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From insufficient rainfall to livelihoods: understanding the cascade of drought impacts and policy implications

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Abstract. A cascade of drought impacts refers to a series of interconnected events that trigger a chain reaction of effects, extending beyond water scarcity to influence agricultural production, socioeconomic conditions, and the environment. This paper explores the role of society in mitigating drought impacts, particularly through policy responses. Conducting a case study in Ceará State, Northeast Brazil, we used a globally rare dataset of continuous drought monitoring encompassing 3.5 years (February 2019 to October 2022), complemented by interviews with smallholder farmers and agricultural extension technicians. Additionally, we analyzed policy documents related to public policies implemented at the local level. Using a classification of drought impacts as our analytical framework, our findings indicate that social, environmental, and economic impacts of drought are less frequently reported, suggesting that development policies are mitigating cascading effects on livelihoods. Most reported impacts are associated with hydrological drought, revealing the unintended consequences of investments aimed at increasing water supply. We emphasize the significant contribution of public policies in mitigating the cascading effects of drought, which go beyond increasing water availability and focus on strengthening the local economy.

1 Introduction

The guidelines of the Integrated Drought Management Programme (IDMP) for developing national drought policy in 2013 begin with a preface by Michel Jarraud, the then Secretary General of the World Meteorological Organization, who stated that "[b]oth at the national and regional scale, responses [to drought] are known to be often untimely, poorly coordinated and lacking the necessary integration. As a result, the economic, social, and environmental impacts of droughts have increased significantly in many regions of the world. We simply cannot afford to continue in a piecemeal mode, driven by crisis rather than prevention. We have the knowledge, we have the experience, and we can reduce the impacts of droughts. What we need now is a policy framework and action on the ground for all countries that suffer from droughts. Without coordinated national drought policies, nations will continue to respond to drought in a reactive way" (WMO and GWP, 2014). Many countries that regularly experience droughts now have both dedicated drought policies and other policies designed to increase resilience and reduce drought impacts. But how do we know if these policies are working? This study analyzed a continuously monitored drought impacts dataset, stakeholder interviews, and policy documents to assess if we have progressed since Michel Jarraud's statement and if drought policies are now coordinated, integrated, and focused on prevention rather than reaction.

Due to the complexity of drought, scholars are continuously engaging with and stay informed about the latest discussions and advancements in the subject because there is no universal definition of drought. This ongoing engagement highlights the multidisciplinary interest in the subject (Mishra and Singh, 2010; Lloyd-Hughes, 2014; Wilhite

and Glantz, 1985). In the context of climate change, defining drought becomes even more challenging as it is difficult to establish climatological norms for the various components of the local water balance. As human activities increasingly impact the environment, there is a growing need for an integrated approach that considers both natural and human factors. Recent research suggests that drought should be viewed and understood as a process, not merely a product. It involves complex interactions between natural and human-induced changes, such as climate change, land and water management, and human decision-making (AghaKouchak et al., 2021).

Different categories of drought are understood based on the specific context and disciplinary perspectives through which they are examined. For example, meteorologists might define drought in terms of precipitation deficits, focusing on meteorological drought, which is characterized by prolonged periods of insufficient precipitation, often coupled with increased evapotranspiration, affecting large geographic areas (Wilhite and Glatz, 1985). Agricultural scientists, on the other hand, might emphasize soil moisture levels and the impact on crops, leading to a focus on agricultural drought, which occurs when a lack of soil moisture prevents plants from growing, often due to precipitation shortages and/or high evapotranspiration rates (Wilhite and Glatz, 1985). Hydrologists typically concentrate on the availability of surface and groundwater resources, categorizing drought from a hydrological perspective, which includes negative anomalies in surface and groundwater, such as below-normal groundwater levels, reduced water levels in lakes, shrinking wetlands, and diminished river discharge (Van Loon, 2015). Another category, often considered by ecologists, is environmental or ecosystem drought, which refers to a temporary shortfall in water availability that pushes ecosystems beyond their vulnerability limits, disrupts ecosystem services, and triggers feedback loops within both natural and human systems (Crausbay et al., 2017).

When attempting to describe the social components intertwined with complex interactions, such as those found in socioeconomic drought, important questions arise about where the physical aspects of drought end and the human impacts begin. Socioeconomic drought has traditionally been linked to the imbalance between water supply and societal water demands (Wilhite and Glantz, 1985). However, this type of drought is not merely about the physical scarcity of water but rather the broader societal and economic consequences that arise from it. While recent reflections have expanded the concept of socioeconomic drought to include indirect impacts beyond just the lack of water (Kchouk et al., 2023), many still rely on indices based on physical data to assess these droughts. For instance, indices like the Water Resources System Resilience Index (WRSRI) are used to more accurately identify the onset and duration of socioeconomic drought events (SEDEs) (Wang et al., 2023b). The transition from meteorological and hydrological drought to socioeconomic drought has been analyzed using linear methods (Wang et al., 2023a). However, a significant limitation of these approaches is the absence of direct social data, such as the impacts on populations, economic activities, social vulnerability, or the public response to drought conditions.

Each of these drought types is closely intertwined with different societal impacts. For instance, hydrological drought may lead to diminished water availability for human and animal consumption, irrigation, and industrial purposes. Agricultural drought is distinctly associated with crop development impacts. Socioeconomic droughts impact people's lives, ecosystems, and economic activities. Meteorological drought is a key driver for all other drought impacts (Van Loon et al., 2016; Mishra and Singh, 2010). In this paper, we use these different types of drought impacts as an analytical framework by categorizing and evaluating the diverse impacts associated with each type of drought.

