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Exploring drought risk scenarios for bioenergy systems for adaptation to climate change in the Upper Tocantins basin, Brazil

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ABSTRACT

The generation of electricity from sugarcane bagasse plays an important role in Brazil's energy mix, particularly in complementing hydropower during the dry season and in mitigating the impacts of climate change. However, sugarcane is facing increasing challenges due to the occurrence of droughts. This study assesses drought risk of sugarcane, with a particular focus on its role in bagasse-based electricity generation. The IPCC AR5 Risk Assessment Framework was employed to evaluate two global climate change models, two representative concentration pathways (RCPs), and three land use scenarios. The present study employs a dynamic approach to analyse the interconnectivity of risk components, thereby contributing to the development of a methodology to compare risk scenarios considering changes in the system. Spatial analyses of hazard, exposure, and vulnerability were conducted, revealing dynamic risk across nine scenarios. This highlights the necessity of understanding the interconnectivity for a comprehensive risk analysis and the implementation of effective measures to mitigate risk. The findings emphasise the necessity of tailored risk management strategies to effectively address drought risks, focusing on the planning of sugarcane expansion and, more specifically, on the reduction of vulnerability. The results indicate that the reduction of vulnerability is dependent on the implementation of early warning systems, which serve as a crucial mechanism for the timely dissemination of drought information. Furthermore, access to water reservoirs (e.g. dams) and the implementation of efficient irrigation systems play a pivotal role in enhancing resilience and reduce further vulnerability within the sector. The analysis facilitates the identification of the strengths and the weaknesses of the systems for the implementation of targeted mitigation measures. These measures are intended to strengthen the sector's resilience and sustainability, aligning with national objectives.

1. Introduction

The transition to renewable energy plays a crucial role in mitigating climate change. However, this shift introduces new challenges, particularly in understanding and managing climate-related risks to the energy system. As climate variability and extreme weather events become more frequent, analysing whether the electricity system is susceptible to extreme events, identifying the type of hazards that may impact it, and determining the vulnerabilities linked to the system is increasingly critical (Brás et al., 2023; Gonçalves et al., 2024; Waseem and Manshadi, 2020).

Drought events are of particular relevance to renewable energy generation (Brás et al., 2023; World Economic Forum, 2023) as they can impact the cooling systems (Byers et al., 2020; ReRisk - Regions at Risk of Energy Poverty, 2009), water availability for solar panel cleaning, increase dust accumulation affecting the efficiency of PV panels (Gupta et al., 2019; Atirah et al., 2021), reduce water availability for irrigation, ground water availability, water levels in dams, and crop yield (Cronin et al., 2018; Kumler et al., 2025). During periods of drought, the allocation of water resources is typically prioritised for essential uses such as drinking, domestic consumption, irrigation, and more recently, ecological flow requirements (L'Organisation de Coopération et de Développement Économiques, 2015; Nelson, 2022; Tezcan et al., 2022). It is therefore of significant importance to conduct a comprehensive assessment of the risks associated with drought, particularly in relation to the impact on hydropower energy generation and the renewable energy sources that can complement it.

Climate-related risk analysis of energy systems is not a new or recent

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endeavour, Troccoli et al. (2010) highlighted the necessity of evaluating the energy systems in the context of climate change scenarios to ensure energy security. Studies have highlighted the importance of conducting regionally detailed assessments of energy systems in order to effectively manage the complex relationship between energy transformation and the impacts of climate change This evaluation should encompass consideration of socio-economic dynamics and cross-sectoral linkages, whilst exploring the implications of climate subject to greater variability (Aall et al., 2022; Cai et al., 2012; Di Maio et al., 2022; Doukas et al., 2019; Emodi et al., 2019; Lammers et al., 2020).

The currently available models, frameworks, and methodologies for climate-risk-informed decision-making are not easily applicable by governmental institutions and are challenging to implement, particularly in adapting energy systems to climate change. This adaptation is a common concern for many governments worldwide, as numerous countries have incorporated the need to adapt their energy systems into their policies and governmental instruments. The Intergovernmental Panel on Climate Change (IPCC) risk framework presented in the Fifth Assessment Report (Field et al., 2015) encompasses hazard, exposure, and vulnerability analysis. Considering these three components is crucial for the adaptation of energy systems to climate change including not only the technical part, but also the environmental and social aspects. This paper applies the IPCC risk framework to the analysis of the bioenergy system in Brazil under different climate scenarios, following a methodology similar to that presented in Campos Zeballos et al. (2022).

Brazil's National Adaptation Plan, 2016 (NAP) acknowledges the necessity of enhancing the energy sector to cope with the impacts of climate change (Ministry of Enviroment, 2016). Brazil primarily relies on hydroelectric power for electricity, with other renewable energy sources and fossil fuels supplementing the power grid. Seasonal variations in weather conditions affect power generation from renewable sources, necessitating complementarity between them. For example, during dry months with lower river flows, biomass electricity generation, particularly from sugarcane, becomes more productive (World Wide Fund for Nature, 2012). Brazilian sugarcane mills are self-sufficient in electricity thanks to an integrated system which generates electricity from sugarcane. The process involves collecting and crushing sugarcane to produce juice for sugar and ethanol. The fibrous byproduct, known as bagasse, is combusted in boilers to generate steam which drives turbines, producing electricity. This electricity was initially used to meet the mills' internal energy demands, but the opening of the energy market have since enabled surplus electricity to be supplied to the national grid (Fioranelli and Bizzo, 2023). Currently, biomass generation contributes 8% of Brazil's total electricity production (Empresa de Pesquisa Energética, 2023). As the Brazilian energy system is moving towards the inclusion of different renewable energy sources in its matrix, it is important to comprehend the risks that emerging energy sources will introduce to the matrix. The proposed methodology was applied to the sugarcane bagasse industry, which has great potential to complement hydropower, the country's main source of energy. To fully understand how sugarcane bagasse-based electricity can be affected, hazards based on climate change scenarios, increasing, or changing exposure, and socio-economic-technological vulnerability were considered thoroughly in a total of nine scenarios. This paper aims to answer how climate change scenarios, changes in exposure, and socio-economic-technological vulnerability affect the risks and strengths of the sugarcane-bagasse-based energy system.

This paper is structured as follows: The paper commences with an overview of the location of the case study and details of the methodology applied. The methodology is presented according to hazard, exposure and vulnerability criteria. The subsequent section presents a detailed account of the risk scenarios, followed by an analysis of the components of the risk assessment scenarios. This is then followed by a presentation of the results of the aforementioned components and risk scenarios. Finally, the discussion and conclusions are presented.

2. Materials and methods

2.1. Location

Sugarcane in Brazil is mostly cultivated in the North-Northeast and Centre-South regions. It is expanding mainly in the Cerrado biome (Arruda et al., 2017), particularly in the states of Goiás, Paraná and Minas Gerais (Arruda et al., 2017; Rodrigues and Ross, 2020); therefore, the region must act quickly to adapt the system. In this sense, our analysis will focus on this region, particularly in Goiás State which is located in central Brazil (Fig. 1).

The study narrowed down its focus to the region encompassing the Rio das Almas and Rio Maranhão watersheds. In particular, the main sub-basin being analysed is the Rio dos Patos, where the vast majority of sugarcane is grown and the primary sugarcane mill in the area operates. The area is located in the heart of the Cerrado biome, known for the continuous growth of the sugarcane sector (Arruda et al., 2017).

2.2. Risk assessment methodology adaptation and components

The IPCC defines risk as the potential negative impact on human or ecological systems. In the context of climate change, risk can be understood as the potential for adverse consequences resulting from both the phenomenon of climate change itself and human responses to it. Risk is analysed based on the interaction between the hazard, exposure and vulnerability (Field et al., 2015).

The framework was applied to a sugarcane-bagasse-based electricity generation system consisting of two main sub-systems, the agricultural and the industrial (Fig. 2). The agricultural subsystem is influenced by climatological characteristics, water availability and soil characteristics. The harvested sugarcane is transported to the industrial subsystem, which requires a minimum amount of water to process the cane. It is therefore influenced by the availability of water in the basin. Sugar, ethanol, and other products are produced and then transported to national and international markets. The electricity produced can be exported to the Brazilian national grid.

Following the methodology proposed by Campos Zeballos et al. (2022), the indicators to assess the drought risk components were selected in consultation with experts in the sugarcane sector and aim to assess the relevant characteristics of the socio-ecological agricultural subsystem and the eco-technological characteristics of the industrial subsystem. In the following sections, details on each component can be found.

