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ORIGINAL PAPER

Climate change in Brazilian agriculture: vulnerability and adaptation assessment

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Abstract
The agricultural sector is essential for economic growth, especially for the poor in developing countries. This study investigated the degree of susceptibility, coping capacity, and adaptive capacity of agricultural establishments in Brazil to assess their vulnerability to climate change. Different databases were used, relating socio-environmental, economic, and demographic characteristics. The means of susceptibility, coping capacity, and adaptive capacity were 48%, 35%, and 51% in Brazilian municipalities. North and Northeast are the most vulnerable regions, while South is the least one. Looking how vulnerability behave across biomes, Amazônia, Pantanal, Caatinga, Cerrado, and Mata Atlântica present vulnerability index higher than 50%. Regarding whether determinants, the temperature is related to higher levels of vulnerability and more precipitation with lower levels. Agricultural policies to reduce susceptibility and increase coping and adaptation capacities are necessary to reduce the vulnerability of farming establishments in the Brazilian regions studied. We provided here a guide showing more vulnerable areas and biomes for further action.

Keywords Agricultural establishments · Climate change · Susceptibility · Vulnerability

Introduction

The agricultural sector is essential for economic growth, especially for poor people in developing countries. It generates employment and income by producing food and raw materials with more significant benefits for the poorest, pointing to agriculture as a powerful tool against poverty (Todaro and Smith 2009). However, social and environmental vulnerabilities, agricultural land scarcity, and climate change challenge the farm sector. Even though current and future climate changes threaten humanity as a whole (Haden et al. 2012; Shikuku et al. 2017), they have a higher impact on those who have historically contributed the least to the problem – the poor (Tol 2018; Jamshidi et al. 2019).

The inequality of effects across country income levels is due to three factors. First, agriculture, the main sector affected by climate change, is relatively more important in developing countries, e.g., the Brazilian economy is 3.6 times more intensive in agriculture than the average for eurozone countries and 6.5 times more than the US economy (World Bank 2021).[1] Second, developing countries are in tropical and subtropical areas, regions predicted to experience further higher temperature and variability (Bathiany et al. 2018). Third, developing countries are less able to adapt to climate change (Menezes et al. 2018).

There is consensus that countries, regions, and groups are differentially vulnerable and that climate risks and adaptation options vary significantly according to these systems' socioeconomic and structural situations (Birkmann et al. 2021; Dos Santos et al. 2021). The literature presents a vulnerable climate scenario for Brazil, including temperature increases in drought-prone regions (Sharma et al. 2018; Kotz et al. 2021) and more intense summer rains (Mahmoud 2020). The organizational and socioeconomic structure, mainly of Brazilian agricultural

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[1] In Brazil, agriculture as a share of GDP was 5.9% in 2020. For the same year, the Euro area and the U.S. values were 1.6 and 0.9%, respectively (World Bank 2021).

establishments, can intensify or mitigate the effects of climate change.

Brazilian agricultural establishments correspond to a unit of production and exploitation of agricultural, forestry, or aquaculture activity, whose production purpose is subsistence or commercialization, and differ in size, location, and legal forms. About 5 million agricultural establishments in Brazil are distributed throughout the territory, occupying 41% of the country's territorial area (IBGE, 2017). Thus, as the farm sector is one of the most vulnerable to climate change, efforts are being made to delineate and understand the different levels of vulnerability and their components.

Indeed, several studies with multiple proxies and definitions of agricultural vulnerability have been carried out (Birkmann et al. 2013; Jamshed et al. 2020a, 2020b; Hoque et al. 2022). However, vulnerability measured from a structural and systemic view of Brazilian agricultural establishments is unknown and becomes essential to fill the research gap. The vulnerability of these groups depends on risk exposure and the social, economic, political, demographic, and environmental characteristics into which they are inserted. Thus, even if the group is affected by the same climatic variations or risks, the less vulnerable tend to suffer lower impacts.

Furthermore, unlike previous studies, the vulnerability considered here does not consider exposure as part of the vulnerability, but only the components of susceptibility, coping capacity, and adaptability, definitions updated from the IPCC 2014 reports. Vulnerability is a crucial concept in several areas and can be measured using different methods, such as variable assessments and indicators approach (Birkmann et al. 2013; Acheampong et al. 2014; Hoque et al. 2022). In this study, we used the indicator approach due to its ability to express all the main components of the theoretical concept. The main advantage is that this method can be used at any level, such as national, regional, groups, and communities, and can be useful for shaping and comparing the vulnerability of various systems and subsystems (Hoque et al. 2022).

In this sense, the adequacy and consistency of updated vulnerability concepts incorporating accessible indicators are crucial for defining and measuring the vulnerability to which agricultural establishments are exposed. Thus, the objective of this study was to analyze the main components of the updated concept of vulnerability at the level of farming establishments, estimate the degree of vulnerability and the relationship with climate change and identify their location in the Brazilian territory. So that the results found are helpful as a decision-making tool for planning and intervention.

Literature review

The literature on vulnerability to climate change is extensive (Deschenes and Greenstone 2007; Dell et al. 2009; Green et al. 2010; Dell et al. 2012; Leonard et al. 2013; Nelson et al. 2014; Challinor et al. 2014; Viswanathan and Kavi Kumar 2015; Kreslake et al. 2016; Roser-Renouf et al. 2016; Barbier and Hochard 2018; Tol 2018; Diffenbaugh and Burke 2019; Dos Santos et al. 2021) with most studies devoted to climatic explanations and information regarding specific hazards (Birkmann et al. 2022). Climate change increases risks unevenly within and between regions of the world, significantly impacting communities and people who contribute the least to this effect (IPCC 2014; Bathiany et al. 2018).

Most studies in Brazil are linked to vulnerability to future risks and impacts (Gomes 2001; Confalonieri 2008; Marengo 2008; Nobre 2008; Margulis et al. 2010; Maluf and Rosa 2011; Obermaier et al. 2011; Obermaier 2013). This is important, but it is necessary to foresee how to reduce the current socioeconomic vulnerability identified by the forms of adaptation without depending on the future climate to establish and improve future adaptation measures (Obermaier 2013).

Broader policies can increase social and environmental adaptation and resilience while reducing the short-term vulnerability of family farmers in the semi-arid Northeast of Brazil (Obermaier 2011). This should consider the origins of current vulnerability, as the lack of public policies, access to information, perception and income can limit the adaptive capacity of these populations (Obermaier 2013).

Poverty and low adaptive capacity led to a higher vulnerability of Brazilian Amazonian municipalities to climate change (Menezes et al. 2018). Low rainfall and institutional and socioeconomic factors increased the vulnerability in the semiarid region of the Ceará state, Brazil, as well (Lindoso et al. 2014). Deforestation, loss of biodiversity, pollution, and their interactions adversely affect the capacities of ecosystems, communities, and individuals to adapt to climate change. In addition, the loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for people and local communities directly dependent on ecosystems to meet basic needs (IPCC 2022). Changes in precipitation alter hydrological systems by reducing the quantity and quality of water resources (IPCC 2014). Furthermore, they increase migration and facilitate interactions between terrestrial and freshwater species and, consequently, current and future vulnerability. The climatic history of the semiarid region of Northeast Brazil suggests that this region is more vulnerable to climate variability, with droughts affecting its population, ecosystem, and agriculture (Marengo 2008).

The perception, beliefs, and socioeconomic characteristics of farmers willingness to adapting to climate change were studied in the Rio das Contas Basin, Bahia state, Brazil. Climate change negatively affected adaptation behavior and how farmers perceive it (De Matos Carlos et al. 2020). Furthermore, high vulnerability and sensitivity and low adaptive capacity degrees were identified in municipalities with low socioeconomic development and in biomes with more significant anthropogenic degradation (Dos Santos et al. 2021; Nogueira et al. 2021).