Although this classification is useful for presenting the results, we are in line with recent arguments that drought should not be perceived as an isolated event but as a continuous and interconnected phenomenon that evolves over time. Moreover, drought impacts cascade through society and economy at different speeds, affecting various groups and regions with varying intensities and timings, potentially far from where the drought originated (Van Loon et al., 2024). Therefore, there is a need for a comprehensive understanding of the compound and cascading impacts of droughts by considering interconnected natural and social systems and the complex interactions between different sectors affected by the impacts (de Brito et al., 2024).

We take the approach in which physical and social impacts are closely interconnected and in which drought impacts can cascade, wherein one impact is connected to another, forming a chain reaction of impacts (de Brito, 2021). For example, insufficient rainfall results in low soil moisture, leading to reduced crop development, which in turn yields reduced harvests. This translates to diminished earnings for the farmer, which contributes to higher food prices due to shortages, ultimately culminating in heightened food insecurity. Despite the consequences of these cascading impacts, we still have limited understanding of the relationships between them. Furthermore, research on the effects of response measures on the attenuation or exacerbation of cascading impacts is scarce (de Brito et al., 2024). To address these gaps here we focus on the societal aspects of drought impacts, a significant dimension often overlooked in drought monitoring, which traditionally concentrates more on the hydrometeorological drivers of these impacts (Kchouk et al., 2022).

Progress has been made in understanding the human impact on drought aggravation, such as the influence of reservoirs on hydrological processes (Ribeiro Neto et al., 2022; Ribeiro Neto et al., 2024) and groundwater depletion due to abstraction (Apurv et al., 2017). Yet there remains a notable gap in understanding the societal role in mitigating drought, which could be tackled by including social sciences in or-

der to capture the complexity of relationships of society and the environment in drought research (Kchouk et al., 2022; Savelli et al., 2022; Walker et al., 2022; G. Ribeiro Neto et al., 2023). Here, we expand on our previous study, which highlighted the importance of monitoring drought impacts in assessing drought, and advocate for the ongoing monitoring of impacts (Walker et al., 2024). We take a step further in this by approximating policy sciences to drought management by generating knowledge from the following research question. *How do drought impacts cascade and how do policy responses evolve to alleviate the impacts?* This paper aims to understand the role of society in mitigating drought impacts, particularly through policy responses. Through this research, we will explore the intersection of drought management and policy sciences by generating insights into the role of public policies in alleviating the impacts of drought.

To explore this question, we consider Ceará, Northeast Brazil, because it is the state with the most advanced implementation of Drought Monitor (*Monitor de Secas*), Brazil's official drought monitoring initiative led by ANA and partners. The state is in the final step of incorporating local on-the-ground impact data from agricultural extension technicians, hereinafter referred to as observers. Our analysis integrates three distinct qualitative datasets. The first dataset is a globally rare example of continual spatially distributed impact monitoring conducted by observers who provide agricultural assistance to farmers. The second comprises information gathered through interviews of smallholder farmers and observers during fieldwork. The third consists of policy documents related to public policies implemented in the region.

In this study, we leverage data from traditionally low-data environments, recognizing the significance of these often-overlooked sources as a valuable epistemic contribution to the study of droughts. We integrate and validate these datasets to demonstrate their critical role in enhancing our understanding of drought dynamics, particularly in regions that are among the most vulnerable to drought, yet lack robust on the ground information. Our focus is specifically on the impacts on smallholders, commonly collectively referred to as family agriculture in Brazil, as they represent one of the groups most vulnerable to the effects of climate extremes.

2 Methodology

This research constitutes a case study investigating the role of policy responses in alleviating the impacts of drought. Specifically, we delve into the context of Ceará State to obtain insights by examining the effects of particular policies implemented in the region on mitigating drought impacts.

2.1 Study area

The map of Fig. 1 illustrates the geographic layout of Ceará State, located in Northeast Brazil, which covers a total area of approximately 148 920 km^2. The state is divided into 184 municipalities, as outlined by the purple boundaries on the map. These municipalities are home to around 9 million people. In addition to the municipal boundaries, the map highlights the semiarid region of Ceará with a light orange shading. This semiarid delimitation is significant as it encompasses areas that are particularly susceptible to droughts and related environmental challenges. The semiarid region covers a substantial portion of the state, influencing both the climate and the socioeconomic conditions of the municipalities within this area.

The state has various economic activities, with key sectors including industry, particularly textiles and automotive manufacturing, and tourism driven by its tropical beaches and wind sports. Additionally, agriculture plays a crucial role, featuring crops like sugarcane, corn, beans, and fruit. This agricultural sector, particularly family farming, is most impacted by drought, affecting both medium to large farmers and smallholder farmers (Pereira and Cuellar, 2015).

The region is semiarid, with a history of drought events (for more details on drought in the region, see Marengo et al., 2017). The most recent multi-year drought event (2012–2018) affecting the region led to a state of emergency and impacted the economic growth of the municipalities (De Oliveira, 2019). During this drought, the Drought Monitor was implemented after a lengthy period of political and technical negotiations (for more information, see Cavalcante et al., 2023; Gutiérrez et al., 2014), starting in 2014 with the Northeast Region. It has since incrementally been expanded to cover all Brazilian states. Within the context of this tool, a map of drought severity is developed and published online every month at https://monitordesecas.ana.gov.br/ (last access: 12 August 2024).. Overall, it is a tool to support dialogue between states and the federal government in addressing drought risks and conditions and drought preparedness planning.