2.2.1. Hazard

The drought hazard associated with sugarcane bagasse-based electricity in the agricultural subsystem was analysed based on total precipitation and distribution, temperature, river flow, crop yield and agricultural planning (Campos Zeballos et al., 2022). Each of these groups was assessed using indicators as shown in the figure below (Fig. 3). These characteristics and indicators were selected for their relevance to the growth of sugarcane. The beginning and end of the precipitation season have a direct impact on the planning of sugarcane plantations and harvesting. The total precipitation and its distribution during the season directly affect the crop yield, as do high temperatures. Preserving ecological flow is crucial for the environment, as both sugarcane systems require water for irrigation and processing.

The weights were determined based on expert opinion already incorporated in Campos Zeballos et al. (2022). During fieldwork, experts were consulted and their opinions served to inform the weights applied to the indicators. Embrapa experts were able to review the values and proposed changes based on their experience in the field.

River flow and crop yield were modelled under the climatological and land use scenarios using the SWAT hydrological model. The model was calibrated and validated using the SWAT CUP. Available daily streamflow data were found for four points and ranged between 2007

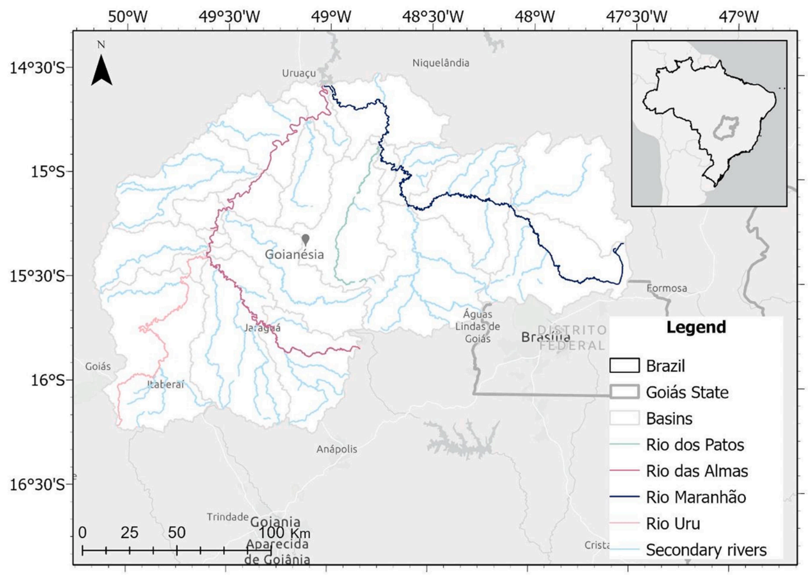

Fig. 1. Study area location. Main rivers depicted in pink, purple and dark blue. Secondary rivers in light blue. Databases sources: Administrative boundaries (DIVA-GIS, 2015), main rivers (Sistema Estadual de Geoinformação, 2014).

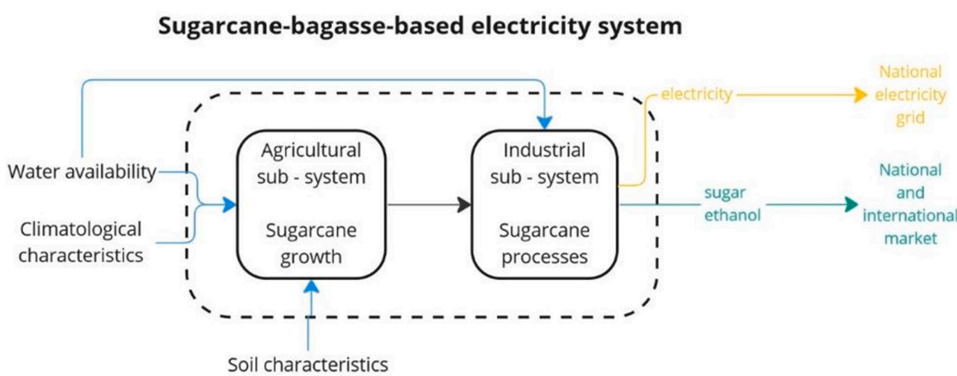

Fig. 2. Sugarcane-bagasse-based electricity generation system graphic description. The system under analysis is comprised of two subsystems, which are represented by black boxes. The inputs to the system are indicated by the blue line, while the electricity and other products output are represented by yellow and green, respectively.

and 2016. Crop yield data were available for the region for the years 2000 to 2015.

The industrial hazard was analysed based on the availability of water for industrial purposes without compromising the ecological flow. The overall annual hazard is the most severe hazard value, whether agricultural or industrial, observed in a given year within the basins under consideration. For instance, if the agricultural drought event is characterised by a numeric value of 0.4, while the industrial hazard is identified as 0.6, the overall hazard value is set at 0.6.

The results were analysed by precipitation and temperature station, catchment and sugarcane land use, and interpolated to produce spatially explicit results.

2.2.1.1. Hazard thresholds and frequency. According to the analysis and results by Campos Zeballos et al. (2022), thresholds to identify drought events can be established for the system. The years 2007 and 2010 experienced the strongest droughts, with 2007 being the most severe. In this year, the agricultural hazard was 0.61 and the industrial hazard was 1. During the drought event between 2010 and 2012, the agricultural hazard was 0.42 and the industrial hazard was 1. This paper considers that for the agricultural hazard, 0.42 is a point at which drought becomes a concern, and 0.61 is an extreme drought in the agricultural sub-system. On the other hand, we considered that for the industrial sub-system, a drought event with a severity of 0.85 should be considered concerning and a severity higher than 0.9 should be considered an extreme drought event.

The drought frequency was based on the average return interval. The lowest value between the agricultural and industrial frequency of droughts was employed as the hazard frequency for the basin under consideration. For example, if the frequency of droughts in the agricultural system was every four years and in the industrial system was every three years, the overall frequency of droughts in the system would be three years. Furthermore, an evaluation was conducted of the duration of consecutive extremely drought events.

2.2.1.2. Climate change projections. The hazard analysis methodology was applied to two climatological models and two Representative Concentration Pathways (RCPs) (MIROC5 and HadGEM2 under RCP2.6 and RCP 4.5). These models were selected based on the project Wandel's criteria, which focused on downscaled projections for further analysis of climate change impacts on energy systems. In the case of Brazil it was the RCP4.5 by the Earth System Science Center (CCST in Portuguese), National Institute for Space Research (INPE in Portuguese) (Centro de Ciência do Sistema Terrestre, 2016).

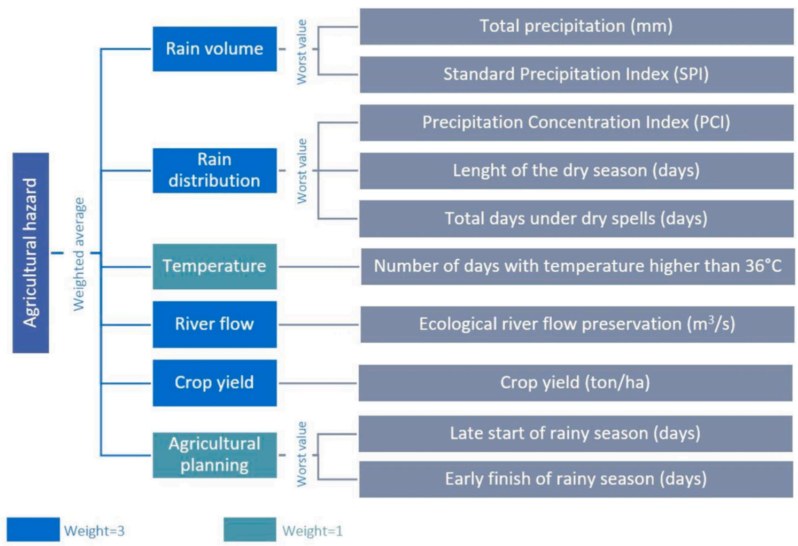

Fig. 3. Agricultural hazard components. Blue and green represent the groups to be analysed for agricultural drought. Grey shows the indicators for these groups, and in top of the brackets the methodology used to calculate group value when multiple indicators are present is also presented.

The projected precipitation and temperature values were evaluated based on historical data indicators and thresholds. River flows and crop yields were modelled using the projected weather data and evaluated based on proposed indicators and historical thresholds.

