

region. Considering the significant disparities in economic, climate, and environmental factors, applying an average value of productivity shocks may not fully capture the diverse effects of climate change. Nonetheless, an average shock has been applied across the region to prevent potential spillovers between areas experiencing shocks and those that are not.

Table 4.8 reports the results of the impact of climate change on key economic indicators within the state of Minas Gerais, under RCP 4.5 and RCP 8.5 for 2050. The results for the year 2080 are presented in the Appendix section. According to projections from the IMAGEM-MG model, considering the differences between scenarios with and without climate change, climate change would negatively impact all key economic indicators within the regions of Minas Gerais.

The primary factor driving the decline in real GDP is the reduction in agricultural activity, resulting from decreased productivity of agricultural land due to climate change. This productivity loss necessitates increased land usage to maintain production levels, leading to a rise in land prices. Consequently, demand for other production factors like labor, capital, and intermediate inputs diminishes due to the limited resources available, redirected towards land. This shift in resource allocation alters firms' cost structures, making domestic products less competitive and adversely affecting export levels. Additionally, reduced demand for primary factors reduces household and firm incomes, dampening consumption of both intermediate and final goods. Ultimately, reduced consumption may lead to contractions in investment, negatively impacting employment and overall production levels.

Notably, economic indicators in Table 4.8—real GDP, household consumption, investments, exports, and employment—all exhibit negative trends in the regions of Minas Gerais, except for Varginha and Pouso Alegre. Under the RCP 4.5 and RCP 8.5 scenarios, Pouso Alegre shows positive variations in household consumption (0.15%), investments (0.77%), and employment (0.15%). Varginha, on the other hand, exhibits modest increases in investments under both scenarios (0.33% and 0.37%, respectively) and increases in household consumption and employment (0.04%) only under the more pessimistic scenario.

Patos de Minas is the region that exhibits the most significant negative variations in household consumption, investment, and employment under both scenarios. Uberaba, on the other hand, would be the most impacted region in terms of export reduction, with decreases of -0.89% and -0.31% under the two climate scenarios, respectively. This may suggest some vulnerability in export-oriented sectors, possibly due to climate impacts on production or increased costs.

Table 4.8 – Macroeconomic Results: 2050 (Cumulative Deviation %)

Region	Hous. Consump.		Investments		Exports		Employment	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Belo Horizonte	-0.06	-0.01	-0.14	-0.03	-0.20	-0.09	-0.06	-0.01
Montes Claros	-0.13	-0.04	-0.20	-0.08	-0.39	-0.14	-0.13	-0.04
Teófilo Otoni	-0.13	-0.02	-0.37	-0.08	-0.40	-0.15	-0.13	-0.02
Governador Valadares	-0.17	-0.03	-0.51	-0.13	-0.40	-0.15	-0.17	-0.03
Ipatinga	-0.16	-0.04	-0.51	-0.20	-0.28	-0.11	-0.16	-0.04
Juiz de Fora	-0.38	-0.11	-1.27	-0.53	-0.49	-0.20	-0.38	-0.11
Barbacena	-0.07	-0.03	-0.08	-0.04	-0.22	-0.09	-0.07	-0.03
Varginha	-0.01	0.02	0.33	0.37	-0.55	-0.24	-0.01	0.02
Pouso Alegre	0.15	0.04	0.77	0.33	-0.25	-0.11	0.15	0.04
Uberaba	-0.10	-0.08	-0.96	-0.54	-0.26	-0.11	-0.10	-0.08
Uberlândia	-0.24	-0.02	-0.77	-0.06	-0.89	-0.31	-0.24	-0.02
Patos de Minas	-1.36	-0.46	-3.87	-1.56	-0.37	-0.12	-1.36	-0.46
Divinópolis	-0.33	-0.10	-0.86	-0.29	-0.20	-0.08	-0.33	-0.10

Source: Compiled by the author based on IMAGEM-MG results.

Although the shocks used to simulate the climate change scenario in this study are applied directly only to agriculture, their effects indirectly impact other sectors due to the interdependence of production chains in a real economy. Consequently, reductions in agricultural land productivity extend to various sectors and regions involved in the trade of goods and inputs. Hence, it is crucial to observe these effects at the sectoral level to assess the true magnitude of the impact of climate change on the economy.

It is clear that the impacts of climate change vary significantly from one region to another. It is imperative to take into account the specific reliance of each region on different agricultural crops. The fluctuations in productivity, whether losses or gains, will result in a wide range of effects on economic activity levels, contingent upon the significance of each crop within its respective region. Table 4.9 illustrates the contribution of the agricultural crops analyzed in this study to the overall agricultural output of each region.

Table 4.9 – Share of Crops to Total Agricultural Output by Region (%)

Sector&Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice&Cereals	0.07	0.07	0.07	0.18	0.02	0.01	4.98	0.25	0.29	0.46	0.22	0.15	0.01
Maize	5.46	6.72	6.42	6.66	1.74	3.32	31.87	4.35	4.91	6.92	8.29	12.30	7.02
Cotton&Fibers	0.06	0.36	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.83	0.00
Sugarcane	11.18	6.07	0.03	0.03	0.03	0.56	10.77	4.05	2.15	16.79	22.74	32.44	14.16
Soybeans	2.28	14.02	15.11	11.37	2.26	3.79	2.62	2.17	0.43	54.26	11.31	12.18	6.73
Temporary C.	59.51	1.79	1.44	0.17	0.15	0.28	0.04	1.56	0.25	3.27	14.38	0.39	24.04
Orange	1.54	17.26	18.04	12.33	1.95	3.54	27.15	2.65	8.76	7.91	5.57	15.19	3.57
Coffee Beans	1.90	9.00	45.56	45.74	90.39	84.36	12.65	81.37	76.31	9.28	36.00	25.34	41.73
Permanent C.	18.01	44.71	13.35	23.51	3.46	4.15	9.92	3.61	6.88	1.10	1.48	1.19	2.75

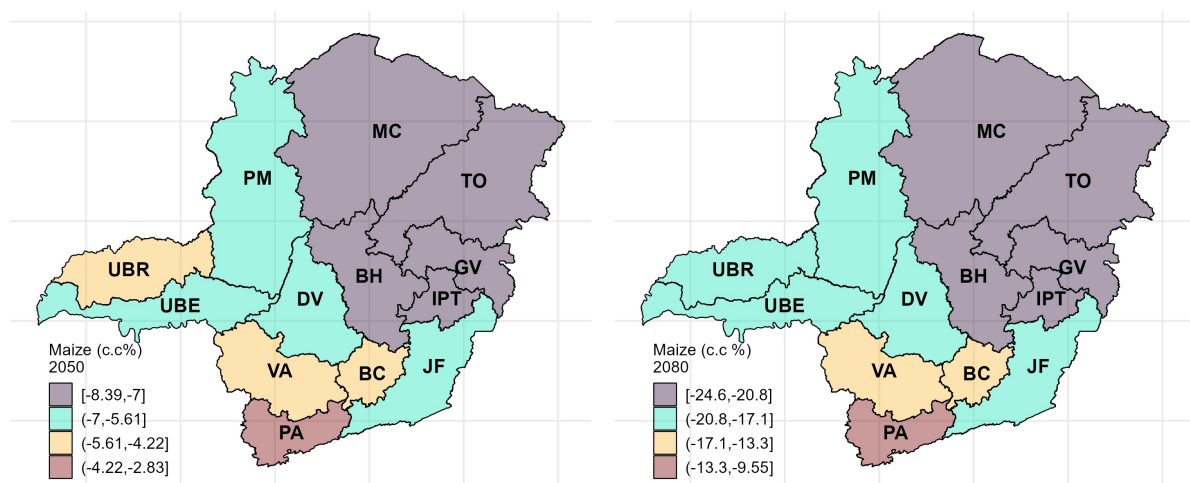
Source: Compiled by the author based on IBGE (2015).

Figures 4.1 to 4.14 illustrate the cumulative deviation of regional sectoral production compared to the baseline scenario. These results are categorized into 30 sectors of the economy, as previously mentioned. However, the following figures specifically highlight sectors involved in the production of coffee, oranges, maize, sugarcane, soybeans, and both permanent and temporary crops. These sectors, significantly affected by the productivity shock of the land, are economically significant in Minas Gerais and thus warrant individual analysis. For the results of other sectors, please refer to Tables A4 through A7 in Appendix A.

Figure 4.1 illustrates the projected maize production results by region under the RCP 4.5 scenario. Barbacena is expected to experience the most significant reduction in production, since maize accounts for 31.9% of its total agricultural production. Conversely, Pouso Alegre is projected to have the smallest reduction in production (2.84%), which is anticipated given the low contribution of maize cultivation to the region's agricultural output (approximately 5%).

The simulation further indicates that the magnitude of losses would intensify by 2080, with maize production projected to decrease by up to 20% compared to the baseline scenario, particularly in regions Patos de Minas (20.56%) and Barbacena (14.56%).

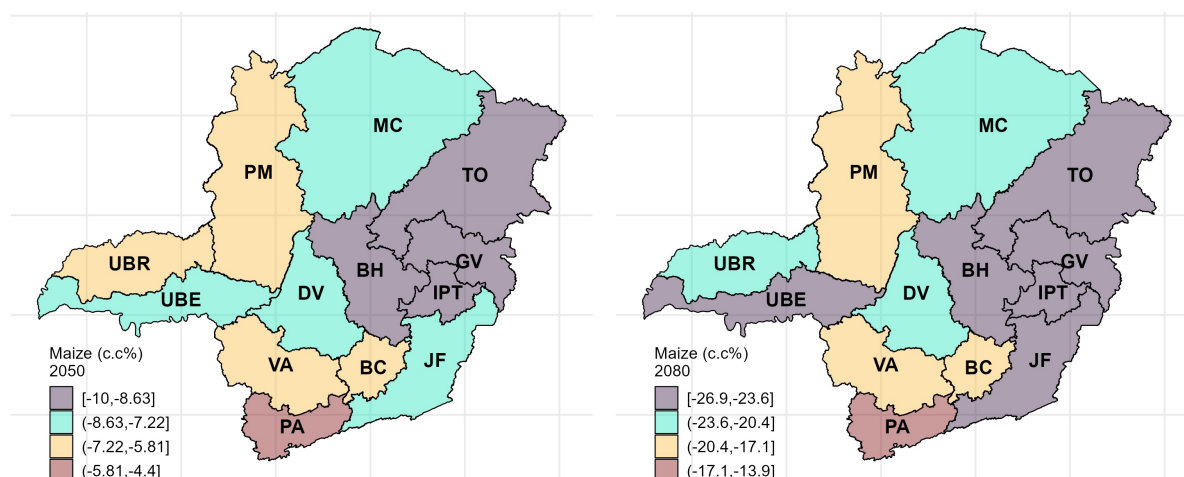
Figure 4.1 – Maize Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

In Figure 4.2, under the RCP 8.5 scenario, simulations indicate a greater magnitude of decline in maize production compared to the RCP 4.5 scenario. Once again, Barbacena are expected to face significant reductions due to the substantial share of maize in their agricultural production.

Figure 4.2 – Maize Output: Cumulative % Change (RCP 8.5)



Source: Elaborated by the author.

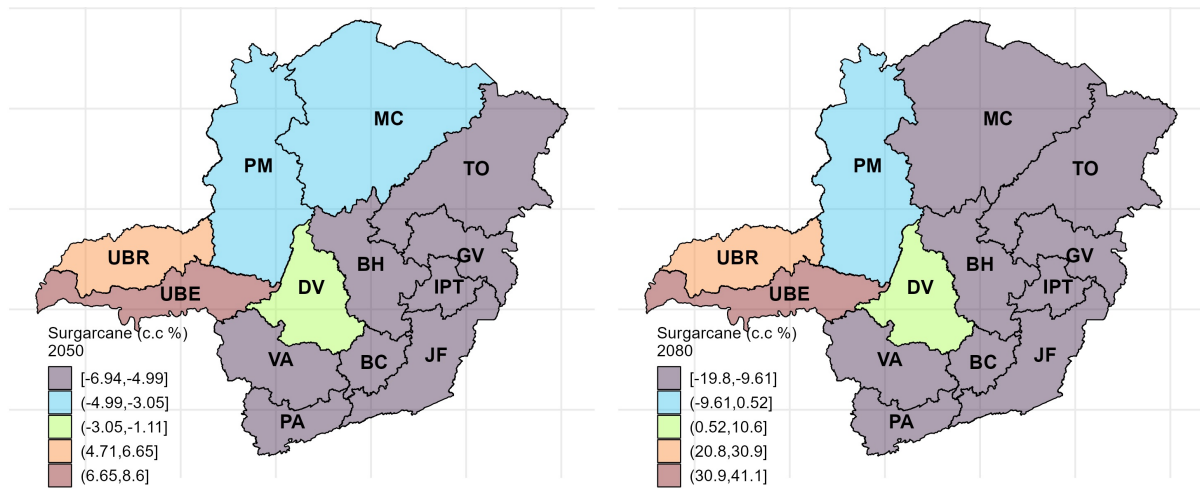
The sugarcane sector holds significant economic relevance due to its production of sugar and biofuels. Uberaba, Patos de Minas, and Uberlândia together account for about 80% of the state's sugar production, and they are the regions with the largest share in biofuel production: 51.10%, 33.75%, and 6.75%, respectively.

Figure 4.3 presents the results for the RCP 4.5 scenario. Sugarcane output is projected to decrease in all regions by 2080, except for Uberaba and Uberlândia, which would see increases of 41% and 29.8%, respectively, compared to the baseline scenario. This could be associated with the crop's productivity gains due to its better adaptation to higher temperatures.

Sugarcane also plays an important role in the agricultural production of Divinópolis, accounting for 14% of the total. Under the RCP 4.5 scenario, sugarcane cultivation is projected to gain productivity, with its production in 2080 being approximately 0.5% higher compared to the baseline scenario.