Micro-level analyzes are critical, as the impact of climate change differs across sectors and population groups (de Matos Carlos et al. 2020; dos Santos et al. 2021; Nogueira et al. 2021). The general objective was to study the susceptibility, coping capacity, and degree of adaptive capacity of agricultural establishments in Brazil to assess their vulnerability to climate change. Susceptibility, coping capacity, and adaptive capacity were combined by linking 30 socio-environmental, economic, and demographic indicators from the databases of the Brazilian Institute of Geography and Statistics (IBGE), Ministry of Agriculture, Livestock and Supply (MAPA), and Institute for Space Research (INPE) of Brazil. This database provided detailed information, covering a significant sample and generating valuable data.

Materials and methods

Definition of vulnerability

The definition of the concept of vulnerability is multiple, and its interpretations vary according to the context and dimension in which it is inserted (Birkmann et al. 2013; Jamshed et al. 2020a). However, in recent decades, the definition of vulnerability has become more systemic, considering not only human systems but also social, economic, physical, and environmental systems and their characteristics. In general, vulnerability is seen as a "*product of structural inequality and is systemic in nature*" (Birkmann et al. 2021). According to the IPCC (2014), the vulnerability in the context of climate change is defined as "*the predisposition of individuals or systems from being adversely affected by hazards. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of ability to cope and adapt*" (IPCC 2014). Thus, vulnerability is measured from socioeconomic and physical factors and the environmental and human conditions in which individuals or systems are inserted (Birkmann et al. 2021).

Susceptibility is the probability of a community or individual suffering damage or loss due to an eventual natural hazard or climate change. Susceptibility refers to the structural, economic, nutritional, and infrastructure conditions and characteristics to which communities and individuals are exposed (Welle and Birkmann 2015). The worse these characteristics, the more susceptible they become to possible dangers. Coping capacity is defined as the ability of an individual, community, or system to use its resources to deal with and cope with emergencies, abnormal conditions, and disasters caused by events (UNISDR 2009; Welle and Birkmann 2015). Coping capacity is already available and is short-term and ex-post actions (Cardona et al. 2012). They aim to maintain the system and its functions in adverse scenarios (Welle and Birkmann 2015). Adaptive capacity, on the other hand, refers to the strategies communities and individuals use that allow them to change to minimize the expected negative consequences of climatic events and disasters. It can thus be defined as long-term strategies linked to a specific hazard, considered ex-ante actions. Therefore, the ability to adapt involves changes and requires processes and reorganization (Cardona et al. 2012; Welle and Birkmann 2015).

Calculating the vulnerability index

The vulnerability concept applied in this study captures vulnerability in terms of its main components: susceptibility, coping capacity, and adaptability. The vulnerability in this study was based on the index method. Indices approaches are widely accepted in economic and environmental studies because they can explain elusive issues such as vulnerability to climate change (OECD, 2008; Birkmann et al. 2013; Jamshed et al. 2020a). Data for this research were identified through secondary data. The selection and characterization of the subcomponents and their respective indicators were based on studies by Welle and Birkmann (2015)[2] and extracted from the literature according to available data (see Welle and Birkmann 2015 and Table 1).

The set of variables was used to improve the understanding of the indicators that make up vulnerability, including those related to environmental, socioeconomic, and demographic issues faced by Brazilian agricultural establishments. Overall, vulnerability is calculated by 30 indicators: 13 refer to the concept in the sphere of susceptibility, nine related to coping capacity, and eight attributed to the idea of adaptive capacity. For aggregation, all indicators were transformed into dimensionless classification levels between 0 and 1, following Welle and Birkmann 2015. Table 1 shows the respective indicators, their explanation, the transformation method, and the corresponding literature.

[2] Welle and Birkmann (2015) introduced an instrument to assess country risk and vulnerability. The World Risk Index (WRI) is composed of 28 indicators involving the sphere of exposure and the sphere of vulnerability. In this study, in addition to the WRI vulnerability indicators, other indicators from the literature were considered.

Table 1 Selected indicators, justification, transformation method, and literature for the Susceptibility (S), Coping Capacity (CC), and Adaptive Capacity (AC) components. Source: Adapted of Birkmann et al. (2021)

	Indicators	Explanation	Transformation method	Literature
	Susceptibility			
S1	% of the population residing in households without access to the water supply network	The lack of access to clean water increases people's susceptibility. Climate change affects water supply and can increase the number of deaths from waterborne diseases	Scaled to 0 to 1	Jamshed et al. (2020a); Birkmann et al. (2021)
S2	% of the population residing in households without access to treated sewage	Populations without adequate sanitation facilities are more susceptible to diseases and infections, especially after hazards	Scaled to 0 to 1	Jamshed et al. (2020a); Birkmann et al. (2021)
S3	% of establishments without access to electricity	Electricity is essential for carrying out basic household tasks and survival. Climate change affects the supply of electricity. The lack of access to energy makes the population more vulnerable	Scaled to 0 to 1	Gupta et al. (2020)
S4	% of establishments without access to irrigation	Irrigation is one of the essential means for any agricultural activity. The lack of irrigation combined with low rainfall can make soils unproductive and the population more vulnerable	Scaled to 0 to 1	Dos Santos et al. (2021) Nogueira et al. (2021) Dos Santos et al. (2022)
S5	Presence of fire	The practice of burning increases pollutant gas emissions, intensifying climate change and making the population more susceptible to respiratory diseases	Min–max normalization	Wolff et al. (2018). Birkmann et al.(2021)
S6	% of establishments without vehicles	Having agricultural production resources like vehicles allows for greater susceptibility to displacement and transport	Scaled to 0 to 1	Gupta et al. (2020)
S7	% of establishments where the farmers reside on the property	Farmers who reside in the establishment are more susceptible to environmental hazards, as they tend to be located in regions further away from the urban area	Scaled to 0 to 1	Dos Santos et al. (2021) Dos Santos et al. (2022)
S8	% of the establishments that produce only for their consumption	Farmers who produce only for self-consumption tend to be more susceptible because, in the event of a disaster, there is a possibility of a loss of production, consequently supplying domestic consumption	Scaled to 0 to 1	Dos Santos et al. (2021) Dos Santos et al. (2022)
S9	% of the establishments in which the responsible producer has income from agricultural activities higher than income from other activities	The significant dependence on the income generated in agricultural activity makes the population more susceptible. Any agricultural loss can make the people more vulnerable	Scaled to 0 to 1	Dos Santos et al. 2022
S10	% of establishments where the responsible producer is a woman	Women are more vulnerable to climate change due to limited access to information, resources, and decision-making	Scaled to 0 to 1	Cutter et al.(2003); Eastin (2018)
S11	% of establishments that are considered family farmers	Family farmers produce for self-subsistence and sell the surplus. They are highly dependent on agricultural income and therefore susceptible to adverse environmental damage to production	Scaled to 0 to 1	Dos Santos et al. 2021 Nogueira et al. (2021) Dos Santos et al. (2022)

Table 1 (continued)

