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Extreme Weather Events and Birth Outcomes

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Extreme Weather Events and Birth Outcomes

Dissertação apresentada ao Programa de Pós-Graduação em Economia Aplicada da Universidade Federal de Juiz de Fora, como parte dos requisitos para obtenção do título de Mestre em Economia Aplicada.
Área de concentração: Economia Social e Trabalho.

Orientador: Prof. Dr. Flávia Lúcia Chein Feres

Coorientador: Prof. Dr. Igor Vieira Procópio

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Resumo

GUIMARÃES, Beatriz Sá. **Extreme Weather Events and Birth Outcomes**. 2025. 53 f. Dissertação (Mestrado em Economia) – Faculdade de Ciências Economicas, Universidade Federal de Juiz de Fora, Juiz de Fora, 2025.

Eventos climáticos extremos, caracterizados por intensidade ou frequência superiores aos padrões históricos, têm se tornado mais recorrentes e provocado impactos relevantes sobre a saúde. Este trabalho investiga os efeitos da seca sobre variáveis de nascimento, analisando dois episódios distintos: a seca de março de 2020 no Rio Grande do Norte e a seca de janeiro de 2022 nos estados do Sul — Paraná, Rio Grande do Sul e Santa Catarina. Utilizando microdados do Sistema de Informações sobre Nascidos Vivos (SINASC/DATASUS) vinculados aos registros oficiais de desastres do Atlas de Desastres do CEMADEN, construímos coortes gestacionais expostas ou não aos eventos e estimamos modelos de Diferenças-em-Diferenças para identificar efeitos causais. Os resultados mostram que, no Rio Grande do Norte, a exposição à seca esteve associada a uma redução estatisticamente significativa no peso ao nascer, enquanto, na Região Sul, o impacto predominante ocorreu por meio do encurtamento da duração gestacional, evidenciando heterogeneidade regional na sensibilidade das gestações aos eventos de seca.

Palavras-chaves: Evento Climático Extremo, Seca, Variáveis de Nascimento, Saúde. Códigos JEL: I14, J13, I18.

Abstract

GUIMARÃES, Beatriz Sá. **Extreme Weather Events and Birth Outcomes**. 2025. 53 p. Dissertation (Master of Economics) – School of Economics, Federal University of Juiz de Fora, 2025.

Extreme weather events, characterized by intensity or frequency that exceeds historical patterns, have become increasingly common and have produced significant impacts on health. This study investigates the effects of drought on birth outcomes by examining two distinct episodes: the drought that occurred in March 2020 in Rio Grande do Norte and the drought of January 2022 in the southern states of Paraná, Rio Grande do Sul, and Santa Catarina. Using microdata from the Live Birth Information System (SINASC/DATASUS) linked to official disaster records from the CEMADEN Disaster Atlas, we constructed gestational cohorts exposed or unexposed to the events and estimated Difference-in-Differences models to identify causal effects. The results show that, in Rio Grande do Norte, exposure to drought was associated with a statistically significant reduction in birth weight, whereas in the Southern Region the predominant impact occurred through a shortening of gestational duration, revealing regional heterogeneity in the sensitivity of pregnancies to drought events.

Keywords: Extreme Weather Event, Drought, Birth Outcomes, Health. JEL Codes: I14, J13, I18.

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Sumário

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1 Introduction

Extreme weather events, as described by the Oswaldo Cruz Foundation (FIOCRUZ, 2024), are those that affect the daily life of a community, causing material, human, and animal losses, damage to the environment, and health risks. They are, at the same time, physical and social events. It is the result of a serious interruption in the normal functioning of a community or society that affects its daily life. This abrupt shutdown simultaneously involves material and economic losses, as well as damage to the environment and the health of populations through illnesses and diseases that can cause immediate and subsequent deaths.

There is evidence of problems caused by the occurrence of extreme events, such as heat waves, intense rainfall, droughts, wildfires, and tropical cyclones, as these have a strong impact on human life and can lead to a reduced food supply, worsen air and water quality, and compromise human health, both physically and mentally, in addition to making it difficult to provide assistance in critical moments. Dias (2014) highlights the unprecedented vulnerability of the population to these events, especially the growing urbanization that leads to the occupation of risk areas.

In this dissertation, we estimate the impact of two extreme drought events on birth outcomes, including birth weight. We examine the droughts that occurred in Rio Grande do Norte in March 2020 and in the Southern Region of Brazil in January 2022. The analysis considers two primary mechanisms: the scarcity of resources, such as water and food, necessary for proper fetal nutrition, and the stress placed on pregnant women as a consequence of the event. However, these specific pathways will not be disaggregated in this analysis.

According to the annual Intergovernmental Panel on Climate Changes (IPCC, 2023) report released in the last decade, the global surface temperature increased by 1.1 Celsius degrees as a consequence of human behavior. The events are becoming more common each year, as published by the World Meteorological Organization (WMO, 2024). In 2021, the Dixie fire in California burned a record-breaking 390,000 hectares. The European Environment Agency (EEA, 2024) also reports that, in June 2024, the devastating floods in Germany caused several fatalities and significant economic damage. In a report published in may 2024 by the WMO, 12 extreme weather events were recorded in Brazil in 2023, including droughts, wildfires, floods, and heatwaves. The main causes were human activities and the El Niño climate phenomenon.

In the study titled "2024 – The Hottest Year in History,"conducted by the Brazilian Ocean Literacy Alliance (2024), a total of 64,280 climate-related disasters occurred in 5,117 Brazilian municipalities—or 92% of all municipalities—during the 32 years from 1991 through 2023. Half of the recorded disasters were droughts, while flooding, torrential rains, and high water levels made up 27% of the total. More than 219 million people were affected by outcomes such as death, displacement, homelessness, and illness, with 78 million of those individuals affected in the last four years alone.

The impact of the events is numerous, and it is increasingly becoming an important public issue, as it has direct implications for the country's healthcare system, such as the Brazilian system, Sistema Único de Saúde (SUS). The World Health Organization (WHO, 2022) states that leading climate-related causes of death, illness, and suffering result from exposure to increasingly frequent and more intense extreme weather events, including heatwaves, wildfires, floods, and storm surges, as well as slow-onset events such as droughts. To exemplify, the State of Global Air 2020 report (HEALTH EFFECTS INSTITUTE, 2020) showed that air pollution accounts for 20% of newborn deaths worldwide (almost 500,000 infant deaths in 2019), most related to complications of low birth weight and preterm birth.

Drought, the extreme weather event analyzed in this dissertation, is defined by Coles and Eslamian (2017) as a prolonged period of dry weather caused by a lack of rainfall, resulting in water shortages that can lead to public health issues. As reported by the Centers for Disease Control and Prevention (2024), extreme climate conditions can make it challenging to maintain adequate hydration levels and limit access to food, compromising nutrition not only for the mother but also for the fetus. Although drought conditions require water conservation, these efforts may jeopardize proper sanitation and hygiene. One direct consequence of drought is an increased risk of infectious diseases, often associated with malnutrition and dehydration.

A series of papers has addressed the relationship between environmental events and birth outcomes.The stress caused by these extreme conditions can also lead to mental health disorders. Stanke et al. (2013) highlight that malnutrition, especially in resource-poor regions, and the risk of infectious diseases are common outcomes of drought.

Rocha and Soares (2015) described the effect of water scarcity and birth outcomes in the Brazilian Semiarid, finding out that water scarcity is linked to poorer birth outcomes, including lower birth weight and higher chances of preterm births. Conte Keivabu e Cozzani (2022) presents that exposure to extreme heat is associated with adverse birth outcomes, particularly low birth weight and preterm births, especially during the later stages of pregnancy.

Baharav et al. (2023) examine the effects of extreme weather events, such as hurricanes, heatwaves, and floods, on perinatal health outcomes. The main conclusion is that exposure to extreme weather is linked to adverse perinatal outcomes, including increased risks of preterm birth, low birth weight, and complications during delivery, mainly affecting vulnerable populations with limited access to healthcare and support during and after such events.

Kress et al. (2024) found that even relatively low prenatal exposure to drought is associated with adverse birth outcomes. Pregnant individuals who experienced a higher-than-average proportion of drought during their pregnancy had 2.55 times the odds of preterm delivery and, on average, a gestation period that was half a week shorter. Additionally, this higher exposure is linked to a lower mean birth weight. A similar result is found by Howells et al. (2025), who report that water insecurity and heat stress can negatively impact the health of pregnant and lactating individuals.