Special attention should be given to the Patos de Minas region, where production is projected to be 8.65% lower compared to the scenario without climate change. This could have significant negative implications for its economic activity levels, given that sugarcane is the crop with the largest share in the region's total agricultural production (32%).

Figure 4.3 – Sugarcane Output: Cumulative % Change (RCP 4.5)

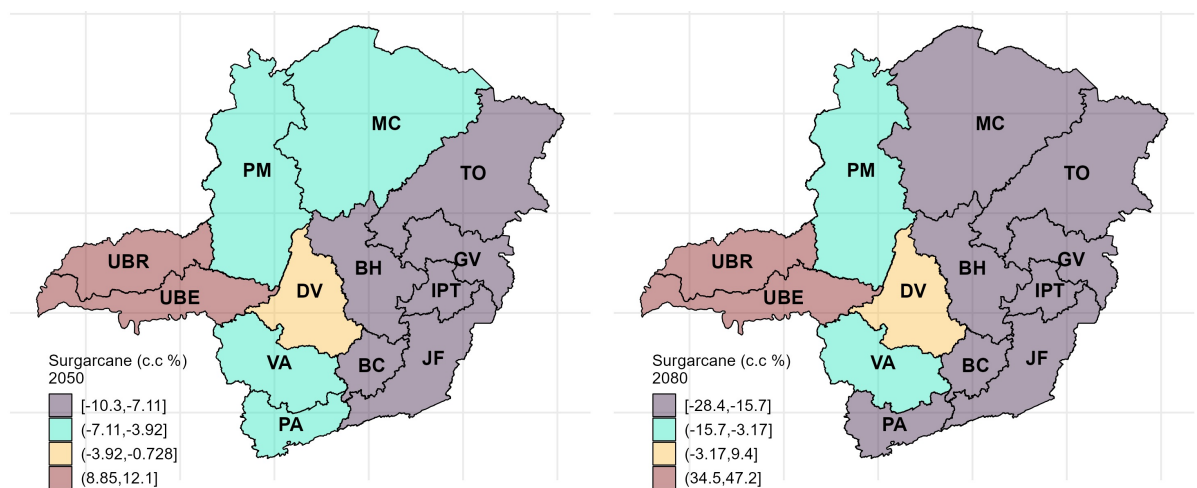


Source: Elaborated by the author.

Figure 4.4 showcases the simulation results under the RCP 8.5 scenario, highlighting a significant intensification. Generally, regions experiencing benefits would witness a rise in sugarcane output, whereas those adversely affected would undergo a heightened reduction.

Uberaba and Uberlândia would continue to benefit the most from increased sugarcane productivity, with production rising by 12% and 9% by 2050, and over 47% and 36% by 2080, respectively. In Divinópolis, sugarcane productivity is projected to improve by 2080, with production nearly 2% higher compared to the baseline scenario.

Figure 4.4 – Sugarcane Output: Cumulative % Change (RCP 8.5)



Source: Elaborated by the author.

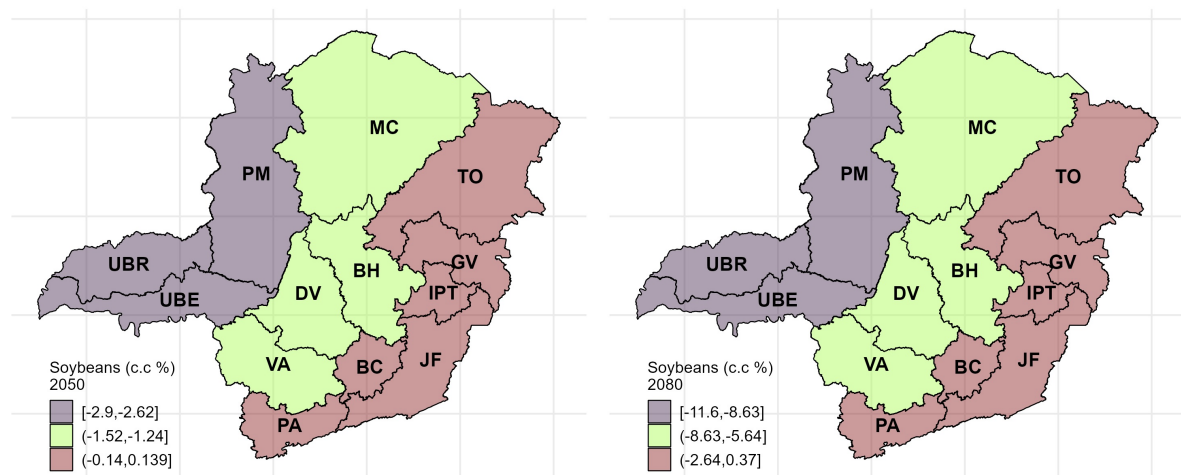
Regarding soybean cultivation, Uberaba, Uberlândia, and Patos de Minas account for approximately 85% of the total production in Minas Gerais. Additionally, soybeans play a significant role in the total agricultural output of each region. In Uberaba, soybean production

represents about 55% of the total agricultural production, while in Uberlândia and Patos de Minas, it accounts for around 12%.

Figure 4.5 illustrates the cumulative deviation of soybean production under the RCP 4.5 scenario. In both years, Uberaba, Uberlândia, and Patos de Minas would experience the largest cumulative deviations. By 2080, production in these regions would be approximately 10% lower compared to the scenario without climate change, which could result in significant economic losses for farmers and the agricultural sector.

Additionally, it is important to highlight the potential significant losses for Montes Claros and gains for Teófilo Otoni and Governador Valadares, where soybeans are the third-largest crop in terms of contribution to the region's agricultural production, accounting for about 14% of the total production. By 2080, production in this Montes Claros would be approximately 6% lower and 0.3% higher in Governador Valadares and Teófilo Otoni.

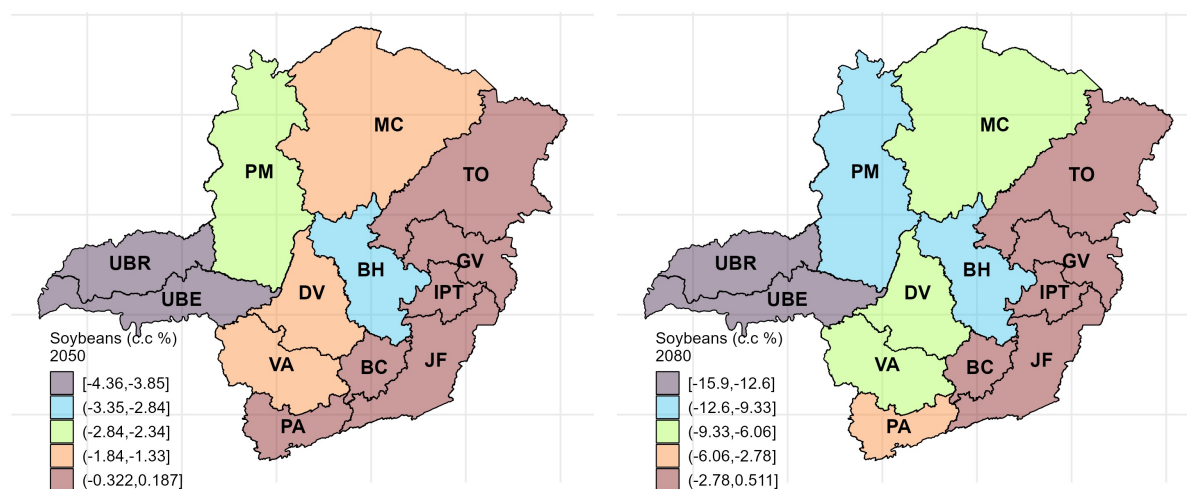
Figure 4.5 – Soybeans Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

Under the RCP 8.5 scenario, as illustrated in Figure 4.6, soybean production losses would intensify for Uberlândia, Uberaba, and Patos de Minas, which would continue to experience the greatest declines, with cumulative deviations ranging from 11% to 15%. In Montes Claros, soybean output is projected to be 8% lower, while Teófilo Otoni and Governador Valadares would see slight increases of 0.5%.

Figure 4.6 – Soybeans Output: Cumulative % Change (RCP 8.5)



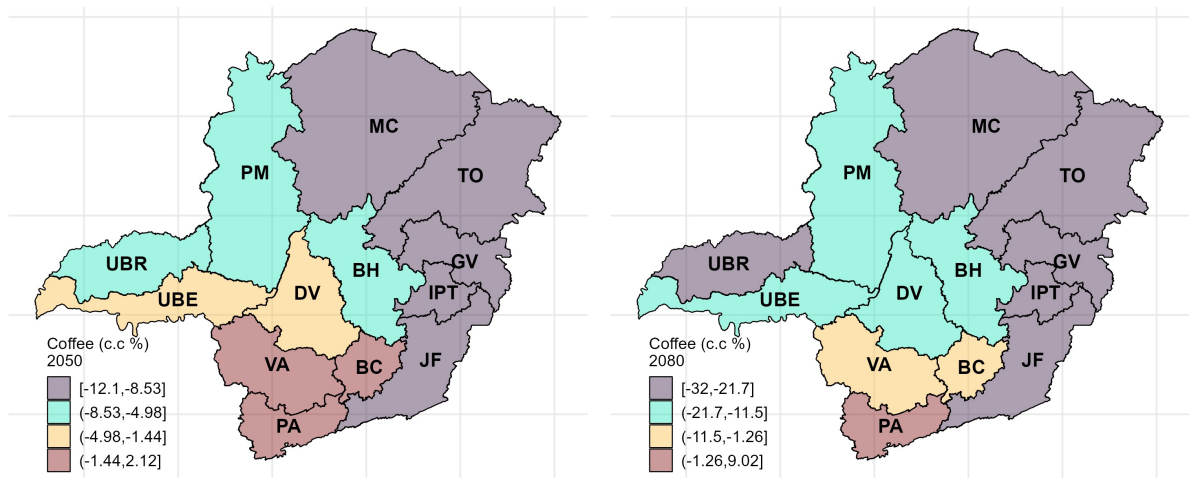
Source: Elaborated by the author.

Minas Gerais is the largest coffee producer in Brazil, accounting for over 50% of the national production (IBGE, 2021). As depicted in Table 4.9, coffee holds significant importance in the total agricultural production of the following regions: Ipatinga (90%), Juiz de Fora (84%), Varginha (81%), Pouso Alegre (76%), Governador Valadares (45%), Teófilo Otoni (45%), Divinópolis (41%), Uberlândia (36%), and Patos de Minas (25%).

Figure 4.7 illustrates the cumulative changes in coffee output under the RCP 4.5 scenario. Output variations would be observed across different regions, with some experiencing gains while others incur losses, and this trend is expected to intensify over time. In 2050, Varginha and Pouso Alegre would experience the least reductions in coffee productivity, and therefore, modest increases in production (0.49%, 2.10%, respectively). However, by 2080, this trend would not hold for Varginha, where there would be a cumulative reduction of 2.47%. In contrast, Pouso Alegre would see an increase of nearly 9% compared to the baseline scenario, even though the coffee productivity in the aforementioned would have decreased during this period (by about 4%).

On the other hand, the following regions, whose agricultural production heavily relies on coffee, would experience the highest decline in production: Governador Valadares (32%), Teófilo Otoni (30%), Ipatinga and Juiz de Fora (26%), Uberlândia (25%), and Patos de Minas (21%).

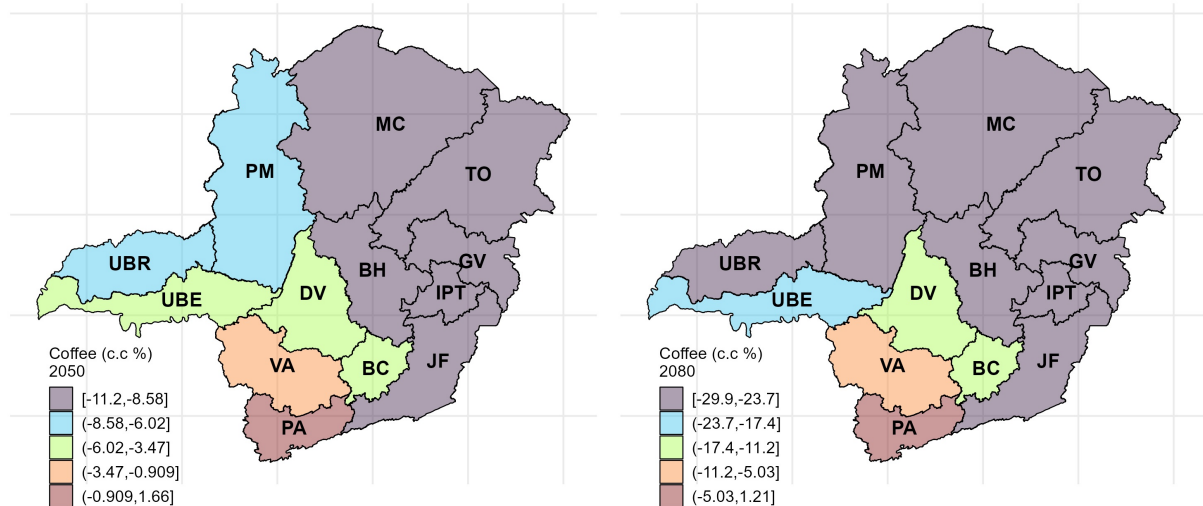
Figure 4.7 – Coffee Beans Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

Under the RCP 8.5 scenario (Figure 4.8), declines in coffee production are apparent across all regions except Pouso Alegre, which is forecasted to witness a modest increase of slightly over 1% by 2080, despite a decrease in coffee productivity of about 27%. Conversely, Varginha would undergo the smallest decline (1.63%), while the other regions with a significant share in coffee production mentioned earlier would encounter a cumulative reduction of more than 23%.

