When climate changes, so does violence: examining the link between climate and crime in Pernambuco, Brazil*

Álvaro Robério† Federal University of Juiz de Fora

Luziane da Silva Federal University of Juiz de Fora

Filipe Santiago Federal University of Juiz de Fora

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Abstract

We examined the impacts of climate shocks on crime rates in Pernambuco–Northeast, one of the states in Brazil most affected by natural disasters. We show that adverse climate shocks in the form of droughts have a significant effect on increasing the incidence of violent crimes and property crimes. These effects persist beyond the agricultural season and in the medium term, and they are heterogeneous with respect to local and criminological characteristics. We also document that the persistent response of crime rates to adverse weather conditions is driven by the reduction in agricultural and livestock income, as well as overall economic activity. Furthermore, we have discovered that adverse climate shocks affect other determinants of crime, such as labor market conditions and the budgetary capacity of local government. Regarding policies, our results suggest that investments in water infrastructure, water supply, irrigation systems, agricultural diversification, and access to credit for family farmers help mitigate the economic effects of climate shocks on crime.

Keywords: Climate shocks; drought; crime; agriculture; Northeast of Brazil.
JEL Classification: O1; O13; Q54.

1 Introduction

Increases in carbon emissions have led to changes in the global climate, making extreme weather events such as droughts and floods more common. These events undoubtedly affect economic conditions and tend to exacerbate existing social dilemmas in developing regions(Blakeslee & Fishman, 2018; Ishak, 2022). A pressing issue in economics is the possibility that income variations may increase society's propensity to engage in illicit activities. Because adverse weather shocks can affect legitimate sources of income, the opportunity cost of entering the world of crime may decrease, with the economic benefits outweighing the moral costs and the risk of incarceration(Becker, 1968; Ehrlich, 1973). This study provides new evidence on this economic issue in a predominantly semi-arid state of Brazil, where weather shocks can negatively affect both livelihoods and crime. Unlike previous studies, we utilized both aggregated and disaggregated data that had not been previously explored and examined the transmission and mitigation mechanisms of climate shocks on crime.

In this context, this paper aims to assess the impact of weather shocks on violent and property crimes in the municipal economies of Pernambuco, one of the states in Brazil most affected by weather disasters (Ceped, 2013). Pernambuco has 88.6 percent of its territory in the Brazilian Semiarid region, and about 42.5 percent of its population depends directly or indirectly on rain-fed agriculture[1]. Although Pernambuco is the seventh most populous state in Brazil (9.7 million inhabitants, slightly less than the population of Portugal), it had the seventh-lowest gross per capita income in 2020 ($3,850), which is economically comparable to that of El Salvador. This precarious socioeconomic situation contributes to the high vulnerability of the state, where almost half of the population lives below the poverty line. At the same time, Pernambuco is one of the most violent

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†**Correspondence:** Álvaro Robério, Federal University of Juiz de Fora, Minas Gerais, Brazil. E: alvaro.roberiosa@gmail.com.

[1] The Brazilian semiarid region has an average annual rainfall of less than 800 mm, a Thornthwaite Aridity Index of 0.50 or less, and a drought risk of 60 percent.

areas in Brazil, the Northeast, and the world. In 2018, the state ranked tenth in the national ranking of violence and fifth in the regional scale. Pernambuco's homicide rate is also eight times higher than the global average (6.1 per 100,000 inhabitants). These high levels of violence, socioeconomic vulnerability, and exposure to weather risks are also observed in other states in the Northeast region, making Pernambuco an appropriate and representative case study area (Oliveira, 2019).

Our identification strategy explores the variation of rainfall records in municipalities over time and in seasons aligned with the agricultural calendar. It is based on the assumption that climatic shocks, conditioned on municipality and year fixed effects, are not correlated with other determinants of crime. This assumption is plausible since it is impossible to accurately predict a rainfall shock in an area and at a specific time within the state.

We begin by examining the direct effects of climate shocks on crime. Our results show that rainfall shocks, in the form of drought, substantially increase rates of violent crime and property crime. These effects persist beyond the agricultural season and in the medium term. The response of criminality to climate shocks is heterogeneous regarding the characteristics of municipalities, with greater effects observed in areas with small populations, rural areas, and semi-arid regions. Additionally, adverse weather shocks lead to a surge in violent crime rates in the marijuana polygon, one of the most violent territorial areas in the state. By examining criminological heterogeneity, we show that adverse climate shocks mainly affect violent crimes against male victims and the use of firearms while increasing nearly all types of property crimes. Surprisingly, we found that climate shocks do not affect rates of violent crimes motivated by criminal activities or community conflicts in the state, implying that there are other crucial determinants for criminal behavior, such as socioeconomic vulnerability. The baseline result indicates that a one standard deviation reduction in the Standardized Precipitation Index (SPI), compared to the average, increases the rate of violent crimes by 16 percent and the rate of property crimes by 32 percent.

To rule out the possibility that the observed effects were related to the data availability period (2012-2018), we estimated the effects of weather conditions using a second database with nearly 20 years of homicide information, covering the period from 2000 to 2018. Our results suggest that a one-standard-deviation reduction in the SPI leads to a 12 percent increase in homicide rates, with similar effects observed in areas with small populations, rural areas, and semi-arid regions. These effects persist over time and are associated with adverse weather conditions during the agricultural season. We also found that a one-standard-deviation reduction in the precipitation index increases the male homicide rate by 13 percent and the youth homicide rate by 27 percent.

After assessing the effects of weather shocks on the incidence of crime, we analyzed the mechanisms by which these effects might have been transmitted. The basic results suggest that the effects of adverse weather on crime are not limited to agricultural seasons but extend to non-agricultural seasons as well. However, adverse weather conditions are likely to have a greater impact on rural activities because they are traditional and labor-intensive(Costa et al., 2021). Based on our empirical findings and the literature addressing the determinants of crime, we focused on five factors that could potentially explain the documented effects of weather shocks on criminal activity: agricultural losses (Bignon et al. (2017); Blakeslee and Fishman (2018); Ishak (2022) and Mehlum et al. (2006)); general economic activity (Dell et al. (2012); Dix-Carneiro et al. (2018); Fajnzylber et al. (2002); Ishak (2022) and Cook and Zarkin (1985)); labor market conditions such as wages and employment (Dix-Carneiro et al. (2018); Fougère et al. (2009); Goin et al. (2017); Montolio (2018); Peng and Zhan (2023) and Lin (2008)); local government capacity or provision of public goods (Chioda et al. (2016); Dix-Carneiro et al. (2018); Linke and Ruether (2021) and Lochner and Moretti (2004)); and psychological factors such as stress and depression (Baysan et al. (2019) and Fazel et al. (2015)).

First, we document that climate shocks, such as droughts, increase losses in rainfed agriculture, primarily affecting small-scale farmers. Unfavorable weather conditions also reduce agricultural and livestock production, leading farmers to seek government food purchase programs for a stable income. These effects of climate shocks extend to other sectors, causing income reduction in both rural and urban areas. In addition to decreasing levels of economic activity, adverse climate shocks also result in a decline in formal employment rates, labor income, government revenues, and social expenditures on education, health, and human resources. These factors directly impact the capacity of local governments to control crime. The prevalence of these opportunity cost mechanisms supports a persistent response of violent crimes and property crimes to unfavorable climate conditions. In contrast, climate shocks have a null contemporaneous effect on suicide rates, suggesting that non-economic factors play a minimal role in the increase in crime. Instead, our results highlight a significant correlation between the rate of violent crimes and the rate of cargo and vehicle theft, which has a strong economic motivation. This finding is crucial as the rate of violent crimes is one of the main indicators in this study.

Next, we examine the mechanisms of adaptation and mitigation of adverse climatic conditions. Recent studies have emphasized the effectiveness of investments in water supply and water infrastructure in rural areas, along with microinsurance for economic losses, in mitigating the impact of adverse climate shocks on agricultural production and sectoral production in the Brazilian semiarid region (Costa et al., 2021; Oliveira, 2019). In a study conducted by Marengo et al. (2022), in response to the increasing climate disasters in the Northeast region, adaptation measures were identified, such as risk management, investment in water resources, optimization of natural resources, agricultural diversification, and support for small farmers. In Pernambuco, investments are directed toward these dimensions and sustainable environmental and agricultural practices(Milhorance et al., 2018).

Given this scenario, our results suggest that investments in water infrastructure (dams, weirs, irrigation, and access to water in rural areas), as well as conservation of water coverage, diversification of rain-fed agriculture, and access to credit for rural establishments through the *Programa Nacional de Fortalecimento da Agricultura Familiar* (PRONAF) help mitigate the economic impacts of weather shocks on crime. These investments represent an adaptation mechanism for rural producers to adverse climatic conditions. Therefore, public policies that prioritize investments in adaptation and mitigation mechanisms for weather shocks are essential to maintain income levels and relieve direct impacts on crime determinants in vulnerable areas.

In light of the above, this article contributes to the growing body of literature examining the effects of weather shocks on crime. In particular, it provides new evidence from a large semiarid region of the developing world on how violent and property crime are affected by adverse weather shocks. This is particularly important because the state examined in this study is one of the most affected by weather disasters in Brazil, the largest country in Latin America, and has rates of violence comparable to those of economies in civil war or armed conflict. While most studies in this area have focused on the effects of weather shocks on crime in developed countries (Brunsdon et al. (2009); Horrocks and Menclova (2011); Jacob et al. (2007); Ranson (2014) and Ranson (2014)) and in the context of wars and civil conflicts (Burke et al. (2009); Goin et al. (2017); Harari and Ferrara (2018); Hsiang et al. (2013); Nordkvelle et al. (2017); Papaioannou (2016), and Hsiang and Burke (2014)), this article complements a narrower set of studies documenting the effects of weather shocks on crime rates in developing regions (Blakeslee and Fishman (2018); Ishak (2022); Sekhri and Storeygard (2014), and Miguel (2005)).

This study also advances the understanding of the mechanisms behind the effects of weather shocks on crime rates. In particular, we go beyond the economic factors that are commonly associated with developing countries, such as reduced agricultural and livestock productivity (Blakeslee and Fishman (2018); Ishak (2022) and Maystadt and Ecker (2014)), to show that unfavorable weather conditions also affect overall economic activity, labor market conditions, and the budget destined to the provision of public services (Chioda et al. (2016) and Bachner and Bednar-Friedl (2019)). Moreover, these results suggest that weather shocks are unlikely to satisfy the exclusion restriction condition imposed by an instrumental variable estimator commonly used to assess the effects of income shocks on crime and violence, as in Koren (2018), Mehlum et al. (2006), and Miguel (2005).