The mapping process for drought involves integrating relevant regional meteorological databases and remote sensing analyses to compute indices. Validation follows ground observations of drought impacts from networks of observers. This collaborative effort aims to establish ground truth in the Drought Monitor using monthly questionnaires completed by every municipality. It was initiated in Ceará in 2019 by the state government's rural and agricultural extension service (in Portuguese, *Empresa de Assistência Técnica e Extensão Rural do Ceará*), hereafter referred to as *Ematerce*. The collected data validate the mapping process and contribute to refining drought monitoring systems. Although the research had a weakness in starting monitoring during a non-drought period, it still provided insightful findings on the effects of

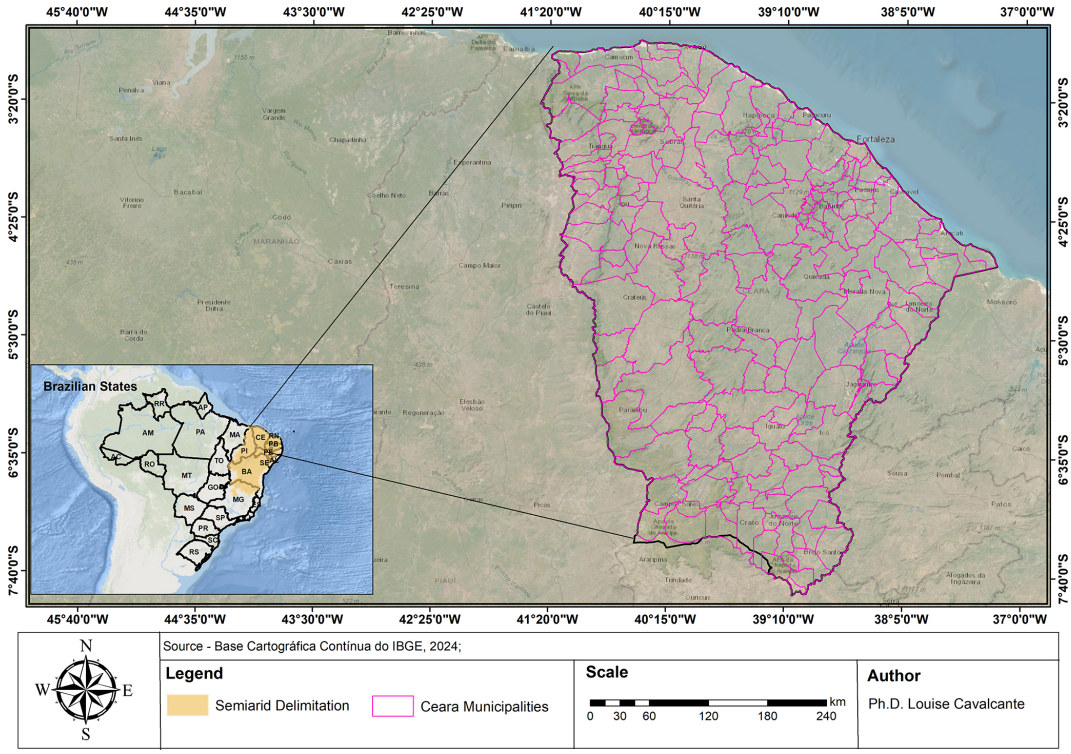

Figure 1. Geographic overview of Ceará State, Brazil.

drought in the area, even in years that were not considered statistically dry.

2.2 Study data

This research uses a range of qualitative data asynchronously gathered in a multi-step approach. We used three qualitative datasets (1) obtained from an innovative drought monitoring instrument in Brazil, (2) interviews with smallholder farmers and observers during fieldwork in Ceará State, and (3) policy documents on public policies implemented in the region (Table 1).

The data collection process for this study was designed to capture the multifaceted impacts of drought in the region. We employed a comprehensive approach by triangulating multiple data sources and methodologies to capture a holistic understanding of the phenomenon. Figure 2 presents a workflow outlining the sequential steps involved, each corresponding to a specific dataset. For a more comprehensive overview with steps and codes, we refer readers to Sect. S1 in the Supplement and to another study using the drought monitoring dataset (Walker et al., 2024).

2.2.1 Drought impacts monitoring data

Observers collected the first dataset as part of their job routine. In addition to their various tasks, they regularly complete monthly questionnaires for each municipality, providing information on drought impacts and other relevant information. Employed by *Ematerce*, these observers are based across the state, with most offices overseeing two or three municipalities, covering 184 municipalities. Thematic analysis was conducted on the responses in order to identify recurring patterns and themes. This type of analysis is particularly suitable for areas lacking empirical research and provides a rich description of predominant themes across the dataset (Braun and Clarke, 2006). Data validation interviews were conducted with observers to ensure the accuracy and comprehensiveness of the reported information.

In the homogenization step, we were interested in finding a common terminology to unify the understanding of local impacts observations, to achieve simplicity and manageability of data, to add clarity and focus regarding the most common patterns, and to increase readability. The outcome of this effort was the identification of 14 distinct impact types (Table S3 in the Supplement), which were then classified into impacts due to drought impacts classification, i.e., the hydrological, agricultural, and social–environmental–economic impacts of drought.

2.2.2 Fieldwork data

Interviews and/or casual conversations were conducted with 60 smallholder farmers across multiple visits to the study area. Questions were formulated to encourage participants to describe the drought risks, impacts, and factors increasing

Table 1. Summary of datasets used in this research.

Dataset	Period of data collection	Scale
Drought impacts monitoring data	February 2019 to October 2022	municipality level
Fieldwork data	July 2019, November and December 2021 April 2022	household level
Policy documents data	not applicable	national and state levels