Figure 4.8 – Coffee Beans Output: Cumulative % Change (RCP 8.5)



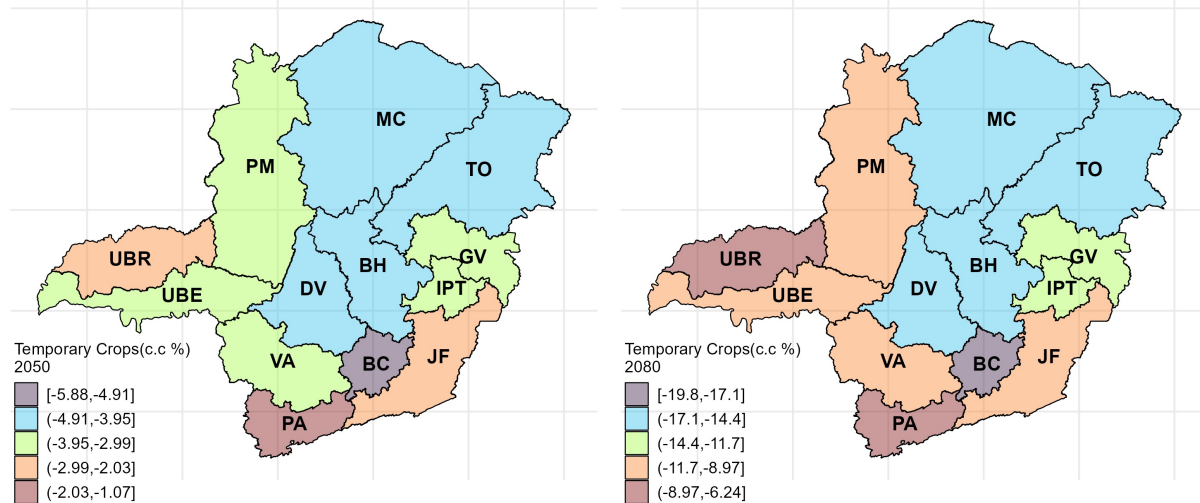
Source: Elaborated by the author.

In terms of temporary crop production, Belo Horizonte, Divinópolis, and Uberlândia stand out: the cultivation's share within the regions is 60%, 24%, and 15%, respectively.

Figure 4.9 presents the results of the deviation in production for the RCP 4.5 scenario. By 2080, Belo Horizonte, Divinópolis, and Uberlândia would experience a decrease in productivity

for these crops. Consequently, production would be approximately 15% lower in Belo Horizonte and Divinópolis, and 6% lower in Uberlândia, compared to a scenario without climate change.

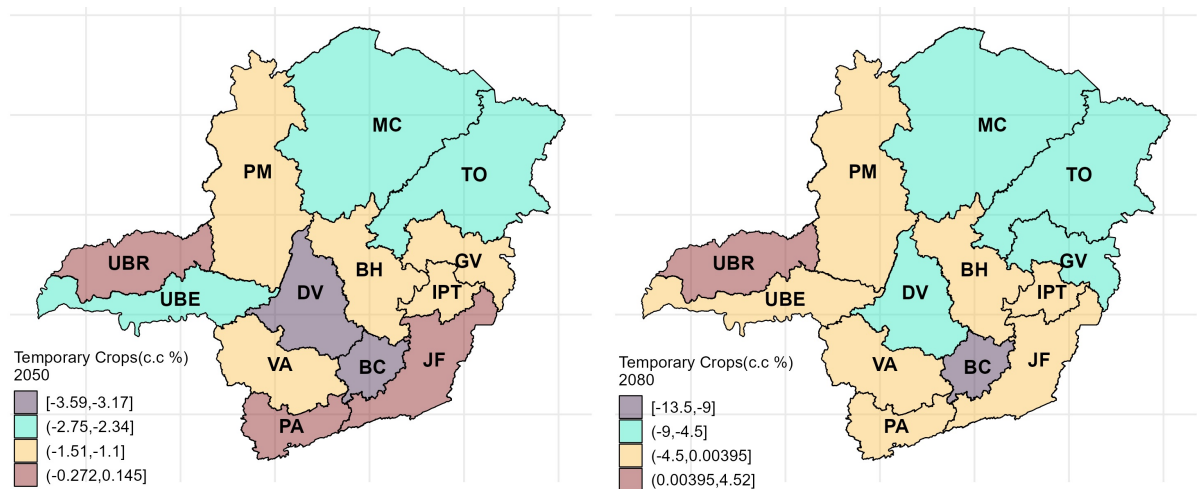
Figure 4.9 – Temporary Crops Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

In a more pessimistic scenario depicted in Figure 4.10, Belo Horizonte and Divinópolis would remain the most affected regions, but the magnitude of variation would be smaller compared to the RCP 4.5 scenario (3.5% lower in Belo Horizonte and 9% lower in Divinópolis). In contrast, Uberlândia would experience productivity gains in temporary crops (26%) and consequently, its production would be approximately 4.5% higher compared to the baseline scenario.

Figure 4.10 – Temporary Crops Output: Cumulative % Change (RCP 8.5)



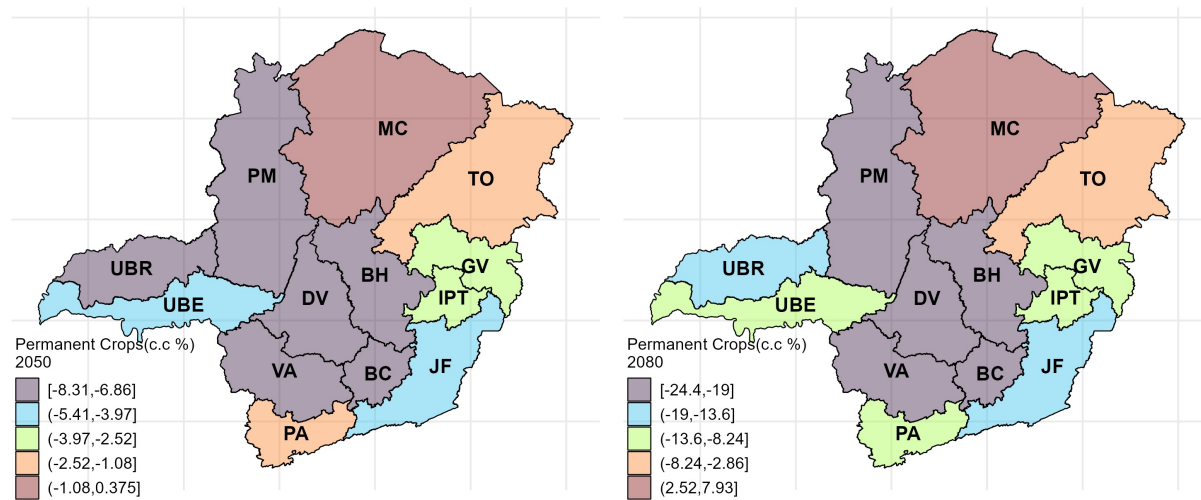
Source: Elaborated by the author.

Montes Claros, Governador Valadares, and Belo Horizonte have a significant portion of

agricultural production concentrated in permanent crops. Figure 4.11 presents the cumulative deviation in output for the RCP 4.5 scenario.

In both years, in addition to having the highest share in the state's production, Montes Claros would be the only region experiencing increases in production: 0.37% and 7.89%, respectively. This phenomenon may be attributed to the cultivation of crops that are more resilient to higher temperatures and low levels of precipitation. Nevertheless, Belo Horizonte would experience a 8% decrease in production, and Governador Valadares around a 4% decrease.

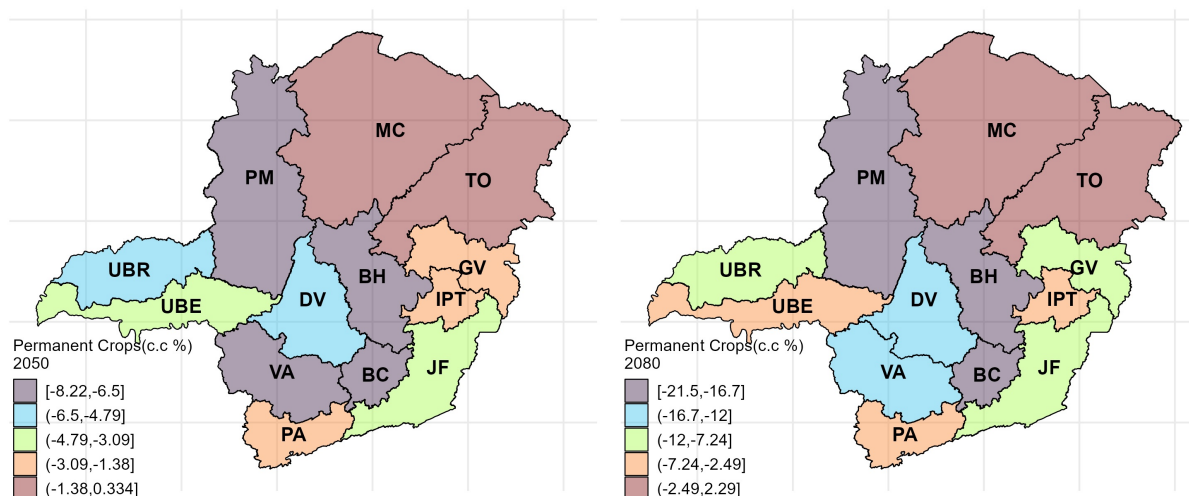
Figure 4.11 – Permanent Crops Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

Figure 4.12 below presents the results under the RCP 8.5 scenario, where losses and gains would intensify compared to the RCP 4.5 scenario. Montes Claros would show gains in output, which would be 2.27% higher compared to the baseline scenario. In contrast, Belo Horizonte and Governador Valadares would still undergo declines in permanent crop productivity and consequently, in their production, which would be 21% lower for Belo Horizonte and 10% lower for Divinópolis by 2080.

Figure 4.12 – Permanent Crops Output: Cumulative % Change (RCP 8.5)

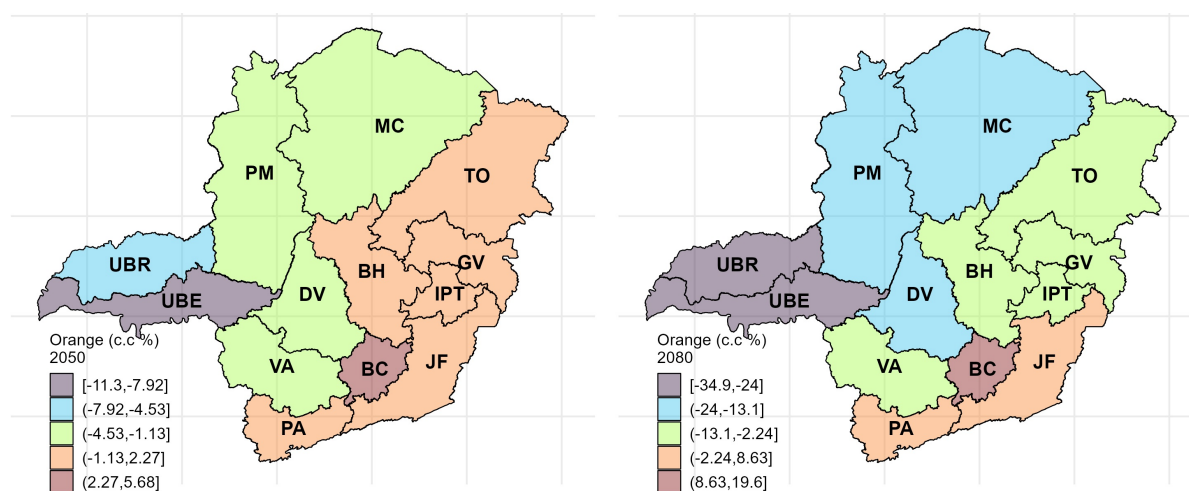


Source: Elaborated by the author.

Orange production, which is also a permanent crop, is one of the main crops in Barbacena (27%), Teófilo Otoni (18%), Montes Claros (17%), Patos de Minas (15%) and Governador Valadares (12%).

As depicted in Figure 4.13, under the RCP 4.5 scenario, Montes Claros and Patos de Minas would be the most impacted regions, given their high dependence on this crop. Orange production in Montes Claros and Patos de Minas would be approximately 16% lower, and in Teófilo Otoni and Governador Valadares, 4% and 6% lower compared to the baseline scenario. Conversely, Barbacena would experience gains in orange productivity (14%) and consequently in its production, which would be about 19.5% higher compared to the baseline scenario by 2080.

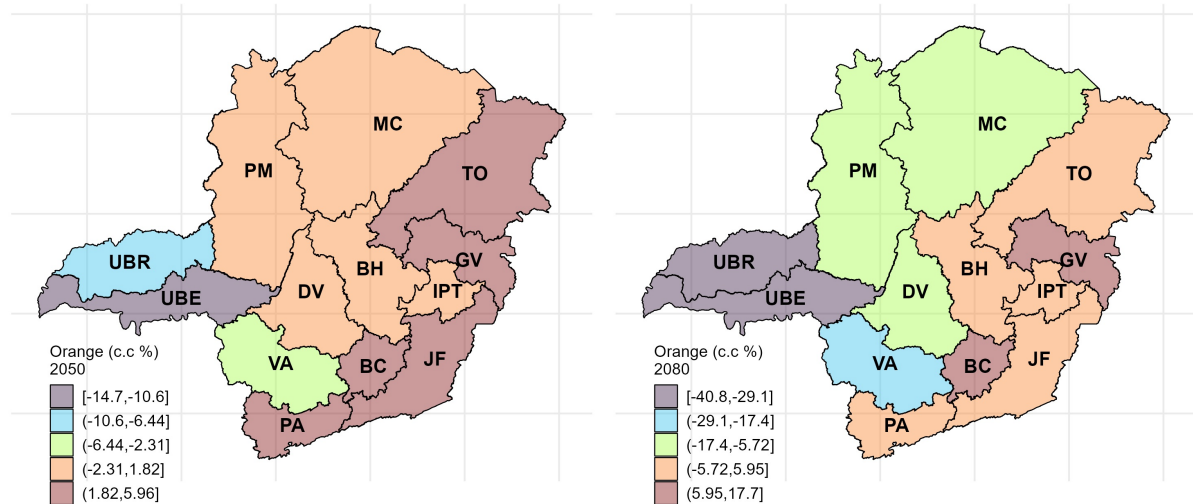
Figure 4.13 – Orange Output: Cumulative % Change (RCP 4.5)



Source: Elaborated by the author.

