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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 impacts, extending beyond water scarcity, to affect agricultural production, socio-economic factors, and the environment. This paper aims to understand the role of society in mitigating drought impacts, particularly through policy responses. Conducting a case study in Ceará state, northeast Brazil, we used a global rare dataset of continuously drought monitoring, complemented by interviews with smallholder farmers and agricultural extension technicians. Additionally, we analyzed policy documents related to public policies implemented at the local level. Employing a classification of drought impacts as our analytical framework, our findings indicate that socio-environmental-economic impacts of drought are less frequently reported, suggesting that development policies are mitigating cascading effects on livelihoods. Most impacts are associated with hydrological impacts of drought, suggesting unintended consequences of investments in increasing water supply. We emphasize the significant contribution of public policies to mitigating the cascading effects of drought, which do not necessarily involve increasing water availability, but strengthen the local economy.

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1. Introduction

The Integrated Drought Management Programme (IDMP)'s guidelines for developing national drought policy begin with a preface by Michel Jarraud, the then secretary-general of the World Meteorological Organization, who stated in 2013: "Both 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 & 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 drought policies are now coordinated, integrated and focused on prevention rather than reaction.

Droughts are often classified into different categories depending on their duration, spatial extent and intensity (Tsakiris et al., 2007). For instance, insufficient precipitation characterizes metereological drought, potentially accompanied by an increase in evapotranspiration, persisting for a prolonged duration across extensive geographic regions (Wilhite et al., 1985). Soil-moisture drought, also referred to as agricultural drought, is a lack of water in the soil that prevents plants from growing, instigated by precipitation shortages and/or high evapotranspiration rates (Wilhite et al., 1985). Hydrological drought encompasses negative anomalies in surface and groundwater, such as below-normal groundwater levels, reduced water levels in lakes, shrinking wetlands, and reduced river discharge (Van Loon, 2015). Socioeconomic drought was often linked to the unbalance between water supply and societal water demands (Wilhite & Glantz, 1985). However, this type of drought is not about the physical lack of water itself, but rather about the societal and economic consequences of drought. As such, recent reflections have broadened the concept of socioeconomic droughts to include indirect impacts beyond a lack of water (Kchouk et al., 2023).

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 (Mishra & Singh, 2010; Van Loon et al., 2016). 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.

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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., n.d.). 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 drought impacts can cascade, in which 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 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; Ribeiro Neto et al., 2023). Here, we expand on our previous study, which highlighted the importance of monitoring drought impacts in assessing drought, and advocates for 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 most advanced state in Brazil with the implementation of the Drought Monitor, with the final step of incorporation of local on-the-ground impacts 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 spatially distributed, continual impacts monitoring conducted by observers, who provide agricultural assistance to farmers. The second comprises information gathered through

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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 focus on the impacts on smallholders. In Brazil, this is referred to as family agriculture, because they are one of the most vulnerable group to climate extreme impacts.

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

Ceará State, located in Northeast Brazil, has a total area of 148,920 km^2 and approximately 9 million people living in 184 municipalities. The state has various economic activities, mainly the industrial, textile and automotive sectors, and tourism related to its tropical beaches and wind sports. Additionally, agriculture plays a crucial role, featuring crops like sugarcane, corn, beans, and fruits. It is this agricultural sector, particularly family farming, that is most impacted by drought, affecting both medium to large farmers and smallholder farmers (Pereira & 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 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, and has since incrementally expanded to cover all Brazilian states. Within the context of this tool, a map of drought severity is elaborated and published online every month at https://monitordesecas.ana.gov.br/. 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 ground truth in the Drought Monitor using monthly questionnaires completed per municipality. It was initiated in Ceará in 2019 by the state government rural/agricultural extension service (in Portuguese, *Empresa de Assistência Técnica e Extensão Rural do Ceará)* for now on referred to as Ematerce. The data collected validates the mapping process and contributes 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 drought in the area, even in years that were not considered statistically dry.