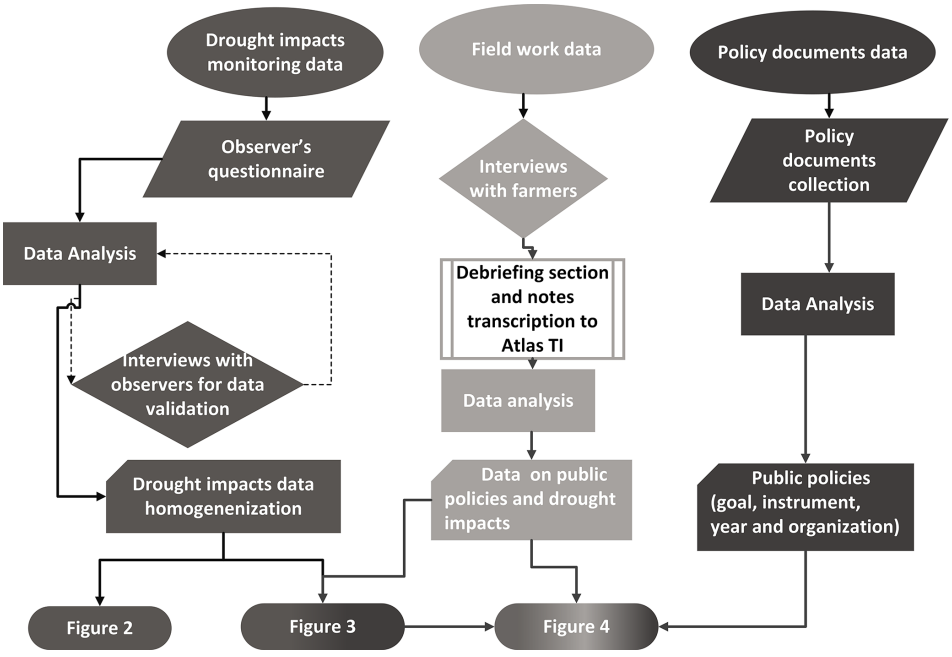

Figure 2. Summary of data collection and analysis methodology.

or decreasing the likelihood of impactful drought over time in the study area. The interviewees were randomly chosen. Some were more in-depth interviews that lasted 1 h, in other cases a short conversation, depending on the person's availability. All the interviewees provided consent before being interviewed. The interviews were not recorded but fieldwork notes were written up either while the interview was ongoing or immediately afterwards. Fieldwork notes were transcribed and analyzed using Atlas.ti software to identify key themes and patterns related to drought impacts and public policies.

2.2.3 Policy documents data

Policy documents specifically related to supporting farmers, their families, and rural communities were collected to gain a complete understanding of the objectives, strategies, and implementation frameworks of these relevant policies and programs within the study area. They were analyzed for descriptive information and coded for key elements such as goals, instruments, and responsible organizations.

One limitation is that policy documents may not always accurately reflect the actual implementation or impact of a policy. To overcome this limitation, we also used our fieldwork experience and interviews to understand the nuances about the implementation of policies and their influences on livelihoods on a local level.

2.2.4 Analysis and synthesis

We used deductive reasoning to categorize the three types of impacts of drought. With this framework, we started to develop the different cascades in relation to the most common impacts recognized in our fieldwork campaigns. The relationship between drought impacts and policy responses was explored to elucidate how policies evolve to mitigate the cascading effects of drought.

3 Results

Figure 3 presents 1933 reported impacts*[1], categorized into three main types: hydrological, agricultural, and social–environmental–economic impacts of drought. These impacts were assessed based on an open question where observers were given the freedom to express what they considered relevant during that period. Consequently, the reported impacts were not limited to drought alone; for instance, impacts related to pests and socioeconomic impacts that may or may not have been aggravated (or alleviated) by drought were reported.

The bars reveals that most impacts are linked to hydrological drought ($N = 1.187$), with agricultural drought ($N = 718$) being the next most common. In contrast, social–environmental–economic impacts of drought ($N = 28$) exhibit the lowest frequency. Due to scale considerations, this bar's details are unclear. These impacts include wildfires (8), high production costs (9), and socioeconomic impacts* (11).

An intriguing finding was the equal frequency of impacts (238) related to crop losses caused by excessive rainfall and insufficient rainfall. Subsequent interviews with observers confirmed that excessive rainfall caused losses, including both waterlogging of low-lying areas and untimely rains during harvest. This refers to high-intensity rainfall or excessive rainfall at unexpected times, rather than simply high volumes. From our interviews, we learned that beans are the crop type most impacted by excessive water.

Drought impacts cascade in various directions. In Fig. 4, we illustrate several potential directions based on the main impacts reported in the observer's monthly questionnaires (Fig. 3), complemented with fieldwork notes about the cascade in a local level. This is a simplification of a full range of cascading impacts.

Cascade direction number 1, insufficient rainfall causing hydrological, agricultural, or social–environmental–economic impacts of drought. This direction can follow various paths, directly extending from the primary driver to others. Insufficient rainfall can lead to localized water scarcity, crop development impacts, and increased risk of wildfires. For example, municipalities have indicated that the absence of rainfall, coupled with low air humidity and elevated temperatures, has led to fires in certain regions.

Cascade direction number 2, hydrological impacts of drought to social–environmental–economic impacts of drought. Low water availability for human consumption may have socioeconomic consequences, necessitating spending on water trucks to fulfill household requirements. For example, in cases of reduced rainwater cistern levels designated for human consumption or low reservoir levels, households turn to buying water from water trucks to replenish their cisterns.

Cascade direction number 3, agricultural impacts of drought to social–environmental–economic impacts of drought. Deficiency in soil moisture can adversely affect the cultivation of crops intended for livestock feed, leading to the purchase of expensive animal feed. For example, the decrease in soil moisture in the allocated floodplain area designated for the cultivation of grass and sorghum for silage provision during dry periods has led to a consequential shift in agricultural practices. Consequently, some farmers have decided to sell a portion of their livestock, thereby reducing the size of their herds, enabling farmers to buy extra complements like soybeans to feed their animals.

Cascade direction number 4, agricultural impacts of drought leading to hydrological impacts of drought. Reduced soil moisture for crop development requires irrigation, prompting individuals to draw water from reservoirs, potentially resulting in diminished reservoir levels. For example, in 2015, the Pirabibu reservoir's water level dropped to zero due to human pressure on irrigation for producing forage during a period of precipitation deficit. This process is explained in details by Kchouk et al. (2023)

Cascade direction number 5, hydrological impacts of drought leading to agricultural impacts of drought. The hydrological impacts of low reservoir levels (resulting in reduced streamflow and low groundwater levels) and soil-moisture drought can affect the growth of crops and lead to insufficient water available for irrigation. For example, such conditions are applicable to maize cultivation, where insufficient soil moisture hinders fruit development, leading to a deceleration in the growth of the plant.