Also of particular importance are the evidence we present regarding the role of water infrastructure and other measures of adaptation and response to adverse climatic conditions. These mechanisms not only help maintain sources of income and employment in urban and rural areas of municipalities but also address the economic and social challenges associated with adverse weather conditions, including their potential impact on crime and violence (Ishak (2022), Gatti et al. (2021), and Harari and Ferrara (2018)). The evidence suggests that policymakers in developing regions such as Pernambuco in Northeast Brazil should closely monitor rising crime rates, as regional climatic conditions are increasingly susceptible to impacts resulting from the accumulation of carbon emissions and other anthropogenic processes (Marengo et al. (2019)).

The remainder of the article is organized as follows. Section 2 presents the context of the state of Pernambuco, Northeast Brazil. Section 3 provides a description of the data and the empirical approach. Section 4 discusses the main results and robustness tests. Section 5 examines the possible channels of transmission and mitigation of the economic impact of climate shocks on crime. Section 6 provides the discussions and conclusions with policy implications.

2 The context of Pernambuco: a state in Northeast Brazil

Pernambuco is a state in Northeast Brazil with 66.5 percent of its municipalities located in the semi-arid region, where there is a high risk of droughts and heat waves (Figure 1). These weather events are mainly associated with large-scale phenomena such as El Niño and La Niña (Marengo et al., 2017). The state covers an area of 98,311 km², which is equivalent to 1.2 percent of Brazil's total area and 6.3 percent of the Northeast region's area. This area is comparable to the size of Hungary.

The population size of municipalities varies in Pernambuco, with Recife, the state capital, being the largest with 1.6 million inhabitants, and Ingazeira the smallest with 4.5 thousand inhabitants. In more than half of the state's municipalities, more than 30 percent of the population lives in rural areas. These areas face water constraints, and their inhabitants rely on agricultural activities for their subsistence. The gross agricultural production of Pernambuco is $1,636.97 million, which is equivalent to the primary production of Latvia in 2020. This value represents 10.25 percent of the agricultural production of the Northeast region, highlighting the economic importance of state agriculture. However, as in most economies, rural production accounts for less than 5 percent of the state's total gross production. Additionally, about 521.6 thousand people are employed in agriculture, including farm and other professionals working in the field. Of these, approximately 63 percent (328.1 thousand) are family farmers[2].

Figure 1: Map of Pernambuco State, Northeast, Brazil

Dryland agriculture predominates in Pernambuco. Out of the 284.5 thousand rural establishments, 75 percent produce temporary crops and belong to family farms (85 percent). Traditional agriculture continues to be an important source of livelihood and income for families and farmworkers, particularly in the semiarid region. On a national level, the state ranks as the seventh-largest producer of sugarcane and the second-largest producer of sheep and goats, with a total of 6.6 million animals[3].

Extreme events have a serious impact on agriculture and livestock in Pernambuco. From 1995 to 2014, the state recorded significant agricultural losses due to climatic disasters, totaling R$4 billion ($1.7 billion), or 13.1 percent of regional losses. During the same period, livestock losses in the Northeast totaled R$9.7 billion ($4.1 billion), with Pernambuco responsible for

[2] The information regarding production was obtained from the *Instituto Brasileiro de Geografia e Estatística* (IBGE). The data concerning occupation are from the *Censo Agropecuário 2017*- IBGE.

[3] The information is from the *Pesquisa Agrícola Municipal* (PAM) and *Pesquisa Pecuária Municipal* (PPM), both from IBGE. Information regarding agricultural establishments is from the *Censo Agropecuário 2017* - IBGE.

25 percent of this amount[4].

Between 2012 and 2015, the state also suffered a catastrophic loss of half a million animals during one of the worst droughts in the last 100 years. During this period, the state's agricultural production declined by 15.3 percent. The impact of weather also extended to safety spending, which declined by about 15 percent in the state during the drought. In addition, weather projections for Pernambuco are alarming. From 2041, a temperature increase of 2.7 to 3.7 °C is forecast, combined with a possible decrease in precipitation of up to 40 percent[5].

At the same time, violence has increased disproportionately in Pernambuco and in the Northeast region of Brazil. Between 2010 and 2018, the homicide rate per 100,000 inhabitants in the state rose alarmingly from 38.05 to 43.44, an increase of 14.2 percent. Following this trend, the regional homicide rate increased by 22.7 percent, from 34.33 to 42.13[6]. According to data from the *Secretaria de Defesa Social do Pernambuco* (SDS-PE) in 2018, the number of victims of intentional lethal violent crimes in the state exceeded 4,170. This level of lethality surpasses that of countries affected by civil wars and armed conflicts, such as Somalia and Iraq[7]. During this period, the state also recorded over 95,300 cases of property crimes, which is equivalent to more than 260 cases per day. Moreover, this number of property crimes represents nearly one-third of the total number of robberies in São Paulo, the largest capital city in Latin America.

3 Data and empirical approach

In this section, we provide a comprehensive overview of the data sources, the weather and crime variables, and the empirical specification of the baseline.

3.1 Data

The study used unexplored microdata from the *Anuário da Criminalidade*, a publication of the *Secretaria de Defesa Social* (SDS) that provides comprehensive criminal information for the municipalities of Pernambuco. For our analysis, we chose a balanced panel dataset that includes municipal crime rates per 1,000 inhabitants and covers the period from 2012 to 2018. The selection of this time horizon was necessary because reliable and comprehensive disaggregated crime data are no longer available for municipalities after 2018, as microdata disclosure by SDS was discontinued in 2019. To increase confidence in our results, a second set of crime data from 2000 to 2018 was also included in the analysis[8]. In this second set of data, we consider homicide rates per thousand inhabitants obtained from DATASUS (*Departamento de Informática do Sistema Único de Saúde*), which tend to be less susceptible to measurement problems (Fajnzylber et al., 2002).

We examined the relationship between crime and weather using two indicators: intentional lethal violent crime (ILVC) and property crime (PC)[9]. The ILVC indicator includes intentional homicide, femicide, bodily injury followed by death, and other crimes resulting in death, excluding lethal cases involving security agents[10]. We also analyzed the impact of weather on ILVC, taking into account factors such as sex, weapon, and criminal motivation to gain a more comprehensive understanding. The second indicator covers property crimes, including theft, extortion by kidnapping, and robbery with the restraint of the victim's freedom, excluding robbery followed by death (latrociny) since it falls under ILVC. To improve our empirical investigation, we analyzed the impact of weather on specific categories of PC, such as passerby assault, cargo, and vehicle theft, as well as robberies of commercial and service establishments, residences, and others (bank agencies and buses). To eliminate any notification issues or measurement errors in the data, our econometric strategy controls for systematic differences in municipality crime rates over time.

[4]Access the *Relatório de danos materiais e prejuízos decorrentes de desastres naturais no Brasil (1995-2014)* (CEPED/UFSC).
[5]See *Vulnerabilidade às Mudanças Climáticas*. See also weather projections made for the entire Northeast in Marengo et al. (2019).
[6]For a more detailed overview of crime in Pernambuco, the Northeast, and Brazil, see Appendix Online A.
[7]According to World Bank, the number of deaths due to conflict or civil wars in 2018 was 2,208 in Somalia and 1,257 in Iraq.
[8]Older data are less reliable due to changes in the territorial boundaries of the state and potential accuracy issues stemming from technological limitations
[9]The data for ILVC and PC may slightly differ from the totals of SDS because our analysis only takes into account records with location information. This difference is up to 0.5 percent for PC and up to 0.01 percent for ILVC. To avoid selection bias and account for missing information, we added a constant value of 0.01 to the crime rates to prevent the loss of important data
[10]To ensure reliable numbers, the SDS-PE uses a sophisticated computation method based on cadaver information.

Weather data. We obtained monthly data on temperature, precipitation, evapotranspiration, and water deficit for the municipalities in Pernambuco from TerraClimate, covering the period from 1980 to 2018 (Abatzoglou et al., 2018). Based on this information, we structured a dataset of climate data per month and year for each locality. To obtain climate indicators, we used the Standardized Precipitation Index (SPI) introduced by McKee et al. (1993). The SPI is a widely accepted index for monitoring droughts and floods. It is calculated using 30 years of monthly precipitation data adjusted to a probability function and normalized to a standard distribution. The resulting monthly index is expressed in terms of standard deviations from the historical average precipitation of each municipality. Given its probabilistic nature, the SPI provides historical context and facilitates the comparison between localities with different climatic characteristics.

The annual SPI represents the average of 12 months, with higher values indicating favorable weather conditions (moisture) and lower values indicating a tendency toward drought. Figure B.4 (A) in Appendix Online B, displays the average annual SPI values for Pernambuco. We also calculated the SPI for both the agricultural station (winter and summer seasons) and non-agricultural station (off-season), using the same approach. The agricultural season encompasses the months of June to September (winter season) and December to March (summer season), while the other months of the year correspond to the off-season (nonagricultural)[11]. These indicators enable us to evaluate the impact of weather variability on crime during the most economic importance period for family farmers, rural producers, and other local activities that directly or indirectly depend on rural production (Cunha et al., 2015). A similar approach was employed by Blakeslee and Fishman (2018), who utilized monsoon seasons to capture deviations from seasonal weather conditions aligned with agricultural production and their impact on crime rates in India.

The SPI has been previously employed by Nordkvelle et al. (2017) and Linke and Ruether (2021) to examine the impact of weather shocks on community and civil conflicts in Nigeria and Syria, respectively. However, a limitation of the SPI is its failure to consider other variables that influence the climatic conditions of a location (Vicente-Serrano et al., 2010). To address this potential bias, we incorporated climatic water deficit, actual evapotranspiration, and average temperature as control variables.