	Indicators	Explanation	Transformation method	Literature
S12	Gross domestic product per capita—GDP per capita	Vulnerability increases with decreasing per capita income. Higher GDP per capita means more significant economic development and less susceptibility	Min–max normalization	Welle and Birkmann (2015); Wu et al. (2018);
S13	GINI index	Greater income inequality means greater vulnerability to climate hazards	Scaled to 0 to 1	Cutter et al. (2016); Birkmann et al. (2021)
	Coping Capacity			
CC1	% of establishments whose responsible farmer has received technical guidance	Access to technical assistance positively impacts strategies to face climate change. More excellent assistance, more coping capacity to handle events	Scaled to 0 to 1	Dos Santos et al. (2021) Nogueira et al. (2021) Dos Santos et al. (2022)
CC2	% of establishments whose responsible producer participates in some class association or unions	Participation in associations and cooperatives allows access to information and social interactions: the more information, the greater the individual's ability to deal with climate change	Scaled to 0 to 1	Dos Santos et al. (2021) Nogueira et al. (2021) Dos Santos et al. (2022)
CC3	Number of policies contracted by municipality	Insurance provides security against financial losses caused by weather events. Insured producers are less vulnerable	Min–max normalization	Welle and Birkmann (2015); Cutter et al. (2016)
CC4	% of establishments whose responsible producer is the owner of the establishment	Owning the property allows the producer to obtain financing and take out insurance and financial credit, making him less vulnerable	Scaled to 0 to 1	Dos Santos et al. 2021 Nogueira et al. 2021 Dos Santos et al. 2022
CC5	% of establishments that obtained funding	Financing is an economic resource that allows the producer to deal with the adverse events of climate change, making him less vulnerable	Scaled to 0 to 1	Welle and Birkmann (2015); Birkmann et al. (2021)
CC6	% of establishments whose responsible producer has other income from activities carried out outside the establishment	Income diversification allows the producer greater resilience and makes him more capable	Scaled to 0 to 1	Gupta et al. (2020) Dos Santos et al. (2021)
CC7	% of establishments whose responsible producer earns other income from activities carried out in the establishment	Being pluriactive in agricultural production means incomes from different agricultural activities. Thus, possible dangers will not make pluriactive producers more vulnerable	Scaled to 0 to 1	Gupta et al. (2020) Dos Santos et al. 2021
CC8	% of establishments with production storage units	Having agricultural production resources such as storage and storage allows for the availability of stored production in the period of agricultural scarcity	Scaled to 0 to 1	Gupta et al. (2020)
CC9	Human development Index	The human development of a population says a lot about its ability to face climate impacts. Greater human development, greater coping capacity	Scaled to 0 to 1	Welle and Birkmann (2015); Birkmann et al. (2021)
	Adaptative Capacity			

Table 1 (continued)

	Indicators	Explanation	Transformation method	Literature
AC1	% of establishments where the producer can at least read and write	Illiterate individuals may find it difficult to obtain information about climate change. Literate people can access health, finance, and opportunities to adapt to the climate	Scaled to 0 to 1	Welle and Birkmann (2015); Hoffman and Blecha (2020)
AC2	% of establishments whose spouse of the responsible producer can read and write	Farmers or their illiterate spouses may find it difficult to obtain information about climate change. Literate people can access health, finance, and opportunities to adapt to the climate	Scaled to 0 to 1	Jamshed et al. (2020a)
AC3	% of establishments where the producer has higher education	High levels of education allow for greater social mobility and the ability to adapt to climate threats	Scaled to 0 to 1	Almeida et al. (2016); Birkmann et al. (2021)
AC4	Municipality where the political representative is a woman	Female representation in the public office allows environmental policies to be implemented rigorously. Thus increasing adaptive capacity and minimizing vulnerability to climate change	Scaled to 0 to 1	Welle and Birkmann (2015); Richler (2019)
AC5	% of establishments with access to some of water resource	The presence and conservation of water resources increase adaptive capacity and minimize the population's vulnerability and natural habitats	Scaled to 0 to 1	Klein et al. (2014); Welle and Birkmann (2015)
AC6	% of establishments that practice at least one conservation practice	Sustainable agricultural management can provide opportunities to develop better climate adaptation	Scaled to 0 to 1	Webb et al. (2017); Welle and Birkmann (2015);
AC7	% of natural vegetation cover in the municipality	The absence of natural vegetation caused or not by deforestation induces climate change and increases vulnerability	Scaled to 0 to 1	Wolff et al. (2018); Birkmann et al.(2021)
AC8	% of establishments that use fertilizer	Using sustainable inputs allows sustainable agricultural development, generating wealth without degrading the environment	Scaled to 0 to 1	Webb et al. (2017); Birkmann et al. (2021)

The techniques used to calculate the vulnerability index were based on studies by Welle and Birkmann (2015). Welle and Birkmann (2015) addressed the concept of the world risk index (WRI) by assessing a society's vulnerability to being adversely affected by climate change and disasters (see Welle and Birkmann 2015). Welle and Birkmann (2015) introduced th instrument the World Risk Index (WRI) to assess country risk and vulnerability. The World Risk Index is composed of 28 indicators involving the sphere of exposure and the sphere of vulnerability and was calculated for 173 countries. In this study, in addition to the WRI vulnerability indicators, other indicators from the literature were considered. The selection of WRI indicators is based on the Millennium Development Goals and the Hyogo Framework for Action of the United Nations. The WRI raw data were extracted from several world banks and aggregated in each category (susceptibility, coping capacity and adaptive capacity), with their respective weights and converted into percentage values for better understanding. The indicators received the weights so that they were equally relevant in the final vulnerability calculation. The weighting was in accordance with the literature based on the judgment of technical experts. Although each indicator has different weights, the components (susceptibility, coping ability and adaptability) were equally weighted (Welle and Birkmann 2015; Birkmann et al. 2022).[3]

The susceptibility component estimates the probability of suffering damage. It encompasses issues related to infrastructure characteristics (S1 to S4), housing conditions (S5 to S7), nutritional and structural aspects of poverty and dependence (S8 to S11), and economic and income (S12 and S13). The susceptibility index was calculated using Eq. 1, according to Welle and Birkmann's (2015) weighting and procedures.

$$\begin{aligned}\text{Susceptibility}\,(S) =\, & (2/7 * (0.25 * (S1 + S2 + S3 + S4))) \\ & + (1/7 * (1/3 * (S5 + S6 + S7))) \\ & + (2/7 * (0.25 * (S8 + S9 + S10 + S11))) \\ & + (2/7 * (0.5 * (S12 + S13)))\end{aligned} \tag{1}$$

The coping capacity component indicates the ability of a population or individual to reduce the negative consequences of impacts, to characteristics linked to governance and communication (CC1 and CC2), insurance coverage (CC3 to CC5), and medical services and emergency strategies for climate risks (CC6 to CC9). The coping ability index was calculated using Eq. 2.

$$\begin{aligned}\text{Coping Capacity (CC)} \\ = & (0.45{*}(0.5{*}(CC1 + CC2))) \\ & + (0.1{*}(1/3{*}(CC3 + CC4 + CC5))) \\ & + (0.45{*}(0.25{*}(CC6 + CC7 + CC8 + CC9)))\end{aligned} \tag{2}$$

Adaptive capacity identifies long-term strategies for social change. This study corresponds to eight characteristics associated with education and research (AC1 and AC2), gender equity (AC3 and AC4), environmental protection (AC5 and AC6), and ecosystem protection (AC7 and AC8) (Eq. 3).

$$\begin{aligned}\text{Adaptative Capacity (AC)} \\ = & (0.25{*}(0.5{*}(AC1 + AC2))) \\ & + (0.25{*}(0.5{*}(AC3 + AC4))) \\ & + (0.25{*}(0.5{*}(AC5 + AC6))) \\ & + (0.25{*}(0.5{*}(AC7 + AC8)))\end{aligned} \tag{3}$$

The final vulnerability index of Brazilian municipalities with the contribution of each component was as Eq. 4:

$$\text{VI} = 1/3 * \{S + (1 - \text{CC}) + (1 - \text{AC})\} \tag{4}$$

The components of vulnerability correspond to the presence of susceptibility, absence of coping capacity, and absence of adaptative capacity, so in Eq. 4, the CC and AC components were subtracted from 1 (Welle and Birkmann 2015; Birkmann et al. 2022). The contribution of each indicator and vulnerability index was calculated per Brazilian municipality. The Choropleth map was generated with the R Software.