The impact of a climate event can be significant for an adult, but it is even greater for a child, especially an infant. As noted by Nicholas Rees of the United Nations Children's Fund (UNICEF), when introducing the Children's Climate Risk Index (2021), child nutrition is directly linked to low birth weight. It is also influenced by maternal nutrition on the Child Vulnerability Scale. In examining how climate change affects child health, Weeda et al. (2024) highlight that the most severe effects stem from temperature extremes, which increase the risks of preterm birth and low birth weight. In a study focused on Brazil, Salvador et al. (2022) analyzed the short-term effects of varying levels of drought severity in macro-urban areas between 2000 and 2019. They found that these effects are commonly related to water scarcity, contamination (both chemical and microbiological), and subsequent food shortages. Mental health disorders caused by water scarcity were also reported, especially by the European Environment Agency (2025).

The World Economic Forum (2024) recently highlighted the increasing frequency, intensity, and duration of heat waves, which have been linked to rising rates of preterm labor. Additionally, prolonged droughts and extreme heat affect both the quantity and quality of breast milk, further compromising infant health, especially growth and development. Fan et al. (2023) found that pregnant women are especially vulnerable to the health harms resulting from climate change, namely, preterm birth, small for gestational age, hypertensive disorders of pregnancy, and other adverse reproductive health and birth outcomes.

Fetal growth restriction is a common clinical problem that has received attention from governments worldwide through booklets given to mothers at the beginning of prenatal care. It is also associated with increased perinatal morbidity and neonatal mortality. According to the World Health Organization (2022), the term Low Birth Weight (LBW) refers to babies born weighing less than 2,500 grams, regardless of gestational age. LBW has been identified as a key factor in malnutrition. It reflects the nutritional status of both the newborn and the pregnant woman. It is a significant public health problem, as it is associated with neonatal mortality, influences child growth and development, and, in the long term, has repercussions on adult health.

Ha (2022) reports that environmental disasters such as extreme heat, floods, and droughts are associated with a higher risk of complications. These adverse outcomes include a greater chance of preterm birth, low birth weight, and restricted fetal growth, with both short-term and long-term exposure appearing to be significant.

Howells et al. (2025) present that exposure to heat stress during pregnancy challenges key physiological adaptations and placental function, elevating risks for both the mother and fetus. Pregnancy induces thermoregulatory changes to dissipate excess heat, yet high ambient temperatures can overwhelm these mechanisms, potentially leading to gestational hypertension, pre-eclampsia, and coagulopathies. Heat and water stress also impair placental development and function by reducing uterine blood flow, triggering oxidative stress and inflammatory responses, and potentially compromising fetal oxygen and nutrient supply. These alterations can precipitate adverse outcomes such as fetal growth restriction and preterm labor, underscoring the placenta's critical role in mediating the detrimental effects of maternal heat exposure on fetal health.

Almond et al. (2005) claim that the problem is less significant than expected. They conducted several analyses with different specifications and samples and found that health interventions that reduce the incidence of low birth weight may not necessarily reduce infant mortality. What can be said is that the group of newborns weighing less than 2,500 g is heterogeneous, as it results from two adverse conditions, prematurity or intrauterine growth retardation (IUGR), which can act in isolation or synergistically in varying degrees (Ramos and Cuman, 2009).

Previous studies have identified plausible causes of low birth weight, with remarkably consistent results on the relationship between LBW and parity among preterm and full-term newborns. Lin et al. (2021) reported that the highest percentages of preterm births and low birth weight were found in women over 35 years old. In particular, Goisis et al. (2017) highlight that advanced maternal age is associated with an increased risk of low birth weight (LBW) and preterm birth among both primiparous and multiparous women. Falcão et al. (2020) found that low birth weight was associated with infants born to mothers with lower educational levels, who were black, unmarried, received an insufficient number of prenatal visits, were aged between 35 and 49 years, and whose newborns were their first child and/or were female.

An important factor to consider is the mother's nutrition, which directly influences the fetus in utero. The high prevalence of nutritional disorders worldwide draws attention because they are preventable risk factors. In developed countries, obesity is the main dietary disorder, while in developing countries like Brazil, there is a coexistence of obesity and malnutrition, especially in poorer regions such as the Northeast (Melo et al., 2008). Consistent with issues of poor nutrition and hydration, Da Mata et al. (2023) describe that exposure to cisterns in the Brazilian Northeast helped increase fetal weight gain, about 1.7 grams per week, indicating that women with access to drinking water can have a healthier pregnancy with fewer complications and give birth to healthier babies.

The Early Childhood Scientific Council (2024) at Harvard University states that higher temperatures may reduce placental blood flow, leading to dehydration and inflammation, which can trigger preterm birth. They also present that during times of high temperatures, there are increased rates of stillbirths as well as more premature and lower birth weight babies, all of which are linked to a greater risk of a range of poor outcomes later in life, including impaired cognition, reduced growth, and chronic health issues such as cardiovascular disease and diabetes in adulthood.

All things considered, only recently have pregnant women been recognized as among the groups most vulnerable to climate stress, and the literature suggests that women with lower income, especially from poorer families, tend to suffer more from these climate events. Chersich et al. (2020) note that most preterm births occurred after heat wave exposure, indicating that higher temperatures can directly impact pregnancy duration.

Analyzing spatial factors such as altitude, Lin and Zhang (2012) found that, at the individual level, extreme temperatures negatively affect fetal weight; both hot and cold days are more likely to result in lower birth weights. Simeonova (2009) discovered that mothers exposed to an extreme weather event were more likely to give birth prematurely. Rancière et al. (2024) reported that pregnant women during the 2003 French heat wave were more likely to have a small-for-gestational-age baby at term compared to those who did not experience a heat wave during pregnancy. This association was stronger when the heat wave occurred during the first trimester. Graber et al. (2024) show that climate stress during pregnancy and preterm birth can negatively impact the fetus, leading to adverse health outcomes such as low birth weight, and impairing cognitive, behavioral, motor, reproductive, emotional, social, neurological, and skeletal development, which can result in various pediatric health issues.

The psychological effects caused by environmental stress can affect the fetus in various aspects, making it difficult to breastfeed as a consequence of trauma, or even reducing access to high-quality nutrition. Prior research has shown that violence and fear are likely to induce psychological stress that affects the mother, and especially in the first trimester of pregnancy, this can lead to prematurity or low birth weight (Koppensteiner and Manacorda, 2015).

Research highlights how extreme weather events act as pregnancy stressors, negatively impacting birth outcomes. Zhu et al. (2010) found that stress during the first trimester of pregnancy correlates with reduced birth weight. In Nepal, Diamond-Smith et al. (2023) found that first-trimester drought exposure is associated with lower birth weight. Similarly, Abiona et al. (2023) concluded that harvest droughts decrease birth weight by approximately 4%, attributing this to maternal malnutrition and food insecurity.

Intrauterine aspects, such as birth weight, represent the risk factor that most influences child survival and development.

In previous studies, birth weight has been linked to future health problems and educational outcomes, such as cognitive ability (Victora et al., 2015). It has long-term effects on human capital (Almond and Currie, 2010). Using birth registry data from Norway, Black et al. (2007) analyzed twin comparisons to distinguish the effects of low birth weight. They found significant variation in birth weight between twins with the Wald estimator and observed a strong positive effect on height, BMI (body mass index), and IQ, which increases the likelihood of high school graduation. They also note that there is weight variation, especially among twins, and some differences in later outcomes for the heavier twin.

With the creation of the Unified Health System (SUS) in Brazil, the agency responsible for reorganizing Brazilian public health, women gained access to prenatal care and, consequently, could monitor their own health and that of their fetuses.

Having stated this, this study seeks to contribute to the literature by focusing on the impact of an extreme weather event on health outcomes, both intrauterine and postnatal, considering two of the most vulnerable groups: pregnant women and the fetus. The main objective of this dissertation is to fill a gap in the literature by providing evidence on the impacts of the drought shock in March 2020 on birth outcomes in the state of Rio Grande do Norte, and by comparing these impacts with those of a drought event in January 2022 in the southern states of Brazil — Paraná, Rio Grande do Sul, and Santa Catarina.

2 Background

2.1 Rio Grande do Norte and Southern Brazil

According to the Center for Strategic Management and Studies (2012), the water supply in Brazil's Northeast primarily comes from rainfall within hydrographic basins entirely within the region. Rainfall is concentrated over four months, and this condition—coupled with high evapotranspiration rates and shallow soils with limited water storage capacity—leads to the region's semi-arid climate and Caatinga biome. This is particularly evident in the state of Rio Grande do Norte, where conditions of sub-humidity and semi-aridity are prevalent. This places the state on alert regarding water availability, as noted by Lucena et al. (2018). Troleis and Silva (2018) highlight that 90% of the state's municipalities are encompassed by the Drought Polygon, an area characterized by semi-arid conditions.