To enhance the analysis, we also estimated the non-linear effects of weather on crime. To accomplish this, we divided the SPI into various intensity bins to capture both negative (drought) and positive (moisture) weather shocks. In Appendix Online B, Figure B.4 shows the fluctuation of negative shocks throughout (droughts) the year in Pernambuco. It is worth noting that certain periods experienced no drought in any location, while others impacted over 90 percent of municipalities. Over the past decade, numerous municipalities have encountered drought, evidencing the significance of these weather shocks. In this context, we further examined the impact of these events by implementing a threshold for the SPI[12]. We followed the approach of Branco and Féres (2021), who explored the effects of drought on labor allocation in Northeast Brazil, by considering a threshold below -1 to calculate moderate to extreme drought months. Additionally, we conducted robustness tests by calculating long-term temperature deviations. The results of these tests are available in Appendix D and will be presented subsequently.

Other variables. The IBGE provides annual data on population and territorial extent, which are used to calculate the demographic density of municipalities. The 2010 Census also offers valuable information on demographic characteristics, such as urbanization rates and population proportions in terms of rural areas, males, blacks, young individuals, and illiterate individuals. Other factors taken into account are the divorce rate, the rate of workers in security and protection services, the active economic population rate, and royalty revenue (resource transfer). To verify spatially heterogeneous effects, in addition to small to medium-sized, rural, semiarid municipalities, and more than 100 km from Recife (state capital), we also consider those with high levels of diversification in rainfed agriculture (above 50 percent) and those located in the polygon of marijuana (*Polígono da Maconha*)[13]. This is an inland region of Pernambuco, washed by the São Francisco River and composed of about 13 municipalities known for high marijuana production in support of drug trafficking, both regionally and nationally. The list of municipalities that make up this area can be found in Online Appendix B.

Other data are used to examine the transmission channels of the effects of weather on crime, such as agricultural losses

[11]According to the *Agência Pernambucana de Águas e Clima* (APAC), Pernambuco experiences two distinct climatic seasons: rainy (winter) and drought (summer) seasons, with no significant temperature variations and other meteorological conditions remaining relatively constant throughout the year

[12]A negative SPI indicates a drought month, and its value determines the severity of the drought. On the other hand, values above zero do not indicate negative precipitation events

[13]Rural municipalities are those with more than 15 percent of the rural population, as defined by the OECD, while small/medium municipalities are those with less than 150 thousand inhabitants.

and rural income (agriculture and livestock), economic activity, government budgets (government capacity to provide public goods), labor market outcomes such as employment and average labor income (average wage), and suicide rates (psychological factors). We also consider local characteristics that may mitigate the effects of weather on crime, such as natural resources (water and forests), irrigated land, agricultural diversification, credit for family farmers, water infrastructure (dams and weirs), and water supply in rural households. Tables B.1 and B.2 (Appendix B) provide a detailed description of these and other variables used, including descriptive statistics.

3.2 Empirical strategy

To estimate the effects of weather on municipal crime, we use a baseline specification that takes the following form:

$$C_{m,t} = \alpha + \sum_{k=0}^{2} \beta_{1k} SPI_{m,t-k} + \mathbf{X'}_{m,t}\Psi + \mathbf{FE}_t + \mathbf{FE}_m + \xi_{m,t} \quad (1)$$

Where $C_{m,t}$ are the crime rates of a municipality m at time $t \in \{2012, 2013, \ldots, 2018\}$. Each crime rate examined is the number of occurrences per 1,000 inhabitants. $SPI_{m,t-k}$ is the weather indicator of interest included at time $t-k$, whose lags are calculated from 2010. The sum of the coefficients of interest ($\sum_{k=0}^{2} \beta_{1k}$) captures the contemporary and lagged effects of weather on crime rates. The lagged terms offer two direct advantages. First, they allow for accounting for the correlation of weather variability by discerning the possibility of temporal displacement of effects, resulting in one best estimation of the impact of contemporary shocks. Second, they enable the identification of the persistence of effects over the ongoing period. If the climatic effects are persistent, the linear combination of contemporary and lagged coefficients (sum) should not be zero[14] (Ishak, 2022). The vector of covariates ($\mathbf{X'}_{m,t}$) includes basic controls: temperature, evapotranspiration, water deficit, and population density. We also included fixed effects of the municipality ($\mathbf{FE}_m$), which capture all unobservable and time-invariant determinants of crime. Year fixed effects ($\mathbf{FE}_t$) control for temporal trends common to municipalities, including seasonal fluctuations in crime rates, macroeconomic conditions, and state policies. Finally, Ψ is a parameter vector and $\xi_{m,t}$ is a random error term.

A feature of our data is their spatial correlation. Most studies of weather and crime implicitly assume that observations are spatially independent, without accounting for the spatial and temporal dependence of the residuals (Harari & Ferrara, 2018). We address this problem by applying a spatial HAC correction for standard errors that is robust to serial and spatial autocorrelation within a radius of 100 kilometers[15], following the approach of Conley (1999). This method creates a spatially weighted covariance matrix where the weights start at 1 and drop linearly to 0 when a predetermined threshold is reached. In Online Appendix D, we also present results using standard errors clustered at local and microregional levels, as well as other cutting distances.

Identification. To establish the causal link between weather and crime, a natural experiment is crucial. This type of experiment creates a counterfactual scenario that allows determining the crime rate in a municipality if it were not affected by weather shocks. In economics, the weather is considered stochastic, meaning it is orthogonal to the aggregated choices of individuals regarding involvement in criminal activities (Dell et al., 2014). It is presumed that annual and seasonal weather indicators (agricultural and non-agricultural seasons) based on the monthly SPI are assumed to be random because they are measured as deviations from long-term precipitation in each area. Therefore, the identification strategy explores the variation of the municipalities' weather conditions in crime rates as part of a natural experiment (Nordkvelle et al., 2017).

Our identification assumption is that weather indicators are not correlated with other determinants of crime when considering municipality and year fixed effects, along with the aforementioned controls. Specifically, we account for time-varying factors that could influence both weather and crime rates, including temperature, water deficit, evapotranspiration, and population density (Hsiang et al., 2011). Population density serves as a control for the scaling effects of violence, since more densely populated municipalities generally have higher crime rates. Furthermore, other climatic variables allow us to control for vari-

[14] Online Appendix B provides the results of time series tests for the SPI during the period from 2000 to 2018. The tests indicate that the SPI does not have a unit root in level or first difference, and reject the null hypothesis of no serial autocorrelation. These tests suggest that we are dealing with random variations in weather conditions and justify the inclusion of lagged SPI.

[15] A circle with a radius of 100 km has an area of 31,416 km², which corresponds to 31.96 percent of the total area of Pernambuco

ous weather conditions that are associated with precipitation and crime rates in different areas (Ishak, 2022). Internal characteristics of state regions and common shocks to municipalities within the same regions may be particularly important for crime rates. Therefore, in alternative specifications, we include year and region fixed effects interactions and a specific time trend for region (Ankel-Peters et al., 2023). To account for unknown spatial and temporal correlations, we employ the standard errors proposed by Conley (1999). After presenting our basic results, we address specific threats to internal validity and demonstrate that our causal identification condition remains valid.

4 Results

4.1 Summary statistics

In our study, we investigated the relationship between weather and crime in Pernambuco, which we considered to be a representation of Northeast Brazil. The analysis covered the period from 2012 to 2018. We found that only 4.6 percent and 1.2 percent of observations did not record instances of Intentional Lethal Violent Crimes (ILVC) and Property Crimes (PC), respectively. Therefore, more than 95 percent of the sample is composed of municipalities where crimes occurred. Table B.2 (see online appendix) presents a descriptive summary of the main variables used in the empirical analysis.

The average annual Standardized Precipitation Index (SPI) is -0.27, indicating a predominance of drought conditions during the period. The average SPI for agricultural stations (-0.32) and non-agricultural stations (-0.16) further emphasizes the prevalence of droughts in Pernambuco. It is worth noting that the SPI of the agricultural station reflects climatic conditions during the winter and summer harvest. Between 2012 and 2018, the average number of drought months in the municipalities was 2.6, with a standard deviation of 1.65. This implies that, on average, more than 22 percent of the annual time horizon is characterized by below-normal rainfall. The average standardized deviation of local temperature is 0.34, indicating higher-than-average temperatures during the studied period. The average temperature during this period was 23.5 °C, while the values for real evapotranspiration and climatic water deficit were 54.68 mm and 60.83 mm, respectively. The average population density of the localities is 260 inhabitants per km², indicating a high population density.

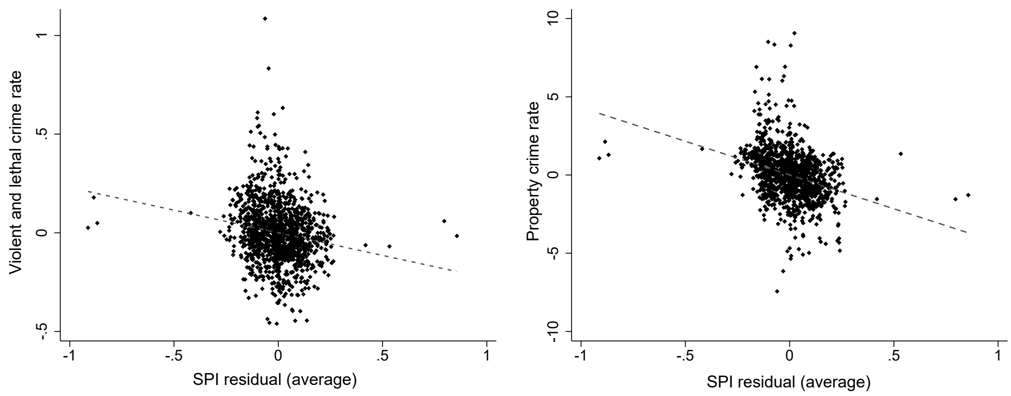

Figure 2: Correlation between crime rates and SPI

This period was very violent, with ILVC and PC rates of 0.39 and 3.84 per thousand people, respectively. Figure 2 illustrates the relationship between weather and crime rates after accounting for the municipality and year fixed effects. The dashed line represents the statistically significant linear fit at 1 percent, with slopes of -0.22 for ILVC and -4.31 for PC. As observed, most observations cluster where negative SPI values coincide with high crime rates. This means that unfavorable weather conditions (droughts) are associated with high crime rates, while more favorable weather conditions (moisture) are associated with low crime rates. Such a result supports a linear relationship between weather and crime, as seen in Ishak (2022) and Harari and Ferrara (2018). However, as part of the robustness check, we also analyzed the non-linear effects of weather on crime.