Location of vulnerability distribution

To analyze the characteristics of IV distribution in Brazilian municipalities, we used spatial autocorrelation using the Exploratory Spatial Data Analysis (ESDA) technique. The autocorrelation in this study is based on Moran's I, which designates a value score range from + 1 to −1, indicating the spatial pattern between neighboring regions and observations. According to Hoque et al. (2019), Moran's I score close to + 1 shows a strong pattern of similarity between high and low values, while – 1 reflects a strong pattern of dissimilarity, indicating a varied pattern of high and low values. However, the Local Indicators of Spatial Association (LISA) identifies four types of spatial clusters—(high-high), (high-low), (low–high), and (low-low)—at the local level. A high-high value indicates a region of high vulnerability values surrounded by other regions of high vulnerability values and is referred to as a 'hot spot'; while low-low values represent a region with low vulnerability scores bordered by less vulnerable regions and are referred to as 'cold spot' (Hoque et al. 2019). The high-low and low–high areas are those with

[3] Specific details can be found at: https://www.preventionweb.net/files/21709_worldriskreport2011.pdf.

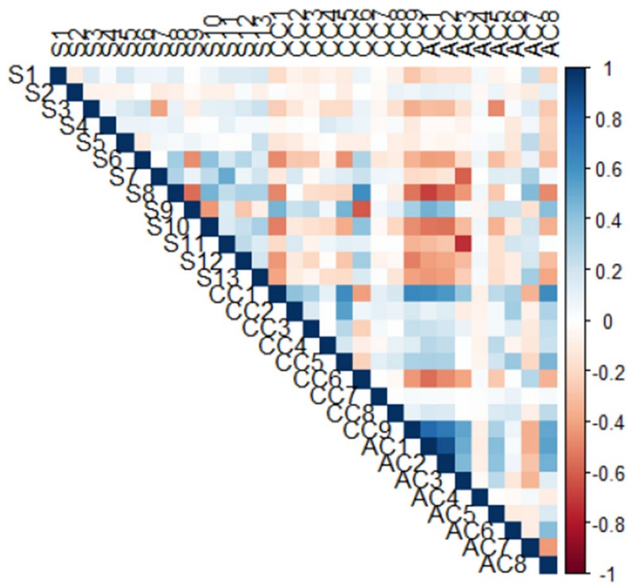


Fig. 1 Correlogram of our indicators. Source: Own elaboration. Notes: The red and blue squares correspond to negative and positive correlations, respectively. Light colors represent lower correlations, and darker colors correspond to higher correlations

extreme values, reflecting a negative spatial autocorrelation, and are called 'spatial outliers' (Hoque et al. 2019). Spatial autocorrelation analysis was performed using the GeoDa-1.20 software following the methodology of Hoque et al. (2019).

Validation of index

We discuss the validity of our index in several ways in this subsection. First, we employed a canonical correlation analysis to understand how each variable can predict the other – very high levels of correlation would indicate redundant indicators. Results in Fig. 1 showed that redundancy is not a concern. The higher positive correlation was 0.87 (AC1, AC2), and the higher negative correlation was -0.73 (AC3, S11). All other pairs present a very low correlation; the average correlation between our indicators is roughly 0.04.

Second, we used Cronbach's Alpha and Guttman's Lambda to test inherent consistency. Following Welle and Birkmann (2015), we procedure the reliability analysis using the correlation between the model output (our vulnerability index) and our 30 input indicators. Cronbach's Alpha was 0.88, and Guttman's Lambda was 0.91, indicating good inherent consistency. Third, we procedure the Kaiser–Meyer–Olkin (KMO) test for sampling adequacy to determine if our database is 0.86, meaning that our data is suitable for factorial analysis.

Data source and treatment

The data sources of the variables to obtain the components and to assess the vulnerability of agricultural establishments in Brazilian municipalities were: (i) database provided by the Terrestrial Hydrology Research Group (THRG) of Princeton University, following the procedures described (Sheffield et al. 2006) for the climatic variables; (ii) Agricultural Census 2017 by IBGE and the *Ministério da Agricultura, Pecuária e Abastecimento* (MAPA) to obtain the characteristics of the agricultural establishment, the responsible farmers and rural insurance; (iii) *Atlas Brasil* – INPE, for the heat source and vegetation cover variables; and (iv) IBGE to obtain the Gini Index and HDI.

The data obtained from the Census of Agriculture were used mainly to determine the variables that make up each vulnerability component. This census portrays the reality of Brazilian agricultural establishments, investigates agricultural activities, the characteristics of farmers, and the economy and employment in agriculture, agribusiness, and livestock in rural areas (IBGE, 2017). The 2017 Agricultural Census data are available in the IBGE Portal by the Sistema IBGE de Recuperação Automática (SIDRA) per municipality, aggregating agricultural establishments and preserving the identification of rural producers.

Agricultural establishments per Brazilian municipality are the units analyzed in this study. The maximum number of observations corresponds to 5,563 municipalities visited by the census takers of the Agricultural Census in 2017, with 5,073,324 agricultural establishments (IBGE, 2019). The reference period of the Agricultural Census was October 1, 2016, to September 30, 2017.

Results and discussion

Results: Descriptive analysis of climate change and indicators

To investigate the vulnerability to climate change of Brazilian agricultural establishments, the study initially presents an analysis of the main climate variables in Brazil in the period from 1949 to 2016. The period from 1949 to 2016 was chosen because it refers to the 68 years before the realization of the agricultural census survey and available data. To talk about climate change, it is necessary to consider the long-term pattern of climate variables (Nogueira et al. 2021; Dos Santos et al. 2021). The average annual temperatures (AGT), average summer temperature (December to February) (AST), and average Brazilian winter temperature (June to August) (AWT) were considered. In addition,

Table 2 Average (Av.), maximum (Max.), minimum (Min.) and deviation (Dev.) of the average general (AGT), summer (AST) and winter (AWT) temperatures and of the average general (AGP), summer (ASP) and winter (AWP) precipitation in the Brazilian municipalities. Source: Terrestrial Hydrology Research Group (THRG)

	AGT	AST	AWT	AGP	ASP	AWP
Av	$23.75^{2.82}$	$25.35^{1.75}$	$21.69^{4.06}$	$117.12^{35.91}$	$173.00^{72.50}$	$60.69^{56.45}$
Max	28.56	29.13	28.84	272.94	343.67	403.29
Min	15.1	18.62	11.56	33.00	35.69	0.48
Dev	−0.55	0.35	−0.63	− 4.46	14.38	−8.89

Superscript values are the standard error of the mean

mean annual precipitation (AGP), mean summer precipitation (ASP), and mean winter precipitation (AWP) were analyzed (Table 2).

The AST average was higher than the AWT average in all Brazilian municipalities. In addition, the AWT maximum was higher than the AGT maximum. Positive values of the 2016 average deviation from the historical average (1949–2016) show that this last year's average summer temperature was higher than the average of the 68 previous summers. The average monthly rainfall in the Brazilian municipalities was 117.12 mm, with higher values in the summer in most municipalities. The negative results of the deviations show precipitation was below the average in 2016 compared to the previous 68 years.

The statistical analysis of the 30 indicators considered in this study is presented (Table 3).