Given this long history of recurrent droughts, the Northeast region has prompted numerous policy discussions and government initiatives to mitigate its impact. Paiva et al. (2018) note that formal attention to the issue began in the late 1950s under President Juscelino Kubitschek with the creation of SUDENE (Superintendency for the Development of the Northeast). More recently, the drought that affected the region between 2012 and 2015 was unprecedented in its intensity and impact, destroying crops and disrupting water supplies (Marengo et al., 2017). In response to these intensifying events, Marengo et al. (2016) note that governments have made significant strides in expanding hydraulic infrastructure, which has dramatically increased water security. These efforts include incentivizing the construction of large reservoirs, drilling tube wells, and distributing cisterns. Furthermore, Ferreira and Figueiredo (2016) describe crucial emergency policies such as Bolsa Estiagem and Garantia-Safra, as well as the 1 Million Cisterns Program, which has been formalized as a public policy for drought adaptation.

In contrast, Brazil's South region comprises three states—Paraná, Santa Catarina, and Rio Grande do Sul. According to the *Atlas Climático da Região Sul do Brasil* (Wrege et al., 2012), its predominant climate is subtropical, characterized by four distinct seasons with significant temperature variations. As the coldest region in the country, it experiences frost and even snow in some areas during winter. However, even with its temperate climate, Brazil's South region has experienced an increase in the frequency of extremely hot, dry events over the past decade. Cunha et al. (2019) point to the 2014–2015 drought in the South and Southeast regions, which triggered a severe water crisis with significant impacts on water supply and hydropower generation. By contrast, Marengo et al. (2024) The unprecedented floods that hit Rio Grande do Sul from April to May 2024 affected over 90% of the state, causing significant impacts in vulnerable areas of the Porto Alegre Metropolitan Region and nearby municipalities. This disaster highlighted the urgent need for an objective risk assessment and reinforced flood infrastructure to build resilience against this and future, more extreme events. Piedra-Bonilla et al. (2025) highlight that extreme climatic events are expected to increase in frequency and intensity. However, the study also notes that crop diversification can serve as an effective adaptive measure to reduce vulnerability to climate risks in Brazil.

While disaster prevention and mitigation policies have traditionally been concentrated in Brazil's Northeast, there is a clear need to expand these actions to the South, as highlighted by Junior et al. (2024). Nóia-Júnior et al. (2025) state that Southern Brazil is facing significant threats to its agricultural stability due to fluctuating seasonal weather patterns. In recent years, this region has experienced severe, unprecedented summer droughts followed by extreme flooding.

This comparative analysis reveals a significant disparity in how Brazil's two major regions, the Northeast and the South, have historically prepared for and responded to climatic challenges. The Northeast, with its long-standing history of drought and institutionalized policies, has developed a form of social and governmental resilience to deal with extreme weather events. In contrast, the South, while traditionally seen as having a temperate climate, is now experiencing an alarming increase in the frequency and intensity of unprecedented events, such as severe droughts and extreme floods. This stark contrast leads to the central hypothesis of this study: that the long-term, institutionalized resilience in the Northeast may mitigate the adverse effects of extreme weather on birth outcomes more effectively than in the South, where these events represent a newer and more destabilizing challenge to both society and infrastructure.

3 Methodology

3.1 Data

To access information on birth outcomes, we used data from the Unified Health System's Information Technology Department (DATASUS). The primary data used in this study come from the SINASC (Sistema de Informação sobre os Nascidos Vivos) platform, which provides information on live births and the mother and household in which the baby is born. From this system, it is possible to extract information about the baby's birth weight, the mother's age and educational level, the municipality where the mother lives, the municipality where the baby is born, the duration of the pregnancy in weeks, and whether the pregnancy was single or multiple.

To examine the effect of the drought event, we used the municipality where the mother lives, as she experienced the drought during the pregnancy. Using the birth date and the reported gestational age in weeks, we estimate the conception date for each birth by subtracting the gestational duration in days. This calculation is critical for analyzing the potential impact of events such as drought on maternal and fetal health, given that different stages of pregnancy may respond differently to environmental stressors. This method allows us to determine during which trimester of pregnancy each woman was exposed to the extreme weather event. However, we interpret our estimates as Intention-to-Treat effects, recognizing that exposure to climate stress may influence the reported gestational age.

In particular, we focus on the drought in Rio Grande do Norte in March 2020 and compare it with the drought in the Southern states of Brazil (Paraná, Rio Grande do Sul, and Santa Catarina) in January 2022. This comparison is essential because it allows us to evaluate whether the health impacts of climate shocks on birth outcomes are consistent across regions with different socioeconomic conditions, health system structures, and climate vulnerabilities, or whether the effects vary by local context. The dataset also includes important control variables such as maternal age, infant sex, type of delivery, and maternal education. Both datasets are merged using the IBGE municipality code. The analysis calculates the conception date for each birth to determine whether the fetus was exposed to the climatic shock *in utero*.

For data on climate-related issues, the Digital Atlas of Disasters in Brazil *(Atlas Digital de Desastres no Brasil, CEMADEN)* provides access to data on disaster occurrences across Brazil. The data used to develop it are collected from records maintained by states and municipalities in the Integrated Disaster Information System (S2ID). Since 2011, extreme weather events have been standardized, following a survey that each municipality must complete to report a disaster. Variations in data entry are expected, as different cities may employ various methods to report emergencies. This diversity can be attributed to local conditions, resources, and the experience of those responsible for data entry, leading to notable differences across regions. However, analyzing these reporting discrepancies and their root causes is beyond the scope of this dissertation. Our research focuses on studying the impact of documented drought events on birth outcomes, using official disaster data to estimate causal relationship effects.

For this analysis, we integrated the two main datasets, the climate and the birth related ones. The Digital Disaster Atlas of Brazil is filtered to identify specific drought events in two distinct regions and time periods. For Rio Grande do Norte in the Northeast region, the analysis examines the March 2020 drought event, using data from May 2019 (9 months before the event) to December 2020 (9 months after) to capture the whole gestational exposure window. For the Southern region, the analysis focuses on the January 2022 drought event in Paraná, Santa Catarina, and Rio Grande do Sul, with data from March 2021 to November 2022 used to establish appropriate pre- and post-treatment periods.

We focus specifically on drought events, which are formally characterized as prolonged periods of deficient precipitation resulting in a substantial hydrological imbalance. This precise conceptualization is critical for delineating the specific type of climatic shock under investigation and for evaluating its potential impacts on maternal and child health outcomes.

The following Table 1 presents the descriptive statistics for Rio Grande do Norte over the period from May 2019 (40 weeks before the event) to December 2020 (40 weeks after the event).

Table 1 – Descriptive Statistics for Rio Grande do Norte

Variable	Control Group	Treated Group
Number of Live Births	10,567	14,542
Birth Weight (g) - Mean (SD)	3252.86 (575.72)	3225.89 (554.48)
Birth Weight (g) - Min	220	100
Birth Weight (g) - Max	6200	6410
Gestational Weeks - Mean (SD)	38.63 (2.31)	38.46 (2.17)
Gestational Weeks - Min	20	19
Gestational Weeks - Max	45	45
Mother's Age - Mean (SD)	26.31 (6.77)	26.55 (6.81)
Mother's Age - Min	11	11
Mother's Age - Max	50	49
Male (%)	50.96	50.5
Cesarean Section (%)	49.58	68.28
Multiple Pregnancy (%)	1.7	1.69
Elementary School (%)	43.82	36
High School (%)	49.58	53.64
Higher Education (%)	5.74	9.35
Married (%)	46.42	52.29
Divorced (%)	0.55	0.67
Single (%)	52.27	45.9
Marital - Others (%)	0.77	1.13

Source: Author's elaboration.

For the Rio Grande do Norte state, the sample sizes for both groups are substantial, with 10,567 births in the control group and 14,542 in the treated group. On average, there are minimal differences in the health outcomes and demographics of the mothers. The mean birth weight is very similar, at 3,252.86 g for the control group and 3,225.89 g for the treated group, with comparable standard deviations. Likewise, the mean gestational weeks are nearly identical (38.63 vs. 38.46), indicating a balanced baseline for pregnancy duration. The average maternal age is also very close, at 26.31 years and 26.55 years for the control and treated groups, respectively (Table 1).