Figure B.4 in Appendix Online B shows the spatial distribution of crime rates average and from the SPI for the entire period. There is some heterogeneity in violent and property crime, with a tendency toward higher concentrations in the coastal region and the two immediately adjacent regions: Agreste and Zona da Mata. Although adverse climatic conditions show spatial heterogeneity, they tend to be more concentrated in the semiarid region, especially in the Sertão Pernambucano. In summer, the semiarid region has more unfavorable weather (drought) than the coastal regions, while in winter the opposite is true. On average, drought months are evenly distributed throughout Pernambuco, although they are more frequent in the semiarid region. Nevertheless, there is an increasing trend of adverse climatic conditions in the coastal regions of the Brazilian Northeast(Marengo et al., 2019).

4.2 Effects of weather on crime

In Table 1, we present the results of the effect of climatic conditions on the crime rate using different indicators and empirical specifications. The estimates show that the coefficient of the annual SPI is negatively associated with the rates of intentional lethal violent crime (ILVC) and property crime (PC) in all columns. Thus, a decrease in the SPI that indicates less precipitation or drought leads to a statistically significant increase in ILVC and PC rates. As noted in Columns 1 and 6, the contemporaneous annual SPI and its first lag are statistically significant. Moreover, the cumulative coefficient estimates for both crime indicators are significant and suggest a persistent effect of rainfall shocks in the form of drought on crime rates.

Next, we examine the effects of SPIs from agricultural and non-agricultural stations to capture the effects of weather variability that occurs during specific periods of the rural calendar[16]. In Pernambuco, the agricultural season is economically important for rural populations and local markets. Climatic variations during this season may cause real income changes in terms of expected income changes for rural populations and change the opportunity cost of engaging in crime. If climatic conditions also affect crime during the non-agricultural season, this suggests persistent effects on criminal activity throughout the year, suggesting a link to economic losses in both the rural and non-rural sectors(Blakeslee & Fishman, 2018).

The estimates show that adverse climatic conditions during both agricultural and non-agricultural seasons significantly increase rates of violent (Columns 2-3) and property (Columns 7-8) crimes. The contemporaneous coefficients of the SPI for the agricultural season are relatively higher than those for the non-agricultural season, indicating that unfavorable climatic variations during the harvest season have a stronger impact on crime in Pernambuco. The results clearly show that unfavorable climatic conditions outside the agricultural season also have an impact on crime, suggesting that economic activities in urban areas may also be affected. In addition, both contemporaneous and lagged coefficients for both agricultural and non-agricultural season SPIs are statistically significant, suggesting that a decrease in precipitation during these periods has relatively persistent effects on violent and property crime. The cumulative coefficients of the agricultural and non-agricultural seasonal SPIs confirm this, as they are negative and statistically different from zero at the 1 percent significance level.

To verify the importance and persistence of the effects, we performed a robustness test by separating the weather variations into winter and summer and including them in the model simultaneously (see Appendix D). The results show that both winter and summer SPIs significantly increase ILVC and PC rates, with persistent effects on crime throughout the agricultural season. While summer has higher contemporaneous coefficients due to hotter and drier conditions, the accumulated effects of adverse weather conditions are greater in winter when the municipality's main crop is typically planted.

The seasonal measures provide suggestive evidence that the effects of weather on crime are mediated by economic factors related to agriculture, although they are not limited to it. For the remainder of the study, however, we used the annual SPI to capture the overall effect of climatic conditions on crime. We chose this approach because it has lower measurement error and is able to capture the effects of climatic conditions that may affect agriculture and economic activity at any time of year, justifying the documented effects on crime(Ishak, 2022).

Both specifications show a consistent sign and a statistically significant contemporary annual SPI coefficient for both lethal violent crimes and property crimes. Putting the coefficients in perspective, we document that a one standard deviation reduction in the contemporary annual SPI below the municipality average increases lethal violent crime rates by 12-16 percent and property crime rates by 32-38 percent, respectively – depending on the specification[17]. The cumulative effect shows an increase of 27-32 percent in rates of ILVC and 44-49 percent in rates of PC. Previously, Blakeslee and Fishman (2018) had also

[16]The agricultural season represents about 66.7 percent of the annual weather variability (8 months), while the non-agricultural station captures only 33.3 percent of the variability in climatic conditions (4 months). Both are associated with the seasons and aligned with the agricultural calendar.

[17]Note the standard deviation of within-SPI is 0.420.

found that the effect of weather shocks on crime rates was larger for property crimes than for violent crimes in India. Our results are consistent with this perspective and suggest that the relationship between weather and crime operates through an economic mechanism. We will explore the mechanisms in detail later.

4.2.1 Heterogeneity

Now we present a detailed analysis of the effects of climatic conditions on crime by examining the heterogeneity of criminological and municipal characteristics. The results can be found online in Appendix D.

Criminological. Adverse weather shocks in the form of drought have a persistent effect on rates of violent crime against male victims and firearms (Table D.1). Surprisingly, we found no significant effects of weather fluctuations on rates of violent crime by motives, such as criminal activity, community conflict, and other types (under investigation). This finding suggests that the influence of weather events on criminal behavior is not uniform and may depend on specific circumstances and contexts. Moreover, socioeconomic conditions and individual characteristics may be more relevant than the weather itself in motivating criminal behavior. In general terms, a one standard deviation decrease in the SPI increases rates of violent crimes against male victims and crimes involving firearms by 17 percent and 19 percent, respectively. Weather fluctuations in the form of drought, in turn, affect virtually all types of property crime (Table D.2). The effects of climatic conditions persist over time on rates of property crimes involving passersby (assault), cargo and vehicles, and residences. For commercial establishments, there is a compensatory effect with significant lags of one and two years with opposite signs. Specifically, a one standard deviation decrease in the contemporaneous SPI implies a 38 percent increase in robberies for passersby, 30 percent for cargo and vehicles, 25 percent for residential robberies, and 29 percent for other thefts (banks and buses).

Municipal. Climate fluctuations in the form of drought have a significant and persistent effect on ILVC and PC rates in sparsely populated, rural, and semiarid areas (Table D.3). The effect of weather shocks in the form of drought is greater on rates of property crime in these areas, which are not only economically dependent on agriculture but also more susceptible and vulnerable to weather change. This is consistent with the transmission of the weather effect on crime through an economic channel. Specifically, a one standard deviation decrease in the contemporary SPI increases ILVC rates by 27 percent and PC rates by 31 percent in rural municipalities. In municipalities with small populations, the increase was slightly smaller at 17 percent for ILVC rates and 32 percent for PC rates, while in semiarid municipalities, it was 21 percent and 53 percent, respectively. We also found that a one standard deviation decrease in SPI increased ILVC rates by 57 percent in the municipalities that make up the *Polígono da Maconha*. However, we did not find statistically different effects from zero for the PC rates. In municipalities more than 100 km from the state capital (Recife), we found a 22 percent increase in ILVC rates and a 53 percent increase in PC rates due to a decrease in SPI. For municipalities with agricultural diversification indices above 50 percent, we document that a one standard deviation decrease in SPI causes an increase in ILVC and PC rates of 15 percent and 49 percent, respectively.

Evidence of external validity. These results are consistent with other studies. Miguel (2005) found that extreme rainfall events increased homicide rates by about 20 percent in rural Tanzania. Sekhri and Storeygard (2014) found that a one standard deviation decrease in annual rainfall increased dowry deaths by about 8 percent in India. Our results also fall within the range of coefficients found in a meta-analysis by Hsiang et al. (2013) on the effects of weather on crime and conflict around the world. Similarly, results from Peng and Zhan (2023) suggest that a one standard deviation increase in the extreme weather index increases crime rates in Chinese provinces by 18 percent. Studies that have examined other shocks in the literature have also reached similar conclusions. For example, Iyer and Topalova (2014) showed that the relationship between trade shocks and crime is similar to the relationship between weather shocks and crime in India. Following this perspective, Dix-Carneiro et al. (2018) estimated that a one standard deviation reduction in trade tariffs leads to a 46 percent increase in crime rates in Brazil. Overall, these results suggest that the effects of negative shocks, such as those related to weather and trade, have a significant impact on crime rates and thus on welfare reduction.

4.3 Robustness checks

We show that adverse weather shocks in the form of droughts have a persistent impact on crime in Pernambuco. We now present a series of robustness checks to ensure the reliability of the estimates presented in Table 1. These checks will help us internally validate our findings and support the conclusions from our initial analysis.

Municipal characteristics. The analysis shows a strong relationship between weather and crime in Pernambuco, but sociodemographic factors of the municipalities (illiteracy, urbanization, and population characteristics) may also play a role. We used data from the 2010 census to capture these initial characteristics of the municipalities, allowing them to vary from 2012 onwards. Columns 1 and 8 show just that for rates of violent and property crime (Table 2). A closer examination of the estimates shows that a one standard deviation decrease in the contemporary SPI increases the rates of ILVC and PC by 15 percent and 22 percent, respectively. This suggests that the coefficient of SPI for property crime rates is 42 percent lower than the baseline results. This decrease is explained by the importance of sociodemographic characteristics of the local population in determining property crime rates (Bignon et al., 2017; Fajnzylber et al., 2002).

Additional controls. The estimation of the impact of climatic conditions on crime rates in Pernambuco has so far been analyzed in a simplified way, which means holding constant other heterogeneous factors that could be spuriously correlated with weather fluctuations and crime at the municipal level. Nevertheless, it may be interesting to examine the effects of other characteristics that may influence crime rates in municipalities, such as the transfer of royalties from natural resource exploitation (Hsiang et al., 2013; Ishak, 2022).

Brazil's abundant natural resources are heavily exploited, generating significant tax and royalty revenues for both producing and non-producing municipalities. Recent evidence indicates that resource-rich municipalities, including those with oil and natural gas reserves, as well as those that receive a share of these resources, also face social costs such as higher crime rates. These costs are likely the result of changes in economic and social dynamics due to increased production and income levels (Ishak, 2022).

The results for royalty revenues are shown in Columns 2 and 8, respectively. We found a positive and statistically significant effect at the 5 percent level of royalty revenues on property crime. More specifically, a 10 percent increase in royalty revenues increases the rate of property crime by about 0.7 percent – relative to the unconditional mean. Even after including this control, the effects of climatic conditions on crime rates remain stable in terms of sign, magnitude, and statistical significance.