Cascade direction number 6, within the social–environmental–economic impacts of drought. These impacts are interconnected with the livelihoods and well-being of farmers and households. For example, agricultural losses, which result in less feed for animals, cascade into an extra expense for formers, forced to buy feed in the market. Consequently, there is a reduced margin and loss of income. Therefore, farmers will sell their assets – livestock – resulting in a greater loss of income.

Figure 4 demonstrates how policy responses intervene to alleviate the ongoing drought impact cascade. To enhance readability and comprehension, policies are represented with pictures taken during fieldwork. Table 2 provides a comprehensive overview of these policies, detailing the specific issues addressed by them, the type of instruments employed to address each problem, the year of enactment, and the managing organization.

Policy response path A. From hydrological drought impacts to agricultural impacts of drought, two policies are implemented: one is the *production cistern* (A1), 52 m^3 rainwater harvest reservoirs providing water for livestock and small-scale irrigation to guarantee food security for households.

[1]* "Socioeconomic impacts" combines rare examples of impact codes such as "loss of income" (one occurrence), "migration to urban areas" (one occurrence), "livestock farmers suffering" (four occurrences), "reduced economy" (one occurrence), "social impacts" (one occurrence), and "worrying situation" (three occurrences).

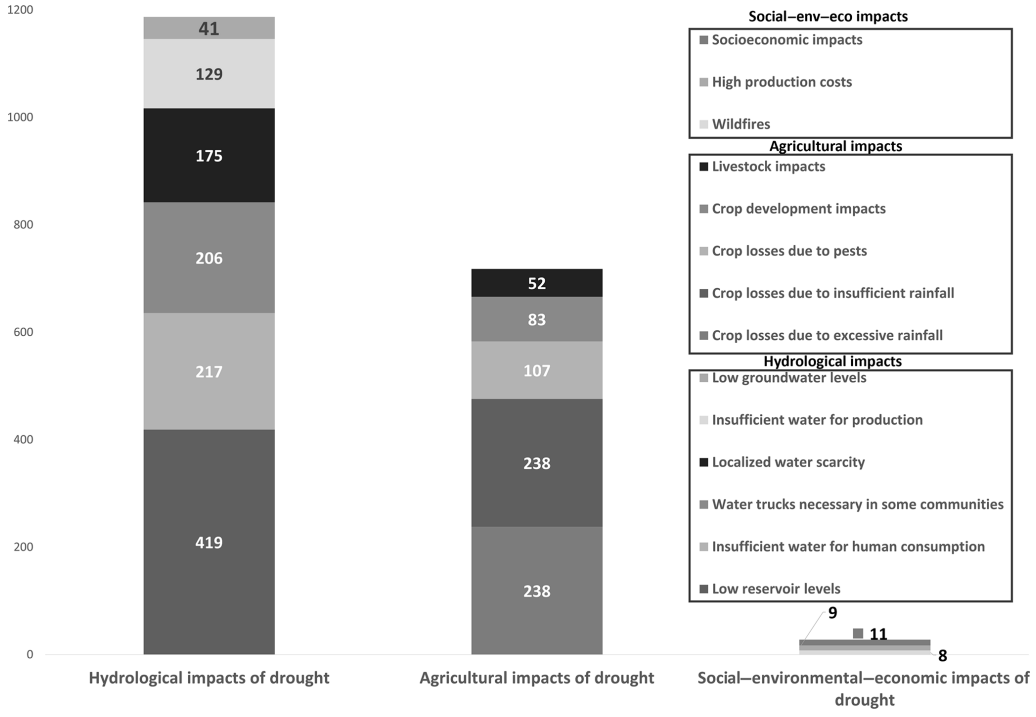

Figure 3. Number of impacts reported by observers in relation to categories of drought.

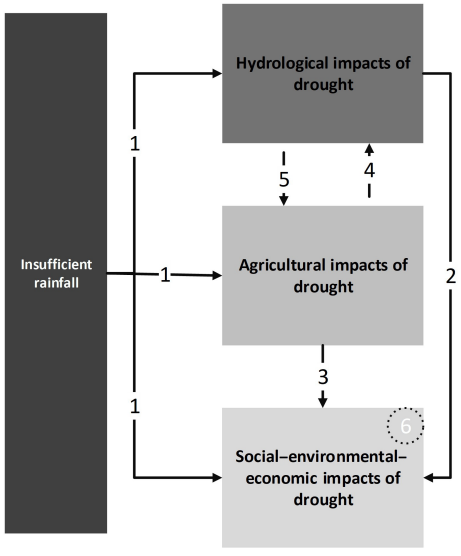

Figure 4. Schematic illustration depicting various directions for the cascading of drought impacts.

Another is *Hora de Plantar* (A2), the distribution of beans and maize seeds with high genetic potential for drought resistance to smallholder farmers prior to the rainy season. This is the only policy specific to Ceará State; all others are national policies.

Policy response path B. From hydrological to social–environmental–economic impacts of drought, two policies are represented: one is the *cistern* (B1) with 16 m^3 rainwater harvest reservoirs for domestic purposes. Second is *water trucks* (B2) for distributing water for domestic uses, coordinated by the federal government in collaboration with the Ministry of National Integration and the Ministry of Defense.