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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).

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
Field work data	July 2019, November and December 2021 and April 2022	Household level
Policy documents data	Not applicable	National level and State level

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 1 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 the supplement materials section S.1., and to another study using the drought monitoring data set (Walker et al., 2024).

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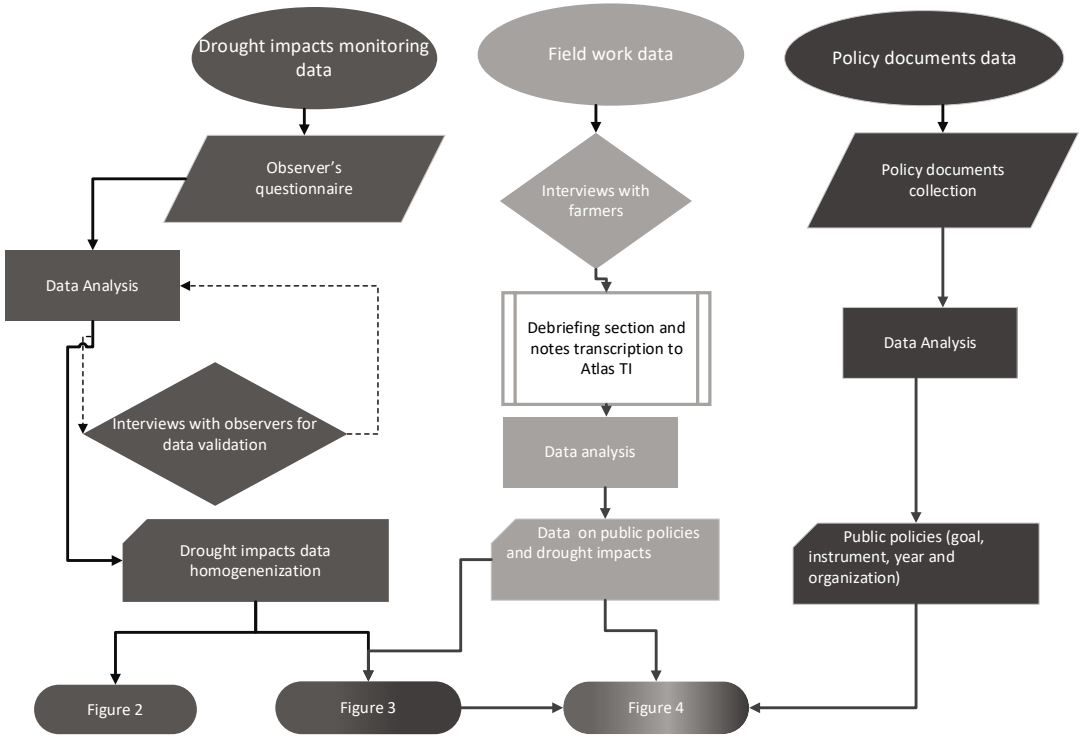

Figure 1: Summary of data collection and analysis methodology

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 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 & 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 on the most common patterns, and to increase readability. The outcome of this effort was the identification of 14 distinct impact types (S.3 in the Supplementary material), which were then classified into impacts due to drought impacts classification, i.e. hydrological, agricultural, and socio-environmental-economic impacts of drought.

2.2.2. Fieldwork data

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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 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 an hour, 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 either written up while the interview was ongoing or written up 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 were collected to understand the objectives and strategies of relevant policies and programs in 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 elaborate the different cascades in relation to the most common impacts recognized in our field work 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 2 presents 1,933 reported impacts*, categorized into three main types: hydrological, agricultural, and socio-environmental-economic impacts of drought. These impacts were reported in a 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 were reported, that may or not have been aggravated (or alleviated) by drought.

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, socio-environmental-economic impacts of drought (N = 28) exhibit the lowest frequency. Due to scale considerations, this bar has its details unclear. These impacts include: (8), high production costs (9), and socioeconomic impacts* (11).