15% of the Brazilian population does not have access to the water supply network (S1), and about 26% do not benefit from sewage treatment (S2). Regarding agricultural establishments, about 15% do not have access to electricity (S3), and 89% do not use irrigation mechanisms (S4). Hotspots equivalent to 0.17 (S5) in Brazilian municipalities were found, mainly in Brazilian forests. 72% of agricultural establishments do not have vehicles on their properties (S6), 67% of farmers live in the farm area (S7), and 33% produce only for consumption at home (S8). Of the total agricultural establishments interviewed, 43% have agricultural income generated above non-agricultural income (S9). A small portion of 15% of the establishments is represented by women (S10), and most of the farmers (72%) are considered family farmers (S11). The average GDP per capita of the municipalities is equivalent to 20.02 (S12), with the Gini index represented by 0.494 (S13).

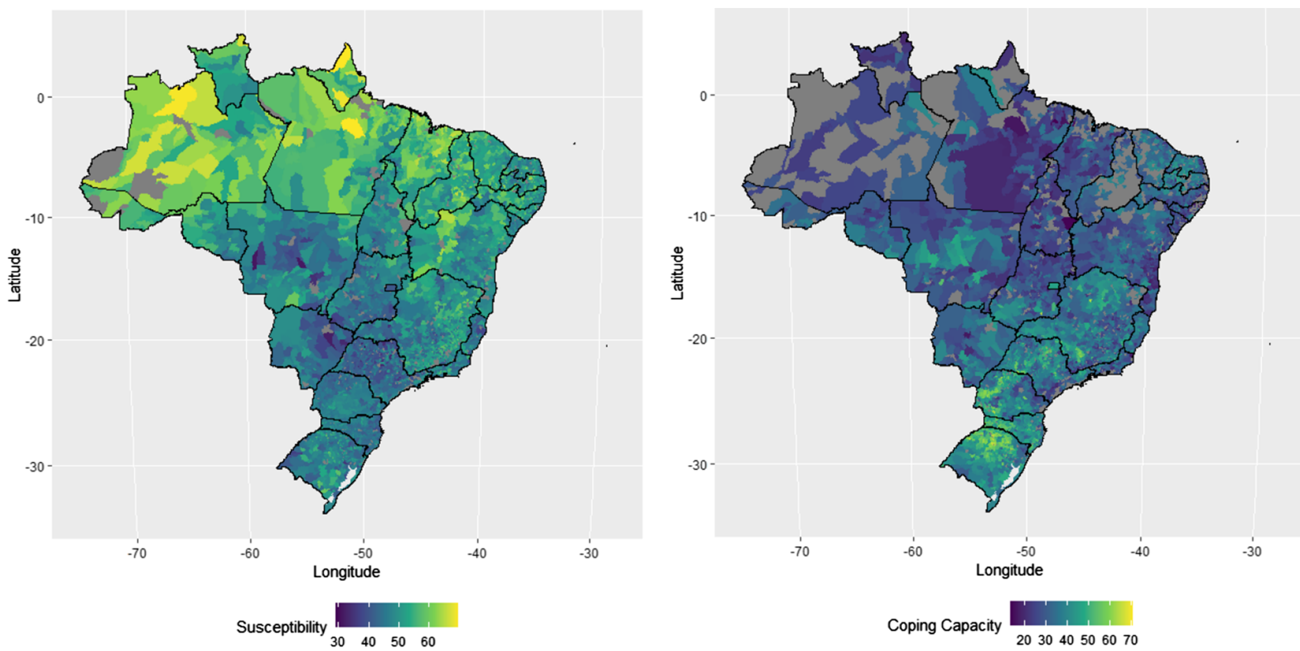
In terms of indicators referring to coping capacity (CC), only 28% of establishments receive technical assistance (CC1), and 38% are associated with some institution (CC2). The average number of rural insurance policy contracts per municipality is equivalent to only 13 (CC3), even though a large part of the farmers own their establishments, 81% (CC4), in addition, only 16% contracted financing (CC5). Fortunately, income diversification and pluriactivity are present in the establishments; 69% of farmers have income from other non-agricultural activities (CC6) and only 7.4% from other agricultural activities (CC7). However, a small portion of 6.8% of establishments has storage units (CC8). The HDI of Brazilian municipalities is equivalent to 0.659 (CC9).

For the adaptative capacity, most farmers know how to read and write, 82% (AC1), as well as their spouses, 86% (AC2); however, only 8.6% have higher education (AC3). In Brazil, in 2017, only 11% of municipalities were politically represented by women (AC4). 83% of establishments have access to water resources (AC5), and only 54% perform some conservation practice (AC6). The natural vegetation cover of the municipalities is equivalent to 38%, on average (AC7), and about 47% of agricultural establishments carry out some fertilization (AC8).

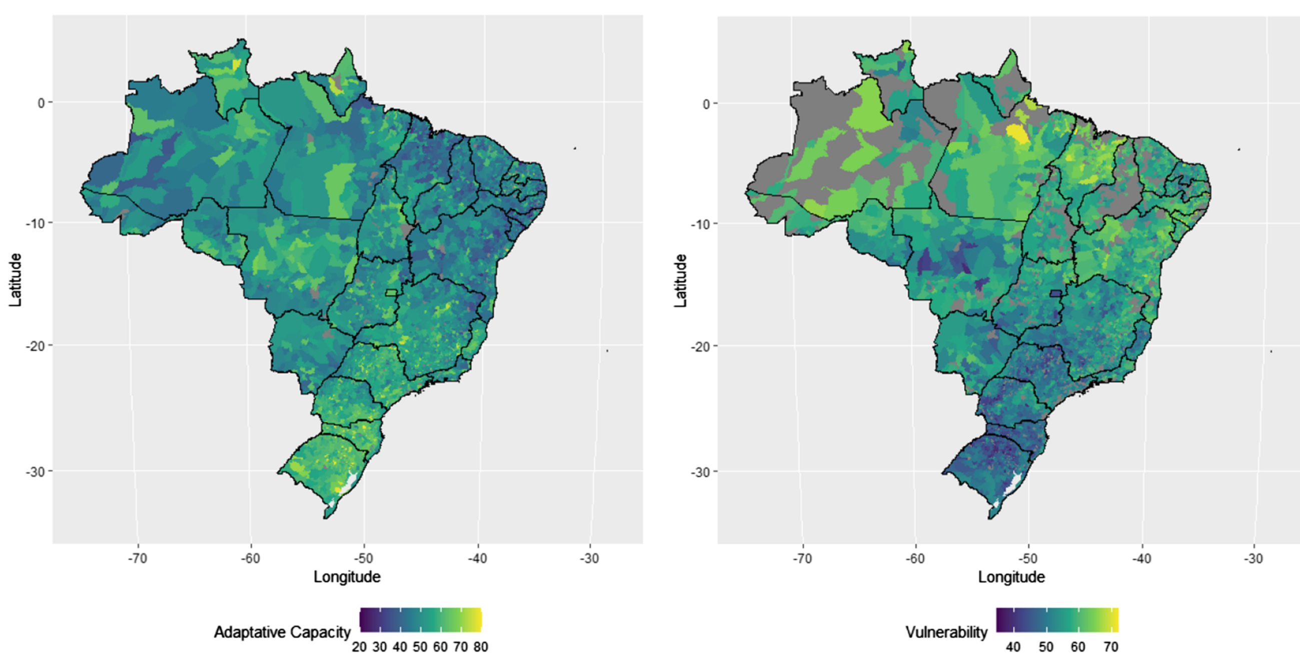
Table 3 Statistical analysis of selected indicators. Source: Own elaboration with IBGE/INPE/MAPA data