However, the analysis in Table 1 shows a notable disparity in the proportion of births by Cesarean section. The treated group had a significantly higher percentage of C-sections (68.28%) compared to the control group (49.58%). This difference may be due to factors specific to the treated municipalities, and it is a crucial variable to control for in the regression analysis. Additionally, while the percentage of mothers with a high school education is similar between the groups, the treated group has a higher proportion of mothers with higher education (9.35%) than the control group (5.74%). The marital status breakdown also shows differences: a higher percentage of married mothers and a lower percentage of single mothers in the treated group.

The next table, Table 2, presents the descriptive statistics for the Southern Region over the period from March 2021 (40 weeks before the event) to October 2022 (40 weeks after the event)

Table 2 – Descriptive Statistics for Southern Brazil

Variable	**Control Group**	**Treatment Group**
Number of Live Births	180.089	59.574
Birth Weight (g) - Mean (SD)	3172.97 (548.95)	3165.85 (543.2)
Birth Weight (g) - Min	100	210
Birth Weight (g) - Max	6660	6565
Gestational Weeks - Mean (SD)	38.33 (2.02)	38.26 (2.08)
Gestational Weeks - Min	19	19
Gestational Weeks - Max	45	45
Mother's Age - Mean (SD)	27.75 (6.52)	28.19 (6.55)
Mother's Age - Min	11	11
Mother's Age - Max	60	54
Male (%)	51.13	50.97
Cesarean Section (%)	62.54	70.07
Multiple Pregnancy (%)	2.28	2.32
Elementary School (%)	23.09	22.16
High School (%)	56.74	55.64
Higher Education (%)	19.32	21.79
Married (%)	48.04	49.82
Single (%)	49.30	47.78
Divorced (%)	1.86	1.57
Marital - Others (%)	0.81	0.83

Source: Author's elaboration.

Table 2 presents the descriptive statistics for births in Southern Brazil, comparing the control and treatment groups. The Control Group, comprising 180,089 live births, consists of municipalities that were not exposed to the drought event. The Treatment Group, with 59,574 births, includes municipalities affected by the January 2022 drought.

This data analysis demonstrates a remarkable balance between the two groups. The mean values for continuous variables, such as birth weight (3172.97 g in the control versus 3165.85 g in the treatment), gestational weeks (38.33 vs. 38.26), and mother's age

(27.75 years vs. 28.19 years), are very similar. This closeness suggests that, on average, the babies and their mothers had comparable characteristics even before the drought.

The same pattern is observed in the categorical variables. The proportions of male births (51.13% vs. 50.97%) and cesarean sections (62.54% vs. 70.07%) are comparable, as is the distribution of mothers' education level and marital status.

3.2 Research Design and Empirical Strategy

The present study adopts a quasi-experimental design to estimate the causal impact of climatic shocks on birth outcomes in Brazil's Southern region. The primary identification strategy is a Difference-in-Differences (DiD) model, based on a cohort approach as in Currie (2022), which compares changes in birth outcomes between cohorts conceived before and during the disaster period. Specifically, the model contrasts municipalities affected by a climate disaster (the treatment group) with unaffected ones (the control group), controlling for pre-existing differences and common time trends.

This process creates the `tratados` variable, which flags the municipalities comprising the treatment group in each regional analysis. Municipalities that experienced multiple shocks within their respective analysis periods are excluded to ensure a clean identification strategy. Birth data from corresponding periods were collected from the SINASC database using the `microdatasus` package. Key outcomes of interest are birth weight and gestational age.

Our Difference-in-Differences model specification establishes the beginning of the month as the reference event date for both regional analyses. This approach is justified by the temporal distribution of drought events observed in the disaster records. In Rio Grande do Norte, the March 2020 drought events, which occurred throughout the month, showed a higher concentration in the initial weeks. Similarly, in the Southern region, the January 2022 drought events were distributed across the entire month but with greater frequency during the first half. Using the start of the month as the event date provides a consistent, well-defined reference point for estimating conception dates and determining in-utero exposure periods, while accommodating the temporal spread of disasters within each month. The core of the analysis is the DiD model, specified as follows:

$$Y = \beta_0 + \beta_1 T + \beta_2 P + \delta(T \times P) + \beta_3 \mathbf{X} + \epsilon$$

Where:

- Y is the outcome of interest (birth weight and duration).
- T is a dummy variable that equals 1 for municipalities affected by the drought and 0 otherwise;
- P is a dummy variable that equals 1 for the cohort in utero during the drought period and 0 otherwise;
- δ is the Difference-in-Differences estimator, the primary coefficient of interest. It captures the average causal effect of the drought on the outcome variable.
- $\mathbf{X}$ is a vector of control variables, including maternal age, type of pregnancy, education, and type of delivery;
- ϵ is the error term.

To identify whether a birth was exposed to drought *in utero*, we compute the estimated date of conception using the reported gestational age for each birth:

$$\text{Conception Date} = \text{Birth Date} - (\text{Gestational Age} \times 7)$$

It is important to note that while we use the observed gestational age to determine the conception date and thus exposure timing, we interpret our estimates as Intention-to-Treat (ITT) effects. This is because gestational age itself may be endogenous to the drought exposure—environmental shocks could potentially alter pregnancy duration.

Using this information, we define the variable P to equal one if the gestation period overlaps with the drought event and 0 otherwise. This approach allows the identification strategy to capture the causal effect of being exposed to a climatic shock during fetal development, rather than relying solely on birth timing.

To build the affected and non-affected groups, we considered municipalities that were isolated from other extreme weather events within a 40-week window before the drought and a 40-week window after. This analysis used maps that visualize the 9 months before and after each identified disaster, providing crucial spatial and temporal context. The primary objective of these maps is to demonstrate that the treated regions were isolated from other significant climatic shocks during the analysis period. This visual evidence supports the plausibility of our identification strategy by reinforcing the assumption of a clear treatment and control group.

To illustrate the geographical distribution of affected municipalities, Figures 1 through 4 show maps of municipalities exposed to droughts in both Rio Grande do Norte and the Southern states.

Figure 1 – Spatial distribution of drought in Rio Grande do Norte - 9 months before the event (May 2019 - March 2020)

Figure 2 – Spatial distribution of drought in Rio Grande do Norte - 9 months after the event (April 2020 - December 2020)

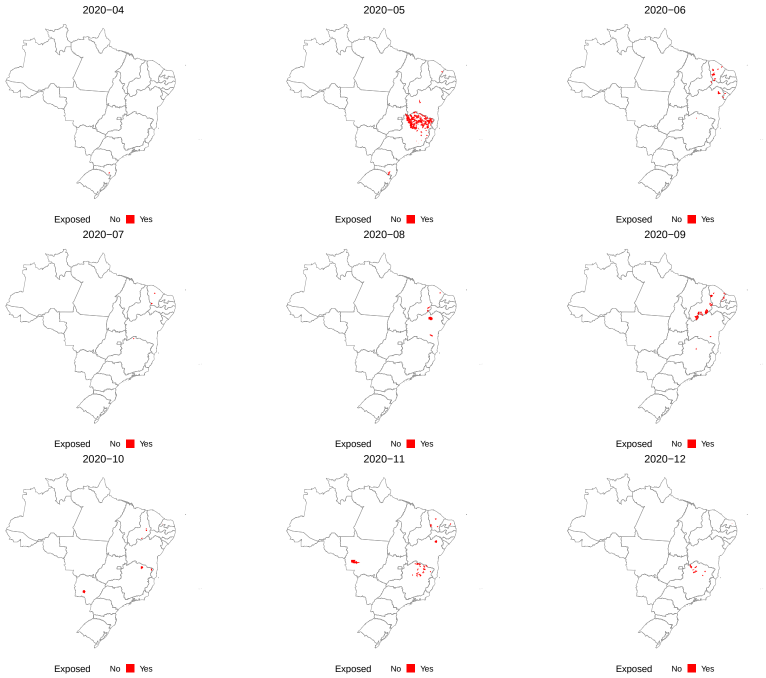


Figure 3 – Spatial distribution of drought in Southern states - 9 months before the event (March 2021 - January 2022)