It is important to note that precipitation varies naturally from year to year due to atmospheric circulation patterns, El Niño and La Niña, oceanic conditions such as sea surface temperatures and ocean currents, and local characteristics such as the South Atlantic Convergence Zone, the Intertropical Convergence Zone, monsoon systems or the Madden-Julian Oscillation (Ambrizzi and Ferraz, 2015; Barros et al., 2000; Chou et al., 2014; Laureanti et al., 2024), etc.; in addition, climate change is modifying precipitation patterns and amounts (Fan et al., 2017; Lin and Qian, 2019; Trenberth et al., 2003). In that sense, each General Circulation Model (GCM) simulates the response of global climate based on the physical processes of the atmosphere and ocean (Gettelman and Rood, 2016; Mechoso and Arakawa, 2015). Despite recent endeavours to develop systematic parameter optimisation methods, these remain inapplicable to fully coupled climate models due to their inherent complexity. Consequently, each model is tuned to represent the optimal combination of parameters influencing the output projections and uncertainty (Balaji et al., 2022; Flato et al., 2013).

GCMs simulate the entire climate system, including the atmosphere, oceans, and land surface. These models typically use a time step of 30 min (Baede et al., 2001). There are two main components to GCMs: the Atmospheric GCMs, which often use time steps of around 10–30 min (Petoukhov et al., 2003), and the Ocean GCMs. Ocean models may utilise longer time steps, typically spanning from hours to a day, due to the slower evolution of oceanic processes in comparison to atmospheric processes. GCMs are also required to adhere to a strict format and metadata standards. Among the most critical output fields are the monthly and daily data, as well as the three-hourly two-dimensional (latitude and longitude) atmospheric results (Meehl et al., 2007).

The HadGEM2 (Collins et al., 2011) and MIROC5 (Watanabe et al., 2010) models employed in the analysis utilise disparate data sources, initialisation methods and model-specific purposes. MIROC5, for instance, places particular emphasis on the monsoon and El Niño phenomena. These differences influence the variability in the models' outputs, resulting in different projected data. Furthermore, their differential sensitivities to variables give rise to variable annual precipitation totals.

In this analysis, the first quartile of historical precipitation data was used as a threshold reference for drought (1316 mm). This was determined as it is a commonly referenced value in the sector for forecasting future conditions and it is the minimum precipitation amount required by the crop. With regard to temperature, the growth of sugarcane is affected by temperatures exceeding 33°C and falling below 10°C.

The Appendix I contains the average data projections by the models.

2.2.1.3. SPI adaptation. In particular, for the Standard Precipitation Index (SPI), the indicator analysis was adjusted to allow for scenario comparisons.

The SPI was developed by McKee et al. (1993) as an indicator to characterise and monitor drought events. It is calculated by taking the mean of a precipitation dataset by period and fitting it to a gamma function, subsequently, the quality and the length of the data set affect the SPI results (Wu et al., 2005). The deviation of the analysed precipitation data points is examined using the inverse normal. The gamma fitting function is calculated as follows (Zuo et al., 2021):

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \tag{1}$$

Where x is the precipitation volume, α and β are the shape and scale parameter correspondingly, and $\Gamma(\alpha)$ denotes the gamma function. α and β are estimated by:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{\frac{4A}{3}}\right) \tag{2}$$

Where A is calculated by

$$A = ln(\overline{x}) \;\; - \frac{\sum ln(x)}{n} \tag{3}$$

$$\beta = \frac{\overline{x}}{\alpha} \tag{4}$$

To ensure comparability between the scenarios, the projected data were analysed using the gamma fitting of the historical data. This involved calculating α and β values based on the historical values.

2.2.2. Exposure and land use scenarios

In the context of risk analysis, exposure is defined as the assets that will be impacted by the hazard in a given area (Field et al., 2015). Within the scope of this analysis, exposure pertains to the agriculture and industrial subsystems elements in Fig. 2 that are exposed to drought.

In the case of agricultural exposure, it is the percentage of the analysed area under sugarcane. The study area predominantly comprises non-irrigable pastureland (39%), followed by forest (22%) and cerrado (15%) (Table 1). Sugarcane cultivation, on the other hand, accounts for only 5% of the land cover mostly concentrated in the centre of our study area, Rio dos Patos basin (Fig. 4).

Most of the area considered suitable for sugarcane is currently under pasture, both irrigable and non-irrigable. The paper defines suitable sugarcane land as terrain with a slope of under 12%, a criterion established by the Ministério da Agricultura, Pecuária e Abastecimento (2009), while also excluding areas covered by native vegetation or forest. Under those considerations, around 619,500 ha can be covered by sugarcane.

The study includes land-use scenarios consisting of a non-expanding scenario, two scenarios in which sugarcane expands to half of the 619,500 ha (around 309,700) and a second scenario in which it expands to 75% (circa 464,600 ha).

It was assumed that the initial spread of sugarcane would occur in irrigable areas, before expanding into non-irrigable areas. This process was expected to commence in pasture areas, subsequently extending to agricultural land and finally to grassland. The expansion was also expected to occur first in areas where sugarcane was already present and close to established mills. The decision to expand every five years was made because land leases typically last for ten years. During this time, farmers and agricultural managers plan the land use. Therefore, the area planted with sugarcane does not necessarily increase significantly each year. For the scenario analysis, land use change developed at different rates between 2025 and 2045, depending on the targeted percentage of expansion.

In the case of industrial exposure, the exposure is the percentage of installed potential in the area. According to Agência Nacional de Energia Elétrica (2024), Brazil has around 200 GW of installed potential, of which close to 12.4 GW is based on sugarcane. Goiás represents circa 12% of this 12.4 GW, mostly located in the north and south of the state. Within the study, five sugarcane mills are installed, representing around 2% of the installed potential based on sugarcane in Brazil (see Fig. 5).

In the expansion scenarios, mills may need to increase their capacity to accommodate increased sugarcane production. The authors assumed that this increase would also involve greater installed energy potential. As a result, the installed potential, the industrial exposure, would increase. For reasons of economic sustainability, sugar mills harvest sugarcane from an average radius of 25 km (NovaCana, 2025). Therefore, it is also assumed that new mills would be needed to cover the new sugarcane production (see Fig. 5).

Table 1
Land use characterisation. Where (i) stands for “possible irrigation”.

Land Use	Study area		Area suitable for sugarcane	
	ha	Percentage	ha	Percentage of corresponding land use
Agriculture (i)	37,845	1.10%	37,845	100%
Agriculture	196,657	5.70%	63,545	32%
Pasture (i)	148,957	4.30%	148,957	100%
Pasture	1,349,515	39.10%	354,631	26%
Grassland (i)	8,853	0.30%	8,853	100%
Grassland	214,884	6.20%	5,704	3%
Sugarcane (i)	85,287	2.50%	-	-
Sugarcane	82,783	2.40%	-	-
Barren soil	975	0%	Not considered	-
Cerrado	519,789	15.10%	Not considered	-
Forest	773,128	22.40%	Not considered	-
Urban	23,252	0.70%	Not considered	-
Water	11,713	0.30%	Not considered	-
Total	3,453,638		619,534	-

2.2.3. *Vulnerability indicators*

In the context of risk analysis, vulnerability is defined as the propensity of the system under assessment to experience negative outcomes when exposed to hazardous events (Field et al., 2015). Within the framework of this analysis, the vulnerability assessment encompassed the socio-ecological and technological elements of the system in place, which determine its resilience to drought events.

The agricultural vulnerability considers the Lack of Adaptive Capacity (LAC), Lack of Coping Capacity (LCC), Social Susceptibility (SoS), and Ecosystem susceptibility and Ecosystem robustness (ESR). Each aspect or section was evaluated using groups and indicators that were averaged. The baseline for these indicators was established through a questionnaire in 2019 by Campos Zeballos et al. (2022). Their aspects and their respective indicators and assumptions are listed in Table 2.

The industrial vulnerability was evaluated based on the likelihood of the industrial processes experiencing harm in case of drought. It was analysed based on the volume of fresh water required per tonne of sugarcane processed (the less water required, the less vulnerable to drought risk), the percentage of water recovered and reused from sugarcane (the more recovered, the less vulnerable), the percentage of water losses in the system (the less water loss the less vulnerable), the water drawn from a dam for industrial purposes (the more water required is sourced from a dam the less vulnerable to low flow conditions), the electricity generated per tonne of sugarcane processed (the more efficient the less vulnerable) and the electricity consumed per tonne of sugarcane processed (the less energy needed per tonne the less vulnerable). The thresholds were established based on the characteristics of the region. The results of both the agricultural and industrial subsystems base lines were evaluated and published in Campos Zeballos et al. (2022) and assumptions can be found in Table 2. The vulnerability of the system is the average between the agricultural and industrial vulnerabilities.

Changes to the sugarcane-bagasse-based electricity system have varying impacts on vulnerability values. The values of vulnerability indicators will vary depending on the scenarios analysed. To evaluate these changes and dynamic values, we considered several assumptions discerned from questionnaires and interviews with farmers and mill managers in the region.