As for the RCP 8.5 scenario (Figure 4.14), by 2080, Montes Claros and Patos de Minas would still undergo declines in orange output (8% and 17% lower, respectively). In contrast, Teófilo Otoni and Governador Valadares would experience modest reductions in orange productivity (less than 10%), and therefore their production would be 5% and 8% higher compared to the baseline scenario. For Barbacena, there would be a productivity gain of 7%, and orange production would be almost 18% higher compared to a scenario without climate change.

Figure 4.14 – Orange Output: Cumulative % Change (RCP 8.5)

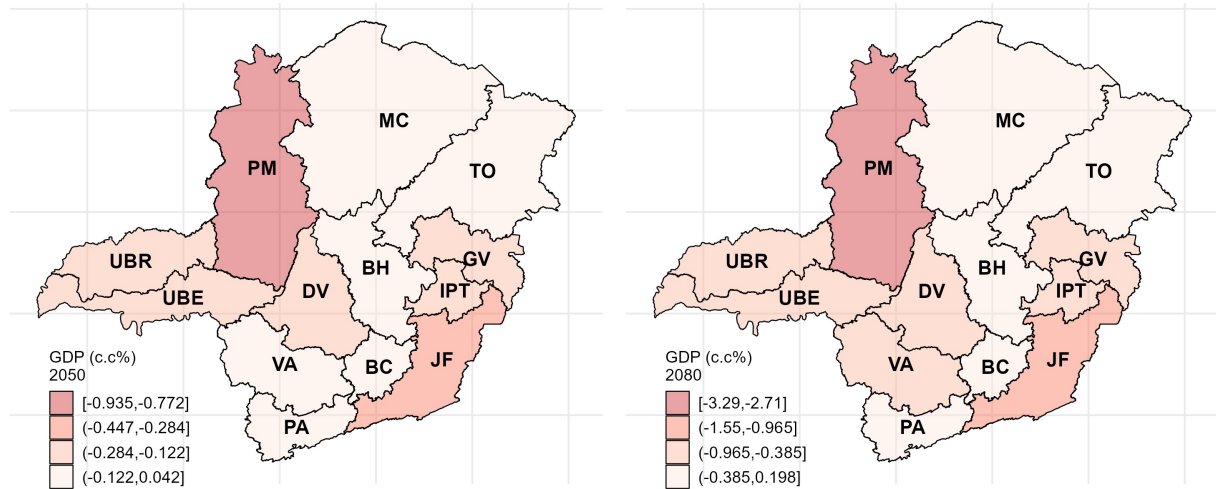


Source: Elaborated by the author.

The indirect effects of declining land productivity in the agricultural sectors reverberate throughout the rest of the economy, but this impact is conditioned by a range of factors. The more closely linked sectors are to agriculture, the greater the observed effects. Notably, this includes sectors that use agricultural products as inputs, such as the food sector, and sectors that produce agricultural inputs, like the fertilizer and agrochemicals. The results for these sectors can be found in Tables A2 to A7 in Appendix A.

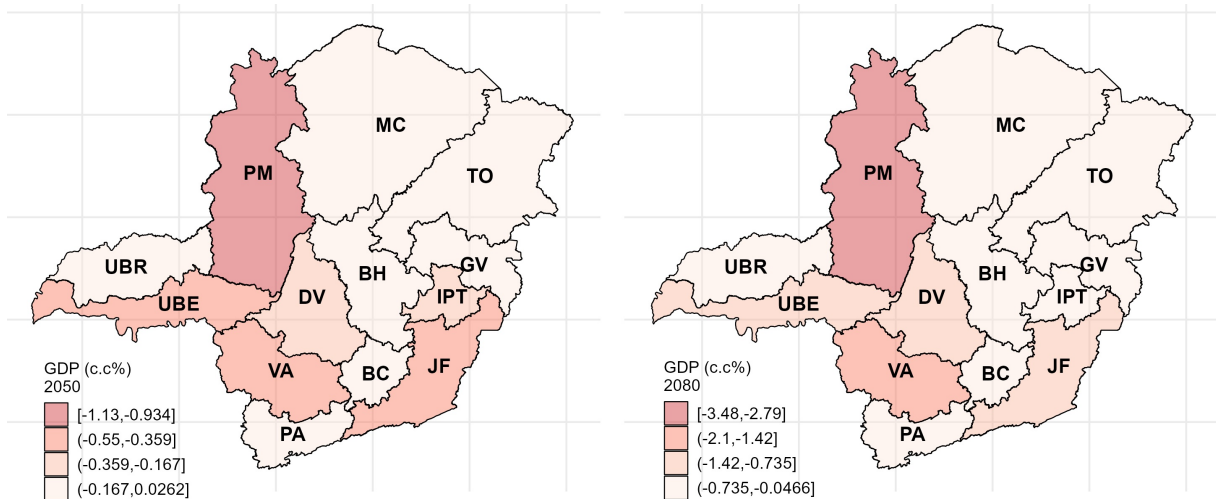
Therefore, the results of the variations in agricultural productivity and production discussed in the previous sections are essential for understanding the fluctuations in the GDP of the regions. Figures 4.15 and 4.16 illustrate the impact of climate change on GDP across regions in Minas Gerais, examining climate scenarios RCP 4.5 and RCP 8.5 for 2050 and 2080. We notice that regions are not uniformly affected. Generally, the effects are more pronounced in the pessimistic scenario (RCP 8.5), intensifying over time. Six distinct groupings can be identified in both scenarios.

Figure 4.15 – Real GDP (RCP 4.5) - Cumulative Deviation % from Baseline Scenario



Source: Elaborated by the author.

Figure 4.16 – Real GDP (RCP 8.5) - Cumulative Deviation % from Baseline Scenario



Source: Elaborated by the author.

The first consists of Patos de Minas and Juiz de Fora, which are the regions with the largest cumulative negative deviation in GDP. The former has the highest share of agriculture in the state's GDP composition (22%), while the latter has one of the lowest (7.3%).

In Patos de Minas, the performance can be attributed to a more diversified agricultural production concentrated in three main crops: sugarcane, coffee beans, and oranges, which hold some of the highest shares in Minas Gerais and within the region. Together, these crops account for over 70% of production. However, several of these key crops face significant productivity declines. The reduction in sugarcane productivity, in particular, can notably impact biofuel production (by about 2.5% under the RCP 8.5 scenario), since Patos de Minas is the second-

largest producer in the state, and more than 95% of the sugarcane produced in the region is used for ethanol and other biofuels production.

The impact on GDP can be intensified by the reduction in the production of these crops on the food and beverage sector (where 67% of orange production and 20% of coffee production are allocated) and on the fertilizer and agrochemicals sector, with 30% of production used in sugarcane cultivation and about 40% used in the cultivation of coffee, oranges, and soybeans.

In Juiz de Fora, production is heavily concentrated on coffee (84.3%), which would also experience a significant decline in productivity. Furthermore, the negative impact on GDP could be intensified by the reduction in manure and fertilizer production, as over 60% of these inputs are utilized for coffee cultivation.

The second group, comprising the regions of Belo Horizonte, Ipatinga, and Barbacena, exhibits the lowest share of agricultural activity in the composition of GDP compared to other regions of the state. We observe that both Belo Horizonte and Barbacena have the smallest cumulative deviations in GDP in the face of a climate change scenario. This observation indicates that the relatively low significance of agricultural activity, particularly in Belo Horizonte, may be a contributing factor to these outcomes. In the case of Barbacena, where nearly 60% of agricultural production is concentrated in maize and oranges, the productivity gain of oranges in all scenarios may have mitigated the negative effects, as maize experiences a significant decline in productivity. Furthermore, the variation in the region's GDP may be linked to the reduction in activity levels in the fertilizer and agricultural pesticides sectors, which are largely used in the cultivation of maize.

On the other hand, despite the low weight of agriculture in the composition of GDP in Ipatinga, the variations in GDP are still significant due to the high contribution of coffee (90%), which suffers from a loss in productivity. Additionally, the reduction in the production of fertilizers and agrochemicals, over 60% of which are used in coffee cultivation, further exacerbates the impact on GDP.

The third group, consisting of Varginha and Uberaba, exhibits similar cumulative GDP deviations. Additionally, they have the second and third highest shares of agricultural activity in GDP composition (18.1% and 14%, respectively) among all regions in the state. Production in Varginha is concentrated in coffee (over 80%), while in Uberaba it is focused on soybeans (54.2%) and sugarcane (16.8%).

In Varginha, the cumulative negative deviation may be attributed to the loss of coffee productivity in both scenarios and consequently the reduction in the production of fertilizers, manure, and agrochemicals, as over 60% of the region's production is used as input for coffee cultivation.

In Uberaba, even with significant gains in sugarcane productivity and consequent increases

in biofuel production and the food and beverages industry, since more than 50% and 40% of sugarcane output goes towards these two industries respectively, the substantial losses in soybean productivity, the region's largest crop, could undermine these gains. This would significantly impact exports and the food and beverages industry.

The fourth group, composed of Uberlândia, Divinópolis, and Teófilo Otoni, shares similar shares in their GDP composition, ranging from approximately 8.5% to 10%. In Uberlândia and Divinópolis, agricultural production is primarily concentrated in coffee, sugarcane, and temporary crops, which together account for about 70% of the regions' total production. Teófilo Otoni, on the other hand, has its production more concentrated in coffee (45%) and oranges (18%).

Uberlândia would experience productivity gains in sugarcane, leading to a consequent increase in economic activity in the food and beverage industry, as almost 80% of the output is used in this sector. However, coffee, the largest crop in the region, would undergo a significant decline in output, which would have considerable negative impacts on the fertilizer and agrochemical sectors, as their production is largely used for coffee cultivation and temporary crops.

The substantial losses in coffee beans and temporary crops in Divinópolis, despite some gains in sugarcane productivity, would negatively impact the region's GDP. The decline in these major crops, combined with the negative effects on the food and beverage sector that relies on these products, would outweigh the benefits from increased sugarcane productivity, leading to an overall economic downturn.

In Teófilo Otoni, significant losses in coffee would be observed under both scenarios, and orange cultivation would suffer under the RCP 4.5 scenario. Although soybeans, the third-largest crop in the region, would experience gains, these would not be sufficient to offset the negative impacts on coffee and orange production. The decline in GDP could also be attributed to the reduced production of coffee and oranges affecting the food and beverage sector, as 33% of coffee output and 54% of orange output are used by this sector.

As for the fifth group, the cumulative GDP deviation for Montes Claros and Governador Valadares remains negative but relatively stable under the RCP 4.5 and RCP 8.5 scenarios. Both regions have similar shares of agriculture in GDP composition (6.2% and 7.7%, respectively). Permanent crops represent the largest share in Montes Claros and the second-largest in Governador Valadares, where the primary crop is coffee.

It is important to note that although there is a relatively minor decrease in the productivity of permanent crops in Montes Claros, production still shows a positive cumulative deviation compared to the scenario without climate change. However, the significant losses in orange and soybean productivity, the second and third-largest crops in the region, may offset these gains.

Additionally, this effect on GDP could be intensified given that over 40% of the orange output is used as input in the food and beverage sector and for domestic consumption.

Similarly, given the considerable reduction in coffee and orange production in Governador Valadares, there could be a direct impact on the food and beverage sector, which uses more than 40% of these inputs. This would likely result in a negative effect on GDP.

In Pouso Alegre, agriculture comprises only 6% of GDP composition. Coffee cultivation represents roughly 76% of the region's agricultural production, followed by orange cultivation at 8.7%. Notably, Pouso Alegre was the sole region to exhibit a modest positive cumulative deviation in GDP following productivity shocks. This can be attributed to the fact that these crops experienced the least reductions in productivity or even increases. For instance, results show that orange and coffee output would present a positive cumulative deviation under all scenarios.

Furthermore, the impact on other non-agricultural sectors, such as the food and beverage industry, which uses coffee and oranges as inputs in the region, would also be low compared to other regions, contributing to the better GDP performance. However, by 2080 under the RCP 8.5 scenario, the magnitude of productivity changes intensifies (especially for coffee), potentially accounting for the negative cumulative GDP deviation witnessed in the region during this period.

In general, the results found in this study align with those reported in the literature (Assad et al., 2008; Margulis; Dubeux, 2011; Faria, 2012) in an analysis for Brazil, particularly concerning the increase (or decline) in the productivity of various agricultural crops. Sugarcane, for instance, would show productivity gains in regions of western Minas Gerais, similar to the findings of Margulis and Dubeux (2011), in an analysis of two climate scenarios in Brazil for the years 2050 and 2070: the more pessimistic A2-BR scenario, and the more optimistic B2 scenario. On the other hand, maize, soybeans, and coffee would be the most impacted crops, similar to the findings in this study. However, the analyses conducted by the aforementioned studies identify the crops that may be most impacted but do not provide a more detailed regional analysis to quantify the loss (or gain) in production and its impacts within the regions in Brazil, given its high level of economic and geographical heterogeneity.

Additionally, the results of this study align with those presented in the report developed by FEAM (2011) on the impacts of climate change on land use, energy, and agricultural productivity in Minas Gerais. The report indicates productivity gains for sugarcane and losses for soybeans, maize, and coffee. Moreover, it emphasizes that, although the statewide impact suggests low vulnerability for the analyzed crops, the impact varies significantly among the micro-regions. The relatively higher costs are particularly notable in the micro-regions located in the North and Northeast of Minas. The West, Southeast, and South of Minas also show costs that exceed their contributions to the state's GDP. Moreover, industrial sectors can be strongly affected, as demonstrated in the present study, especially those that supply inputs for agricultural production and those that rely on the sector.