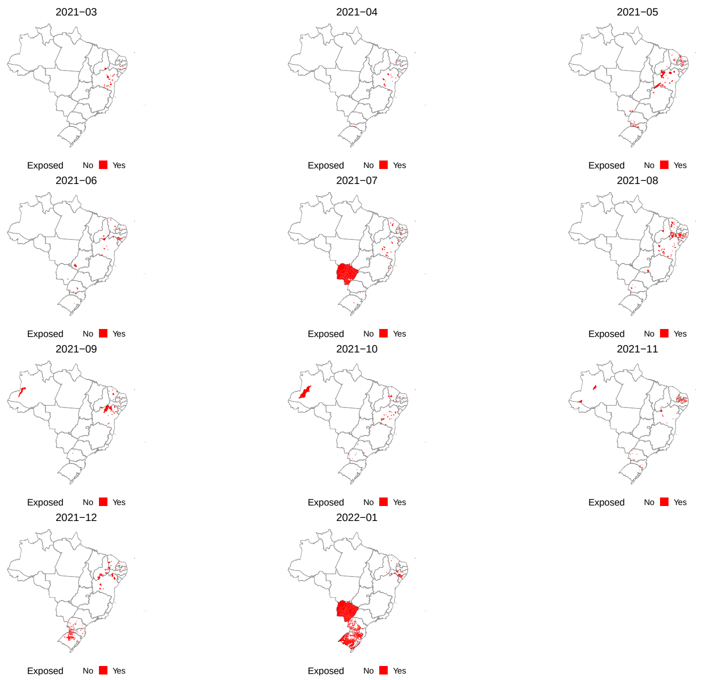
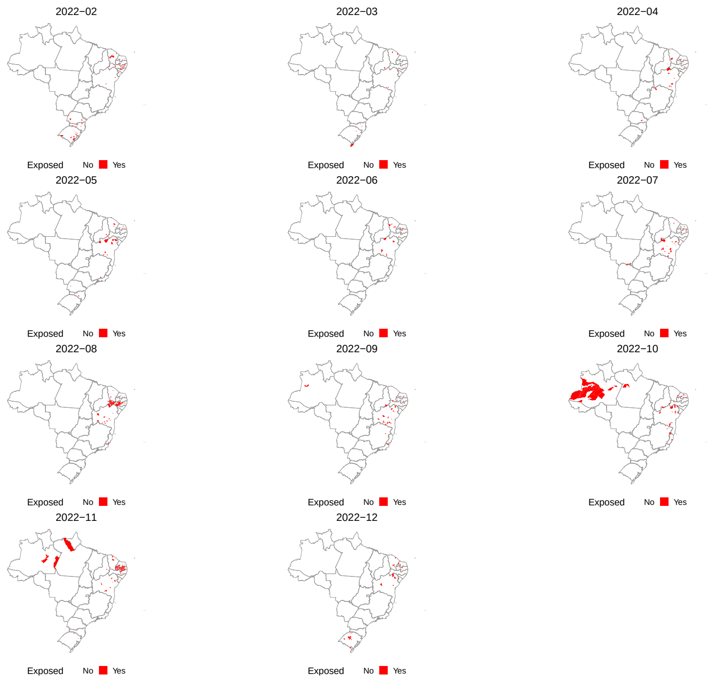


Figure 4 – Spatial distribution of drought in Southern states - 9 months after the event (February 2022 - December 2022)



To test the robustness of the results, a placebo analysis was performed. Municipalities unaffected by the drought were randomly assigned to a pseudo-treatment group, keeping the same proportion of treated units as in the primary analysis. This procedure simulates random exposure to drought conditions while preserving the data structure. The model was then re-estimated using the pseudo-treatment indicator. The absence of significant effects in this placebo test supports the validity of the identification strategy and reduces concerns about spurious correlations.

4 Results

4.1 Rio Grande do Norte

The Difference-in-Differences estimates provide evidence that in-utero exposure to drought shocks negatively affects birth weight in Rio Grande do Norte, Brazil, with the impact varying significantly by both the timing of exposure and the fetus's gender.

The primary result for the full sample shows that average exposure throughout gestation leads to a reduction in birth weight of approximately 25.7 grams, an effect statistically significant at the 10% level. When disaggregated by trimester, the coefficients are consistently negative, suggesting a pervasive effect, though they lack individual statistical significance in the pooled sample (Table 3).

The analysis by gender, however, reveals a more nuanced and striking pattern. Female fetuses exhibit a statistically significant sensitivity to first-trimester exposure, with a substantial reduction in birth weight of 55.4 grams. In contrast, for male fetuses, the most significant impact occurs during the third trimester, with a decrease of 54.2 grams, significant at the 5% level. This suggests distinct critical periods of vulnerability: female fetal development appears to be most susceptible to shocks early in pregnancy, whereas male fetal development is more vulnerable to late-pregnancy stresses.

This gendered pattern challenges simplistic narratives of vulnerability and suggests that the physiological pathways through which environmental shocks affect fetal growth may differ fundamentally by sex.

Next, the results for gestational duration (Table 4) reveal that the drought's impact on pregnancy duration is more temporally specific and statistically subtle than its effect on birth weight, with notable differences emerging when considering the full sample versus gender-specific models.

For the whole period, the effect appears concentrated in the late stages of pregnancy. The interaction for third-trimester exposure is negative and marginally significant, suggesting a reduction in gestational age of approximately 0.13 weeks (just under one day). In contrast, the coefficients for the first and second trimesters are negligible and statistically insignificant. This pattern suggests that exposure to the drought shock during the final trimester may be one of the drivers of shortened gestation, potentially acting as a physiological stressor that precipitates earlier parturition. This finding aligns with

Table 3 – Difference-in-Differences Results for Birth Weight (grams) - Rio Grande do Norte

	Full Period Coefficient (SE)	**Trimester Specification Coefficient (SE)**
All Births		
Treat × In Utero	-25.711*	
	(14.013)	
Treat × 1st Trimester		-21.056
		(20.925)
Treat × 2nd Trimester		-25.785
		(20.483)
Treat × 3rd Trimester		-28.778
		(18.275)
Females		
Treat × In Utero	-24.203	
	(19.656)	
Treat × 1st Trimester		-55.390*
		(29.332)
Treat × 2nd Trimester		-24.021
		(28.610)
Treat × 3rd Trimester		-3.561
		(25.716)
Males		
Treat × In Utero	-24.386	
	(19.743)	
Treat × 1st Trimester		16.125
		(29.509)
Treat × 2nd Trimester		-19.542
		(28.980)
Treat × 3rd Trimester		-54.177**
		(25.670)
Observations	25,108	25,108
R-squared	0.056	0.056

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mother's age, twin pregnancy, and education levels. The table presents two specifications of the Difference-in-Differences model.

Source: Author's elaboration.

evidence from Rocha and Soares (2015), who also documented shorter gestation periods associated with drought exposure in their study of the Brazilian semiarid region.

When the sample is stratified by gender, the precise pattern becomes less pronounced. For males, the point estimate for third-trimester exposure remains substantial (-0.118 weeks), though it loses statistical significance, likely due to reduced sample size. Interestingly, the coefficients for early and mid-pregnancy exposure for males are positive, albeit small and insignificant. For females, none of the trimester-specific interactions are statistically significant, and the coefficients are smaller in magnitude than those for males in the third trimester. This suggests that while the pooled model points to a late-pregnancy effect, the gender-stratified results hint at a potential vulnerability for male fetuses, mirroring the pattern observed for birth weight, where males were significantly affected in the third trimester.

To summarize, the drought shock appears to shorten gestational age primarily when experienced in the final trimester. The gendered pattern, while not statistically robust, is consistent with the hypothesis that male fetal development is susceptible to late-pregnancy environmental stresses, affecting both the pace of growth (birth weight) and the timing of birth (gestational duration). This finding aligns with McCarthy (2019), who also documents that male fetuses appear to be more vulnerable to maternal stress exposures during pregnancy, particularly in later stages of gestation.

Table 4 – Difference-in-Differences Results for Gestational Age (weeks) - Rio Grande do Norte

	Full Period Coefficient (SE)	**Trimester Specification Coefficient (SE)**
All Births		
Treat × In Utero	-0.063	
	(0.056)	
Treat × 1st Trimester		-0.009
		(0.083)
Treat × 2nd Trimester		-0.011
		(0.081)
Treat × 3rd Trimester		-0.128*
		(0.073)
Females		
Treat × In Utero	-0.091	
	(0.079)	
Treat × 1st Trimester		0.028
		(0.117)
Treat × 2nd Trimester		-0.058
		(0.114)
Treat × 3rd Trimester		-0.030
		(0.115)
Males		
Treat × In Utero	-0.032	
	(0.078)	
Treat × 1st Trimester		0.065
		(0.117)
Treat × 2nd Trimester		0.012
		(0.115)
Treat × 3rd Trimester		-0.118
		(0.102)
Observations	25,108	25,108
R-squared	0.043	0.043

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mother's age, twin pregnancy, and education levels. The table presents two specifications of the Difference-in-Differences model.

Source: Author's elaboration.