2.3. *Risk assessment scenarios*

As previously mentioned, the risk assessment considers nine scenarios (see Table 3). The scenarios are run under RCP2.6 or 4.5 projections for the MIROC5 climate model and under RCP2.6 for the HadGEM2 climate model. Scenarios are also run under land use change. Both inputs, the hazards from the climatological models and the land use changes, contribute to the vulnerability of the region. These changes are also included in the analysis as we aimed to examine all possible outcomes for different policy pathways for energy adaptation and risk reduction. Table 3 shows the scenarios under analysis.

3. Results

The risk and its component scores range from zero to one, with one being the most severe risk. The results of the paper are spatially explicit and provide an easy-to-understand view of where drought risk may be more severe. The maps are presented in Fig. S 7.

3.1. *Hazard*

The number of extreme drought events was evaluated based on the values mentioned in Section 2.2.2, similar to the drought frequency. Fig. S 8 illustrates both the frequency and the length of the drought risk

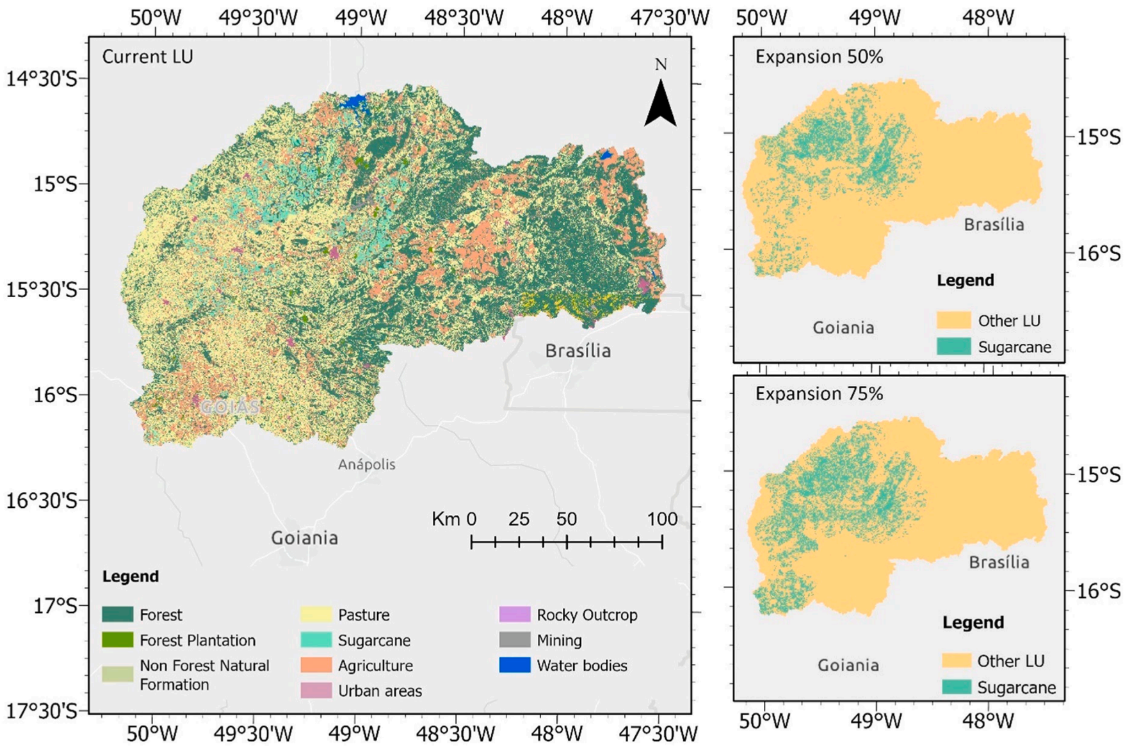

Fig. 4. Current Land Use map (based on Projeto MapBiomas (2024)) (left), and possible expansion scenarios (right) (top map depicts the scenario with 50% of expansion, and low map the scenario with 75% of expansion).

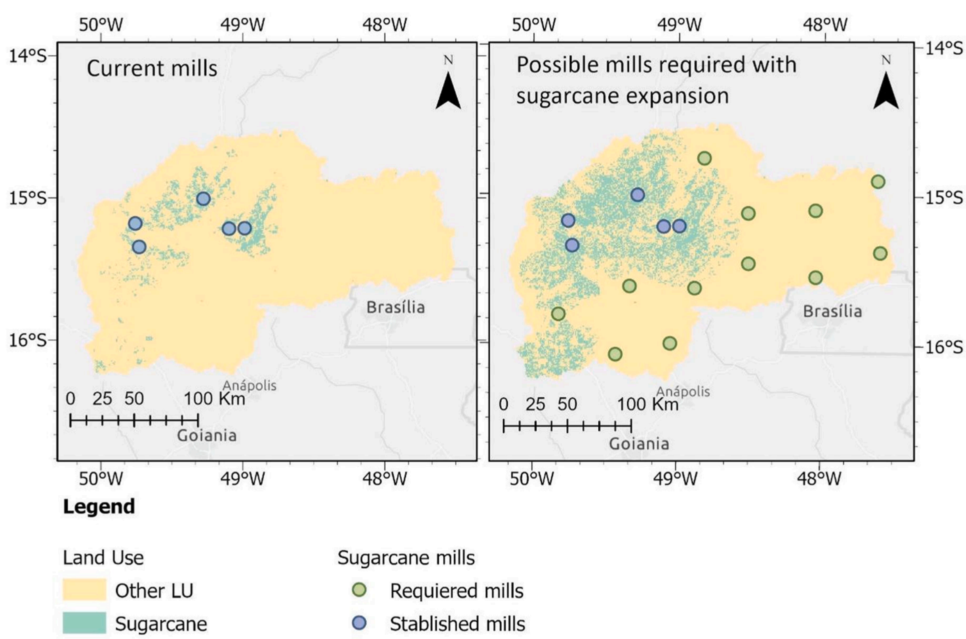

Fig. 5. Sugarcane mills location under the current scenario (left, current mills in blue), and possible required mills under sugarcane expansion (right, possible required mills in green).

event per scenario. The matrix illustrates a range of blue-purple shades, representing the combination of the various scenarios. for example, in the case of the scenarios under the model H26, the eastern and western regions of the region are characterised by a permanent drought (in pink and purple), whereas basins situated more centrally and to the north experience drought events less frequently (every five years on average) and for shorter periods (in light blue) (on average every 2.4 years). From scenario H26_0 to H26_50, the frequency of droughts is slightly higher, but not statistically significant, while the length of droughts remains unchanged. Between scenarios H26_50 and H26_75, the frequency of droughts is slightly lower, though not statistically significant, while the length of droughts is slightly longer, though not statistically significant.

In accordance with the M26 model, the majority of the region is characterised by a single prolonged drought event, which can be considered a permanent state of drought. It should be noted that there are exceptions to this general pattern. In the eastern area, for instance,

Table 2
Vulnerability assumptions for dynamic future analysis per indicator.