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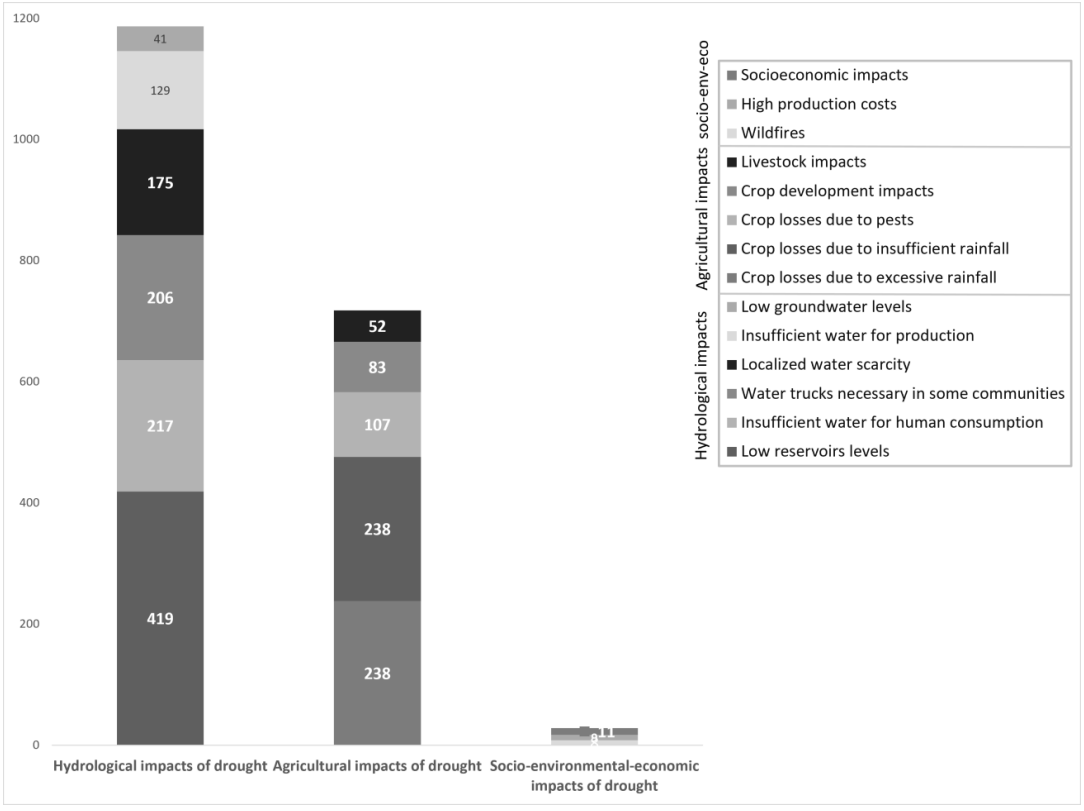

Figure 2: Number of impacts reported by observers in relation to categories of drought

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

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 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 Figure 3, we illustrate several potential directions based on the main impacts reported in the observer's monthly questionnaires (Figure 2), and complemented with fieldwork notes about the cascade in a local level. This is a simplification of a full range of cascading impacts.