The analysis of the weight-for-gestational-age ratio, presented in Table 5, provides a synthesized measure of fetal growth efficiency, revealing a pattern of trimester-specific vulnerabilities that aligns with, and refines, the findings from the separate analyses of birth weight and gestational age.

Throughout the entire period, the interaction coefficients remain consistently negative, indicating a general negative impact of the drought on fetal growth proportionality. However, none reach traditional levels of statistical significance, implying that the average effect is dispersed when fetal factors are not considered sex.

The gender-stratified results, in contrast, uncover a clear and significant temporal pattern. For female fetuses, the most substantial and marginally significant effect occurs with first-trimester exposure, reducing the weight-gestation ratio by 1.32 units. For male fetuses, the largest and slightly significant effect is observed with third-trimester exposure, reducing the ratio by 1.07 units. This pattern is strikingly consistent with the individual results for birth weight, where females were most affected in the first trimester and males in the third.

In conclusion, the ratio analysis reinforces that the drought's impact was not solely on the absolute size of the newborn or the duration of pregnancy, but on the very efficiency of fetal growth. The distinct trimester-specific vulnerabilities by sex suggest different underlying biological mechanisms, with female fetal development being more sensitive to early insults and male fetal development to late-pregnancy stresses.

Table 5 – Difference-in-Differences Results for Weight/Gestational Age Ratio - Rio Grande do Norte

	Full Period Coefficient (SE)	**Trimester Specification Coefficient (SE)**
All Births		
Treat × In Utero	-0.542	
	(0.336)	
Treat × 1st Trimester		-0.507
		(0.431)
Treat × 2nd Trimester		-0.540
		(0.498)
Treat × 3rd Trimester		-0.470
		(0.430)
Females		
Treat × In Utero	-0.491	
	(0.475)	
Treat × 1st Trimester		-1.323*
		(0.709)
Treat × 2nd Trimester		-0.471
		(0.691)
Treat × 3rd Trimester		0.022
		(0.621)
Males		
Treat × In Utero	-0.480	
	(0.479)	
Treat × 1st Trimester		0.396
		(0.717)
Treat × 2nd Trimester		-0.474
		(0.704)
Treat × 3rd Trimester		-1.066*
		(0.623)
Observations	25,108	25,108
R-squared	0.032	0.033

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mother's age, twin pregnancy, cesarean delivery, infant sex, and education levels. The table presents two specifications of the Difference-in-Differences model.

Source: Author's elaboration.

4.2 Southern Brazil

From the beginning, Table 6 shows that the analysis for the South Region reveals a notably different pattern from that observed in Rio Grande do Norte, with generally weaker, statistically non-significant effects of drought exposure on birth weight. For the full sample, the interaction coefficients between the treatment and the exposure periods are small in magnitude and not statistically significant. The point estimates are negative for the first and second trimesters but turn positive for the third trimester, though none are distinguishable from zero. This suggests that, on average, the drought shock did not have a clear, significant impact on birth weight in the South Region.

When examining the results by gender, the coefficients for females are consistently more negative than those for males across all specifications. The largest negative effect is observed in the second trimester (-12.6 grams), while for males, the effects are mixed, with a slight positive coefficient in the first and third trimesters. This pattern hints at a potential gendered effect, with female fetuses being more adversely affected, but the large standard errors prevent any definitive conclusions.

In contrast to the Northeast, the South Region shows no significant impact of drought on birth weight. The weaker results could be attributed to several factors, including better infrastructure, higher socioeconomic resilience, or less severe drought conditions in the South, which may have buffered households against the environmental shock.

Table 6 – Difference-in-Differences Results for Birth Weight (grams) - South Region

	Full Period Coefficient (SE)	**Trimester Specification Coefficient (SE)**
All Births		
Treat × In Utero	-2.958	
	(4.999)	
Treat × 1st Trimester		-4.391
		(7.507)
Treat × 2nd Trimester		-9.805
		(7.375)
Treat × 3rd Trimester		2.644
		(6.607)
Females		
Treat × In Utero	-5.497	
	(6.903)	
Treat × 1st Trimester		-7.507
		(10.410)
Treat × 2nd Trimester		-12.574
		(10.189)
Treat × 3rd Trimester		0.229
		(9.138)
Males		
Treat × In Utero	-0.562	
	(7.147)	
Treat × 1st Trimester		0.225
		(10.840)
Treat × 2nd Trimester		-9.534
		(10.539)
Treat × 3rd Trimester		5.474
		(9.432)
Observations	215,783	215,783
R-squared	0.048	0.048

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mothers' age, twin pregnancy, and education levels. The table presents two specifications of the Difference-in-Differences model.

Source: Author's elaboration.

In the following analysis, depicted in Table 7, we examine Gestational Duration in the Southern Region. In stark contrast to the results for birth weight, this analysis reveals statistically significant and consistent negative effects of drought exposure. These findings suggest that, although the drought did not substantially impair fetal growth, it shortened pregnancy duration.

The results are consistent across different specifications. For the entire sample, the interaction between the treatment and any exposure period is negative and highly statistically significant, indicating a decrease in gestational age of about 0.09 to 0.11 weeks.

The effect appears throughout the entire gestational period and is similarly significant when analyzed by trimester.

This pattern of reduced gestational age across multiple trimesters for both female and male fetuses suggests a consistent association between drought exposure and shorter pregnancy duration in the South Region. However, the observational nature of our data prevents definitive conclusions about the underlying physiological mechanisms. While the results are consistent with the hypothesis that environmental stress could trigger earlier parturition, we cannot rule out other pathways or confounding factors that might explain this association across the region.

Table 7 – Difference-in-Differences Results for Gestational Duration (weeks) - South Region

	Full Period Coefficient (SE)	Trimester Specification Coefficient (SE)
All Births		
Treat × In Utero	-0.096*** (0.019)	
Treat × 1st Trimester		-0.087*** (0.028)
Treat × 2nd Trimester		-0.114*** (0.028)
Treat × 3rd Trimester		-0.088*** (0.025)
Females		
Treat × In Utero	-0.096*** (0.019)	
Treat × 1st Trimester		-0.076* (0.039)
Treat × 2nd Trimester		-0.146*** (0.038)
Treat × 3rd Trimester		-0.066* (0.034)
Males		
Treat × In Utero	-0.096*** (0.019)	
Treat × 1st Trimester		-0.100** (0.040)
Treat × 2nd Trimester		-0.080** (0.039)
Treat × 3rd Trimester		-0.106*** (0.035)
Observations	215,783	215,783
R-squared	0.038	0.038

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mother's age, twin pregnancy, and education levels. The table presents two specifications of the Difference-in-Differences model.

Source: Author's elaboration.

Table 8 presents the analysis of the weight-for-gestational-age ratio in the South Region, revealing a counterintuitive yet insightful pattern that synthesizes the previous findings on birth weight and gestational age. While the drought significantly shortened pregnancy duration, it appears to have had a neutral or even slightly positive effect on fetal growth efficiency.

Over the entire period, the interaction coefficients are generally positive, with a marginally significant effect in the third trimester. This suggests that fetuses exposed to the drought shock in late pregnancy were actually proportionally heavier for their gestational age at birth. This pattern is driven primarily by male fetuses, who show a similar marginally significant positive effect in the third trimester.

Table 8 – Difference-in-Differences Results for Weight/Gestational Duration Ratio - South Region

	Full Period Coefficient (SE)	**Trimester Specification Coefficient (SE)**
All Births		
Treat × In Utero	0.098	
	(0.118)	
Treat × 1st Trimester		0.050
		(0.179)
Treat × 2nd Trimester		-0.075
		(0.167)
Treat × 3rd Trimester		0.256*
		(0.151)
Females		
Treat × In Utero	-0.004	
	(0.164)	
Treat × 1st Trimester		-0.102
		(0.248)
Treat × 2nd Trimester		-0.099
		(0.242)
Treat × 3rd Trimester		0.107
		(0.217)
Males		
Treat × In Utero	0.195	
	(0.169)	
Treat × 1st Trimester		0.240
		(0.256)
Treat × 2nd Trimester		-0.081
		(0.249)
Treat × 3rd Trimester		0.367*
		(0.223)
Observations	215,783	215,783
R-squared	0.035	0.034

Notes: Standard errors clustered at municipality level in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$. The Full Specification controls for infant sex and cesarean delivery; the Trimester Specification does not include cesarean delivery. Both control for mother's age, twin pregnancy, and education levels.

Source: Author's elaboration.

To summarize, the primary impact of the drought in the South was a stress-induced shortening of pregnancy. However, this did not equate to impaired fetal growth. The ratio analysis reveals that the fetuses born were, on average, well-adapted to their shorter gestation periods, suggesting that the nutritional conditions necessary for growth were maintained mainly until the point of early delivery.