Policy response path C. Addressing the agricultural and social–environmental–economic impacts of drought is *Garantia Safra* (C), a cash transfer insurance program that provides payments to farmers facing 50 % or more crop losses due to drought or excess water. Smallholders are required to enroll in the program annually within their municipality. The financial responsibility for *Garantia Safra* is distributed among farmers, municipal administrations, federal states, and the federal government. This policy response helps mitigate the socioeconomic consequences of crop losses by providing financial support to the affected farmers, thereby preventing further cascading impacts.

Policy response path D. From insufficient rainfall to social–environmental–economic impacts of drought, one policy is *Bolsa Família* (D2), a conditional cash transfer (≈ USD 120) for families. Conditionalities ensure that children attend school and receive necessary vaccinations. Second, the Food Acquisition Program (*PAA*) and the National School Feeding Program (*PNAE*) (D1) are public procurement policies that promote social inclusion and poverty reduction by connecting small-scale farmers with government institutions that procure food. Regarding the *PAA*, one farmer mentioned that "the [*PAA*] … during the dry season is helpful because it is guaranteed, and you can already count on the

Table 2. Policies implemented in the region.

Policy response*	Problem the policy address	Instrument	Year of enactment	Managing organization
National Program for Strengthening Family Agriculture (*PRONAF*)	lack of access to credit by smallholders	rural credit lines	1995	Ministry of Agriculture, Livestock and Supply
Crop Guarantee (*Garantia Safra*)	crop losses	cash transfer	2002	Ministry of Agrarian Development and Family Agriculture
Family Allowance (*Bolsa Família*)	families in extreme poverty conditions	cash transfer	2003	Ministry of Development and Social Assistance, Family and Fight Against Hunger
Cisterns (*Programa 1 milhão de cisternas*)	water access for domestic uses	rainwater harvest reservoirs	2003	Ministry of Social Development
Second water cisterns (P1 + 2)	water access for productive uses	rainwater harvest reservoirs	2015	Ministry of Social Development
Food Acquisition Program (*PAA*)	insufficient market for smallholder farmers	public procurement contracts with smallholder farmers	2003	Ministry of Social Development
National School Feeding Program (*PNAE*)	insufficient market for smallholder farmers	public procurement contracts with smallholder farmers to supply schools	2010	Ministry of Education
Water trucks (*Operação Carro Pipa*)	lack of water for domestic purposes	distribution of water	2012	Ministry of National Integration and the Ministry of Defense
Time to Plant (*Hora de Plantar*)	lack of drought resistant seeds and seedlings	distribution of seeds and seedlings of high genetic potential to smallholder farmers	1987	Ceará State – Secretary of Agrarian Development
Family Health Strategy (*Estratégia Saúde da Família*)	human diseases	basic healthcare (doctors, nurses, hospitals)	1991	Ministry of Health

* Policy response translated to English with the equivalent name in Portuguese in brackets.

resources." Third is the National Program for Strengthening Family Agriculture (*PRONAF*) (D3). Access to rural credit enables farmers to obtain financing under favorable conditions tailored to their needs and interests.

The data analysis indicates that social–environmental–economic impacts have the lowest frequency of reporting, suggesting that public policies may have been effective in alleviating some of the cascade of impacts. However, this should not be generalized to environmental impacts, as farmers and observers might not have reported on the state of ecosystems, including forests, freshwater systems, and water quality in lakes and rivers. Additionally, no specific policies targeting the alleviation of environmental impacts were identified. It is important to acknowledge that the low frequency of reported socioeconomic impacts may not necessarily indicate a reduction in these impacts. Instead, it could reflect the way the data were collected or what people chose to focus on. Tangible impacts, such as reduced crop yields, are often easier to notice and record compared to less tangible or indirect impacts like migration or reduced income. Therefore, drawing conclusions about the effectiveness of policies based solely on the frequency of mentions is limited. A more robust analysis would require quantitative measurements of individual impacts or evidence that the low number of mentions is not due to biases in data collection or reporting.

Fieldwork interviews revealed that droughts at present are less impactful because of the social protection net that exists with programs like *Bolsa Família*. One interviewee mentioned that in the 1993 drought, they did not experience thirst, but this drought left a significant mark because they were pregnant with their first daughter at the time. Food was scarce, and they had to resort to eating a local bird, a low-nutrition food that they would never eat if it were not an emergency. There was no assistance from the government; they said "with money, one could buy everything". This drought's main impacts were on food, water, and later finances. In contrast, they mentioned that during the 2012–2018 drought, fish died in the mud, and only one water truck ($16\,m^3$) would come per month for 20 families. This scarcity led to conflicts, albeit minor. They received crop insurance, and the impacts were primarily related to water scarcity. Despite the 2012–2018 drought being statistically more severe than the 1993 drought, the support of social programs made the impacts less severe.

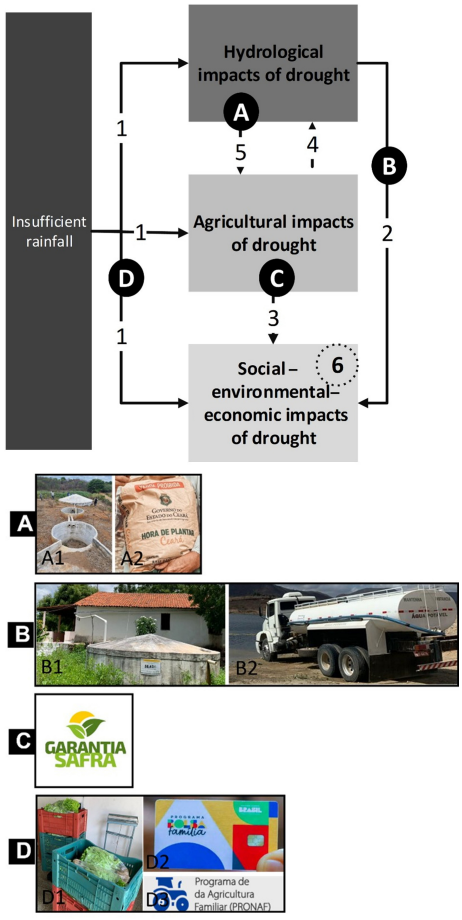

Figure 5. Policy responses and their role in alleviating the cascade of drought impacts.