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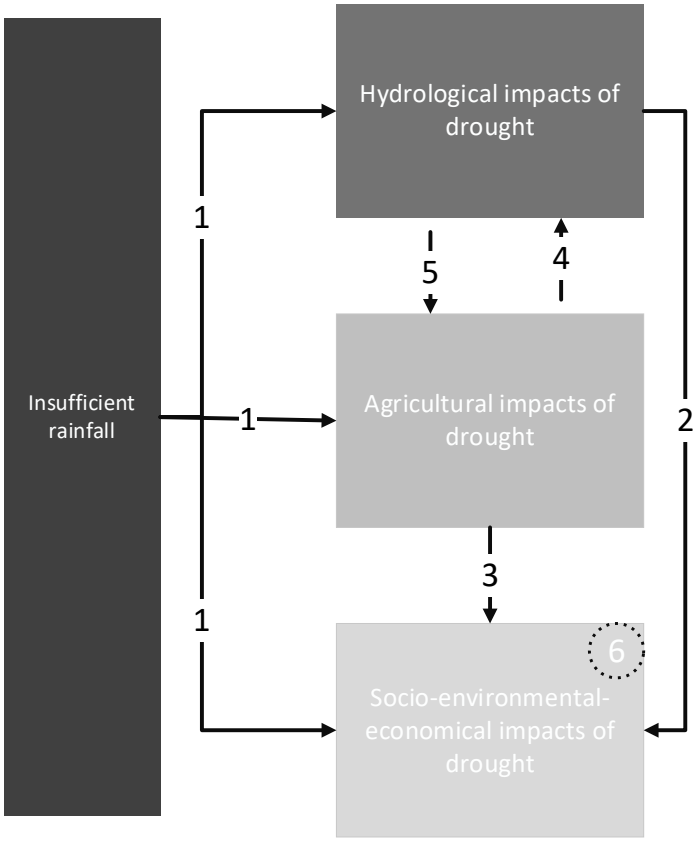

Figure 3: Schematic illustration illustrating various directions for the cascading of drought impacts.

Cascade direction number 1, insufficient rainfall causing hydrological, agricultural or socio-environmental-economical 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. E.g. 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 socio-environmental-economical impacts of drought. Low water availability for human consumption may have socioeconomic consequences, necessitating expenses on water trucks to fulfill household requirements. E.g. 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 socio-environmental-economical impacts of drought. Deficiency in soil moisture can adversely affect the cultivation of crops intended for feeding livestock, leading to the purchase of expensive animal feed. E.g. The

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decrease of 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. E.g. 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 stream flow and low groundwater levels) and soil-moisture drought can affect the growth of crops and insufficient water available for irrigation. E.g. 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, whithin the socio-environmental-economic impacts of drought. These impacts are interconnected with the livelihoods and well-being of farmers and households. E.g. Agricultural losses, which result in less feed for animals, cascading into an extra expense by having to buy feed in the market, consequently there is a reduced margin and loss of income. Therefore, farmers will sell their assets - the livestock -, resulting in more loss of income.

Figure 4 demonstrates how policy responses intervene to alleviate the ongoing drought impacts cascade. To enhance readability and comprehension, policies are represented with pictures taken during fieldwork. Table 3 provides a comprehensive overview of these policies, detailing the specific issues addressed by them, and the type of instruments employed to address each problem, the year of enactment, and the managing organization.