Indicator	Average	Indicator	Average	Indicator	Average
S1	15% (0.30)	S11	72% (0.14)	CC8	6.8% (0.10)
S2	26% (0.43)	S12	20.02 (13.4)	CC9	0.659(0.07)
S3	15% (0.14)	S13	0.494 (0.66)	AC1	82% (0.16)
S4	89% (0.13)	CC1	28% (0.23)	AC2	86% (0.13)
S5	0.17 (0.87)	CC2	38% (0.21)	AC3	8.6% (0.07)
S6	72% (0.17)	CC3	13.2 (49.9)	AC4	11% (0.15)
S7	67% (0.17)	CC4	81% (0.15)	AC5	83% (0.15)
S8	33% (0.30)	CC5	16% (0.12)	AC6	54% (0.25)
S9	43% (0.21)	CC6	69% (0.17)	AC7	38% (0.27)
S10	15% (0.07)	CC7	7.4% (0.08)	AC8	47% (0.28)

Values in parentheses are the standard error of the mean



a Susceptibility and Coping Capacity levels of the Brazilian municipalities



b Adaptative Capacity level and Vulnerability Index of the Brazilian municipalities

Fig. 2 **a** Susceptibility and Coping Capacity levels of the Brazilian municipalities **b** Adaptative Capacity level and Vulnerability Index of the Brazilian municipalities Note: Gray areas refer to missing data. Source: Own elaboration

Assessment of components and vulnerability

The vulnerability level components and the classification of the final vulnerability of the municipalities were calculated (Fig. 2a and Fig. 2b).

The average susceptibility level of the Brazilian municipalities was 48%, with the highest and lowest values in Oiapoque Amapá State (69%) and Sebastianápolis do Sul, São Paulo State (29%). These values were higher and lower

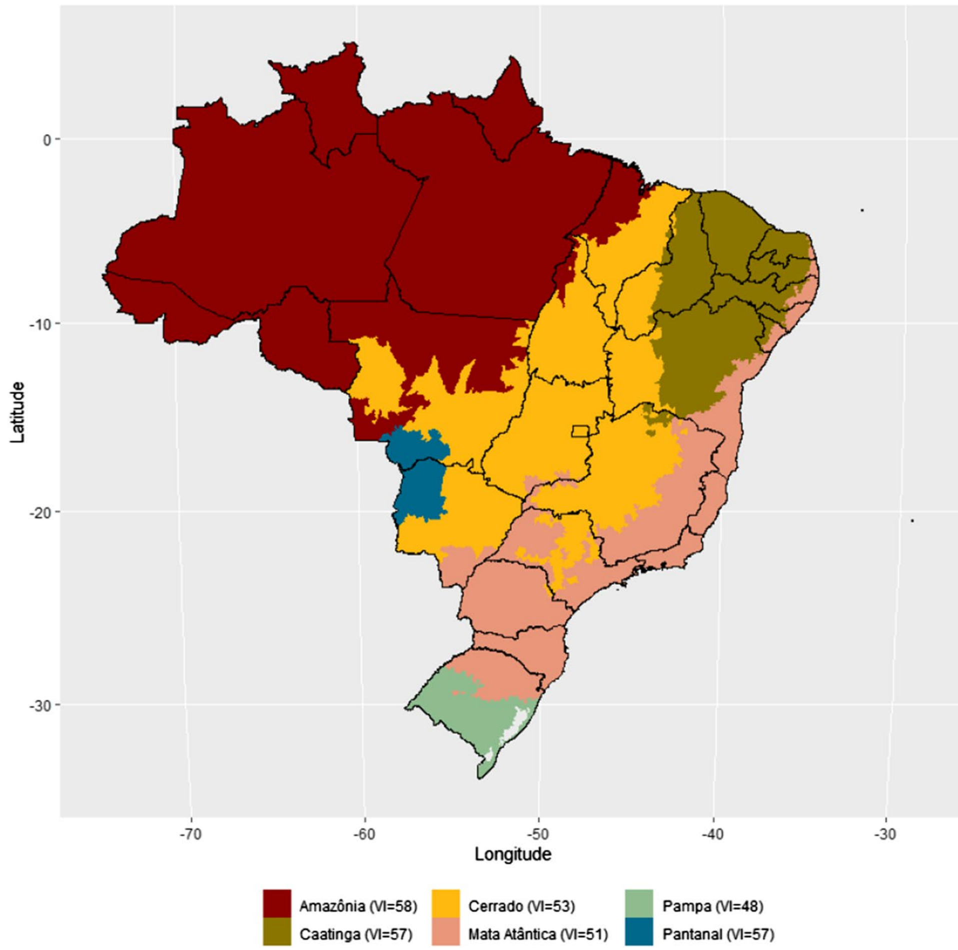


Fig. 3 Localization and Vulnerability Index (VI) of the Brazilian Biomes. Source: Own elaboration

for the North and Midwest regions of Brazil, respectively, to climate change, with an average susceptibility component of 53% and 45%, respectively. The average value of the coping capacity component for the Brazilian municipalities was 35%, with Vista Gaúcha municipality in the state of Rio Grande do Sul and the South region with the highest coping capacity. The average adaptive capacity was 51%, with the highest value in the Sinimbu, Rio Grande do Sul State (80%) and the lowest in Cuité de Mamanguape, Paraíba State (15%) muncipalities and the Northeast (45%) and the highest in the South (59%) regions.

The average vulnerability index (VI) was 53%, with the highest value in Centro do Guilherme, Maranhão State (72%) and the lowest in Presidente Castelo Branco, Paraná State (34%) and with 58%, 58%, 54%, 51% and 47% in the North, Northeast, Midwest, Southeast and South regions.

The vulnerability index values for the Amazônia, Pantanal, Caatinga, Cerrado, Mata Atlântica, and Pampa biomes were, respectively, 58%, 57%, 57%, 53%, 51%, and 48% (Fig. 3).

Indicators that affect the vulnerability of Brazilian municipalities

The relationship between the selected indicators and vulnerability is presented below (Table 4) through Pearson's correlation.

The results showed a significant correlation between all indicators and vulnerability. In the indicators that make up the susceptibility, all had the expected signs, being positively correlated and the GDP per capita variable (S12) negatively correlated. The highest correlation coefficient found in susceptibility was the *% of establishments without vehicles* (S6), in the coping capacity, the *% of establishments whose responsible producer received technical guidance* (CC1), and in the adaptive capacity, the *% of establishments that use fertilizer* (AC8).

The relationship between climate change and the vulnerability of agricultural establishments

To verify the relationship between climate change and the vulnerability of agricultural establishments, Pearson's

Table 4 Correlation between vulnerability and indicators of susceptibility, coping capacity and adaptive capacity in the Brazilian municipalities Source: Own elaboration

Indicator	Coefficient	Indicator	Coefficient	Indicator	Coefficient
S1	0.2884*	S11	0.2305*	CC8	-0.2734*
S2	0.0760*	S12	−0.4418*	CC9	-0.6729*
S3	0.3483*	S13	0.4427*	AC1	-0.6599*
S4	0.1295*	CC1	−0.8300*	AC2	-0.6451*
S5	0.1613*	CC2	−0.5442*	AC3	-0.3608*
S6	0.5136*	CC3	−0.2774*	AC4	-0.1251*
S7	0.0411*	CC4	−0.1721*	AC5	-0.3639*
S8	0.4658*	CC5	−0.6093*	AC6	-0.4471*
S9	0.3872*	CC6	−0.2888*	AC7	-0.2420*
S10	0.5035*	CC7	−0.1555*	AC8	-0.6923*

correlation analysis was performed between vulnerability and its components of the main climatic variables (Table 5).