To complement the regional analysis, we also estimate our models separately for each state (Table 9). This disaggregated approach provides a more detailed view of the drought's impacts across the Southern region, revealing potential variations in effect sizes and statistical significance among Paraná, Santa Catarina, and Rio Grande do Sul. The state-level results are presented next.

Table 9 – Difference-in-Differences Estimates for Birth Weight (grams) by State - South Region

	Paraná		**Santa Catarina**		**Rio Grande do Sul**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Full Period - All Births						
Treat × In Utero	-2.127	0.866	42.256	0.446	-13.853	0.184
	(12.603)		(55.391)		(10.433)	
By Gender - Full Period						
Females	-1.569	0.898	7.875	0.875	-11.102	0.276
	(12.185)		(50.217)		(10.184)	
Males	-2.127	0.866	42.256	0.446	-13.853	0.184
	(12.603)		(55.391)		(10.433)	
Trimester Specification						
1st Trimester	-0.099	0.753	0.082	0.952	-0.109	0.678
	(0.316)		(1.350)		(0.265)	
2nd Trimester	0.094	0.763	1.684	0.197	-0.301	0.237
	(0.312)		(1.304)		(0.255)	
3rd Trimester	0.291	0.290	1.180	0.320	-0.078	0.735
	(0.275)		(1.186)		(0.231)	
Observations	58,161		5,802		14,140	
R-squared	0.087		0.106		0.088	

Notes: Standard errors clustered at municipality level in parentheses. All models control for mother's age, twin pregnancy, and education levels. No coefficients are statistically significant at conventional levels ($p<0.10$).

Source: Author's elaboration.

Despite the lack of statistical significance, the state-level patterns generally corroborate the findings from the regional analysis. In Paraná, the treatment shows no statistically significant effects on birth weight across any specification, with coefficients close to zero and large p-values. For instance, the main effect of in utero exposure is -2.127 grams ($p=0.866$), indicating no meaningful impact.

Santa Catarina presents the most striking results, with positive but imprecise estimates. The main effect shows a substantial 42.256-gram increase in birth weight for full gestational exposure, though this is not statistically significant ($p=0.446$). The trimester-specific effects are consistently positive across all periods, with the second trimester showing the largest point estimate (1.684), though it remains statistically insignificant.

Rio Grande do Sul demonstrates negative treatment effects throughout. The main in utero exposure coefficient of -13.853 grams approaches conventional significance levels (p=0.184), suggesting potential adverse effects. The trimester analysis reveals consistently negative coefficients, with the second trimester showing the largest negative effect (-0.301, p=0.237).

Gender disaggregation reveals important patterns. In Santa Catarina, the positive effects appear concentrated among males (42.256 grams) rather than females (7.875 grams). Similarly, in Rio Grande do Sul, the negative effects are slightly more pronounced in males (-13.853 grams) than in females (-11.102 grams).

The following analysis of gestational duration reveals contrasting treatment effects across states (Table 10).

Table 10 – Difference-in-Differences Estimates for Gestational Duration (weeks) by State - South Region

	Paraná		**Santa Catarina**		**Rio Grande do Sul**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Full Period - All Births						
Treat × In Utero	-0.097***	0.003	-0.159	0.267	-0.090***	0.001
	(0.032)		(0.143)		(0.027)	
By Gender - Full Period						
Females	-0.064	0.155	-0.087	0.651	-0.111***	0.004
	(0.045)		(0.193)		(0.039)	
Males	-0.126***	0.006	-0.242	0.253	-0.068*	0.078
	(0.046)		(0.212)		(0.039)	
Trimester Specification						
1st Trimester	-0.092	0.061	-0.084	0.697	-0.079	0.057
	(0.049)		(0.217)		(0.042)	
2nd Trimester	-0.171***	0.000	-0.156	0.456	-0.071	0.077
	(0.048)		(0.209)		(0.040)	
3rd Trimester	-0.048	0.261	-0.216	0.257	-0.112***	0.002
	(0.042)		(0.190)		(0.036)	
Observations	134,692		20,634		84,336	
R-squared	0.070		0.072		0.083	

Notes: Standard errors clustered at municipality level in parentheses. *p<0.1, **p<0.05, ***p<0.01. All models control for mother's age, twin pregnancy, and education levels. Several coefficients are statistically significant, particularly in Paraná and Rio Grande do Sul.

Source: Author's elaboration.

Considering the length of pregnancy, Paraná shows the most consistent negative effect on gestational duration. The leading DiD coefficient of -0.097 weeks (p=0.003) indicates a statistically significant reduction in gestation time. This effect is particularly pronounced during the second trimester (-0.171 weeks, p=0.000) and shows significant gender disparities, with males experiencing stronger negative effects (-0.126 weeks, p=0.006) than females, for whom the effect is not statistically significant.

Rio Grande do Sul also shows significant negative effects, though with a different pattern. The main effect is -0.090 weeks (p=0.001), with particularly strong impacts in the third trimester (-0.112 weeks, p=0.002). Unlike Paraná, females in Rio Grande do Sul show more pronounced negative effects (-0.111 weeks, p=0.004) across multiple trimesters.

Santa Catarina stands in contrast to the other two states, showing no statistically significant effects on gestational duration across any specification. All coefficients, including the main effect of -0.159 weeks, are not statistically significant (p=0.267), suggesting treatment had minimal impact on gestation times in this state.

The gender analysis reveals important gender-specific responses to the treatment. In Paraná, males consistently exhibit stronger negative effects, while in Rio Grande do Sul, females are more impacted. The trimester-specific analysis shows that the second trimester is most vulnerable to treatment effects in Paraná, whereas the third trimester exhibits more significant effects in Rio Grande do Sul.

The subsequent Gestational Ratio analysis reveals distinct regional patterns in fetal growth efficiency across Brazil's Southern region.

Table 11 – Difference-in-Differences Estimates for Weight per Gestational Week (g/week) by State - South Region

	Paraná		**Santa Catarina**		**Rio Grande do Sul**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Full Period - All Births						
Treat × In Utero	0.125	0.553	1.033	0.246	-0.138	0.427
	(0.210)		(0.891)		(0.174)	
By Gender - Full Period						
Females	0.052	0.859	0.339	0.776	-0.126	0.602
	(0.291)		(1.194)		(0.241)	
Males	0.197	0.509	1.691	0.197	-0.201	0.414
	(0.299)		(1.310)		(0.246)	
Trimester Specification						
1st Trimester	-0.099	0.753	0.082	0.952	-0.110	0.678
	(0.316)		(1.350)		(0.265)	
2nd Trimester	0.094	0.763	1.684	0.197	-0.301	0.237
	(0.312)		(1.304)		(0.255)	
3rd Trimester	0.291	0.290	1.180	0.320	-0.078	0.735
	(0.275)		(1.186)		(0.231)	
Observations	134,686		20,633		84,333	
R-squared	0.052		0.060		0.059	

Notes: Standard errors clustered at municipality level in parentheses. All models control for mother's age, twin pregnancy, and education levels. No coefficients are statistically significant at conventional levels ($p<0.10$). The dependent variable is weight per gestational week (grams/week).

Source: Author's elaboration.

In Paraná, coefficients were predominantly positive but small in magnitude and not statistically significant. The aggregate effect (Treat × In Utero) was 0.125 g/week ($p = 0.553$), with similar patterns between sexes. Trimestral analysis revealed no clear trends, with coefficients ranging from -0.099 to 0.291 g/week. In Santa Catarina, we found the largest positive coefficients among the three states, though accompanied by high standard errors. The aggregate effect was 1.033 g/week ($p = 0.246$), with particular note of the 3.008 g/week coefficient in the second trimester among male newborns ($p = 0.114$), which, while non-significant, suggests a potentially relevant positive trend. On the other hand, Rio Grande do Sul demonstrated a distinct pattern, with predominantly negative coefficients. The aggregate effect was -0.138 g/week ($p = 0.427$), with trimestral analysis revealing negative coefficients across all trimesters for both sexes, though not statistically significant.

The consistent null findings for the interaction terms across all outcomes suggest that the treatment's effects may operate through mechanisms not adequately captured by the simple in-utero exposure timing, potentially involving more complex pathways or cumulative exposures that transcend specific gestational periods.

4.3 Placebo Test - Rio Grande do Norte

To validate our research design and assess the robustness of our empirical strategy, we conducted placebo tests by randomly assigning municipalities within the control group to pseudo-treatment status. The results, presented in Table 12, provide strong evidence supporting the causal interpretation of our main findings.