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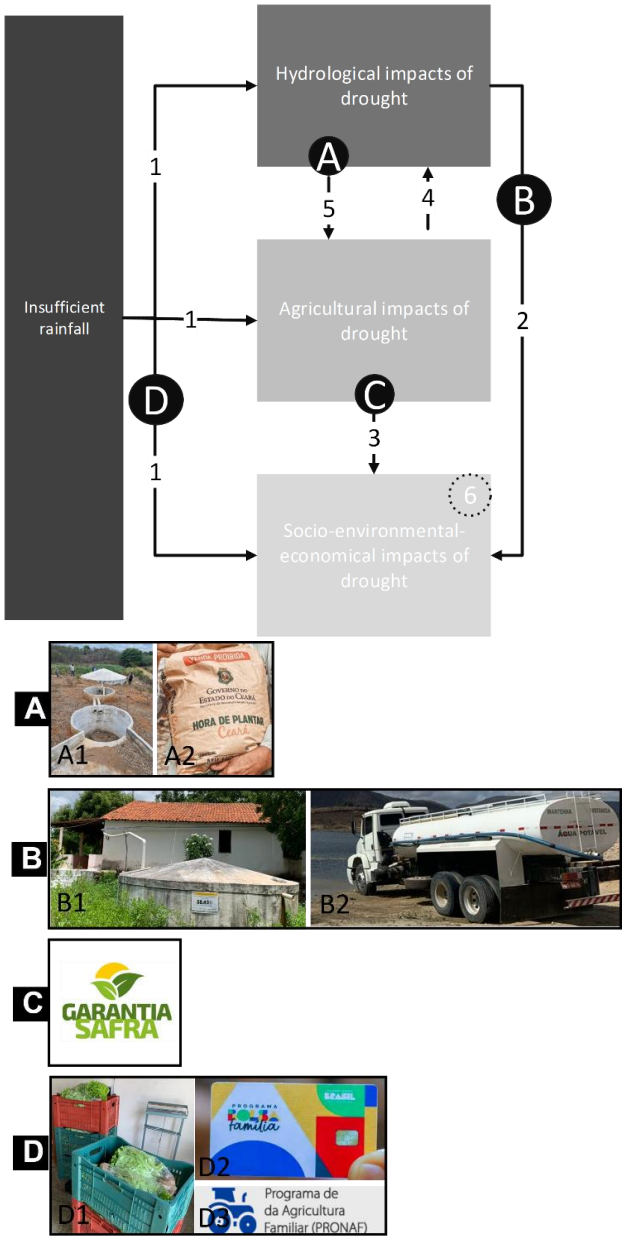

Figure 4: Policy responses and their role in alleviating the cascade of drought impacts.

Policy response path A, from hydrological drought impacts to agricultural impacts of drought, two policies are implemented: One is the *production cistern* (A1), 52m^3 rainwater harvest reservoirs to water livestock and provide small-scale irrigation to guarantee food security for the household. Another is *Hora de Plantar* (A2), the distribution of beans and maize seeds with high

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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 Nacional policies.

Policy response path B, from hydrological to socio-environmental-economical impacts of drought, two policies are represented: One is the *cistern* (B1) with 16m^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, from insufficient rainfall to agricultural impacts of drought, is *Garantia Safra* (C), a cash transfer insurance 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.

Policy response path D, from insufficient rainfall to socio-environmental-economic impacts of drought. One policy is *Bolsa Família* (D2), a conditional cash transfer (~ $120) for families. Conditionalities are ensuring that children attend school and receive necessary vaccinations. Second, are 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 PAA, one farmer mentioned, "*the [PAA]... during the dry season is helpful because it is guaranteed, and you can already count on the 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.

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
2nd water cisterns (P1+2)	Water access for productive uses	Rainwater harvest reservoir	2015	Ministry of Social Development

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Food acquisition program (PAA)	Insufficient market to smallholder farmer's	Public procurement contracts with smallholder farmers	2003	Ministry of Social Development
Food acquisition program for Schools (PNAE)	Insufficient market to smallholder farmer's	Public procurement contracts with smallholder farmers to supply schools	2010	Ministry of Education
Water trucks (*Operação Caminhão 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 Level - Secretary of Agrarian Development
Family Health Strategy (*Estratégia Saúde da Família*)	Health Diseases	Basic health care (doctors, nurses, hospitals)	1991	Ministry of Health

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

The data analysis indicates that socio-environmental-economic impacts have the lowest frequency of reporting, suggesting that public policies have been effective in alleviating the cascade of impacts. Fieldwork interviews revealed that droughts nowadays are less impactful because of the social protection net that exists with programs like *Bolsa Família*. One interviewee mentioned that in the 1993 drought, she did not experience thirst, but this drought left a significant mark on her because she was pregnant with her first daughter at the time. Food was scarce, and she had to resort to eating a local bird, a low nutritious food they'd never eat if it wasn't an emergency. There was no assistance from the government, she said "*with money, one could buy everything*". This drought's main impacts were on food, water, and later finances. She 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.