4 Discussion

Our research findings indicate that policy responses play a crucial role in alleviating the cascade of drought impacts, leading to variations in the distribution of these impacts depending on the extent of local implementation. The reduction in the frequency and severity of impacts, particularly on livelihoods, reflects the positive effects of development policies in fostering economic dynamism within the region. Programs such as *Bolsa Família*, *Garantia Safra*, the Food Acquisition Program (*PAA*), and the National School Feeding Program (*PNAE*) have been instrumental in "breaking" the cascade into socioeconomic impacts by providing crucial financial resources to vulnerable populations, thus giving them the means to cope with drought. Stakeholders, including farmers and observers, noted that recent drought periods (2012–2018) were more manageable compared to the past (1980s and 1990s) when such governmental programs were absent. Today, droughts no longer result in hunger and mass migration in the rural communities of the Brazilian semiarid region as they once did. However, it is important to recognize that while these welfare programs have significantly mitigated the immediate impacts of drought, they may have done so more by providing temporary relief rather than by promoting long-term adaptation strategies. This suggests that while the population is better equipped to manage droughts, they are not fully adapted to the phenomenon, highlighting the need for a continued focus on sustainable adaptation measures (Mancal et al., 2016).

However, while these programs have significantly contributed to "breaking" the cascade of socioeconomic impacts by fostering long-term resilience, their effectiveness is contingent on integration with broader strategies aimed at sustainable development and climate adaptation. This concern is particularly relevant as climate change continues to transform the risks faced by individuals and households, potentially exacerbating poverty, inequality, and social instability. Therefore, while the population is better equipped to manage droughts, they are not fully adapted to the phenomenon, highlighting the need for an integrated approach where social protection is aligned with climate policy to strategically contribute to long-term resilience and wellbeing (Bedran-Martins et al., 2018). Although these programs have succeeded in improving material quality of life and increasing the Human Development Index score, they do not fully address the multifaceted nature of vulnerability in the context of climate change. For example, despite the improvements in material conditions, the subjective wellbeing of households continues to be influenced by factors beyond economic security, such as health status and safety (Costella et al., 2023).

This perspective aligns with other research indicating that the insurance has transformed into a regular cash transfer linked to regular crop losses, serving more as financial support for household expenses rather than cover for productive costs (Milhorance et al., 2020). However, while research suggests *Bolsa Família* has positively impacted income, it does nothing to address the risk of food insecurity during drought events. This indicates a "poverty trap", where families continuously struggle with drought challenges without overcoming the underlying conditions that render them vulnerable (Lemos et al., 2016). During our study, we identified public procurement initiatives supporting family farming as a noteworthy case for overcoming this "poverty trap". Families exhibited greater resilience to drought-related challenges due to increased income, enabling them to enhance and diversify their production for the *PAA* and *PNAE* (Kchouk et al., 2025). Those are not reactive policies aiming to address one cascaded impact but rather to stop the cascade from agricultural impacts to impacts on livelihood, creating economic stability for families that have diversified their production. The *PAA* offers access to a stable market and increases farmers' income by providing a reliable market for their produce (Mesquita and Milhorance, 2019).

Many reports emphasize ongoing water supply challenges, indicating that despite the construction of reservoirs, hydrological drought continues to pose significant challenges in

the semiarid region. While policies have prioritized the extensive construction of reservoirs to enhance water supply (Cavalcante et al., 2022), the persistent issue of water access remains (Gutiérrez et al., 2014). This exhibits signs of maladaptation, leading to increased water consumption and insufficient water redistribution among regions (Machado and La Rovere, 2018). As a result, these are indications of unintended consequences due to the interactions between human activities, water infrastructure, and natural systems (Di Baldassarre et al., 2018; Ribeiro Neto et al., 2022). Another illustration of this is the promotion of non-adapted crops for the region, such as the cultivation of rice. This highlights a pattern wherein reliance on water resources has increased gradually due to incentives for economic activities not aligned with the region's environmental conditions.

The distribution of water trucks by the *Operação Carro Pipa* policy depends on the severity of drought. When municipalities declare an "emergency situation", it is legal recognition by the affected municipality of an exceptional situation caused by a disaster. However, our qualitative data showed that there are other ways in which water trucks are distributed. Some municipalities operate their own water trucks, allowing them to make independent decisions regarding water usage. Farmers also have the option to directly purchase private water trucks. Our interpretation for the high number of impacts reported as "water trucks necessary in some communities ($n = 206$)" is that they cannot always be considered impacts. Rather, it reflects an ongoing regional dynamic – water trucks are part of the water system, used to avoid the cascade into a water shortage – that persists regardless of the formal classification of the period as a severe (or weak or non-existing) drought (Walker et al., 2024).

The focus on environmental drought was to highlight the interconnectedness of natural and human systems (Srivastava and Maity, 2023). The experiences of those directly affected by drought in Northeast Brazil offered powerful insights into the real-world impacts of this phenomenon, revealing that drought extends far beyond water scarcity. While the more visible effects, like reduced crop yields, are often easier to notice and report, the less tangible or indirect impacts on ecosystems frequently go unaddressed. Future studies should aim to bridge this gap by specifically examining ecological drought impacts and how they affect biodiversity, allowing for a better understanding of how these impacts are distributed in ecosystems.