To examine the effect of economic cycles on crime, we introduced the economically active population rate as a control variable (Fajnzylber et al., 2002). To assess local capacity to combat crime, we included the rate of security and protection professionals. This variable also captures the deterrent effect of crime (Chalfin & McCrary, 2018). We also included the divorce rate as a control for family disorganization (Beaulieu & Messner, 2010). After adding these covariates to our analysis, we were able to assess the robustness of our baseline estimates. Our results suggest that the effects of climatic conditions on crime rates (ILVC and PC) remain robust in terms of both sign and statistical significance after controlling for these covariates. The results of the robustness check can be seen in Columns 1-5 for ILVC rates and Columns 7-11 for property crimes. In general, our study shows that climatic conditions have a strong and consistent effect on violent crime, while for property crime, accounting for sociodemographic factors reduces the estimated effect, but at the cost of introducing bias(Hsiang et al., 2013). Moreover, even after including this set of controls, the cumulative coefficient of climatic conditions remained negative and significant for ILVC and PC rates, indicating that these negative effects of weather persist over time.

Thus, we conservatively estimate that a one standard deviation reduction in SPI could increase ILVC rates by 15 percent and CP rates by 22 percent - controlling for municipal characteristics. These estimates are conservative, but provide valuable information about the relationship between weather and crime in Northeast Brazil, based on the evidence for Pernambuco.

Dynamic model. We have now modified our econometric specification to include lagged crime rates in Equation (1). The results of this dynamic model are shown in Columns 6 and 12 of Table 2. We find that the coefficient associated with contemporary SPI remains statistically significant for both violent and property crime. Thus, a one standard deviation decrease in the SPI increases ILVC and PC rates by 15 percent and 27 percent, respectively. We also estimate a robust version of the dynamic model proposed by Kripfganz (2016) using a quasi-maximum likelihood (QML) estimator when the time horizon is short and the number of cross-sectional units is relatively large. Specifically, we estimated a first-difference model with a lagged crime rate. We found that a decrease of one standard deviation in the contemporary SPI leads to a statistically significant increase of 15.5 percent and 18 percent in ILVC and PC rates, respectively (Online Appendix D).

Data extension. To internally validate our findings, we extended our analysis to 2000-2018 and used a new indicator, the homicide rate per thousand inhabitants (Table D.4-D.6 in Appendix D). Our results show that a one standard deviation decrease in the contemporary SPI increases the homicide rate by 11-12 percent. These effects persist over the medium term and are caused by adverse climatic conditions during the agricultural station. The analysis of heterogeneity shows a slightly lower effect on the homicide rate (10 percent) for municipalities with high agricultural diversification, while for municipalities small, rural, semi-arid, and located more than 100 km from the Recife the result is similar to that of the entire state. Moreover, adverse weather shocks have a persistent impact only on small and rural municipalities in the medium term. Examining heterogeneity, we also find that adverse climatic conditions (drought) significantly affect the homicide rate of males and young people (15 to 29 years). In this context, a one standard deviation reduction in the annual SPI increases the male homicide rate (13 percent) and the young homicide rate by 27 percent. For the rate of female homicides, the effects are null. In general, these results with extended data confirm the robustness of the estimates and validate our initial conclusions.

Falsification test. A question that may arise is the presence of omitted variables that change over time and may influence the relationship between crime and weather. Although we have taken into account a wide range of fixed factors and time-varying, there may still be unobserved differences that link weather fluctuations to crime (Ishak, 2022). To rule out this possibility, we shuffled the crime rates and estimated the results in two ways. First, we estimated the effects of contemporary and lagged SPI once against the shuffled crime rates. Second, we repeated the procedure 500 times and compared the estimated contemporary effect with and without shuffling the crime rates. In Online Appendix D, Table D.16 shows that the estimated coefficients of SPI and its lags are all null for violent and property crime rates, including disaggregated homicide rates. Furthermore, the cumulative effect of weather conditions is statistically equal to zero for all estimates. Similarly, Figure D.2 shows that the coefficient of contemporary SPI for each crime rate is significantly different from the other 500 coefficients estimated with shuffled data. This difference is guaranteed at the 1 percent level of statistical significance. Therefore, it is unlikely that the observed baseline results are merely a coincidence between weather conditions and crime rates.

Other robustness checks. In Appendix D online, we present additional robustness checks, including (1) estimating the empirical model without lags in the SPI; (2) adding only one lag in the SPI; (3) adding up to three lags in the SPI; (4) controlling for violent crime categories in the property crime estimates and vice versa; (5) estimating a dynamic model; (6) adding squared SPI terms; (7) using clustered standard errors at the local and microregional levels and bootstrapping (1,000 replications) and use of a cutoff distance of 220 km (Conley); (8) exclusion of outliers from the sample; (9) exclusion of the state metropolitan region; and (10) replacement of average temperature with its long-term deviation. We summarize the results of these robustness tests below[18].

The baseline results are robust in terms of signal and statistical significance, but the contemporaneous coefficients are larger without the inclusion of time lags. A dynamic model does not change the effect of climatic conditions on violent crime rates, and for property crime, the inertia effect reduces the impact, but not beyond the estimated range. The inclusion of the squared SPI reduces the impact of weather on violent crime rates, but not on property crime rates. Calculating the standard errors mentioned above does not change the statistical significance of the effects of weather on violent and property crime rates. Excluding outliers reduces the effect of weather on violent and property crime, but they remain highly significant. Replacing average temperature with its long-term standardized deviation still shows significant and robust effects of the SPI on crime rates. Overall, our estimates are internally valid and consistent with the external evidence.

[18]Other less significant robustness tests are described in the Online Appendix, including the estimation of a quantile regression model and controlling for socioeconomic variables.

4.3.1 Exploring the spatial effects

In this section, we have examined the geographic dependence of crime rates and the spatial spillover effects of climatic conditions, taking a conservative approach. This is justified by the fact that spatial modeling poses a number of econometric challenges similar to those encountered in estimating peer effects. First, to capture the process of spatial dependence, one must specify a spatial structure that is often arbitrary and endogenous to the researcher's choice(Harari & Ferrara, 2018). Second, capturing a neighborhood effect puts us before the reflection problem of Manski (1993) and other related issues, such as simultaneity and collinearity between the variables[19]. Third, the existence of a variety of spatial models makes it difficult to identify the model that is truly generating the study data. In summary, the approach adopted faces problems of collinearity, simultaneity, and selection that can lead to biased estimates and weak causal interpretation. All these problems are discussed in detail in Gibbons and Overman (2012).

Given all these challenges, we have used this approach as a secondary analysis or robustness check to address specific questions in spatial econometrics, such as indirect effects of weather conditions and spatial spillovers of crime (Gibbons & Overman, 2012). It is worth noting that when an endogenous variable is included, estimates are likely to be smaller due to attenuation bias. In this context, we followed a conservative approach by considering a contiguity matrix (W) that expresses the common border between municipalities. Considering this spatial matrix normalized by the spectral method, we estimated the SDM (Spatial Durbin Model) using the quasi-maximum likelihood (QML) approach. This model accounts for the general process of spatial dependence. We then calculated the direct, indirect, and total effects[20](Harari & Ferrara, 2018). The results are presented in detail in Appendix D online.

Using this model, we find that lagged spatially crime rates are positive and statistically different from zero at the usual significance levels. We estimate spatial effects (ρ) of about 0.1 and 0.54 for violent and property crime rates, respectively. For homicide rates, the spatial spillover effect is 0.19, suggesting that municipalities with high crime rates are surrounded by neighbors with high crime rates on their common border.

Our results also show that the spatial lag of contemporary weather conditions is not statistically different from zero for any of the crime rates, indicating no indirect effects. The F-test also shows that the spatial lags of the weather conditions are not different from zero, even when considered together. We conclude that weather variability in a municipality has strictly local effects, i.e., it does not indirectly affect neighboring municipalities.

Although the autoregressive coefficients are statistically significant, our estimates of the direct effects remain within the indicated intervals. Putting the coefficients in perspective, we find that reducing the contemporaneous SPI by one standard deviation increases the violent crime rate (13 percent), the property crime rate (19 percent), and homicide (9 percent). The total contemporaneous effects are 16 percent, 30 percent, and 13 percent, respectively - equivalent to the baseline direct effect.

4.3.2 Alternative weather shocks

Now, we present the baseline results using an alternative weather measure, such as drought shocks and temperature (Online Appendix D). Our results show that a month of moderate to extreme drought increases violent crime rates by 3.5 percent and property crime rates by 6 percent. We also found that a month of drought increases overall homicide rates by 3.8 percent, while male and juvenile homicide rates increase by 4 percent and 8 percent, respectively. These results are similar to those reported by Blakeslee and Fishman (2018) for negative precipitation shocks on homicide rates (2.4 percent) and robbery rates (5.1 percent) in India and by Mehlum et al. (2006) for property crime rates (8 percent) in Bavaria, Germany.

Next, we also estimated the effects of temperature shocks on crime rates. Our estimates show that a one standard deviation[21] increase above the local average temperature significantly increases violent and property crime rates by 14 percent and 24 percent, respectively. We also document a 14 percent increase in homicide rates for males (15 percent) and juveniles (46 percent). It is worth noting that the cumulative effects are statistically different from zero only for homicide rates, suggest-

[19]The problem of reflection in spatial econometrics is particularly relevant when considering the presence of spatial effects that occur when the variable of interest in one region is affected by the characteristics of neighboring regions.

[20]The direct effects refer to the impact that adverse weather events have on crime rates in localities, while the indirect effects result from the impact of these events on crime rates in neighboring or adjacent. Total effects are calculated by summing the direct and indirect effects. For a more general overview of spatial econometric modeling, we recommend reading the work of Elhorst et al. (2014) and for estimation Belotti et al. (2017).

[21]Note the standard deviation of within is 1.127.

ing that there are persistent effects on lethal crimes over time. Although the scale of the variables is different, our results are consistent with the estimates for India by Blakeslee and Fishman (2018).

5 Transmission channels and mitigation mechanisms

In this section, we examine the economic and non-economic factors that can transmit the effects of climatic conditions on documented crime. We then analyze how the impact of precipitation shocks in the form of droughts on crime can be mitigated.