Vulnerability	Section	Group	Indicator	Assumption and effects of sugarcane expansion in indicators
Socio-ecological vulnerability	Lack of Adaptive Capacity (LAC)	Farmer's land covered by sugarcane	Dependency ratio on sugarcane	We assume that the expansion of sugarcane cultivation is likely to lead to an increase in the region's dependence on the crop.
		Income dependency on sugarcane production	Dependency ratio on sugarcane	We assume that the expansion of sugarcane cultivation is likely to lead to an increase in the region's dependence on the crop.
			Complement with income diversification	We assume that expanding sugarcane cultivation in irrigated areas will reduce the income diversification options available to farmers.
		Learning from past experiences: changes in farming practices due to drought	Farmers who have adjusted their farming practices	It was found in the interviews by Campos Zeballos et al. (2022) that implementing alternative practices was found to be challenging and costly. Therefore, we assume that in the absence of sugarcane expansion, practices are anticipated to remain unchanged.
		Perception of drought event frequency	Farmers who believe drought events will be more frequent	The study conducted by Campos Zeballos et al. (2022) revealed that farmers in the region unanimously agreed that droughts were becoming more frequent. It is assumed that this will continue without any changes.
	Lack of Coping Capacity (LCC)	Drought awareness and early systems	Existence of early warning systems (yes/no)	The Early Warning System for Drought and Desertification (SAP, as it is known in Portuguese) is presently accessible to nine northeastern Brazilian states in addition to the northern territories of Minas Gerais and Espírito Santo (Instituto Nacional de Pesquisas Espaciais et al., 2016). The aim of the Decision Support Systems in Agriculture and Livestock (SISDAGRO, known in Portuguese) is to provide information for managing crops (Instituto Nacional de Meteorologia, 2024). The platform offers agrometeorological information that is applicable to crop management in Brazil. Regrettably, data regarding water balance and yield loss is unavailable for sugarcane. The agricultural sector recognises the significance of agrometeorological data and climate projections in crop management. Novacana and Letras Ambientales, a non-profit organisation, report drought alerts for the sugarcane sector (Letras Ambientais, 2021). Additionally, private companies offer crop management services; however, meteorological projections are only available for the upcoming few weeks. It is assumed that by 2030 a better free system will be available to the sector and by 2050 there will be an appropriate system that is easily accessible to all farmers to better plan crop management. An early warning system with seasonal and weekly forecasts for the sector will help to preparedness in the sector and; therefore, reduce the vulnerability of the sector.
		Insurance for drought events	Farmers without access to insurance/drought specifically	Insurance options for sugarcane in Brazil are available, but most farmers only purchase them as a requirement for loan guarantees by the bank. Questionnaire results published by Campos Zeballos et al. (2022) showed that farmers do not trust in the insurance system and they consider that the thresholds for crop losses are low. Therefore, it is assumed that by 2050, a significant portion of farmers will remain uninsured.
		Dam availability	Farmers with access to a dam (own or JM) for sugarcane	Based on data from MapBiomas (Projeto MapBiomas, 2022), increased access to dams and irrigation systems is linked to sugarcane expansion in basins where the crop is significantly more abundant than in others. Therefore, we assumed that sugarcane expansion would likely lead to additional dam construction as it expands to areas that can be irrigated.
	Social Susceptibility (SoS)	Partnership among the farmers	Community organizations	In the baseline, the majority of farmers were affiliated with organizations. Our assumption is that by 2050, all farmers will be affiliated with an organization that represents their interests.
		Trust in the government	Level of trust in the local government	The level of trust in the local government cannot be predicted, therefore we assume that the vulnerability associated with it will remain similar.
	Ecosystem susceptibility and Ecosystem robustness (ESR)	Agriculture inputs	Ecosystem management/ farming practices/soil fertilizers	According to Vision 2030 - the future of Brazilian Agriculture (Empresa Brasileira de Pesquisa Agropecuária, 2018), Embrapa aims to promote the use of quality and organic inputs. We assume that farmers will be utilizing better-quality or less inputs by 2030 and that this trend will continue to improve by 2050. However, we also assume that a fully organic system may not be achievable as it is driven by specific markets.
		Knowledge of protected areas Knowledge of restored areas	Protected areas Restored areas	Expansion of sugarcane cultivation will require farmers to update their CAR documentation; therefore, they will need to look for information about protected areas and the need to restore areas on their land. We assume that this will increase the knowledge about protected areas in the region. Furthermore, RenovaBio is a Brazilian government initiative that commenced in 2020 and provides credits for carbon emissions. These credits are only available for crops grown in areas that have not undergone

(*continued on next page*)

Table 2 (*continued*)

Vulnerability	Section	Group	Indicator	Assumption and effects of sugarcane expansion in indicators
				deforestation (União da Indústria de Cana-de-Açúcar e Bioenergia, 2023).
		Farmers' perception of sugarcane resistance	Sugarcane resistance to drought	Research and sugarcane breeding to increase tolerance to drought events has been in practice in recent years (Cursi et al., 2022; Marcos et al., 2018). We assume that farmers will consider planting it with greater frequency. We also assumed that sugarcane's resistance to drought events will never be entirely assured, as it can be affected by drought events.
Industrial vulnerability	Volume of fresh water per ton of sugarcane processed			Sugar mills are consistently taking measures to significantly reduce the amount of fresh water required to process sugarcane (Revista RPA New, 2020). It is expected that multiple mills will be operating at 0.5 m3/TSC or less by 2026. The information obtained from the regional mills indicates that the target will be achieved by 2027. It was assumed that, by 2028, the regional mills would be functioning at that level of efficiency.
	KWh generated per ton of sugarcane processed			The amount of electricity produced per tonne of sugarcane is dependent on electricity revenues. It is common practice for sugar mills, which are typically self-sufficient in terms of energy generation, to operate at suboptimal efficiency. The rationale behind this strategy is that such mills do not have a requirement to inject energy into the grid. Consequently, some sugarcane mills have already been constructed with the capacity to generate additional electricity and sell it depending on energy prices. Our analysis is based on the bioenergy generation trend over the last ten years. We assumed that the increase in bioenergy participation in the industry will positively impact the efficiency of mills and their electricity generation potential.
	Percentage of water recovered and reused from sugarcane			To diminish the demand for freshwater in the processing of sugarcane, it is necessary to reuse the water generated during the sugarcane production process. We assumed that this is a common practice within the field of study and will continue to be so.
	KWh used per ton of sugarcane processed			Currently, the energy required per TSC surpasses 30 kWh. The Novacana database suggests that energy consumption could be as low as 12 kWh/TSC. Nevertheless, these required changes would necessitate significant investments in the system. On this basis, it is assumed that by 2050, the mills in the region will consume a total of 12 kWh/TSC.
	Percentage of water losses in the system			Currently, the water losses within the system are below 0.5 m3/TSC. It is assumed that this value will remain stable or decrease in the mills within the region.
	Access to a dam to cover the water needed for industrial purposes			On the one hand, as the water supply for processing sugarcane diminishes, the proportion of water sourced from dam coverage rises. On the other hand, the more sugarcane the mill processes, the more water it will require; thus, the greater the amount of water required. Consequently, this variable is dependent on the quantity of sugarcane processed, whether a new plant needs construction, or the mill needs expanding, and the quantity of water needed for the sugarcane processing. We assume that mills will have the possibility to have water dammed for industrial purposes; however, the volume will not grow constantly as the cost and regulation to construct dams is considerable.

Table 3
Risk scenario analysis codification.

Climatological Model	RCP	Land Use Scenarios		
		Non-expansion	50% expansion	75% expansion
MIROC5	2.6	M26_0	M26_50	M26_75
	4.5	M45_0	M45_50	M45_75
HadGEM2	2.6	H26_0	H26_50	H26_75

there is a basin that experiences drought events with greater frequency (every five years) and shorter durations (approximately three and a half years). The frequency and duration of drought events are comparable across the scenarios M26_0, M26_50, M26_75.

Furthermore, under model M45, the scenarios are also similar between the different land use scenarios, with an average frequency of drought events of approximately 15 years and an average length of 8.5 years.

3.2. Exposure

The findings of the analysis on sugarcane expansion indicates that the process will predominantly take place in the western region of the study area where sugarcane is currently present (refer to Fig. S 9).

Currently, sugarcane is concentrated north of Goianésia (Fig. S 9). If sugarcane expands as shown in the previous figure, the existing mill capacity will not be adequate to process the boost in sugarcane production. As a result, the capacity of existing mills will need to be increased, and new mills might be constructed. It was hypothesized that the newly constructed mills would utilise state-of-the-art technology and sustainable practices, thereby maintaining a generation capacity in line with their crush capacity. This added capacity will consequently alter the industrial exposure (Fig. S 10). The results indicate that the H26_75 scenario has significantly higher crop yields, which later translates into a higher need to expand the capacity of sugarcane mills and an increase in potential energy production.

3.3. Vulnerability

Several vulnerability indicators in both the industrial and agricultural phases of the system are affected by the expansion of sugarcane. Vulnerability scenarios are presented based on the climatological models, RCP, and LU change scenarios.

Fig. 6 illustrates the average industrial vulnerability per model per land use scenario, with comparable results and patterns observed across the different models. It is anticipated that most components of industrial vulnerability will be reduced, except for acquiring access to dams to fulfil the water requirements of the mills. This is due to the dam-building limitations in the region, with efforts primarily directed towards irrigation. Consequently, acquiring access to a dam is likely to diminish over time. Nevertheless, the vulnerability continues to decline from approximately 0.30 to values below 0.15 in all scenarios, as the volumes of water provided by dams will remain relatively sufficient to meet industrial demand.

The vulnerability of the agricultural phase shows lower values compared to the industrial phase (see Fig. 7). This can be attributed to the improvement in some of their indicators due to the expansion of sugarcane, as partnering with mills enhanced farmers' access to dams and technology for efficient irrigation, and drought awareness. This is of particular relevance given that efforts to expansion of early warning system are expected to reduce vulnerability. The increased drought awareness that results from this will allow farmers to prepare themselves to expand irrigation systems, manage dams, and plan harvesting in a way that will minimise the impact on crop yield. Of these measures, the development of efficient irrigation systems is of particular significance, given its capacity to positively influence crop yields (Batista et al., 2024; Dias and Sentelhas, 2019). This trend is illustrated in Fig. 7, which shows that the vulnerability values for the year 2025 are similar between the scenarios (0.48, 0.49, and 0.42). However, the vulnerability is reduced to 0.45 under the LU_0 scenario, to 0.41 under the LU_50 scenario, and to 0.36 under the LU_75 scenario.