A cascade typically refers to a series of events or processes linked and often result in a chain reaction. Our approach looked at individual alleviation of drought impacts. It is a simplification representing the cascade as a linear process following from agricultural impacts of drought progressing to hydrological and then to social–environmental–economic impacts, or just connecting one type of drought impact to another. A recent study investigating the 2018–2019 drought in Germany used sequential pattern-mining analysis, revealing that the impacts exhibited simultaneous and distinct patterns (de Brito, 2021). It is worth mentioning that we attempted to analyze our dataset using the same methods to identify patterns of drought impact cascades. However, the limited quantity of data proved insufficient for the machine to detect patterns. This could have helped us recognize additional types of connections between patterns that may not have been apparent through human reasoning alone. Despite our efforts and endorsement for this analysis approach, our attempt was unsuccessful due to methodological limitations.

While studies using machine learning to study drought impacts represent a notable advancement in drought management, we advocate for the integration of social and qualitative data to gather the perspectives of people "on the ground" who directly experience the impacts. This is crucial because the collective capacity of stakeholders across different scales (spatial, jurisdictional, and temporal) determines whether a system adapts, collapses, or shifts in response to drought (Kchouk et al., 2025). Artificial intelligence does not yet capture these nuances of adaptation or impacts that only the experience of local context can provide. Our study, which leverages data from traditionally low-data environments, highlights the importance of integrating and validating these often-overlooked sources. This approach enriches our understanding of drought dynamics, particularly in vulnerable regions, highlighting how such data can reveal the nuanced impacts of drought on smallholders. These smallholders are among the most vulnerable to climate extremes, and their experiences provide valuable insights into how policy measures can better support long-term resilience.

Our recommendation for practice is to invest in climate adaptation projects within the region. It is noteworthy that the region receives less research and financial attention from both the government and international donors than the Amazon region (Santos et al., 2011). We suggest the promotion of local crop varieties and adapted breeds aligned with the cope-with-drought approach (Cavalcante et al., 2022) and the consideration of local practices that have achieved a sustainable balance between their livestock and milk production, enabling them to thrive even during prolonged drought periods (Kchouk et al., 2023). We also propose implementing policies that enhance ecosystem services, such as soil conservation and water retention through agroforestry practices, to further alleviate residual drought impacts in the semiarid region.

In response to Michel Jarraud's claim, our investigation revealed that policy responses have been somewhat effective in alleviating the socioeconomic impacts due to the development policies in place. However, drought-related policies still tend to be reactive, such as implementing crop insurance only after drought impacts have occurred. This reactive approach presents an opportunity for improvement. For instance, moving towards proactive policies, such as utilizing cash transfers based on forecasted impacts rather than responding to those that have already happened, could enhance the effectiveness of drought management. This shift empha-

sizes the importance of forecasting and associated proactive measures. After several years of research and discussion on drought, we advocate that drought should be managed as a cross-cutting issue that impacts multiple sectors simultaneously, necessitating a comprehensive and interconnected approach. Droughts' far-reaching impacts go beyond water scarcity, influencing agricultural production and socioeconomics, as well as increasing the risk of fires. Therefore, we highlight the significant role that public policies can play in mitigating the cascading effects of drought, particularly those impacts not directly related to increasing water availability.

This analysis opens space for further research in other regions of the world where drought impacts are also monitored, for instance the USA (https://droughtmonitor.unl.edu/, last access: 12 August 2024) and central and eastern Europe (https://questionnaire.intersucho.cz/en/, last access: 12 August 2024). This type of analysis should be conducted to assess policy effectiveness to deal with drought impacts, and this can only be done with continual drought impacts monitoring, which is unfortunately lacking in most of the world (Smith et al., 2025). Another avenue for further investigation lies in longitudinal studies covering extended periods, encompassing periods characterized by both drought and rainfall occurrences, thereby comprehensively addressing diverse hydrological circumstances. This aspect, which was not explicitly delineated in the present study, represents a crucial limitation that requires attention in future research.

5 Conclusion

This study aimed to understand the role of society in mitigating drought impacts, particularly through policy responses. Among the least frequently reported impacts were those pertaining to the social–environmental–economic aspects of drought, particularly affecting livelihoods. Most impacts were hydrological, suggesting that the construction of reservoirs may not have adequately addressed the challenges posed by the semiarid region, leading to unintended consequences of overreliance on these reservoirs.

Despite the positive impacts of public policies that stimulate economic activity within the region, persistent socioeconomic impacts of drought persist. Therefore, we emphasize the significant contribution of public policies to mitigating the cascading effects of drought impacts that extend beyond simply increasing water availability.

Our analysis also highlights a tendency towards reactive rather than proactive policy measures, as evidenced by the implementation of crop insurance initiatives post-event. This suggests a need for more proactive policy approaches to drought management, evidenced in our research by the distribution of beans and maize seeds with high genetic potential for drought resistance to smallholder farmers prior to the rainy season.

For drought management, we recommend that drought should be managed as a cross-cutting issue that affects and is relevant to multiple sectors simultaneously, necessitating a comprehensive and interconnected approach to its understanding and addressing. We also raise attention to the limited number of adaptation projects within the semiarid region and a lack of financial and research support compared to more prominent regions in Brazil, such as the Amazon. For future research, we advocate for the integration of social and qualitative data alongside machine learning approaches to comprehensively capture the nuanced dynamics of drought impacts and adaptation strategies.

Data availability. Data are available on the https://data.4tu.nl/ platform. The access link is https://doi.org/10.4121/ee5c62e1-438a-4a29-be00-1d736579b0e1.v1 (Cavalcante et al., 2025).

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Author contributions. LC and DWW initiated the original idea and conceptualized the research in collaboration with SK and GRN. LC, SK, GRN, and DWW conducted fieldwork interviews and the analysis of data. DWW analyzed the impact monitoring data with the support of LC, SK, and GRN. LC analyzed the policy documents data. TMNC and MMdB performed natural language processing and analysis. The research was supervised by WP, DWW, AD, and PRvO. PRvO acquired financial support for the project that lead to this publication. All co-authors contributed to the interpretation of the results and to the article writing.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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