The results showed a significant correlation between all climate variables and vulnerability and its components. Regarding the variables related to temperature, the relationship with the susceptibility component was positive, with the highest value for winter temperature (AWT) (0.419). However, this relationship becomes negative for coping and adaptative capacity components. The highest value was for winter temperature (AWT) (−0.517) in CC and average temperature (AGT) (-0.536) in AC. However, regarding the precipitation variable, the results are the opposite. The susceptibility component showed a negative relationship with all precipitation variables. CC and AC were positively correlated with these variables, except for summer precipitation (ASP), which negatively correlated with coping ability. The correlation between vulnerability and all temperature variables was significant and positive. And for precipitation, it is significant and negative. The variables with the highest correlation coefficient on vulnerability were mean temperature (AGT) (0.597) and mean summer temperature (AST) (0.427).

Spatial analysis of vulnerability

Figure 4 presents the results regarding the local spatial analysis; the Moran scatter plot provided a high Moran I score of 0.729 of the VI. This value indicates that the vulnerability distribution pattern in the study area exhibited evident clustering, exhibiting a strong positive correlation.

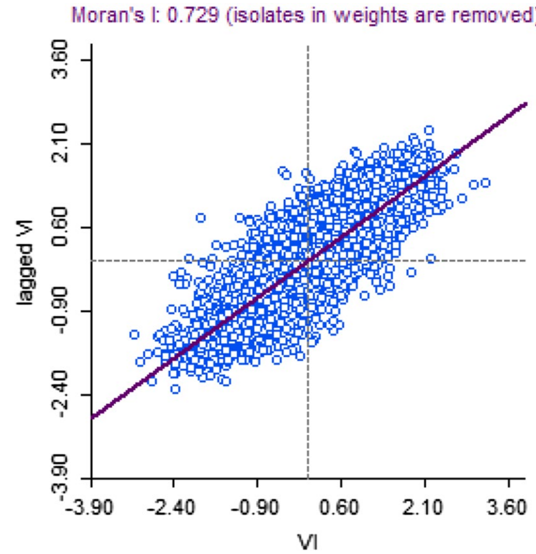


Fig. 4 Spatial analysis showing the pattern of vulnerability distribution across the study area: Moran scatter plot of the VI values

Figure 5 presents the LISA cluster map and significance. The results indicated that there are significant autocorrelations predominant in the high-high and low-low clusters. And a few municipalities are found in high-low and low–high clusters. The distribution shows that the values of the high-high clusters are concentrated in the North and Northeast regions, which were classified with greater vulnerability. However, the values of the low-low clusters were concentrated in the southern region of Brazil. The significance map indicates a strong positive correlation, which means that the vulnerability values of the municipalities are positively related to the vulnerability values of neighboring municipalities.

Discussion

The climatic characteristics in the period indicate that agricultural producers face rainfall deficits and increasing temperature, especially in vulnerable regions. Reduced

Table 5 Correlation between climate variables and vulnerability in the Brazilian municipalities. Source: Own elaboration

	AGT	AST	AWT	AGP	ASP	AWP
Susceptibility	0.404*	0.354*	0.419*	−0.065*	−0.180*	-0.037*
Coping Capacity	−0.457*	−0.237*	−0.517*	0.165*	−0.027**	0.251*
Adaptative Capacity	−0.536*	−0.463*	−0.533*	0.347*	0.252*	0.179*
Vulnerability	0.597*	0.427*	0.361*	−0.307*	−0.162*	−0.231*

Note:*0.01 *p*-value.

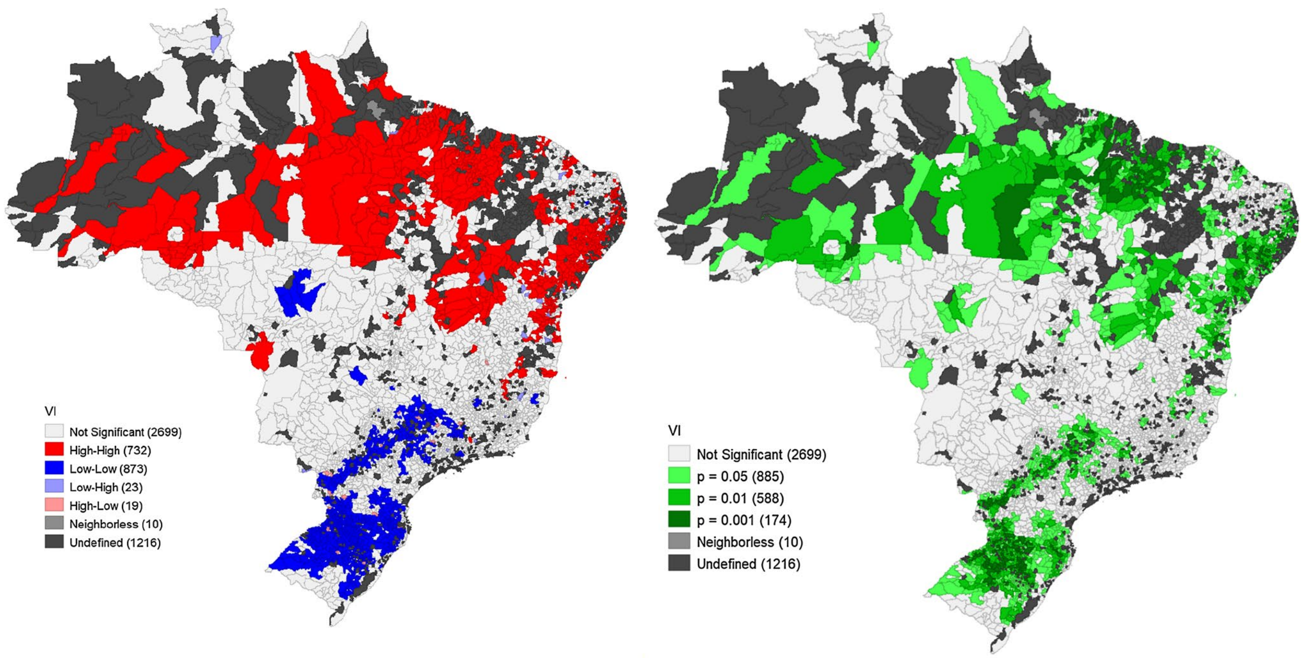


Fig. 5 Spatial analysis showing the pattern of vulnerability distribution across the study area: Left: LISA cluster map; Right: LISA significance map. The red and blue color areas in map indicate 'hot spots' and 'cold spots' of vulnerability distribution, respectively

annual precipitation patterns and rising rainfall extremes impact agricultural production. In Brazil, rains are heavier in the summer with scarcity or excess precipitation periods, intensifying the vulnerability. Moderate events are more frequent and primarily cause socioeconomic losses (Mahmoud 2020). The vulnerability in North Africa was highest in periods of increased temperature and reduced precipitation (Schilling et al. 2020).

Most owners of agricultural establishments in Brazil live in rural residences with total dependence on agricultural activity. Diversifying this activity has increased the total income of family farmers (Simonetti et al. 2013) with great relevance to the environmental agricultural economy and conservation practices (Fortini et al. 2020). In addition, adequate sociodemographic characteristics minimize the negative impacts of climate change. Many farmers own the establishments, guaranteeing access to loans and agricultural insurance (Cunha et al. 2015), even with high costs (Hoeppe 2016). Technical guidance facilitates access to mechanisms and income diversification, especially for farmers and municipalities with lower levels of education. Technical guidance and participation in class associations are mitigation mechanisms (Dos Santos et al. 2021). The scarcity of technical assistance is one of the main weaknesses, as it reduces the adaptation process in regions with less development and greater vulnerability (PBMC 2013; Eiró and Lindoso 2014; Dos Santos et al. 2021).