In summary, climate change impacts exhibit heterogeneity within the same state. Varied geographical features, agricultural practices, and economic structures across regions create distinct vulnerabilities and adaptation needs. This diversity is notably reflected in the differing contributions of agriculture to the GDP across regions, the destinations of production, and the types of agriculture practiced, whether large or small-scale farming. These regional variations underscore the importance of tailored approaches in addressing the impacts of climate change.

4.0.2.4 Results on Regional Inequality

Climate change is expected to have varying impacts on different regions of Minas Gerais. Some regions, such as Patos de Minas, Juiz de Fora, Uberaba, Varginha, and Divinópolis, are projected to experience major negative impacts on agricultural productivity and their economies. Other regions like Ipatinga, Uberlândia, Governador Valadares, Montes Claros, and Teófilo Otoni may face moderate economic impacts due to climate change. Meanwhile, areas such as Barbacena, Belo Horizonte, and Pouso Alegre are likely to experience minor or negative impacts, albeit less severe compared to other regions.

In light of these findings, we calculated the Gini Index using the projected GDP for the regions to assess whether climate change-induced alterations in agricultural productivity are modifying the extent of regional inequalities in Minas Gerais.

The Gini Index is calculated from the Lorenz Curve, which, in turn, depicts the relationship between proportions of GDP and portions of a given population. The Gini coefficient is the value given to the area between the Lorenz curve and the 45-degree line representing perfect income equality among the analyzed population. The index ranges from 0 to 1, where zero signifies income distributed uniformly among the population, and 1 represents income entirely concentrated in one portion of the analyzed population (Medeiros, 2012). The Gini index is expressed as:

$$G = 1 - \sum_{k=0}^{n-1} (X_{k+1} - X_k)(Y_{k+1} + Y_k)$$

- G as the Gini index;
- X as the cumulative proportion of the regions;
- Y as the cumulative proportion of the GDP of the regions.

Table 4.10 presents the results of the Gini Index calculated for Minas Gerais under the baseline scenario (2020), RCP 4.5, and RCP 8.5, using the GDP at current prices for the 13 regions of Minas Gerais in the years 2050 and 2080. It is observed that there would be an increase in inequality (although modest) among the regions resulting from the estimated land productivity shocks according to the climate change scenarios.

Table 4.10 – Gini Index of GDP for Minas Gerais

Climate Scenario	Year	Gini Index	% Change
Baseline	2020	0.4513	-
RCP 4.5	2050	0.4517	0.09%
	2080	0.4527	0.33%
RCP 8.5	2050	0.4518	0.12%
	2080	0.4530	0.40%

Source: Compiled by the author based on the IMAGEM-MG results.

The projected increases in inter-regional inequality by 2080 under both climate scenarios underscore how climate change could exacerbate disparities in Minas Gerais. Shifting economic activity levels across regions will play a pivotal role, influenced significantly by their diverse productive structures. For instance, in the northern and northeastern regions of Minas Gerais, where family farming predominates with a focus on domestic consumption, adaptation strategies may encounter different challenges compared to the southern and western areas dominated by large-scale farmers geared towards exports. These regions are more poised for effective adaptation strategies due to their advanced productive structures and developmental levels.

Such differential impacts could precipitate various social consequences, including livelihood challenges for vulnerable communities, shifts in migration patterns, heightened food insecurity, and increased water scarcity. Addressing these disparities necessitates integrated policies that harmonize economic development with social equity. Tailored adaptation measures must cater to the specific needs and capacities of each region.

5 CONCLUDING REMARKS

This dissertation simulated the economic impacts of climate change in the Brazilian state of Minas Gerais, aiming to identify potential sectoral and regional economic losses. According to the literature, the effects of global climate change are heterogeneous, and few studies have analyzed this relationship in the specific regional context considered here.

The distinctiveness of this work lies in the use of climate scenarios, RCP 8.5 and RCP 4.5, from the IPCC and the regional Computable General Equilibrium (CGE) model, IMAGEM-MG. This model provides regional and sectoral detail, with the ability to adjust prices flexibly and shift factors between sectors and regions of Minas Gerais, making it suitable for capturing the heterogeneity of climate change effects within the regions in the state.

The simulations considered variations in agricultural productivity resulting from changes in precipitation and temperature levels between 2021 and 2080, based on data from INPE and IPCC. In summary, the magnitudes of negative and positive impacts are greater in the more pessimistic climate scenario (RCP 8.5) than in the less pessimistic scenario (RCP 4.5), as expected. This result is consistent with the literature on the topic. The economic projections indicated reductions in GDP and other key economic indicators under both climate scenarios considered. The magnitude of these variations varies by region and crop, especially due to the weight each one has in the region's economy and the productive heterogeneity within each area.

Moreover, from a regional perspective, a markedly distinct spatial pattern was observed. The climatic effects on the economy of Minas Gerais vary significantly across regions. In general, the economic projections showed reductions in GDP and other key economic indicators under both considered climate scenarios. Among the most negatively affected would be those where agriculture has a significant share in the composition of GDP. These regions generally exhibited high losses in land productivity rates for their most important crops.

For instance, Patos de Minas emerges as the region with the most substantial cumulative deviation in GDP across both scenarios. This trend aligns with the significant contribution of agriculture to its GDP composition. Conversely, Pouso Alegre exhibits the least pronounced reductions, possibly attributed to the lesser decline in productivity of its main crop, such as coffee, which may be associated with the region's climatic conditions (reduced frost occurrences, for example), and the lower participation of agriculture in its GDP composition.

It is crucial to emphasize that, according to IMAGEM-MG's projections, the poorest regions were not necessarily the most affected by the GDP reduction. However, this outcome is likely underestimated due to factors such as a high reliance on subsistence economy and informal employment in these areas, which the CGE model fails to capture. For instance, regions

located in the North and East of Minas, like Montes Claros, Teófilo Otoni, and Governador Valadares, primarily focus on family farming, unlike those in the West (Uberlândia, Uberaba), which are typically engaged in large-scale agriculture. Hence, the decline in economic activity could notably affect these regions, particularly concerning their capacity to adapt to climatic diversities, thereby potentially exacerbating regional disparities further.

Overall, productivity reductions were observed across all crops, albeit with some exceptions in specific regions. For example, in Uberaba and Uberlândia, sugarcane would experience productivity gains, which could be explained by their greater adaptability to adverse climatic conditions. The same trend could be observed for Barbacena, which would see productivity gains for oranges. However, despite gains in crops that hold significant weight in these regions, they would still undergo a decline in economic activity compared to a scenario without climate change. This could be attributed to spill-over effects, particularly for sectors heavily reliant on agriculture, such as input suppliers and users.

At this point, two aspects should be highlighted:

- The adaptive behavior of producers in response to climate effects mitigates extreme economic costs. As observed by [Mendelsohn et al. \(1994\)](#), calculations that only consider productivity declines without accounting for the possibility of producers adapting to more profitable activities tend to overestimate economic losses. Therefore, the market adjustment mechanism (including firm adaptation) and pricing incorporated into the CGE model tends to moderate the economic effects of climate change.
- It is worth noting that there are other non-climatic variables that could influence the outcomes but are not accounted for in the study. For example, shifts in trade regulations or subsidies can alter market conditions and affect farmers' profitability. Similarly, changes in labor laws or access to credit can impact agricultural practices and investment decisions. Moreover, socio-economic factors such as urbanization, income distribution, and land ownership patterns can also play a role in shaping the agricultural landscape and economic resilience to climate change.

Despite the comprehensive approach adopted in this study, inherent limitations exist in the models and methodologies used. While we assume that the models accurately estimated productivity variations for all crops, there remains a cascade of uncertainties in the data, projections, and methodological approaches employed. Climatic factors can interact in complex ways. For example, the combination of high temperature and low precipitation can have a different impact than the combination of high temperature and high precipitation; each crop responds differently to climatic variations at different stages of its maturation. Additionally, assumptions about the behavior of economic agents and the flexibility of markets affect the simulations.

These uncertainties can significantly impact the results, underscoring the need for cautious interpretation of the findings.

With these findings, this study sought to contribute to understanding the potential climate-related effects on the economy of Minas Gerais. Identifying potential economic losses resulting from climate change is relevant, given the growing need for implementing mitigation and/or adaptation policies to address and prevent more intense damages in the near future. This is especially crucial as natural disasters have become more frequent in recent decades, leading to greater economic losses. In this context, the agricultural sector requires special attention, as numerous studies highlight its vulnerability to the effects of climate change (Margulis and Dubeux, 2011; FIPE-FEAM, 2011; Domingues et al., 2016; Miyajima., 2018; Tanure, 2020).

In this context, leveraging inputs and technology can effectively mitigate the impacts of climate change on agricultural productivity. The adoption of cleaner and energy-efficient technologies has the potential to rapidly boost productivity, resulting in subsequent production increases. However, realizing these advancements requires investment, underscoring the importance of suitable incentive mechanisms and financing options. Hence, establishing agricultural insurance programs and providing financial aid to help farmers recover from climate-related losses are paramount. Additionally, price incentives and regulations (such as product certification and tariffs in certain areas) play a crucial role in encouraging sustainable practices and resilience to climate change.

Concurrently, facilitating broader access to resources is paramount for promoting the widespread adoption of sustainable agricultural practices. Implementing techniques like soil management and pasture-crop integration is crucial for reducing carbon dioxide emissions. Moreover, investing in research and development is imperative to identify adaptation possibilities and mitigation strategies for climate change, including funding studies to develop crop varieties more resilient to climate change and adaptive agricultural practices.

Moreover, assessing their potential economic implications, including the costs and benefits of adaptation and mitigation, is crucial. This is because the adaptive process is slow, spatially diverse, and varies among different crops, necessitating continuous efforts from producers. Such analysis provides producers and policymakers with valuable insights into the scale and direction of these impacts, ultimately underscoring the significant adaptive measures required to effectively address the challenges posed by climate change.

BIBLIOGRAPHY

- AGNOLUCCI, P.; LIPSIS, V. D. Long-run trend in agricultural yield and climatic factors in europe. v. 159, n. 3, p. 385–405, 2020.
- ALEXANDRATOS, N.; BRUINSMA, J. **World Agriculture Towards 2030/2050: The 2012 Revision**. [S.l.: s.n.], 2012.
- ANNUAL report 2014: CGIAR Research Program on Climate Change, Agriculture and Food Security. 2016. Publisher: CGIAR Research Program on Climate Change, Agriculture and Food Security.
- ASSAD, E. D.; PINTO, H. S.; JR, J. Z.; EVANGELISTA, S. E. M.; OTAVIAN, A. F.; AVILA, A. M. H. Aquecimento global e a nova geografia da produção agrícola no brasil. 2008.
- ASSAD, E. D.; PINTO, H. S.; MARTINS, S. C.; GROPPPO, J. D.; SALGADO, P. R.; EVANGELISTA, B.; VASCONCELLOS, E.; SANO, E. E.; PAVÃO, E.; LUNA, R.; CAMARGO, P. B.; MARTINELLI, L. A. Changes in soil carbon stocks in brazil due to land use: paired site comparisons and a regional pasture soil survey. v. 10, n. 10, p. 6141–6160, 2013.
- ASSUNÇÃO, J.; CHEIN, F. Climate change and agricultural productivity in brazil: future perspectives. v. 21, n. 5, p. 581–602, 2016. Publisher: Cambridge University Press.
- ATLAS Irrigação 2021: Uso da Água na Agricultura Irrigada (2ª edição). 2021.
- AYDINALP, C.; CRESSER, M. The effects of global climate change on agriculture. v. 3, 2008.
- BLUM, R. Agricultura familiar: estudo preliminar da definição, classificação e problemática. v. 3, p. 57–106, 2001. Publisher: EDIUPF.
- BRAGANÇA, A. Mudanças climáticas, adaptação e agricultura no brasil. 2015.
- BRAZIL; (ORGANIZATION), U. N. F. C. on C. C. (Ed.). **Fourth National Communication of Brazil to the UNFCCC**. [S.l.]: Ministry of Science, Technology and Innovations, 2020.
- BRIGGS, D.; KJELLSTROM, T.; Otto; LEMKE, B. Heat, human performance, and occupational health: A key issue for the assessment of global climate change impacts. v. 37, p. 97–112, 2016.
- BRÁS, T. A.; SEIXAS, J.; CARVALHAIS, N.; JÄGERMEYR, J. Severity of drought and heatwave crop losses tripled over the last five decades in europe. v. 16, n. 6, p. 065012, 2021.
- CALZADILLA, A.; REHDANZ, K.; BETTS, R.; FALLOON, P.; WILTSHIRE, A.; TOL, R. S. J. Climate change impacts on global agriculture. v. 120, n. 1, p. 357–374, 2013.
- CAMPOS, P. N. N. Crédito e produtividade rural no brasil: uma análise por bioma e por setores familiares e patronais. 2021. Disponível em: <<https://repositorio.ufmg.br/handle/1843/36076>>.
- CANZIANI, O.; PALUTIKOF, J.; LINDEN, P. van der; HANSON, C.; PARRY, M. **IPCC Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC**. 2007. 976 p.

CARVALHO, T. S. Uso do solo e desmatamento nas regiões da amazônia legal brasileira: condicionantes econômicos e impactos de políticas públicas. 2014. Disponível em: <<https://repositorio.ufmg.br/handle/1843/AMSA-9K9HGJ>>.

CARVALHO, T. S.; DOMINGUES, E. P. Projeção de um cenário econômico e de desmatamento para a amazônia legal brasileira entre 2006 e 2030. v. 26, p. 585–621, 2016. Publisher: Nova Economia.