5.1 Transmission channels

In this section, we examine the economic and non-economic channels that can explain how climatic conditions affect the crime wave in Pernambuco. To do so, we consider the following empirical specification:

$$Y_{m,t} = \alpha + \sum_{k=0}^{2} \beta_{1k} SPI_{m,t-k} + \mathbf{X'}_{m,t}\Omega + \sum_{z\in\mathbf{Z}} \Phi_z(Z \times \mathbf{FE}_t) + \mathbf{FE}_t + \mathbf{FE}_m + \xi_{m,t} \qquad (2)$$

Where $Y_{m,t}$ corresponds to economic and non-economic variables, such as rural production, economic activity, government budget, labor market conditions, and psychological factors (suicide) in the municipality m and year t. We selected these factors based on neoclassical theory of crime economics and existing evidence. The fixed effects and other controls are the same as those in the baseline empirical equation. In addition to the basic covariates ($\mathbf{X'}_{m,t}$), we also included the term $\sum_{z\in\mathbf{Z}} \Phi_z(Z \times \mathbf{FE}_t)$ to control for other aspects of the municipality (Z), such as distance from the capital, semi-arid region, rural area, and population size (small/medium), that interact with a linear time trend. All of these additional controls are binary variables.

As evidenced, economic factors are likely that economic factors are the main channels through which the effects of weather shocks are transmitted to violent and property crime. Our basic results show that adverse climatic conditions in agricultural and non-agricultural seasons increase crime rates. Below, we examine the economic and non-economic factors driving this empirical relationship. Table 3 shows the results.

Agriculture and Livestock. Dryland agriculture is an important sector for generating income for families and agricultural workers, both in the state in question and throughout the Northeast region of Brazil(Costa et al., 2021). However, it should be noted that this economic activity is vulnerable to drought events that can lead to crop failures and high agricultural losses, which can reduce the opportunity cost of engaging in illegal activities(Blakeslee & Fishman, 2018). To examine the validity of this economic mechanism, we regressed the SPI on the rate of loss in dryland agriculture[22]. We also examined the impact of weather conditions on gross per capita income in the rural sector and per capita income from livestock activity. We find that a one standard deviation decline in the contemporary SPI increases the rate of loss in agriculture by 10 percent, while per capita gross income in the rural sector declines by 9 percent and per capita income from livestock by 18 percent. The cumulative coefficient indicates a decline in per capita income in the livestock sector of up to 35 percent.

To examine the impact of weather conditions on farm income, we also calculated the proportion of smallholder farmers participating in the *Programa de Aquisição de Alimentos*(PAA) relative to the size of the economically active population to create a search rate for stable farm income[23]. Our hypothesis is that stable income search should increase over time when adverse weather conditions, such as droughts, reduce smallholder income relative to expected income. As predicted, we found that a one standard deviation decline in the SPI increased the rate of smallholder income stability search by 6 percent. This search for stable agricultural income is persistent over time, probably because small farmers in Pernambuco repeatedly experience negative income shocks.

[22] We use the agricultural loss rate, calculated as the difference between planted and harvested areas, as a proxy for agricultural income loss because it avoids potential problems with endogenous prices and limited productivity data. The agricultural loss rate serves as a more reliable counterfactual measure to capture direct losses in rural production and provides a more accurate representation of actual income losses relative to expected yields(Blakeslee & Fishman, 2018).

[23] PAA purchases food produced by family farms without the need for tendering and distributes it to people experiencing food and nutrition insecurity. PAA's goal is to promote access to food and provide incentives for family farmers.

Economic activity. Losses in the rural sector have an impact on the level of production in non-rural sectors, which can lead to a decline in local demand. This cascading effect can lead to a significant reduction in the opportunity cost of engaging in illicit activities (Ishak, 2022). To analyze this relationship, we regressed the SPI on per capita gross income of the non-rural sector (services and industry) and per capita gross income, which is an indicator of the level of economic activity. The results show that adverse climatic conditions in the form of drought persistently reduce non-rural production levels and overall economic activity. Specifically, a one standard deviation decrease in the SPI results in a 4 percent decline in per capita gross income in the non-rural sector and a 5 percent decrease in overall economic activity. Cumulatively, the declines in both non-rural gross income and economic activity reach 9 percent. These results justify the positive response of criminal activity to adverse climatic conditions outside the agricultural season. This empirical evidence is consistent with the results of Dell et al. (2012), which showed that higher temperatures significantly reduce the level of economic production in poor regions, including those in the rural and industrial sectors. In other words, the effects of weather shocks are not limited to rural production but extend to other relevant economic activities. This conclusion is also confirmed by Oliveira (2019)'s findings that weather disasters such as droughts and floods reduce sectoral production (agriculture and services) in the state of Ceará, which is also located in Northeast Brazil.

Municipal budget. We also investigated the possible relationship between climatic conditions and the reduction in the supply of public goods that affect the opportunity cost of engaging in criminal activity. To measure the impact of climatic conditions on the institutional capacity of local governments to curb crime, we considered social spending on education, health, and human resources (personnel), as well as government revenues. Our estimates show that adverse weather conditions (droughts) have a negative and lasting impact on social spending and government budgets. Specifically, a one standard deviation decline in the SPI is associated with a 47 percent, 46 percent, and 43 percent reduction in education, health, and personnel spending, respectively. Municipal revenues, in turn, decline by 48 percent in the short run and can reach a cumulative decline of up to 57 percent. Regarding the unconditional mean, the impact of unfavorable climatic conditions on social spending and government revenues varies between 6 percent and 8 percent.

Previous studies have shown that policies to increase human capital (Lochner and Moretti (2004)) and ensure access to health care (He and Barkowski (2020)) reduce participation in criminal activity in the United States. Still in this perspective, Chioda et al. (2016) observed that expanding access to Bolsa Família (a conditional cash transfer program) significantly reduced crime in school neighborhoods in the Brazilian state of São Paulo. Therefore, reducing the provision of public goods is a plausible transmission channel for the effect of weather shocks on documented crime.

Labor market. We have already shown that the economic channels through which weather affects crime are agricultural losses and declines in rural incomes. We have found that these negative impacts spill over to the non-rural sector and lead to a significant decline in local demand. Furthermore, we expect these impacts to affect not only workers and families in rural areas but also those in urban areas, particularly through declines in employment and legal labor income. It is worth noting that the formal labor market in Pernambuco is concentrated mainly in urban areas(Dell et al., 2012; Dix-Carneiro et al., 2018).

Our analysis shows that adverse climatic conditions have a significant impact on employment rates and average labor income (wages). For comparison, a one standard deviation decline in the SPI results in a reduction of about 9 percent in municipal employment rates (relative to the unconditional mean) and 1.5 percent in average labor income. It is important to emphasize that this analysis focuses specifically on the response of formal labor market indicators, i.e., those that include legal means of subsistence. Thus, the negative impact of adverse weather shocks, such as drought, affects livelihoods not only in rural areas but also in urban areas, leading to a general reduction in the opportunity cost of engaging in criminal activities (Peng & Zhan, 2023).

Psychological. One of the reasons why weather shocks may increase the incidence of crime is behavioral and psychological changes, such as increased stress in daily life and mental health problems such as depression. To examine whether there is a non-economic driving channel that explains the strong relationship between weather conditions and crime, we look at suicide rates per thousand population. Suicide rates are often used to capture deterioration in mental health due to stress or depression(Baysan et al., 2019; Dix-Carneiro et al., 2018; Ishak, 2022).

The estimates suggest that the contemporaneous effects of SPI are not statistically different from zero. This is consistent with previous studies for Brazil, which showed that exogenous shocks, such as those from weather and foreign trade tariffs, do not affect suicide rates. However, we observe a statistically significant and positive effect of the SPI with a lag of two years on the suicide rate (Ishak (2022) and Dix-Carneiro et al. (2018)). This result does not rule out the possibility that psychological changes resulting from adverse weather shocks have positive effects on crime, although it does not clarify the contemporaneous effects found for the relationship between weather and crime in this study.

In a robustness check presented in Online Appendix D, we included two types of property crime, the rate of robbery of passersby and the rate of theft of cargo and vehicles, in the regression of the SPI against the violent crime rate. As expected, the increase in the rate of theft of cargo and vehicles, a crime with a strong economic motive, is positively correlated with the rate of violent crime. Thus, it is unlikely that the effects of weather shocks on violent crime are not mediated predominantly by economic factors.

5.2 Mitigation mechanisms

In Pernambuco, about a quarter of the population lives in rural areas, and most of them have limited natural, financial, and technological resources to cope with weather crises, especially in the semi-arid region(Costa et al., 2021). In this context, the state has invested in measures to mitigate and adapt to extreme weather events. In addition to water infrastructure, which includes the construction of dams and weirs, investments have been made in the water supply to rural properties, natural resource protection, irrigation systems, and sustainable agrarian practices such as agricultural diversification(Milhorance et al., 2018). Therefore, it is important to investigate whether these interventions implemented can mitigate the impact of weather shocks on municipal crime, as they provide means to maintain agricultural productivity and local economic activity(Marengo et al., 2022; Oliveira, 2019).

Water infrastructure is represented by federal agreements for the construction or execution of dams and weirs in municipalities. In recent decades, only 8.1 percent of municipalities in Pernambuco have benefited from work to combat drought. In turn, the municipal irrigation rate is denoted by the proportion of irrigated land on rural properties in relation to the territorial extension. Irrigated lands represent about 2 percent of the state. The water supply rate corresponds to the proportion of rural domiciles that has access to water (general network, wells, rivers, among others). The share of water supply in the rural area of the state is 70 percent. The water cover corresponds to the water surface in relation to the territorial extension, which is on average 0.9 percent. Sustainable and adaptive agricultural practices are expressed through the dryland agriculture diversification index, which averages 37 percent in the state. Access to credit for family farmers is denoted by the percentage of rural farms benefiting from the *Programa Nacional de Fortalecimento da Agricultura Familiar* (PRONAF)[24], with an average of 21 percent. To test whether these mechanisms mitigate the impact of weather shocks in the form of drought on crime, Equation (1) is re-estimated as follows:

$$C_{m,t} = \alpha + \sum_{k=0}^{2} \beta_{1k} SPI_{m,t-k} + \sum_{k=0}^{2} \theta_{1k} (M_{m,t} \times SPI_{m,t-k}) + \varphi M_{m,t} + \mathbf{X'}_{m,t}\Omega + \mathbf{FE}_t + \mathbf{FE}_m + \xi_{m,t} \tag{3}$$

Where $M_{m,t}$ are the mitigation mechanisms presented, while the term $\sum_{k=0}^{2} \theta_{1k}(M_{m,t} \times SPI_{m,t-k})$ represents the interaction of climatic conditions with the mitigation mechanisms. The other terms of the empirical equation remain as before.