The placebo tests show that when treatment status is randomly reassigned to subsets of the control group, none of the resulting coefficients are statistically significant at conventional levels. This consistent pattern across all specifications—including analyses by gestational trimester and infant gender—indicates that our observed treatment effects are unlikely to be caused by pre-existing trends, unobserved confounding factors, or model misspecification. The lack of false effects in these falsification tests increases our confidence that the observed impacts truly reflect the causal effects of drought exposure.

Table 12 – Placebo Test - Pseudo-Treated vs. Controls (Rio Grande do Norte)

	Birth Weight (g)		**Gestational Weeks**		**Weight/Week (g/week)**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Full Period - All Births						
Pseudo-Treat × In Utero	-25.52	0.322	-0.028	0.784	-0.621	0.316
	(25.77)		(0.103)		(0.618)	
By Gender - Full Period						
Females	-24.11	0.502	-0.009	0.951	-0.483	0.573
	(35.94)		(0.145)		(0.856)	
Males	-23.18	0.526	-0.051	0.728	-0.647	0.463
	(36.53)		(0.147)		(0.880)	
Trimester Specification						
1st Trimester	-71.29	0.063	0.063	0.684	-2.132	0.201
	(38.30)		(0.154)		(0.919)	
2nd Trimester	1.11	0.976	0.024	0.870	0.047	0.958
	(37.29)		(0.150)		(0.895)	
3rd Trimester	-15.77	0.647	-0.117	0.398	-0.151	0.855
	(34.39)		(0.138)		(0.825)	
Observations	10,567		10,567		10,567	
Pseudo-Treated	8,097 (76.63%)		8,097 (76.63%)		8,097 (76.63%)	

Notes: Standard errors clustered at municipality level in parentheses. No coefficients are statistically significant at conventional levels (p<0.10), supporting the validity of the identification strategy.

Source: Author's elaboration.

4.4 Placebo Tests - South Region

To further validate the robustness of our empirical design for the South Region analysis, we implemented a placebo-testing procedure by randomly assigning pseudo-treatment status to various subsets of control municipalities, using the same strategy as for Rio Grande do Norte state. The results, presented in Table 13, provide compelling evidence supporting the causal interpretation of our primary drought exposure estimates for this region.

The analysis provides a robust foundation for concluding that the observed effects represent actual causal impacts of drought exposure.

Table 13 – Placebo Test - Pseudo-Treated vs. Controls (Southern Region)

	Birth Weight (g)		**Gestational Weeks**		**Weight/Week (g/week)**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Full Period - All Births						
Pseudo-Treat × In Utero	3.76	0.453	0.032	0.841	0.045	0.703
	(5.01)		(0.018)		(0.119)	
By Gender - Full Period						
Females	6.76	0.329	0.025	0.333	0.143	0.386
	(6.92)		(0.026)		(0.165)	
Males	1.25	0.861	0.038	0.146	-0.037	0.827
	(7.15)		(0.026)		(0.169)	
Trimester Specification						
1st Trimester	4.18	0.583	0.018	0.515	0.091	0.613
	(7.63)		(0.028)		(0.181)	
2nd Trimester	-3.47	0.640	0.038	0.166	-0.170	0.333
	(7.42)		(0.027)		(0.176)	
3rd Trimester	7.10	0.287	0.026	0.283	0.143	0.366
	(6.67)		(0.024)		(0.158)	
Observations	180,089		180,089		180,089	
Pseudo-Treated	87,475 (48.57%)		87,475 (48.57%)		87,475 (48.57%)	

Notes: Standard errors clustered at municipality level in parentheses. No coefficients are statistically significant at conventional levels ($p<0.10$), supporting the validity of the identification strategy.

Source: Author's elaboration.

4.5 Discussion

To summarize, our trimester-specific analysis reveals significant regional disparities in how drought exposure impacts fetal development. In the Northeast state of Rio Grande do Norte, in-utero exposure to drought significantly reduced birth weight, with an average reduction of 25.7 grams over the entire gestational period. However, a more nuanced investigation uncovered a critical finding: the timing of maximum susceptibility is distinctly gendered. Female fetuses were most sensitive to drought shocks during the first trimester, exhibiting a substantial reduction of 55.4 grams, while male fetuses were most vulnerable in the third trimester, with a significant decrease of 54.2 grams.

This pattern challenges the established literature, which often emphasizes the first two trimesters as the uniformly critical window for environmental shocks (Rocha and Soares, 2015). Our results demonstrate that rather than a uniform vulnerability, female fetal development aligns with the known importance of the first trimester for organogenesis. In contrast, male fetal development exhibits a previously underappreciated vulnerability in the final trimester, potentially tied to different growth trajectories. This gendered pattern of physiological vulnerability is further corroborated by the analysis of gestational duration and the weight-for-gestational-age ratio, which confirmed that drought exposure impaired fetal growth efficiency with the same trimester-specificity by sex.

Conversely, the results for the more developed South Region present a fundamentally different picture. There, the drought did not produce a statistically significant effect on birth weight for the full sample. Instead, its most pronounced and consistent impact was a robust shortening of gestational duration. Exposure to the drought significantly reduced pregnancy length by approximately 0.096 weeks, an effect that was strong and significant across all trimesters for both male and female fetuses. This suggests that in the South, the physiological response to drought stress manifested primarily as earlier parturition rather than impaired fetal growth. In fact, the weight-for-gestational-age ratio showed neutral or even slightly positive effects, implying that fetuses in the South were generally well-adapted to their shorter gestation periods, maintaining efficient growth up to the point of early delivery.

Further disaggregating the Southern data reveals significant heterogeneity among its states. Paraná exhibited a unique positive response, with the drought associated with increased birth weight, particularly for males (+36.6g), and a longer gestational duration. This contrasts sharply with Santa Catarina and Rio Grande do Sul, where the effects were negative. Santa Catarina experienced the strongest adverse effects, with substantial declines in both birth weight (e.g., -77.9g for males) and gestational duration (-1.80 weeks). Rio Grande do Sul showed moderate but consistent negative effects on both outcomes.

Placebo tests showed null effects, strengthening the conclusion that the observed outcomes are genuine impacts of the drought rather than artifacts of pre-existing trends.

The findings of Seposo et al. (2025) corroborate our results, reinforcing the critical importance of trimester-specific vulnerability to prenatal drought exposure. Both studies identify the second and third trimesters as periods of particular significance, while demonstrating weaker associations during the first trimester. Furthermore, our research collectively establishes a compelling trajectory of drought impacts on child development: our work captures the immediate effects through reduced birth weight. At the same time, the authors reveal how these early insults manifest as long-term stunting in children under five. Most importantly, these parallel findings underscore that the timing of in utero drought exposure, rather than its occurrence, is crucial for understanding child health outcomes, thereby advancing beyond analyses that treat gestational exposure as a uniform period.

Diamond- Smith et al. (2023) found from Nepal on the trimester-specific impacts of hydrological extremes, such as drought and intense rainfalls, align with and enhance our understanding of the mechanisms revealed in our Brazilian study. While our research demonstrated a gendered pattern of vulnerability to drought—with female fetuses most affected in the first trimester and males in the third—the Nepal results provide complementary evidence that the first trimester represents a critical window for hydrological stress across diverse geographical contexts. The Nepal study's finding that first-trimester drought reduces birth weight (-82.9g) corroborates our observed first-trimester vulnerability for female fetuses in Northeast Brazil, suggesting this early gestational period may be a universally sensitive developmental phase. Collectively, these parallel findings from Brazil and Nepal strengthen the evidence base for targeted maternal health interventions during critical gestational windows, particularly as climate change increases the frequency of both drought and extreme rainfall events.

5 Final Considerations

In conclusion, the physiological pathway through which the drought affected pregnancies was region-specific. In the Northeast, the key impact was on fetal growth, with clear sex-specific critical windows. In the South, the dominant effect was a stress-induced reduction of pregnancy duration, with significant variation in the intensity and even the direction of these effects across states, highlighting the importance of local contextual factors, infrastructure, and resilience mechanisms.

A promising way to improve the analysis is to use climatic indices, such as the Standardized Precipitation Evapotranspiration Index (SPEI), to measure the intensity of drought exposure during pregnancy. Unlike a simple “drought vs. no drought"measure, the SPEI captures the severity and length of water deficits by combining precipitation and evapotranspiration, and it allows differentiation between mild, moderate, and severe drought events. Using this index as a continuous or categorical variable enables the estimation of the gradual effects of drought on birth weight. It helps determine whether adverse outcomes increase with the severity of the event intensity.

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