Susceptibility, one of the main dimensions of vulnerability, indicates that Brazilian municipalities are more susceptible to temperature when the increase makes the population more vulnerable. However, one of the problems is still due to the low precipitation shortage in the winter period and excessive precipitation in the summers. Many establishments are more susceptible during these periods. The reduction in the number of hotspots and the increase in areas with irrigation reduce the farmer's susceptibility to climate change. Fires, lack of rain, and droughts increase the imbalance and fires, harming producers even in irrigated areas. Access to rural insurance programs and finance can reduce risks and increase adaptation to climate change (Carrer et al. 2021). The lower susceptibility of farmers to climate risks improves economic production stability and continuity (MAPA, 2020a).

The use of rural insurance, one of the indicators of coping capacity, depends on the availability and continuity of programs with government subsidies, in addition to the producer characteristics and risk perception from extreme weather events, insurance premiums, and agricultural productivity (Medeiros 2013; Arshad et al. 2016; Jorgensen et al. 2020; Carrer et al. 2021). The adoption of rural insurance in Brazil has expanded, although with unequal coverage, from 0.1% in 2005 to 15% in 2017, with 21.6 and 193 thousand policies in 2006 and 2020, respectively (Souza and Assunção, 2020; MAPA, 2020b). However, rural insurance programs are not homogeneous in the whole country, with only 41.5% of Brazilian municipalities having agricultural insurance contracts in 2018 (Souza and Assunção, 2020, Carrer et al. 2021). Furthermore, uncertainties regarding climate change affect these and other adaptation measures (Cunha et al. 2015).

The final indicators show the North region as the most susceptible to the climate, a worrying scenario since this region is home to the largest Brazilian forest. During the twentieth century, Brazil had the largest and most extensive temperature increases, especially in the North and Midwest, the most critical areas and with the most significant thermal sensations (IPCC WG2 2014; BRASIL 2016). Susceptibility in the Northeast region was higher in the Bahia state (Dos Santos et al. 2021) and the semiarid regions of Brazil (Lindoso et al. 2014), including rural and urban regions, especially the poorest (Inostroza et al. 2016). Climatic variability alters production, especially in tropical and semi-tropical latitudes (IPCC 2018; dos Santos et al. 2021), making them more susceptible. The high susceptibility scenario shows that many Brazilian municipalities need external help to minimize their vulnerability. The northern region is the most susceptible among Brazilian ones, partly due to the high numbers of heat spots and dependence on irrigation for agricultural production (INPE, 2020). These values were higher than those in Sudan, which increased hunger therein (Mohmmed et al. 2018). Vulnerability to climate change causes food insecurity (FAO, 2018; Onyutha 2018) and raises concern in Brazil, an important agricultural country for domestic and global food supply.

Insufficient or inefficient adaptive capacity can increase vulnerability to climate change (Obermaier 2013; Nogueira et al. 2021). Low coping capacity makes agricultural establishments vulnerable to any unexpected risk. However, the high value of the adaptive capacity component in many Brazilian municipalities is beneficial because it minimizes the effect of climate change and, in some cases, greenhouse gas emissions. Adaptive capacity in Alaska ranged from 51 to 75% (Williams et al. 2019), greater than 50% of Bahia state in the Northeast region and 36% in the semiarid area of Brazil (Lindoso et al. 2014; Dos Santos et al. 2021). This confirms that the Northeast region has the lowest adaptive capacity, increasing concern about environmental changes, as a significant portion of its rural population lives below the poverty line (Bastos et al. 2019).

The medium or high vulnerability index in most Brazilian municipalities is due, in part, to their high susceptibility values and low coping capacity. Disruptions in the socio-economic system increase the vulnerability of populations and the ability to deal with the adverse effects of climate change (IPCC 2014; Dardonville et al. 2021). The average vulnerability in Iran's Hamadan province ranged from 41 to 59%, and on the coast of Vietnam, from 18 to 81% (Huynh and Stringer 2018; Jamshidi et al. 2019). The results found in this research are similar to those of the Amazonian region (Menezes et al. 2018), the semiarid region (Lindoso et al. 2014) and Bahia state (Dos Santos et al. 2021) in Brazil. The Pantanal biome, one of the most vulnerable, 2020 lost 23% of its area due to burning practices, an increase of 380% compared to the previous year (INPE, 2021). The role of Brazil is due to the extension of its forest cover, with a great contribution to climate mitigation by reducing its deforestation and recovering forest biomes (Pinto and Voivodic 2021). The Mata Atlântica biome is home to 70% of the Brazilian population, responsible for 80% of the economy and most of food production (Pinto and Voivodic 2021).

The direct relationships between the indicators considered and vulnerability agree with the vulnerability theory to climate change (Chinwendu et al. 2017; Jamshidi et al. 2019; Dos Santos et al. 2021). Increasing the development of municipalities and fighting inequality is paramount to minimizing environmental vulnerability. (Schilling et al. 2020). Less unequal populations had better life quality and lower vulnerability to climate change. Inadequate education, poverty, inequality, and poor health were strongly correlated with vulnerability to climate change (Senbeta and Olsson; 2009; Mbakahya and Ndiema 2015; Chinwendu et al. 2017).

Planning policies and programs to combat climate change must consider reducing inequality and increasing the development of municipalities, as high susceptibility was the leading cause of their vulnerability. Variables that increase adaptive capacity and coping capacity can minimize the impacts of climate change. Therefore, policymakers must prioritize issues related to the development of municipalities and improving their living conditions.

Conclusion

This study's objective was to assess Brazilian agricultural establishments' vulnerability to climate change and identify indicators that affect it. The susceptibility component was higher in the municipalities of the North region. The highest values of the components of coping capacity and adaptive capacity were in the South region. Low adaptive capacity is a concern, especially in the Northeast region with higher poverty levels.

The three components classified the North and Northeast regions as the most vulnerable to climate change, mainly due to their high susceptibility and low coping capacity. The climatic variables confirm that high temperatures and extreme precipitation tend to increase the vulnerability of agricultural establishments. Thus, the study highlights the importance of rural development in reducing susceptibility. Increasing coping capacity through technical assistance, essential health services, and ease of contracting rural insurance can be favorable to agricultural establishments. In the long term, adaptation measures can minimize the adverse effects of climate change, conserving Brazilian forests and biomes.

The selected indicators and the final vulnerability result inform priority areas to reduce susceptibility and increase the capacity of Brazilian farmers to face and adapt. Including the coping capacity component in the vulnerability index becomes innovative and relevant to current literature, contributing to identifying determinants capable of mitigating vulnerability in the short term. Thus, the inclusion of new indicators in future studies is perfectly replicable, as regions and communities can be influenced by similar indicators.

However, although the approach involving vulnerability indices is widely accepted in the literature, some limitations are worth noting: Given that the indicators need more up-to-date and equated data for the same period, recent approaches are limited. In Brazil, the last agricultural census took place in 2017, and this survey is carried out every ten years, which makes annual and comparative studies unfeasible. The agricultural census results refer to the level of establishments, approaches at the farmer's level would be more interesting, as personal information could be included. The methodology adopted in this research can be improved using statistical models, advanced spatial analysis, and allocating different weights.

The focus of this research was the agricultural establishments and the climate changes that occurred; more in-depth analysis is needed to confirm the dynamics of vulnerability and climate. A detailed study can be carried out in the future to understand how the occurrence of extreme events in the country could impact agricultural establishments and their vulnerabilities.

Author contributions EAS. wrote the draft of this manuscript. EAS., RMF. and LCBC. proposed the idea, supervised the whole work and contributed to the manuscript preparation. EAS. and RMF performed a statistical analysis. JCZ. and LCBC. discussed the results and contributed to the manuscript final preparation. All authors reviewed the final manuscript.

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Declarations

Conflict of Interest The authors declare no conflicts of interest.

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