Table 4 presents the results of the analysis of factors that can reduce or neutralize the impact of adverse weather shocks in the form of drought on crime. Looking at the interaction between the SPI and the mitigation factors, the interaction coefficients were found to significantly reduce or mitigate the impact of adverse climatic conditions on violent and property crime. In Columns 1 and 7, the contemporaneous interaction coefficients with water infrastructure (dams and weirs) are negative and statistically significant. With water infrastructure, the effect of an adverse weather shock on rates of violent and property crime is 57 percent and 77 percent lower, respectively. As for the interaction coefficients with irrigation rates (Columns 2 and 8) and water supply rates in rural properties (Columns 3 and 9), these mechanisms were found to significantly neutralize the effects

[24] See more information on Pronaf.

of weather conditions on crime. Water supply rates, on the other hand, neutralize the effects of weather fluctuations on violent crime rates (Column 4), while reducing the impact on property crime rates (Column 10) by up to 84 percent. Next, we found that agricultural diversification practices (Columns 5 and 11) and the provision of credit to smallholder farmers (Columns 6 and 12) mitigate the impact of climate shocks on crime, providing an adaptive mechanism to sustain agricultural income.

The results suggest that the mitigation mechanisms studied are effective in reducing the negative effects of weather shocks in the form of drought on crime in Pernambuco, both in the short and medium term. Therefore, policies that prioritize these factors provide an adaptive mechanism to maintain agricultural income and local demand in the face of the effects of weather variability, particularly high temperatures and low rainfall (Costa et al., 2021; Oliveira, 2019). This conclusion is supported by recent evidence showing that the water supply and weather change adaptation measures studied help maintain levels of agricultural and non-agricultural production in Northeast Brazil (Marengo et al., 2022). For example, Costa et al. (2021) found that water supply on rural properties mitigates the effects of drought on agricultural production in poor and vulnerable municipalities in the Brazilian semiarid region. Oliveira (2019) shows that water infrastructure and agricultural microinsurance help neutralize the impact of weather disasters on the growth of production in rural and non-rural sectors and on overall economic activity in the state of Ceará, also in the Northeast of Brazil. More consistent with our results are Ishak (2022) and Harari and Ferrara (2018), which show that irrigation schemes and high-quality infrastructure help neutralize the effects of weather shocks on homicides and civil wars in rural Brazil and Africa, respectively.

6 Discussion and conclusions

This article examined the effects of weather shocks on crime rates in the municipalities of Pernambuco, a representative state in the Northeast region of Brazil. Using previously unexplored short-term microdata and a dataset that includes disaggregated homicide rates for the period from 2000 to 2018, this study extends the existing literature by providing robust evidence on the relationship between weather shocks and violent and property crime.

Unlike previous studies that focused on industrialized economies with low crime rates and provided mixed results regarding the effects of weather on violent and property crime rates, our research focuses on Pernambuco, a predominantly semi-arid and developing state in one of the largest countries in the world. Pernambuco is characterized by recurrent droughts and a violence index comparable to that of countries experiencing civil war or armed conflict. This attractive context allowed us to conduct a comprehensive analysis of the relationship between crime and weather. In particular, we were able to identify the factors driving crime responses to adverse weather shocks and the mechanisms by which these effects are mitigated (Blakeslee & Fishman, 2018).

Results suggest that precipitation shocks in the form of drought significantly increase rates of violent crime, including general and juvenile homicide, and property crime. These effects persist after the agricultural station and in the medium term. The response of crime to weather shocks is heterogeneous in terms of municipality characteristics, with larger effects observed in areas with small populations, rural, semi-arid, highly diversified agriculture, and more than 100 km from the state capital (Recife). The heterogeneous effects are significant for property crimes, while they are more uniform for violent crimes, except in municipalities in the marijuana polygon, where violence increases explosively during droughts. This analysis provides suggestive evidence that poor and vulnerable areas exposed to adverse weather shocks are the most affected by the increase in crime and, consequently, face higher social costs.

In examining criminological heterogeneity, we found that weather shocks primarily affect violent crimes against male victims and the use of firearms, while practically all types of property crimes are affected. This finding underscores the need for targeted policies and interventions to address the root causes of these types of crimes, particularly in vulnerable areas exposed to weather shocks. In addition, this discovery highlights the importance of a gender-sensitive approach to crime prevention and response in the municipalities, as male victims may be particularly vulnerable to violent crime in the context of extreme weather events. Disarmament measures are also one way to reduce lethal crimes in scenarios with lower precipitation and higher temperatures.

The persistent response of violent and property crimes to adverse weather conditions is primarily explained by the predominant role of economic mechanisms. The evidence presented in the study suggests that economic losses in rural and urban areas, reductions in local demand and government capacity to provide public goods, as well as variations in formal labor market conditions, mediate the effects of climate shocks in the form of drought on crime rates. Furthermore, the results indicate that during precipitation shocks in the form of droughts, local governments face significant challenges in rationalizing interventions to contain the increase in crime and manage the associated economic and social impacts. In general, we highlight the dominant role of an income mechanism in determining criminal activity in response to adverse climate shocks in developing areas, which is consistent with the recent contributions of Blakeslee and Fishman (2018), Ishak (2022), Ankel-Peters et al. (2023) e Peng and Zhan (2023).

Political Implications. The severe drought from 2012 to 2015 in Northeast Brazil led to a state of emergency and a significant rise in crime rates in Pernambuco(Marengo et al., 2017). The analysis of crime rates, particularly homicides, during and after this period, reveals a persistent impact of adverse weather conditions in the short and medium term. This is worrisome because future projections indicate an increasing frequency of drought events in Northeast Brazil due to ongoing weather changes, with detrimental effects on agriculture and public safety, as documented. Therefore, local governments must urgently implement weather change adaptation strategies and robust public safety measures to address these challenges.

Based on the documented evidence, it is crucial for governments and policymakers in Pernambuco, Northeast Brazil, to invest in water infrastructure, including dams and weirs, for storing water during the rainy season and ensuring a constant supply in the dry season. The expansion of access to water in rural areas and the implementation of irrigation systems can reduce farmers' dependence on erratic rainfall and improve agricultural productivity in the medium and long term(Costa et al., 2021; Harari & Ferrara, 2018; Ishak, 2022). Supporting sustainable agricultural practices, such as crop diversification, enhances resilience to adverse climate conditions. Local governments should also promote water conservation to ensure a sustainable supply for agricultural production and other economic and human activities. Access to credit through public programs like PRONAF can facilitate these actions and support investments in water infrastructure and technologies(Marengo et al., 2022; Oliveira, 2019).

Local governments can also mitigate climate fluctuations by providing climate-indexed insurance, social assistance programs, and water retention technologies. These measures help minimize the impact on rural and urban producers, reducing the economic impact on criminal activity. Investments in police patrols, surveillance, monitoring, intelligence, and crime prevention programs can also enhance public security, especially in vulnerable areas. For these actions to be successful, policymakers must consider temporal and geographical factors related to climate and crime. In conclusion, it is of utmost importance that policymakers in regions with similar characteristics to that of Pernambuco, in Northeast Brazil, give special attention to the potential impacts of climate change on the increase in crime rates.

7 Online Appendix

Access the **Online Appendix** of this article.

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Table 1: Crime and weather

	Violent and lethal crime rate					Property crime rate				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
SPI, t	-0.146***			-0.113**	-0.129***	-2.917***			-3.431***	-3.213***
	[0.0453]			[0.0572]	[0.0500]	[0.727]			[0.778]	[0.651]
SPI, t-1	-0.125***			-0.121**	-0.109***	-1.681***			-1.679***	-1.598***
	[0.0328]			[0.0540]	[0.0378]	[0.445]			[0.476]	[0.389]
SPI, t-2	-0.021			-0.020	-0.023	0.592			0.650	0.320
	[0.0357]			[0.0466]	[0.0342]	[0.600]			[0.674]	[0.452]
SPI (agricultural season), t		-0.125***					-3.097***			
		[0.0405]					[0.627]			
SPI (agricultural season), t-1		-0.109***					-1.105***			
		[0.0304]					[0.376]			
SPI (agricultural season), t-2		0.0522*					1.601***			
		[0.0280]					[0.433]			
SPI (non-agricultural season), t			-0.0694***					-0.894**		
			[0.0261]					[0.405]		
SPI (non-agricultural season), t-1			-0.0890***					-1.501***		
			[0.0213]					[0.382]		
SPI (non-agricultural season), t-2			-0.0868***					-0.999***		
			[0.0220]					[0.386]		
Sum (SPI)	-0.292***			-0.253***	-0.261***	-4.006***			-4.460***	-4.491***
	[0.0635]			[0.0947]	[0.0808]	[1.089]			[0.966]	[0.939]
Sum (SPI agricultural season)		-0.182***					-2.601***			
		[0.0487]					[0.837]			
Sum (SPI non-agricultural season)			-0.245***					-3.394***		
			[0.0481]					[0.784]		
Mean of dep. var.	0.39	0.39	0.39	0.39	0.39	3.84	3.84	3.84	3.84	3.84
N	1295	1295	1295	1295	1295	1295	1295	1295	1295	1295
R^2	0.269	0.268	0.268	0.282	0.271	0.547	0.554	0.538	0.607	0.579
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
Regional x Year FE	No	No	No	Yes	No	No	No	No	Yes	No
Regional trend	No	No	No	No	Yes	No	No	No	No	Yes
Basic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Notes:*The dependent variable is the crime rate per thousand inhabitants. Basic controls include population density, average temperature, average actual evapotranspiration, and average climatic water deficit. The estimation method is Ordinary Least Squares (OLS) with the standard errors of Conley (1999) reported in brackets, robust for spatial correlation within a 100 km radius. Significantly different from zero: *p < 0.10, ** p < 0.05, *** p < 0.01.