In terms of factor sensitivity, it is important to note that the subsystems' vulnerability is the average of its factors whilst the overall vulnerability is the average of the agricultural and industrial vulnerability. Regarding industrial vulnerability, a change of 0.1 in any of the factors results in a 0.017 change in industrial vulnerability and a 0.008 change in overall vulnerability. Regarding agricultural vulnerability, the groups are equally sensitive, but in the case of income dependence on sugarcane production, the factors are less sensitive because they are first averaged to obtain a group value. A change of 0.1 in any of these factors results in a 0.004 change in agricultural vulnerability and a 0.002 change in overall vulnerability, while the remaining groups result in a 0.008 change in agricultural vulnerability and a 0.004 change in overall vulnerability.

The spatially explicit findings highlight that the most vulnerable region is situated in the southern part of the study area (see Fig. S 11).

3.4. Risk values

As illustrated in Fig. 8, the various average risk values per land use scenarios are presented alongside their corresponding average values for hazard, exposure and vulnerability. Furthermore, the maximum values of risk per scenario are presented in addition to the average risk. The results demonstrate that the scenarios associated with RCP2.6 exhibit elevated risk values. This is predominantly attributable to the hazards inherent to the corresponding scenarios. The values under M26 represent the next highest values, which present an important peak when sugarcane is expanded to 50%. However, this reduces when the level is increased to 75%. This is largely attributable to a reduction in vulnerability in areas prone to drought events. The most unfavourable outcome under M26 is nevertheless still inferior to the least favourable outcome under H26.

In accordance with the findings of Campos Zeballos et al. (2022), a risk value approaching 0.32 is a cause for concern and a value of 0.4 indicates high risk. In light of the aforementioned, it was determined that values exceeding 0.4 are indicative of an extreme drought risk, while values exceeding 0.32 are indicative of a significant drought risk. To further categorise drought risks, the average and standard deviation of risk values were calculated for each scenario. Based on the standard deviation, it was determined that values exceeding 0.27 can be considered mild drought risks, while values below this threshold were considered indicative of no drought risk.

It should be noted that not all models present values higher than 0.4

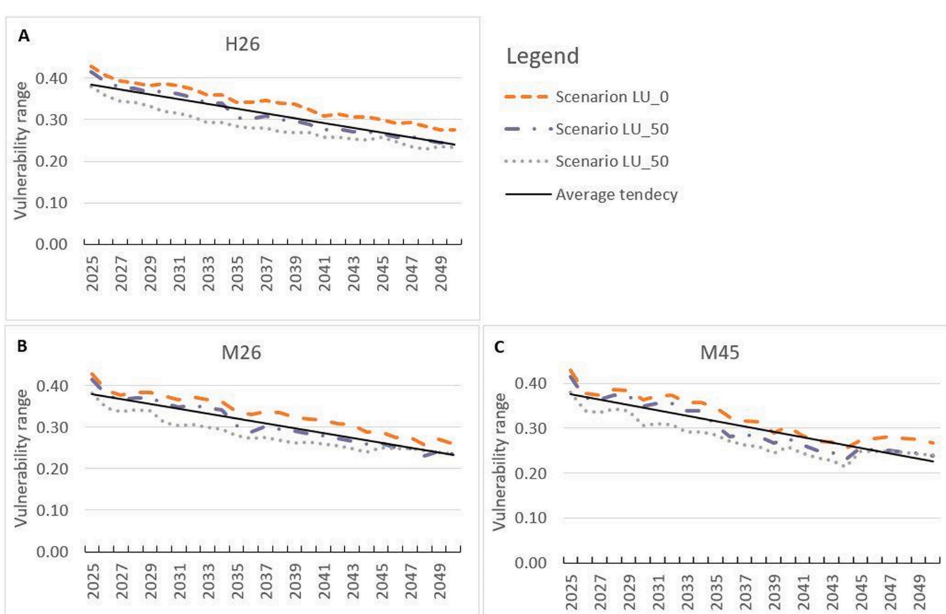

Fig. 6. Average vulnerability values per climatological model and land use. A) referring to the vulnerability scenarios under the climatological model HadGEM2 – RCP2.6. B) referring to the vulnerability scenarios under the climatological model MIROC5 – RCP2.6. C. referring to the vulnerability scenarios under the climatological model MIROC5 – RCP4.5.

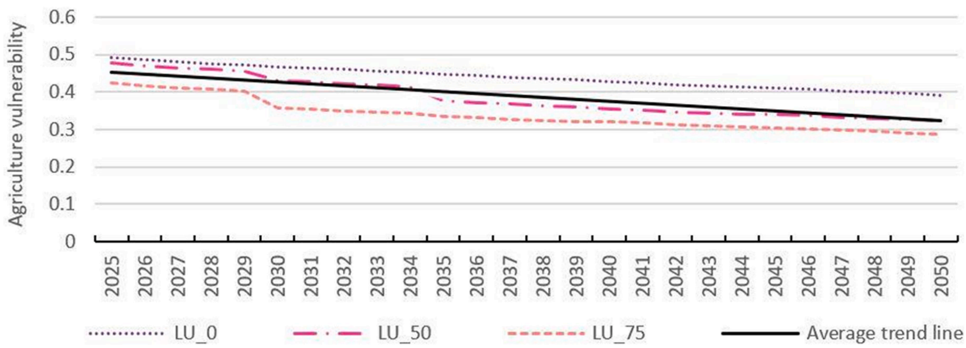

Fig. 7. Agricultural vulnerability per land use scenario including the average trend line.

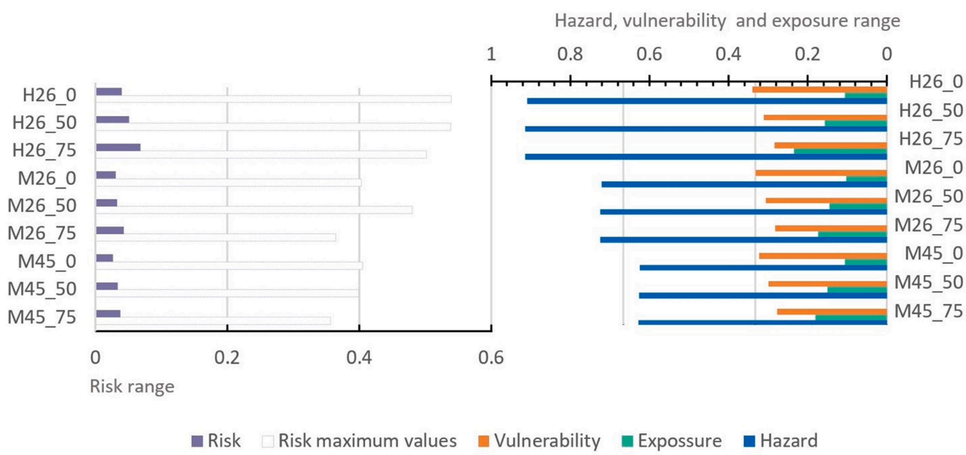

Fig. 8. Average risk, hazard, vulnerability and exposure per scenario. The average risk per scenario in purple is indicated on the left-hand axis, with the risk values ranging below the graph. Maximum risk values are included in the same graph in white with purple boarders. The vulnerability, exposure and hazard average values per scenario are shown on the right-hand axis, with the values indicated at the top.

(Fig. 8). However, all models do present values higher than 0.32. Nevertheless, it is not the case that all average values per scenario present risk values of concern. Under model H26, the region presents extreme risk values, particularly in the south-west. The central area, where the main mill in the region is located, presents mild drought events. It is also noteworthy that, although risk values decrease from extreme to significant drought events, the expansion of sugarcane cultivation occurs in areas that subsequently experience mild drought events. The scenarios under M26 present an extreme and significant risk of drought. In comparison to M26_75, M26_50 exhibits a reduction in the number of areas presenting mild drought risk. This shows that, in contrast to other models, reducing vulnerability is not sufficient to mitigate the risk in general. Spatially explicit results can be found in Fig. S 12.

4. Discussion

The study offers a methodology for examining drought risks through various scenarios, which can be instrumental in shaping drought risk reduction policies and ensuring the sustainable expansion of the sugarcane sector in the region.