CASTELLANOS, E.; AL et. Chapter 12: Central and south america. In: . [S.l.: s.n.], 2022.

CICOWIEZ, M.; MALEK, Z.; OOSTDIJK, S.; BANERJEE, O. **Synergies and Trade-offs Between Policies for Reducing Deforestation in Brazil**. 2022.

COSTA, C. C. d.; GUILHOTO, J. J. M.; BURNQUIST, H. L. Impactos socioeconômicos de reduções nas perdas pós-colheita de produtos agrícolas no brasil. v. 53, p. 395–408, 2015.

COSTA, W.; CORDEIRO, G.; IMPERATRIZ-FONSECA, V.; SARAIVA, A.; BIESMEIJER, J.; GIANNINI, T. **Projected climate change threatens pollinators and crop production in Brazil**. 2017.

DARWIN, R. Climate change and food security. 2001. Disponível em: <<https://ideas.repec.org/p/ags/uersab/33645.html>>.

DePaula, G. The distributional effect of climate change on agriculture: Evidence from a ricardian quantile analysis of brazilian census data. v. 104, p. 102378, 2020.

DIXON, P. B.; JORGENSEN, D. **Handbook of Computable General Equilibrium Modeling**. [S.l.]: Newnes, 2012.

DOMINGUES, E.; HADDAD, E.; PEROBELLI, F.; AZZONI, C.; GUILHOTO, J.; KANCZUK, F.; ALMEIDA, F. Impactos econômicos da mudança do clima no brasil. **ENCONTRO NACIONAL DE ECONOMIA**, v. 38, 2010.

DOMINGUES, E. P.; FERES, G.; HADDAD, E. **Avaliação de Impactos de Mudanças Climáticas sobre a Economia Mineira**. 2011.

DOMINGUES, E. P.; MAGALHÃES, A. S.; RUIZ, R. M. Cenários de mudanças climáticas e agricultura no brasil: impactos econômicos na região nordeste. **Belo Horizonte: Cedeplar**, 2008.

DOMINGUES, E. P.; MAGALHÃES, A. S.; RUIZ, R. M. Cenários de mudanças climáticas e agricultura no brasil: Impactos econômicos na região nordeste. v. 42, n. 2, p. 229–246, 2016. ISSN 2357-9226, 0100-4956.

EVENSON, R. E.; ALVES, D. C. Technology, climate change, productivity and land use in brazilian agriculture. p. 155, 2001. Publisher: Edward Elgar Publishing.

FARIA, W. R. **Modelagem e avaliação de fenômenos relacionados ao uso da terra no Brasil**. text, 2012.

FERES, J.; AL et. **Economia da Mudança do Clima no Brasil: Custos e Oportunidades**. 2009. Disponível em: <https://www.iis-rio.org/wp-content/uploads/2019/10/Economia_do_clima.pdf>.

FILHO, W. L.; BÖNECKE, J.; SPIELMANN, H.; AZEITEIRO, U. M.; ALVES, F.; CARVALHO, M. Lopes de; NAGY, G. J. Climate change and health: An analysis of causal relations on the spread of vector-borne diseases in brazil. v. 177, p. 589–596, 2018.

GATEAU, L.; TANNER, E.; RAPIDEL, B.; MARELLI, J.-P.; ROYAERT, S. Climate change could threaten cocoa production: Effects of 2015-16 el niño-related drought on cocoa agroforests in bahia, brazil. v. 13, 2018.

GOLDEMBERG, J.; COELHO, S. T.; GUARDABASSI, P. The sustainability of ethanol production from sugarcane. v. 36, n. 6, p. 2086–2097, 2008. Publisher: Elsevier.

GUIOT, W.; CRAMER, J. **Risks associated to climate and environmental changes in the Mediterranean region – A preliminary assessment by the MedECC**. 2019.

HAYHOE, K.; CAYAN, D.; FIELD, C. B.; FRUMHOFF, P. C.; MAURER, E. P.; MILLER, N. L.; MOSER, S. C.; SCHNEIDER, S. H. Emissions pathways, climate change, and impacts on california. v. 101, n. 34, 2004. Publisher: Proceedings of the National Academy of Sciences.

HOCHMAN, Z.; GOBBETT, D.; HORAN, H. Climate trends account for stalled wheat yields in australia since 1990. v. 23, 2017.

HORRIDGE, M. The TERM model and its database. In: WITTWER, G. (Ed.). **Economic Modeling of Water**. [S.l.]: Springer Netherlands, 2012. v. 3, p. 13–35. Series Title: Global Issues in Water Policy.

HORRIDGE, M.; MADDEN, J.; WITTWER, G. The impact of the 2002–2003 drought on australia. v. 27, n. 3, p. 285–308, 2005.

(IBGE), I. B. de Geografia e E. **Censo Agropecuário de 2017**. 2017. Place: Rio de Janeiro.

IIZUMI, T.; RAMANKUTTY, N. Changes in yield variability of major crops for 1981–2010 explained by climate change. v. 11, n. 3, p. 034003, 2016. Publisher: IOP Publishing.

IPCC Fifth Assessment Report. 2014. Disponível em: <<https://archive.ipcc.ch/report/ar5/>>.

KURUKULASURIYA, P.; ROSENTHAL, S. Climate change and agriculture: A review of impacts and adaptations. 2013.

LEE, H.; ROMERO, J. (Ed.). **IPCC, 2023**. 2023. Edition: First. Disponível em: <<https://www.ipcc.ch/report/ar6/syr/>>.

MADDEN, J. R. Evidence-based analysis of issues in environment, energy, and disaster risks with CGE models: An introduction to part i. In: **Environmental Economics and Computable General Equilibrium Analysis: Essays in Memory of Yuzuru Miyata**. [S.l.]: Springer, 2020. p. 3–12.

MAGALHÃES, A. S. **O comércio por vias internas e seu papel sobre o crescimento e desigualdade regional no Brasil**. Banco do Nordeste do Brasil, 2011. Accepted: 2020-01-14T16:20:35Z. Disponível em: <<https://www.bnb.gov.br/s482-dspace/handle/123456789/s1dspp01.dmz.bnb:8443/s482-dspace/handle/123456789/108>>.

MARENGO, J. **Riscos das Mudanças Climáticas no Brasil: Análise Conjunta Brasil-Reino Unido sobre os Impactos das Mudanças Climáticas e do Desmatamento na Amazônia**. [S.l.: s.n.], 2011.

MARENGO, J. A.; ALVES, L. M.; ALVALA, R. C. S.; CUNHA, A. P.; BRITO, S.; MORAES, O. L. L. Climatic characteristics of the 2010-2016 drought in the semiarid northeast brazil region. v. 90, p. 1973–1985, 2017. Publisher: Academia Brasileira de Ciências.

MARGULIS, S.; DUBEUX, C. B. S. Economia da mudança do clima no brasil. Instituto de Pesquisa Econômica Aplicada (Ipea), 2011.

MARIN, F. R.; JONES, J. W.; SINGELS, A.; ROYCE, F.; ASSAD, E. D.; PELLEGRINO, G. Q.; JUSTINO, F. Climate change impacts on sugarcane attainable yield in southern brazil. v. 117, n. 1, p. 227–239, 2013.

MARTINS, M. A.; TOMASELLA, J.; DIAS, C. G. Maize yield under a changing climate in the brazilian northeast: Impacts and adaptation. v. 216, p. 339–350, 2019.

MARTINS, N. P.; ASSAD, E. D. Impactos econômicos das possíveis alterações climáticas na cultura do feijão nos estados de goiás e minas gerais. In: **Anais do Congresso Brasileiro de Agrometeorologia**. [S.l.]: Embrapa, 2007.

MASSETTI, E.; GUIDUCCI, R. d. C. N.; OLIVEIRA, A. Fortes de; MENDELSON, R. O. The impact of climate change on the brazilian agriculture: a ricardian study at microregion level. n. 200, 2013.

MASSUDA, A.; HONE, T.; LELES, F. A. G.; CASTRO, M. C. de; ATUN, R. The brazilian health system at crossroads: progress, crisis and resilience. v. 3, n. 4, 2018.

MEDEIROS, M. **Medidas de desigualdade e pobreza**. [S.l.]: Editora UnB Brasília, 2012.

MENDELSON, R.; NORDHAUS, W. D.; SHAW, D. The impact of global warming on agriculture: A ricardian analysis. v. 84, n. 4, p. 753–771, 1994. ISSN 0002-8282. Publisher: American Economic Association. Disponível em: <<https://www.jstor.org/stable/2118029>>.

MERCURE, J.-F.; PAIM, M. A.; BOCQUILLON, P.; LINDNER, S.; SALAS, P.; MARTINELLI, P.; BERCHIN, I. I.; GUERRA, J. B. S. O. de A.; DERANI, C.; JUNIOR, C. L. de A.; RIBEIRO, J. M. P.; KNOBLOCH, F.; POLLITT, H.; EDWARDS, N. R.; HOLDEN, P. B.; FOLEY, A.; SCHAPHOFF, S.; FARACO, R. A.; VINUALES, J. E. System complexity and policy integration challenges: The brazilian energy- water-food nexus. v. 105, p. 230–243, 2019.

MIYAJIMA, D. N. Cenário de mudanças climáticas, efeitos sobre a produtividade agrícola e seus impactos econômicos nas regiões da amazônia legal brasileira. 2018.

MOORE, F. C.; LOBELL, D. B. The fingerprint of climate trends on european crop yields. v. 112, n. 9, p. 2670–2675, 2015.

MORAES, G. I. de; FILHO, J. B. d. S. F. Brasil, mudanças climáticas e economia: o que há estabelecido? **Planejamento e Políticas Públicas**, 2013.

National Research Council. **Climate Change: Evidence, Impacts, and Choices**. [S.l.]: The National Academies Press, 2012.

NEWMAN, J. Climate change and cereal aphids: The relative effects of increasing co2 and temperature on aphid population dynamics. v. 10, p. 5–15, 2003.

NOGUEIRA, L. A. H.; MOREIRA, J. R.; SCHUCHARDT, U.; GOLDEMBERG, J. The rationality of biofuels. v. 61, p. 595–598, 2013.

PARRY, M. L. **Climate Change and World Agriculture**. [S.l.]: Routledge, 1990. ISBN 978-0-429-34510-4.

PORTER, J. R.; XIE, L.; CHALLINOR, A. J.; COCHRANE, K.; HOWDEN, S. M.; IQBAL, M. M.; LOBELL, D. B.; TRAVASSO, M. Food security and food production systems. 2014.

RAY, D. K.; GERBER, J. S.; MACDONALD, G. K.; WEST, P. C. Climate variation explains a third of global crop yield variability. v. 6, n. 1, p. 5989, 2015. Publisher: Nature Publishing Group.

RIBEIRO, R.; NAKAI, A.; ASSAD, E. **Assessments and How an Increase in Temperature may Have an Impact on Agriculture in Brazil and Mapping of the Current and Future Situation**. [S.l.: s.n.], 2018. (Climate Change Risks in Brazil. Springer, Cham).

ROSENZWEIG, C.; HILLEL, D. **Climate change and the global harvest: potential impacts of the greenhouse effect on agriculture**. [S.l.]: Oxford University Press, 1998.

ROSSATO, L.; AL et. **Impact of soil moisture on crop yields over Brazilian Semi-Arid**. 2017.

SALAZAR, A.; BALDI, G.; HIROTA, M.; SYKTUS, J.; MCALPINE, C. Land use and land cover change impacts on the regional climate of non-amazonian south america: A review. v. 128, 2015.

SANGHI, A.; ALVES, D.; EVENSON, R.; MENDELSON, R. Global warming impacts on brazilian agriculture: estimates of the ricardian model. v. 1, n. 1, p. 7–33, 1997.

SANGHI, A.; MENDELSON, R. The impacts of global warming on farmers in brazil and india. 2008. Disponível em: <https://www.academia.edu/8917230/The_impacts_of_global_warming_on_farmers_in_Brazil_and_India>.

SEEG - Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa. 2022. Disponível em: <<https://seeg.eco.br/>>.

SHENTSIS, I.; ROSENTHAL, E. **Hydrological Processes | Hydrology Journal | Wiley Online Library**. 2003.

SIMONATO, T. C. Projeção dos impactos econômicos regionais do desastre de mariana-MG. 2017. Disponível em: <<https://repositorio.ufmg.br/handle/1843/FACE-B9EMG8>>.

SOUZA, B. S. d. **Mudanças climáticas no Brasil: efeitos sistêmicos sobre a economia brasileira provenientes de alterações na produtividade agrícola**. text, 2018.

SOUZA, P.; ASSUNÇÃO, J. **Os Impactos do Crédito Rural na Produção Agropecuária e no Uso da Terra: Uma Análise por Linhas de Crédito, Tipo de Produtor e Finalidade do Crédito**. 2019.

SOUZA-RODRIGUES, E. Deforestation in the amazon: A unified framework for estimation and policy analysis. v. 86, n. 6, 2019.

STERN, N. H. **The economics of climate change: the Stern review**. [S.l.]: cambridge University press, 2007.

STOCCO, L. **Impactos econômicos da redução do hiato de produtividade da pecuária de corte no Brasil**. text, 2018.

SULTAN, B.; DEFRANCE, D.; IIZUMI, T. Evidence of crop production losses in west africa due to historical global warming in two crop models. v. 9, n. 1, p. 12834, 2019. Publisher: Nature Publishing Group.

TANURE, T. M. d. P. Mudanças climáticas e agricultura no brasil: impactos econômicos regionais e por cultivo familiar e patronal. 2020. Disponível em: <<https://repositorio.ufmg.br/handle/1843/33870>>.

TILMAN, D.; BALZER, C.; HILL, J.; BEFORT, B. L. Global food demand and the sustainable intensification of agriculture. v. 108, n. 50, p. 20260–20264, 2011. Publisher: Proceedings of the National Academy of Sciences.