Table 2: Robustness checks: crime and weather

	Violent and lethal crime rate						**Property crime rate**					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SPI, t	-0.137***	-0.136***	-0.135***	-0.137***	-0.137***	-0.157***	-1.970***	-1.959***	-1.921***	-1.903***	-1.910***	-2.493***
	[0.0470]	[0.0466]	[0.0469]	[0.0470]	[0.0470]	[0.0421]	[0.660]	[0.664]	[0.665]	[0.656]	[0.655]	[0.628]
SPI, t-1	-0.149***	-0.148***	-0.148***	-0.149***	-0.148***	-0.118***	-1.286***	-1.267***	-1.281***	-1.272***	-1.266***	-0.614
	[0.0368]	[0.0361]	[0.0363]	[0.0364]	[0.0363]	[0.0341]	[0.446]	[0.447]	[0.446]	[0.444]	[0.449]	[0.465]
SPI, t-3	-0.015	-0.014	-0.014	-0.015	-0.015	-0.0828**	0.238	0.255	0.227	0.237	0.244	0.400
	[0.0348]	[0.0347]	[0.0343]	[0.0343]	[0.0346]	[0.0389]	[0.502]	[0.501]	[0.500]	[0.498]	[0.502]	[0.445]
Log (Royalties revenue)		0.017	0.016	0.016	0.016			0.272**	0.263**	0.268**	0.268**	
		[0.0224]	[0.0224]	[0.0224]	[0.0224]			[0.121]	[0.122]	[0.122]	[0.120]	
Crime, t-1						-0.036						0.450***
						[0.0477]						[0.0850]
Sum (SPI)	-0.300***	-0.298***	-0.298***	-0.300***	-0.300***	-0.358***	-3.018***	-2.971***	-2.975***	-2.938***	-2.932***	-2.707**
	[0.0618]	[0.0601]	[0.0601]	[0.061]	[0.0612]	[0.0629]	[0.953]	[0.951]	[0.947]	[0.939]	[0.944]	[1.116]
Mean of dep. var.	0.39	0.39	0.39	0.39	0.39	0.39	3.84	3.84	3.84	3.84	3.84	3.84
N	1295	1295	1295	1295	1295	1110	1295	1295	1295	1295	1295	1110
R^2	0.303	0.303	0.303	0.304	0.304	0.281	0.641	0.642	0.643	0.644	0.644	0.609
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Basic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear time trend												
Municipal characteristics	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Additional controls												
Royalties	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No
Economy	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No
Security and protection	No	No	No	Yes	Yes	No	No	No	No	Yes	Yes	No
Family disorganization	No	No	No	No	Yes	No	No	No	No	No	Yes	No

*Notes:*The dependent variable is the crime rate per thousand inhabitants. Basic controls include population density, average temperature, average actual evapotranspiration, and average climatic water deficit. Municipal characteristics include the urbanization rate, illiteracy rate (18 to 17 years), and the proportion of the population: male, black, and young (18 to 30 years). Royalty revenue is the total royalty revenue per capita (in thousand reais). Economic control (rate of the economically active population), security and protection (rate of workers in security and protection services), and family disorganization (divorce rate). The estimation method is Ordinary Least Squares (OLS) with the standard errors of Conley (1999) reported in brackets, robust for spatial correlation within a 100 km radius. Significantly different from zero: *p < 0.10, ** p < 0.05, *** p < 0.01.

Table 3: Economic and non-economic mechanisms

Channels	Panel A. Agriculture and Livestock				Panel B. General economic activity		Panel C. Psychological
	Agricultural loss rate (rainfed agriculture)	Log: Rural gross income (per capita)	Log: Income from livestock (per capita)	Log: PAA adherence rate	Log: Non-rural gross income (per capita)	Log: GDP (per capita)	Suicide rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SPI, t	-0.232**	0.219**	0.424**	-0.136**	0.0897*	0.121**	0.010
	[0.106]	[0.109]	[0.201]	[0.0693]	[0.0544]	[0.0538]	[0.0221]
Sum (SPI)	-0.107	0.068	0.829*	-0.352***	0.222**	0.221**	-0.038
	[0.155]	[0.206]	[0.427]	[0.130]	[0.101]	[0.0945]	[0.0322]
Test F (p-value)	0.003	0.051	0.147	0.060	0.121	0.108	0.163
Mean of dep. var.	0.214	6.426	4.839	0.072	9.060	9.243	0.048
R^2	0.278	0.064	0.072	0.148	0.210	0.192	0.037
Channels	Panel D. Government capacity (public goods)				Panel E. Formal labor market		
	Log: Gov. Revenue (per capita)	Log: Gov. Health (per capita)	Log: Gov. Education (per capita)	Log: Gov. Personnel (per capita)	Occupancy rate	Log: Average income from work	
	(8)	(9)	(10)	(11)	(12)	(13)	
SPI, t	1.125*	1.118**	1.099**	1.007*	2.153*	0.0332*	
	[0.608]	[0.485]	[0.538]	[0.558]	[1.299]	[0.0202]	
Sum (SPI)	1.345**	1.206**	1.156**	1.087**	4.624**	0.002	
	[0.622]	[0.514]	[0.566]	[0.550]	[2.003]	[0.0341]	
Test F (p-value)	0.001	0.001	0.000	0.001	0.047	0.191	
Mean of dep. var.	7.592	6.054	6.576	7.029	11.236	7.395	
R^2	0.112	0.094	0.079	0.129	0.094	0.434	
N	1295	1295	1295	1295	1295	1295	1295
Basic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear time trend							
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: The dependent variable is the crime rate per thousand inhabitants. Basic controls include population density, average temperature, average actual evapotranspiration, and average climatic water deficit. Additional controls include distance from the state capital (Recife), small/medium-sized municipalities, and semiarid areas. The estimation method is Ordinary Least Squares (OLS) with the standard errors of Conley (1999) reported in brackets, robust for spatial correlation within a 100 km radius. Significantly different from zero: *p < 0.10, ** p < 0.05, *** p < 0.01.

Table 4: Mitigation mechanism

Mitigation	Violent and lethal crime rate						Property crime rate					
	Water infrastructure	Irrigation	Rural supply	Water coverage	Agricultural diversification	Agricultural credit	Water infrastructure	Irrigation	Rural supply	Water coverage	Agricultural diversification	Agricultural credit
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SPI, t	-0.142***	-0.139***	-0.143***	-0.153***	-0.144***	-0.160***	-2.886***	-2.937***	-3.409***	-2.722***	-2.960***	-3.187***
	[0.0446]	[0.0464]	[0.0535]	[0.0473]	[0.0484]	[0.0537]	[0.718]	[0.714]	[0.868]	[0.727]	[0.655]	[0.725]
SPI, t-1	-0.122***	-0.117***	-0.121**	-0.130***	-0.151***	-0.112**	-1.685***	-1.586***	-1.805***	-1.353***	-1.497***	-1.876***
	[0.0326]	[0.0363]	[0.0553]	[0.0344]	[0.0373]	[0.0477]	[0.444]	[0.448]	[0.673]	[0.438]	[0.442]	[0.535]
SPI, t-2	-0.024	0.001	0.027	-0.004	-0.034	0.016	0.591	0.696	0.486	1.061*	1.052*	0.658
	[0.0352]	[0.0366]	[0.0460]	[0.0375]	[0.0376]	[0.0403]	[0.595]	[0.643]	[0.851]	[0.611]	[0.581]	[0.664]
SPI x Mitigation, t	-0.0612*	-0.005	0.000	0.016	-0.012	0.004	-0.678*	0.004	0.007	-0.433*	-0.670	0.097
	[0.0351]	[0.0097]	[0.00036]	[0.0104]	[0.0487]	[0.0078]	[0.406]	[0.143]	[0.00793]	[0.259]	[0.965]	[0.164]
SPI x Mitigation, t-1	-0.0851**	-0.007	0.000	-0.025	0.055	-0.005	-0.365	-0.135	0.001	-0.829***	-0.440	0.098
	[0.0389]	[0.0123]	[0.0005]	[0.0174]	[0.0553]	[0.0106]	[0.308]	[0.102]	[0.00706]	[0.266]	[0.919]	[0.146]
SPI x Mitigation, t-2	-0.008	-0.0198**	-0.001	-0.0248*	0.071	-0.013	-0.197	-0.078	0.001	-0.456*	-2.352**	0.008
	[0.0374]	[0.0095]	[0.00043]	[0.0149]	[0.0530]	[0.0096]	[0.197]	[0.129]	[0.00765]	[0.268]	[0.967]	[0.154]
Log (Mitigation, t)		0.004		-0.078	0.015	-0.004		-0.052		-2.045**	-0.825	0.188
		[0.0123]		[0.0743]	[0.0688]	[0.0115]		[0.218]		[0.805]	[0.630]	[0.143]
Sum (SPI)	-0.287***	-0.255***	-0.238**	-0.287***	-0.329***	-0.257***	-3.980***	-3.827***	-4.728***	-3.014***	-3.404***	-4.405***
	[0.0624]	[0.0678]	[0.106]	[0.065]	[0.0644]	[0.0835]	[1.088]	[1.117]	[1.529]	[1.048]	[1.102]	[1.357]
Sum (SPI x Mitigation)	-0.154	-0.032	-0.001	-0.034	0.114	-0.015	-1.239	-0.210	0.008	-1.718**	-3.462	0.204
	[0.102]	[0.0268]	[0.00109]	[0.0343]	[0.138]	[0.0234]	[0.838]	[0.325]	[0.0181]	[0.670]	[2.527]	[0.381]
Mean of dep. var.	0.387	0.387	0.387	0.387	0.387	0.387	3.842	3.842	3.842	3.842	3.842	3.842
N	1295	1295	1295	1295	1295	1295	1295	1295	1295	1295	1295	1295
R^2	0.272	0.271	0.271	0.273	0.270	0.270	0.548	0.548	0.548	0.557	0.555	0.549
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Basic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Notes:*The dependent variable is the crime rate per thousand inhabitants. Basic controls include population density, average temperature, average actual evapotranspiration, and average climatic water deficit. The estimation method is Ordinary Least Squares (OLS) with the standard errors of Conley (1999) reported in brackets, robust for spatial correlation within a 100 km radius. Significantly different from zero: *p < 0.10, ** p < 0.05, *** p < 0.01.