The methodology considers the potential impact of climate change on the three components of risk: hazard, exposure and vulnerability. The analysis demonstrated that the components of risk are interconnected. For instance, variable precipitation patterns, both temporally and geographically, impact crop yields, which in turn affect the need for expanded industrial capacity. As sugarcane cultivation expands, the region becomes more reliant on the crop, increasing farmers' vulnerability. This illustrates the necessity for an analysis of risk under scenarios that consider the dynamics and interconnection in order to obtain a comprehensive understanding of risk.

The hazard analysis indicates a range of hazard scenarios, including instances of short drought events, which are less frequent, and long drought events, which are more prevalent. Some of these scenarios are of concern as they indicate prolonged drought events. In particular in model H26 and M26, in which around 43% and 70 - 78% of the region is subjected to an uninterrupted period of drought, respectively.

H26′s less extensive areas of prolonged drought hazard are counterbalanced by its significantly elevated mean values when compared to the other two models. Its mean values are, on average, 1.4 times higher than those of M 26 and 1.5 times higher than those of M45. This is also evident in the risk results, as under this scenario, there are more areas at risk, indicating significant areas of extreme drought events. In contrast, scenarios under M45 have experienced drought events, yet these are not classified as drought risks. This discrepancy underscores the necessity for considering the differences and uncertainties in the projections for risk management purposes. The inherent uncertainty in climatological models is inevitable; nevertheless, rather than perceiving it as a deficiency, it should be utilised to our benefit. By presenting a range of potential future scenarios, it is possible to provide critical insight into a range of possible drought risks. This variability enables the development of adaptive strategies that enhance preparedness and resilience, ensuring that decision-making processes remain flexible and robust in the face of uncertainty.

Those results do not imply that droughts do not occur; in fact, the expansion of sugarcane cultivation has been observed to lengthen the duration of drought hazard values. However, this suggests that the vulnerability has decreased at a greater rate than the hazard has increased. It is important to note that these values are dependent on the assumption that improvements have been made to the systems in place to reduce vulnerability. Without such improvements, more areas would likely be at risk, a limitation that future studies should address. It is also important to note that, although the results of the drought risk assessment are distributed across the different basins in a cell base, the entire region must be considered under a certain level of risk.

With regards to exposure, sugarcane expansion typically follows a pattern where it expands based on objective factors such as the ease of correcting the soil and planting sugarcane, as well as the proximity to existing sugarcane growth. The proposed expansion is likely to be concentrated in the central and western regions of the HMU, overlapping with areas susceptible to strong hazard events. However, it is important to consider that under the present analysis, sugarcane expansion proceeded regardless of the presence of drought conditions. Such conditions would serve to impede further expansion and investments within the sector. Under the drought scenarios M26 and H26, sugarcane expansion is unlikely to proceed. A limitation of the methodology is the inability to control expansion under specific dry conditions in the model.

It is important to consider, however, that the cultivation of sugarcane to meet the demand for ethanol and electricity will require expansion, the use of land, which may give rise to concerns regarding the safeguarding of food security. Nevertheless, previous studies addressing this concern concluded that it is not a significant issue, given that sugarcane is cultivated on degraded pasture and pasture areas (Bordonal et al., 2018; de Souza Souza Ferreira Filho and Horridge, 2017). The present analysis further revealed that even if sugarcane cultivation were to expand significantly, it could mostly occur in pasture areas without leading to the conversion of agricultural land Expansion to 100% of suitable regions for sugarcane would result in the crop covering approximately 18% of the region, with 57% of this area being non – irrigable pasture, and 24% non – irrigable grassland.

It is nevertheless of significant importance to monitor alterations in land use while analysing the principal economic products in the region, given that dairy production represents a crucial contributor to the local economy. This is particularly important as the diversification of the region's income sources can decrease the vulnerability in the region. Moreover, it is essential to implement policies that can shape a sustainable expansion of sugarcane, as evidenced by the policies that were previously implemented to combat sugarcane burning, which also increased the biomass available for energy generation (Goldemberg et al., 2008). More recently, sustainable development policies that take into account water management and irrigation have also encouraged the mindful expansion of irrigated crop production where possible (Poder Executivo, 2023).

In terms of industrial expansion, the analysis has identified that the increasing sugarcane crop yield and possible expanding sugarcane production will require an increase in sugarcane mills' processing capacity and additional sugarcane mills. In the absence of any expansion, yet with a concurrent improvement in crop yield, there is nevertheless a predicted increase in sugarcane production ranging from 10 to 31%. In this study, it was assumed that mills would increase capacity and that new mills would be built. However, a more detailed feasibility study is required to ascertain the economic conditions for industrial expansion, including the optimal market for energy sales. Furthermore, some mills may harvest sugarcane beyond the typical 25 km distance, up to 70 km, which could influence the location and number of proposed mills.

Concerning vulnerability, while sugarcane can provide income security through partnerships with mills, relying solely on agricultural products or services is not advisable as it can increase vulnerability. In the context of agricultural vulnerability, the most critical groups are the awareness of drought, early warning systems, changes in farming practices due to drought, and insurance for drought events. A reduction in these three components by 50% would result in approximately 19% of the agricultural vulnerability being addressed. In the case of industrial vulnerability, the critical indicators are the energy used per ton of sugarcane processed and the access to a dam. The last one impacts both farmers and millers is also a factor that affects vulnerability. However, it is important to mention that organizations associated with the sugarcane and bioenergy industries, as well as the private sector, committed to ambitious improvements in the sector aimed at enhancing water usage and increasing energy efficiency, leading to higher energy injection into the national grid. The reduction in water demand to 0.5 litres per tonne of sugarcane, as opposed to the current water usage of approximately 1.6 litres, indicates a 69% decrease in water demand.

Another example to reduce water demand is the promotion of the use of drought-resistant sugarcane and Embrapa and local farmers engage in sugarcane breeding for several purposes in the region, prioritising the cultivation of drought-resistant sugarcane. This action should also be considered by the insurance sector, as the crop yield thresholds to cover sugarcane losses are relatively low and farmers have issues accessing compensations after a drought event (Fig. 9). It is estimated that reducing this vulnerable group could reduce agricultural vulnerability by 6%.

Another crucial aspect proposed by the Embrapa for mitigation and adaptation to climatic changes in the Brazilian sugarcane sector is the insertion of a sustainable irrigated production system in a fraction of the sugarcane mill production area, and the implementation of efficient irrigation techniques (Fig. 9). Embrapa has been engaged in collaborative efforts with farmers and mills to promote sustainable expansion of irrigated sugarcane, and to enhance the efficiency of irrigation, which is identified as a pivotal strategy for adapting sugarcane to drought conditions and for increasing crop yields (Bufon, 2023; Bufon et al., 2021). To ensure the effectiveness of these actions, it is crucial to implement corresponding regulatory measures that facilitate access to irrigation and dams' investments. This process should be comprehensive, ensuring the maintenance of ecological flow and environmental protection, while also providing farmers with proper technical guidance on the sustainable and efficient use of irrigation systems and dams. Importantly, these measures should avoid overly burdensome bureaucratic procedures, allowing for streamlined implementation and practical support for farmers. The combination of those actions has the potential to reduce the overall vulnerability between 38 to 43%. Based on those findings, measures to mitigate the risks associated with drought events impacting sugarcane-based energy production and develop a sustainable sugarcane system should concentrate on policies and actions established in collaboration with communities, experts, and the private sector. Fig. 9 provides an overview of suggested measures for adaptation in priority order and possible connections between them. Nevertheless, it is imperative to emphasise the necessity for competent actors within the aforementioned stakeholders group depicted in Fig. 9. In the absence of robust organisation, the implementation of actions and policies would be protracted.

To enhance sugarcane expansion plans, it is recommended to engage with farmers' associations from the initial stages, or to create such associations to facilitate the implementation of risk mitigation measures in the agricultural sector (Fig. 9). This approach can also help identify potential issues specific to new areas that were not addressed in this paper. A well-organised sector would help with the collection of data in a systematic manner. The collected data would also inform the portfolio of actions to consider that increase sector resilience and include more regionally appropriate actions. Further consideration could be given to the provision of support for farmers, including access to financial assistance and the access to drought-resistant crops in relevant regions. Furthermore, the monitoring of agro-dependence in the region and land use changes could facilitate a deeper understanding of indirect land use change (iLUC), which is still not well understood (Ferreira Filho and Horridge, 2014) (Fig. 9).