TOWNSEND, R. L.; JANVRY, A. D.; KLYTCHNIKOVA, I.; SADOULET, E.; BYERLEE, D. **World Development Report 2008 : Agriculture for Development**. 2008.

UNDERSTANDING the weather signal in national crop-yield variability - Frieler - 2017 - Earth's Future - Wiley Online Library. 2017.

USDA. **World Agricultural Supply and Demand Estimates**. 2018.

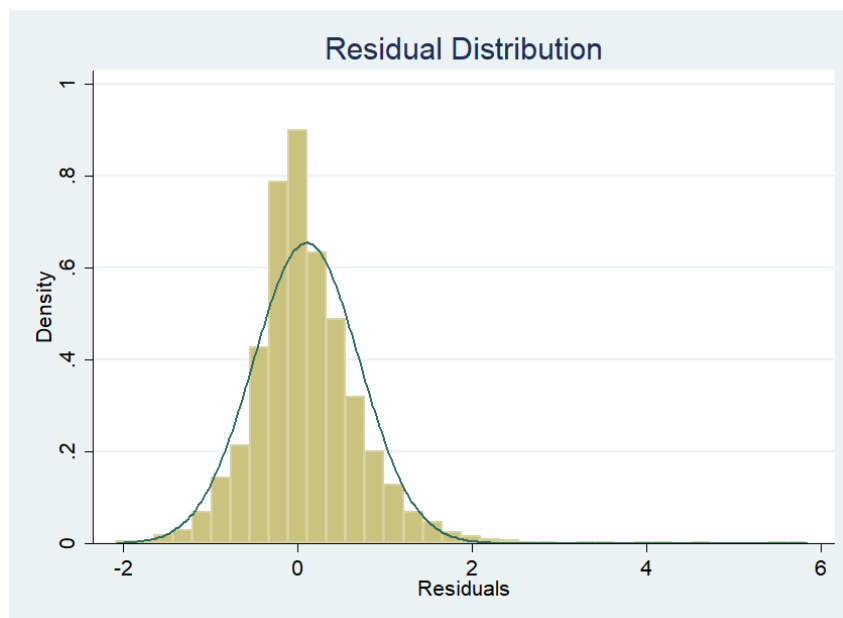
WATER policy implementation in the state of São Paulo, Brazil: Key challenges and opportunities. v. 60, p. 11–18, 2016.

WORLD Bank Group: Climate Change Knowledge Portal. 2021.

World Health Organization (WHO). **Climate and Health Country Profile - Brazil**. 2015.

APPENDIX A –

Figure A.1 – Residual Distribution



Source: Compiled by the author based on the econometric model.

Table A.1 – Climate Change Effects on Crop Productivity: RCP 4.5

RCP 4.5 (2080)							
Region	Coffee	Orange	Permanent Crops	Soybeans	Maize	Sugarcane	Temporary Crops
Barbacena	-0.28	0.14	-0.72	-0.07	-0.31	-0.33	-0.50
Belo Horizonte	-0.54	-0.29	-0.63	-0.21	-0.48	-0.14	-0.35
Divinópolis	-0.44	-0.43	-0.45	-0.19	-0.44	0.16	-0.41
Governador Valadares	-0.75	-0.28	-0.28	-	-0.47	-0.33	-0.37
Ipatinga	-0.67	-0.28	-0.28	-	-0.46	-0.23	-0.34
Juiz de Fora	-0.59	-0.21	-0.45	-0.08	-0.37	-0.24	-0.32
Montes Claros	-0.67	-0.43	0.38	-0.19	-0.52	-0.15	-0.40
Patos de Minas	-0.62	-0.52	-0.51	-0.25	-0.49	-0.01	-0.30
Pouso Alegre	-0.04	0.00	-0.32	-0.10	-0.21	-0.30	-0.27
Teófilo Otoni	-0.71	-0.26	-0.10	-	-0.45	-0.25	-0.42
Uberaba	-0.50	-0.81	-0.15	-0.27	-0.48	1.08	-0.30
Uberlândia	-0.68	-0.69	-0.33	-0.25	-0.50	0.92	-0.17
Varginha	-0.29	-0.40	-0.47	-0.16	-0.33	-0.13	-0.31

Source: Compiled by the author based on the results of the econometric model.

Table A.2 – Climate Change Effects on Crop Productivity: RCP 8.5

RCP 8.5 (2080)							
Region	Coffee	Orange	Permanent Crops	Soybeans	Maize	Sugarcane	Temporary Crops
Barbacena	-0.46	0.07	-0.63	-0.09	-0.40	-0.45	-0.34
Belo Horizonte	-0.63	-0.33	-0.55	-0.30	-0.46	-0.17	-0.10
Divinópolis	-0.58	-0.52	-0.28	-0.26	-0.46	0.33	-0.19
Governador Valadares	-0.74	-0.05	-0.33	-	-0.44	-0.45	-0.15
Ipatinga	-0.70	-0.14	-0.24	-	-0.43	-0.34	-0.12
Juiz de Fora	-0.69	-0.19	-0.36	-0.09	-0.42	-0.33	-0.11
Montes Claros	-0.70	-0.33	0.08	-0.25	-0.43	-0.23	-0.19
Patos de Minas	-0.68	-0.59	-0.41	-0.33	-0.44	0.19	0.02
Pouso Alegre	-0.27	-0.06	-0.18	-0.13	-0.32	-0.38	-0.08
Teófilo Otoni	-0.75	-0.08	-0.13	-	-0.43	-0.38	-0.21
Uberaba	-0.62	-0.90	0.20	-0.37	-0.51	2.79	0.02
Uberlândia	-0.75	-0.79	-0.04	-0.36	-0.51	2.30	0.26
Varginha	-0.48	-0.53	-0.26	-0.23	-0.41	-0.04	-0.06

Source: Compiled by the author based on the results of the econometric model.

Table A.3 – Macroeconomic Results: 2080 (Cumulative Change %)

Region	Hous. Consump.		Investments		Exports		Employment	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Belo Horizonte	-0.06	-0.04	-0.14	-0.11	-0.20	-0.28	-0.06	-0.04
Montes Claros	-0.13	-0.13	-0.20	-0.24	-0.39	-0.48	-0.13	-0.12
Teófilo Otoni	-0.13	-0.08	-0.37	-0.23	-0.40	-0.49	-0.13	-0.08
Governador Valadares	-0.17	-0.11	-0.51	-0.33	-0.40	-0.47	-0.17	-0.10
Ipatinga	-0.16	-0.16	-0.51	-0.53	-0.28	-0.36	-0.16	-0.16
Juiz de Fora	-0.38	-0.41	-1.27	-1.35	-0.49	-0.65	-0.38	-0.41
Barbacena	-0.07	-0.10	-0.08	-0.16	-0.22	-0.30	-0.07	-0.10
Varginha	-0.01	-0.17	0.33	-0.29	-0.55	-0.83	-0.01	-0.17
Pouso Alegre	0.15	0.10	0.77	0.53	-0.25	-0.40	0.15	0.10
Uberaba	-0.10	-0.14	-0.96	-1.36	-0.26	-0.36	-0.10	-0.14
Uberlândia	-0.24	0.00	-0.77	-0.15	-0.89	-1.09	-0.24	0.00
Patos de Minas	-1.36	-1.35	-3.87	-3.87	-0.37	-0.48	-1.36	-1.35
Divinópolis	-0.33	-0.30	-0.86	-0.74	-0.20	-0.29	-0.33	-0.30

Source: Compiled by the author based on IMAGEM-MG results.

Table A.4 – Industry Outputs: RCP 4.5 (2050) (Cumulative Change %)

Sector&Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice&Cereals	0.02	0.00	0.01	0.01	0.01	0.07	0.01	-0.02	-0.01	0.03	0.02	0.07	0.00
Maize	-8.38	-7.36	-8.25	-8.27	-8.36	-6.49	-4.63	-4.65	-2.84	-6.18	-5.47	-6.16	-5.88
Cotton&Fibers	0.01	-0.01	0.00	0.00	0.00	0.07	-0.01	-0.02	-0.02	0.01	0.01	0.05	0.00
Sugarcane	-5.21	-4.79	-5.23	-6.93	-6.92	-6.86	-6.72	-5.05	-4.99	8.59	6.05	-4.88	-1.65
Soybeans	-1.42	-1.43	0.08	0.08	0.09	0.14	0.08	-1.46	0.06	-2.85	-2.90	-2.80	-1.44
Temporary C.	-4.64	-4.70	-4.66	-3.43	-3.42	-2.16	-5.88	-3.48	-1.07	-3.37	-2.18	-3.39	-4.64
Orange	1.83	-3.94	-0.10	-0.10	-0.09	1.73	5.66	-2.09	1.70	-11.32	-7.28	-1.93	-1.97
Coffee Beans	-7.48	-8.74	-10.50	-12.07	-8.85	-8.97	-1.02	0.49	2.10	-2.60	-7.37	-5.77	-2.68
Permanent C.	-8.30	0.37	-1.75	-3.92	-3.77	-4.50	-7.94	-7.38	-1.95	-4.66	-7.04	-8.19	-7.05
Livestock	0.01	-0.13	0.01	0.01	0.01	0.02	-0.06	-0.07	-0.05	-0.02	-0.06	0.00	-0.09
Forestry	-0.01	-0.01	0.00	-0.01	-0.01	-0.02	-0.02	-0.03	-0.02	-0.01	-0.01	0.01	-0.01
Fishing	0.01	0.01	0.01	0.02	0.01	0.02	0.01	-0.01	0.00	0.03	0.02	0.06	0.01
Food&Beverage	-0.02	-0.15	-0.01	0.03	-0.12	-0.04	-0.04	-0.22	-0.05	0.25	0.02	0.02	-0.14
Biofuels	-0.08	-1.81	0.02	0.01	0.01	-0.07	-2.07	-1.75	-1.27	0.69	2.18	-1.78	-0.62
Inorg. Chemical	-0.06	-0.07	-0.10	-0.06	-0.10	-0.03	-0.06	-0.12	-0.03	-0.04	-0.11	0.08	-0.15
Manure&Fert.	-0.93	-0.40	-0.43	-0.50	-0.47	-2.67	-0.29	-0.25	0.13	-0.50	-0.60	-0.86	-0.69
Agrochemicals	-1.13	-1.11	-1.19	-1.24	-1.09	-0.75	-1.29	-0.74	-0.55	-0.31	-0.97	-1.63	-0.92
Oil, Gas&Mining	0.01	0.02	0.02	0.01	0.02	0.03	0.01	0.00	-0.01	0.03	0.03	0.13	0.01
Manufacturing	0.01	0.00	0.01	0.01	0.01	0.01	0.01	-0.01	-0.01	0.00	-0.09	0.10	-0.01
Electronics	0.00	0.01	0.02	-0.01	0.01	0.05	0.00	0.07	0.01	0.07	0.00	0.15	0.01
Other Industries	0.01	0.01	0.01	0.01	0.00	0.03	-0.01	0.03	0.00	0.04	0.01	-0.04	0.00
Electricity	-0.02	-0.04	-0.04	-0.03	-0.03	-0.06	-0.03	-0.05	0.00	-0.07	-0.07	-0.18	-0.03
Water&Sewage	0.00	-0.01	0.00	0.00	0.01	-0.02	0.00	0.00	0.00	0.02	0.01	-0.06	0.00
Construction	-0.03	-0.06	-0.07	-0.08	-0.07	-0.18	-0.04	0.16	0.08	-0.11	-0.11	-0.61	-0.10
Trade	-0.04	-0.10	-0.08	-0.09	-0.08	-0.16	-0.04	-0.09	0.00	-0.28	-0.24	-0.56	-0.14
Freight Transport	-0.02	-0.16	-0.09	-0.08	-0.05	-0.12	-0.04	-0.12	-0.01	-0.20	-0.12	-0.77	-0.12
Services	0.00	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.05	-0.02
Info&Communic.	-0.01	-0.01	0.00	0.00	-0.01	-0.03	-0.01	0.01	0.01	-0.02	-0.02	-0.07	-0.03
Public Sector	0.00	0.00	0.01	0.01	0.00	0.02	-0.01	-0.02	-0.01	0.01	0.02	0.07	0.00
Private Sector	0.00	-0.02	-0.01	-0.02	-0.02	-0.03	-0.01	0.01	0.01	-0.03	-0.04	-0.14	-0.03

Source: Compiled by the author based on IMAGEM-MG results

Table A.5 – Industry Outputs: RCP 4.5 (2080) (Cumulative Change %)