4. Discussion

Our research findings indicate that policy responses play a crucial role in alleviating the cascade of drought impacts, resulting in variations in the distribution of these impacts depending on the extent to which policies are implemented locally. The diminution in frequency of impacts mainly reflects on livelihoods, indicative of positive effects of development policies on creating economic dynamism within the region. However, despite their mitigation effect, the persistence of socioeconomic impacts remains evident. The conditional cash transfer (*Bolsa Família*), the crop insurance (*Garantia Safra)*, the Food Acquisition Program (PAA), the National School Feeding Program (PNAE), are the policies that 'break' the cascade into socioeconomic impacts. Stakeholders, including farmers and observers, expressed that recent drought periods (2012 – 2018) were more manageable compared to the past (80s and 90s) when governmental programs were absent. Nowadays droughts no longer cause hunger and migratory processes in the rural

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communities of the Brazilian semiarid region, with the intensity observed until the mid-20th century. However, this does not mean the population is fully adapted. The impacts of droughts have been mitigated, which may have occurred more due to welfare programs and less due to the implementation of strategies to adapt to the phenomenon (Mancal et al., 2016).

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 than a 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 to PAA and PNAE another (Kchouk et al., n.d.). 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 diversified their production. The PAA offers access to a stable market and increases farmers' income by providing a reliable market for their produce (Mesquita & Milhorance, 2019).

Most impacts are associated with hydrological drought, suggesting that the construction of reservoirs may not have adequately addressed the challenges posed by the semiarid region. While policies 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 & 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 policy '*operação carro pipa*' 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 to avoid the cascade into water shortage – that persists

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regardless of the formal classification of the period as a severe (or weak or no) drought (Walker et al., 2024).

One could argue that all impacts are socio-economic, as insufficient water for human consumption or crop losses directly affect economic livelihoods. Therefore, it can be debated whether other impacts could also be considered socio-economic in nature. We wish to clarify that our decision to use the classification of drought impacts as an analytical framework was deliberate. With this analysis, we progress on measuring the interconnectedness of impacts between natural and social systems (de Brito et al., 2024) by illustrating how one drought impact can serve as input for another impact within the context of Northeast Brazil. Our approach enhances the discussion surrounding the intricate network of impacts. Additionally, this methodology aligns with the overarching goal of our paper, which is to comprehensively understand the role of public policies in mitigating the impacts of drought.

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 to socio-environmental-economic impacts or just connecting one type of drought impacts to the other. 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 cascade of drought impacts. 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., 2023). Artificial intelligence does not yet capture these nuances of adaptation or impacts that only experience of local context can provide.

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 the implementation of policies aimed at

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enhancing the provision of natural values and ecosystem services to further alleviate residual drought impacts.

In response to Michel Jarraud's claim, our investigation revealed that policy responses help alleviate the cascade of impacts on socioeconomic impacts due to the development policies in place. On drought related policies, they remain reactive, such as the crop insurance implement after drought impacts are experienced. After several years of research and discussion on drought, we advocate 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. This highlights the need for a comprehensive and interconnected approach to understanding and addressing drought. It is a cross-cutting issue due to its far-reaching impacts beyond water scarcity, influencing agricultural production, socio-economics, and heightening the risk of fires. For this reason, we highlight the substantial contribution of public policies to mitigating the cascading effects of drought and its impacts that are not 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[1] and Central and Eastern Europe[2]. This type of analysis should be conducted to assess policy effectiveness to deal with drought impacts, and that can only be done with continual drought impacts monitoring, which is unfortunately lacking in most of the world (Smith et al., 2023). 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 socio-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.

[1] https://droughtmonitor.unl.edu/
[2] https://questionnaire.intersucho.cz/en/

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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.

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 field work interviews and analysis of data. DWW analyzed the impacts monitoring data with support of LC, SK and GRN. LC analyzed the policy documents data. TMNC and MMB performed natural language processing and analysis. The research was supervised by WP, DWW, AD and PvO. PvO acquired financial support for the project leading to this publication. All co-authors contributed to the interpretation of the results and to the article writing.

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Competing interests

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

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