The dissemination of information regarding the utilisation of quality and organic inputs in general, as well as the restoration of land with native vegetation, where feasible, represent additional potential

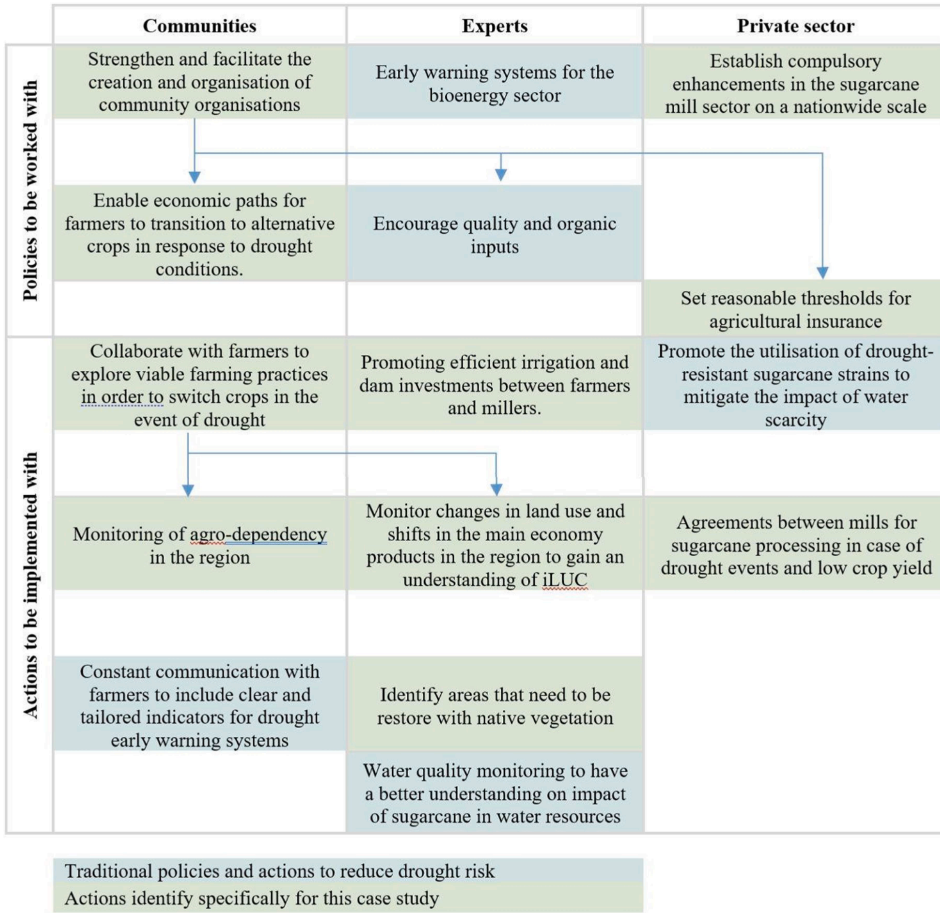

Fig. 9. Policies and actions to reduce risk.

avenues for improvement within this sector. Furthermore, in conjunction with water efficiency, it is vital to conduct year-round monitoring of water quality in rivers, dams and groundwater in order to ascertain the impact of sugarcane on water resources.

In the case of the industrial sub-system, it is recommended that certain enhancements be made mandatory in the sector. Various actors have been working to increase its efficiency, primarily driven by economic motivations. However, reducing freshwater requirements or reusing water from sugarcane during processing not only reduces costs but also reduces technical vulnerability during droughts. In scenarios with prolonged droughts, the agreement between mills on sugarcane allocation strategies will be key, because if production is low, there could be difficulties with sustainable production in monetary terms (Fig. 9).

The implementation of nationwide policies establishing compulsory enhancements in the sugarcane sector, with specifications tailored to each biome when necessary, could potentially facilitate the growth and advancement of the sector towards more efficient processes. However, it is essential to ensure that these processes are monitored and accompanied by incentives to encourage the sector's continued development (Fig. 9).

Regarding limitations, it is crucial to acknowledge methodological constraints that may affect the robustness of the findings. Hazard scenarios were based on projected data by meteorological models that come with their own uncertainties. However, the scenarios of exposure and vulnerability are based on informed assumptions that should be monitored to ascertain whether there are other factors that are impacting the expansion of sugarcane or the vulnerability indicators. In the event that new information becomes available, the aforementioned factors should be adapted accordingly. A further significant limitation of the methodology is the absence of weights employed to assess the vulnerability of the system. In the agricultural vulnerability analysis, some of the groups had few indicators that were averaged; these values were used in their respective section results, which were then used to calculate the vulnerability value. In the industrial sector, the vulnerability value was derived from an average of six factors. While it is possible to apply weights to analyse the vulnerability, this requires additional work to establish a rationale for the weight, which was lacking in this case but should be considered in further analysis.

Addressing the impact on biodiversity remains a gap in the analysis. Future research should incorporate an examination of how sugarcane expansion affects biodiversity, especially in ecologically sensitive areas like the Cerrado and Atlantic Forest biomes.

5. Conclusion

This study sought to understand how different climate change scenarios, changes in exposure, and socio-economic-technological vulnerability impact the risks and resilience of the sugarcane-bagasse-based energy system. The analysis of various scenarios demonstrated the advantages of a thorough drought risk analysis that considers variations in the hazard, exposure and vulnerability and their interconnectivity to inform the development of targeted policies and actions for drought events. The employed methodology effectively facilitated the spatially explicit placement and prioritization of risk mitigation measures. It also underscored the deep interconnections between risk components, which must be continuously monitored and analysed to achieve sustained risk reduction. The insights provided by this methodology, particularly regarding the intensity and geographic distribution of projected hazards, help identify regions requiring more urgent interventions. By illustrating the implications of different climatological scenarios, the study not only presents an overview of probable hazards but also raises awareness of the corresponding exposure and vulnerability, offering a comprehensive risk analysis framework.

Although the analysis incorporated 'what if' scenarios and assumptions to reduce vulnerability, it is important to recognise that these assumptions may vary across different regions, particularly with regard to sector organisation and access to technology. It would be beneficial for future research to evaluate these assumptions in the context of diverse regions in Brazil in order to ensure their accuracy and relevance. Furthermore, it is essential to acknowledge that a further analysis should consider the possibility that under certain drought conditions there would be no sugarcane expansion. Unfortunately, the model response was limited to predetermined expansion areas regardless of precipitation patterns, which does not reflect the reality that precipitation levels may be insufficient for expansion, resulting in sugarcane mills and field managers deciding not to expand.

It is important to acknowledge that the 'what if' scenarios in vulnerability, the sugarcane expansion scenarios and the climatological models possess inherent uncertainties that must be addressed when implementing the methodology. Climatological models have inherent uncertainties due to the complex nature of climate projections, which are contingent on natural variability, data limitations, human influence, and the approximations employed in modelling. The expansion analysis undertaken in this study was guided by standard expansion decisions. However, as previously highlighted, it is evident that certain scenarios exist in which sugarcane expansion may not occur. Consequently, the expansion scenarios may in fact overestimate the potential outcomes. In the context of vulnerability, the indicator can be readily tracked and is subject to change in accordance with developments in the sector.

The findings indicate that Brazil's sugarcane sector has the potential to make a substantial contribution to the energy grid, even in the context of increasing frequency of drought conditions and without the necessity for further expansion. In contrast to other renewable energy sources, the lack of new infrastructure to support electricity generation is not a concern, given that existing mills are already located in the region. Nevertheless, it would be prudent to exercise caution in pursuing further expansion, given that there are still important improvements that are required within the sector. For example, greater efficiency in water utilisation is necessary not only in large and modern mills but also in smaller facilities (Gonçalves et al., 2021), as well as more efficient boilers for the co-generation systems in all mills (Kabeyi and Olanrewaju, 2023), among other improvements. In addition to developments in policy, the objective is to facilitate greater integration into the electricity matrix.

The present analysis established a foundation for a dynamic drought risk analysis of the sugarcane-based energy generation system. Further application in other regions would facilitate a comprehensive understanding of the risk to the system throughout Brazil. Additionally, the risks generated by the sugarcane-based energy generation to other systems such as agriculture or biodiversity could be also assessed. The outcome of such an assessment could further inform expansion scenarios and thus the long term planning process. Biodiversity and the loss thereof could be also incorporated into the risk assessment itself to determine the impact of biodiversity loss on the sugarcane-based energy generation system and its contribution to its vulnerability. A further opportunity for improvement is the inclusion of the potential loss of ecosystems or changes in water quality and availability resulting from other land use changes, that could impact the sugarcane system and could be incorporated into future analyses.

CRediT authorship contribution statement

Jazmin Campos Zeballos: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Vinicius Bof Bufon:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology. **Zita Sebesvari:** Writing – review & editing, Supervision, Methodology. **Jakob Rhyner:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envadv.2025.100631.

Data availability

Data will be made available on request.

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