Sector&Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice&Cereals	0.01	-0.05	0.00	0.00	0.01	0.15	0.00	-0.07	-0.05	0.08	0.05	0.17	-0.02
Maize	-24.56	-23.43	-24.26	-24.27	-24.48	-19.73	-14.57	-14.62	-9.57	-20.47	-20.04	-20.56	-19.57
Cotton&Fibers	0.01	-0.06	-0.01	-0.02	-0.01	0.16	-0.05	-0.06	-0.07	-0.01	0.02	0.15	-0.03
Sugarcane	-13.23	-12.22	-15.26	-19.73	-17.81	-17.67	-19.12	-12.71	-16.28	41.03	29.78	-8.65	0.58
Soybeans	-7.77	-5.95	0.33	0.34	0.36	-1.43	-1.55	-6.05	-1.61	-11.63	-10.09	-9.75	-5.99
Temporary C.	-14.91	-15.16	-15.02	-12.97	-12.89	-9.34	-19.83	-11.58	-7.61	-11.24	-6.26	-11.41	-14.89
Orange	-2.79	-16.62	-3.51	-5.90	-5.73	-0.52	19.50	-11.34	7.03	-34.86	-27.02	-15.71	-13.26
Coffee Beans	-21.68	-24.99	-29.67	-31.96	-25.27	-25.75	-4.94	-2.47	8.97	-13.46	-24.86	-20.65	-11.88
Permanent C.	-24.17	7.89	-3.95	-11.64	-11.21	-14.64	-24.37	-20.12	-8.59	-9.62	-16.44	-22.60	-19.27
Livestock	-0.01	-0.46	-0.06	-0.04	-0.08	-0.03	-0.19	-0.25	-0.16	-0.02	-0.25	-0.14	-0.33
Forestry	-0.05	-0.04	-0.01	-0.03	-0.04	-0.13	-0.08	-0.11	-0.06	-0.07	-0.08	0.00	-0.07
Fishing	0.04	0.02	0.05	0.06	0.05	0.04	0.03	-0.02	-0.02	0.11	0.07	0.16	0.04
Food&Beverage	-0.16	-0.74	-0.15	0.02	-0.59	-0.32	-0.22	-0.91	-0.24	1.63	0.17	-0.36	-0.57
Biofuels	0.39	-4.08	0.35	0.52	0.51	-0.01	-6.12	-4.67	-3.92	3.96	11.86	-2.91	0.24
Inorg. Chemical	-0.23	-0.25	-0.35	-0.21	-0.34	-0.17	-0.23	-0.59	-0.08	-0.21	-0.44	0.17	-0.57
Manure&Fert.	-3.22	-1.46	-1.53	-1.78	-1.67	-9.07	-1.05	-1.16	1.06	-1.70	-1.95	-3.38	-2.67
Agrochemicals	-3.96	-3.88	-4.07	-4.26	-3.77	-2.70	-4.53	-2.44	-2.12	-1.00	-3.50	-5.90	-3.27
Oil, Gas&Mining	0.02	0.04	0.04	0.03	0.04	0.10	0.02	0.00	-0.04	0.04	0.04	0.37	0.05
Manufacturing	0.00	0.02	-0.03	-0.02	0.01	-0.07	0.00	-0.06	-0.04	-0.07	-0.41	0.03	-0.09
Electronics	-0.02	-0.03	0.02	-0.06	0.01	0.10	-0.02	0.09	0.02	0.04	-0.11	0.29	-0.01
Other Industries	0.02	-0.04	-0.01	-0.02	-0.01	0.04	-0.04	0.06	0.01	0.03	-0.06	-0.27	-0.06
Electricity	-0.08	-0.18	-0.17	-0.16	-0.14	-0.29	-0.15	-0.25	0.01	-0.34	-0.32	-0.97	-0.15
Water&Sewage	-0.01	-0.04	-0.02	-0.03	0.00	-0.12	-0.02	-0.02	0.01	0.03	0.02	-0.37	-0.05
Construction	-0.11	-0.21	-0.27	-0.33	-0.30	-0.74	-0.18	0.28	0.34	-0.43	-0.44	-2.48	-0.45
Trade	-0.13	-0.25	-0.29	-0.31	-0.27	-0.57	-0.12	-0.45	0.01	-0.74	-0.72	-2.13	-0.52
Transport	-0.07	-0.50	-0.32	-0.29	-0.16	-0.46	-0.11	-0.51	-0.01	-0.39	-0.23	-2.54	-0.42
Services	-0.02	-0.04	-0.03	-0.04	-0.04	-0.09	-0.04	-0.05	-0.01	-0.03	-0.06	-0.29	-0.09
Info&Communic.	-0.03	-0.05	-0.02	-0.03	-0.07	-0.16	-0.06	0.02	0.04	-0.10	-0.10	-0.39	-0.15
Public Sector	0.00	-0.02	0.02	0.01	0.01	0.05	-0.04	-0.03	-0.04	0.04	0.03	0.19	-0.01
Private Sector	-0.02	-0.07	-0.06	-0.08	-0.07	-0.16	-0.05	0.00	0.06	-0.05	-0.13	-0.61	-0.15

Source: Compiled by the author based on IMAGEM-MG results.

Table A.6 – Industry Outputs: RCP 8.5 (2050) (Cumulative Change %)

Sector&Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice&Cereals	0.02	0.00	0.01	0.01	0.02	0.09	0.01	-0.01	-0.01	0.04	0.03	0.09	0.01
Maize	-10.03	-7.27	-9.88	-9.90	-10.00	-8.12	-6.23	-6.26	-4.41	-7.74	-6.89	-6.04	-7.39
Cotton&Fibers	0.01	-0.01	0.00	0.00	0.00	0.08	-0.01	-0.01	-0.02	0.02	0.01	0.06	0.00
Sugarcane	-8.60	-6.39	-8.65	-10.30	-10.29	-10.22	-10.01	-6.72	-6.65	12.04	9.04	-6.52	-3.28
Soybeans	-2.91	-1.39	0.12	0.12	0.12	0.18	0.11	-1.43	0.09	-4.27	-4.36	-2.75	-1.41
Temporary C.	-1.14	-2.40	-2.37	-1.15	-1.14	0.14	-3.58	-1.19	0.03	-2.36	0.07	-1.11	-3.52
Orange	0.14	-1.78	2.07	2.06	0.14	1.99	5.94	-3.72	1.96	-14.69	-8.83	-1.65	-1.73
Coffee Beans	-9.64	-9.35	-11.11	-11.14	-11.00	-11.13	-4.77	-1.63	1.65	-4.71	-7.95	-7.90	-4.80
Permanent C.	-7.25	0.33	0.31	-2.88	-1.63	-3.52	-6.93	-7.40	-1.97	-4.71	-5.98	-8.21	-6.01
Livestock	0.01	-0.13	-0.01	0.00	-0.01	0.02	-0.07	-0.09	-0.06	-0.01	-0.06	0.02	-0.11
Forestry	-0.01	-0.01	0.00	-0.01	-0.01	-0.03	-0.02	-0.04	-0.02	-0.01	-0.02	0.01	-0.02
Fishing	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.00	0.00	0.03	0.02	0.07	0.01
Food&Beverage	-0.03	-0.15	-0.01	0.04	-0.14	-0.04	-0.05	-0.29	-0.07	0.36	0.07	0.04	-0.19
Biofuels	-0.12	-2.40	0.03	0.01	0.01	-0.12	-3.09	-2.30	-1.69	0.99	3.28	-2.37	-1.15
Inorg. Chemical	-0.08	-0.08	-0.11	-0.07	-0.13	-0.04	-0.08	-0.28	-0.04	-0.05	-0.12	0.09	-0.19
Manure&Fert.	-0.85	-0.49	-0.51	-0.60	-0.55	-3.29	-0.39	-0.52	-0.05	-0.62	-0.58	-1.05	-0.87
Agrochemicals	-1.39	-1.31	-1.33	-1.45	-1.24	-0.95	-1.60	-0.85	-0.79	-0.38	-1.22	-1.94	-1.14
Oil, Gas&Mining	0.01	0.02	0.01	0.01	0.02	0.04	0.01	0.01	-0.01	0.03	0.03	0.15	0.02
Manufacturing	0.01	0.00	0.01	0.01	0.01	0.01	0.01	-0.01	-0.01	-0.01	0.03	0.10	-0.01
Electronics	0.01	0.01	0.01	0.00	0.02	0.06	0.01	0.07	0.01	0.08	0.02	0.18	0.01
Other Industries	0.01	0.01	0.01	0.01	0.01	0.04	-0.01	0.05	0.01	0.04	0.03	-0.05	0.00
Electricity	-0.02	-0.04	-0.04	-0.04	-0.03	-0.07	-0.04	-0.09	-0.01	-0.08	-0.07	-0.22	-0.04
Water&Sewage	0.00	0.00	0.00	0.00	0.01	-0.02	0.00	-0.01	0.00	0.02	0.01	-0.07	0.00
Construction	-0.02	-0.05	-0.05	-0.06	-0.07	-0.19	-0.05	0.12	0.10	-0.13	-0.04	-0.70	-0.11
Trade	-0.03	-0.08	-0.06	-0.07	-0.08	-0.19	-0.04	-0.17	0.00	-0.32	-0.19	-0.63	-0.15
Freight Transport	-0.02	-0.14	-0.07	-0.07	-0.05	-0.15	-0.05	-0.21	-0.02	-0.24	-0.07	-0.90	-0.14
Services	0.00	-0.01	0.00	0.00	-0.01	-0.01	-0.01	-0.02	0.00	0.00	0.00	-0.06	-0.02
Info&Communic.	0.00	-0.01	0.00	0.00	-0.01	-0.03	-0.01	0.01	0.01	-0.02	0.00	-0.07	-0.03
Public Sector	0.00	0.00	0.01	0.01	0.01	0.03	-0.01	-0.01	-0.01	0.02	0.01	0.08	0.00
Private Sector	0.00	-0.02	-0.01	-0.01	-0.01	-0.03	-0.01	0.00	0.01	-0.02	0.00	-0.16	-0.04

Source: Compiled by the author based on IMAGEM-MG results.

Table A.7 – Industry Outputs: RCP 8.5 (2080) (Cumulative Change %)

Sector & Region*	BH	MC	TO	GV	IPT	JF	BC	VA	PA	UBE	UBR	PM	DV
Rice & Cereals	0.01	-0.04	0.01	0.01	0.02	0.18	0.00	-0.06	-0.04	0.12	0.06	0.20	-0.01
Maize	-26.84	-21.39	-26.52	-26.53	-26.76	-23.95	-18.85	-18.88	-13.87	-24.50	-21.95	-20.33	-21.64
Cotton & Fibers	0.00	-0.05	-0.01	-0.02	-0.01	0.19	-0.06	-0.03	-0.05	0.02	0.02	0.16	-0.03
Sugarcane	-18.57	-16.68	-24.21	-28.31	-24.73	-24.59	-27.52	-11.58	-20.72	47.11	36.00	-7.50	1.80
Soybeans	-11.98	-7.64	0.47	0.48	0.49	-1.29	-1.43	-7.75	-3.33	-15.56	-15.89	-11.35	-7.69
Temporary C.	-3.47	-7.20	-8.58	-5.02	-3.45	-1.26	-13.50	-3.64	-1.53	-4.18	4.50	-2.03	-8.83
Orange	-5.33	-8.47	5.40	8.03	-0.25	2.62	17.63	-18.11	5.22	-40.75	-30.94	-17.38	-14.96
Coffee Beans	-25.88	-26.84	-29.78	-29.84	-29.36	-29.87	-14.08	-8.91	1.18	-17.76	-24.88	-24.88	-16.20
Permanent C.	-21.18	2.27	-1.84	-9.93	-6.22	-11.76	-21.49	-16.07	-5.88	-2.98	-9.28	-19.92	-14.88
Livestock	0.01	-0.42	0.06	0.03	-0.07	0.03	-0.24	-0.32	-0.20	0.00	-0.23	-0.13	-0.36
Forestry	-0.06	-0.04	-0.02	-0.03	-0.05	-0.16	-0.09	-0.14	-0.09	-0.06	-0.08	-0.01	-0.08
Fishing	0.05	0.03	0.05	0.06	0.05	0.04	0.04	0.00	-0.01	0.14	0.08	0.16	0.04
Food & Beverage	-0.18	-0.71	-0.12	0.07	-0.66	-0.36	-0.29	-1.12	-0.33	1.93	0.27	-0.43	-0.64
Biofuels	0.48	-5.31	0.46	0.69	0.66	-0.06	-8.94	-4.15	-4.74	4.65	14.43	-2.25	0.70
Inorg. Chemical	-0.26	-0.28	-0.36	-0.25	-0.40	-0.21	-0.28	-1.10	-0.12	-0.22	-0.42	0.14	-0.63
Manure&Fert.	-2.67	-1.62	-1.68	-1.98	-1.83	-10.50	-1.31	-2.05	-0.52	-2.00	-1.65	-3.71	-2.90
Agrochemicals	-4.54	-4.20	-4.27	-4.68	-4.00	-3.20	-5.24	-2.68	-2.74	-1.17	-4.00	-6.33	-3.80
Oil, Gas&Mining	0.02	0.05	0.03	0.03	0.05	0.11	0.03	0.01	-0.03	0.04	0.07	0.37	0.06
Manufacturing	0.00	0.03	-0.03	-0.02	0.00	-0.08	-0.01	-0.09	-0.05	-0.11	0.21	-0.01	-0.11
Electronics	-0.01	-0.02	0.01	-0.03	0.01	0.11	-0.01	0.04	0.03	0.04	-0.06	0.29	0.00
Other Industries	0.02	-0.03	0.00	-0.02	-0.01	0.05	-0.04	0.07	0.02	0.02	0.04	-0.29	-0.06
Electricity	-0.08	-0.19	-0.16	-0.16	-0.15	-0.34	-0.18	-0.41	-0.04	-0.38	-0.29	-1.08	-0.17
Water&Sewage	0.00	-0.03	-0.01	-0.01	-0.01	-0.13	-0.02	-0.06	0.00	0.05	0.05	-0.39	-0.05
Construction	-0.10	-0.21	-0.19	-0.24	-0.28	-0.80	-0.22	0.02	0.27	-0.55	-0.14	-2.56	-0.42
Trade	-0.11	-0.26	-0.20	-0.22	-0.27	-0.62	-0.13	-0.70	-0.05	-0.79	-0.46	-2.22	-0.48
Freight Transport	-0.07	-0.46	-0.20	-0.21	-0.17	-0.52	-0.14	-0.79	-0.07	-0.50	-0.01	-2.61	-0.42
Services	-0.02	-0.04	-0.01	-0.03	-0.04	-0.10	-0.05	-0.08	-0.01	0.00	0.01	-0.31	-0.09
Info&Communic.	-0.02	-0.05	-0.01	-0.02	-0.07	-0.17	-0.06	-0.01	0.04	-0.10	-0.02	-0.41	-0.15
Public Sector	0.00	-0.01	0.01	0.01	0.01	0.06	-0.04	0.00	-0.03	0.06	0.03	0.19	0.00
Private Sector	-0.01	-0.07	-0.03	-0.05	-0.07	-0.17	-0.05	-0.05	0.05	-0.02	0.01	-0.61	-0.14

Source: Compiled by the author based on IMAGEM-MG results.