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.

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.

Due to the complexity of drought, scholars are continuously engage with and stay informed about the latest discussions and advancements in the subject because there is no there is no universal definition of drought. This ongoing engagement highlights the multidisciplinary interest in the subject (Mishra & Singh, 2010; Lloyd-Hughes, 2014; Wilhite & 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—characterized by prolonged periods of insufficient precipitation, often coupled with increased evapotranspiration, affecting large geographic areas (Wilhite et al., 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 et al., 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

75 diminished river discharge (Van Loon, 2015). Another category, often considered by ecologists, is
76 environmental or ecosystem drought, which refers to a temporary shortfall in water availability that
77 pushes ecosystems beyond their vulnerability limits, disrupts ecosystem services, and triggers
78 feedback loops within both natural and human systems (Crausbay et al., 2017).

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

93

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

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

110 We take the approach in which physical and social impacts are closely interconnected, and drought
111 impacts can cascade, in which one impact is connected to another, forming a chain reaction of
112 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 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 referred to as family agriculture in Brazil, as they represent one of the most vulnerable groups 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 illustrates the geographic layout of Ceará State, located in Northeast Brazil, which covers a total area of approximately 148,920 square kilometers. 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 socio-economic conditions of the municipalities within this area Figure 1.

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

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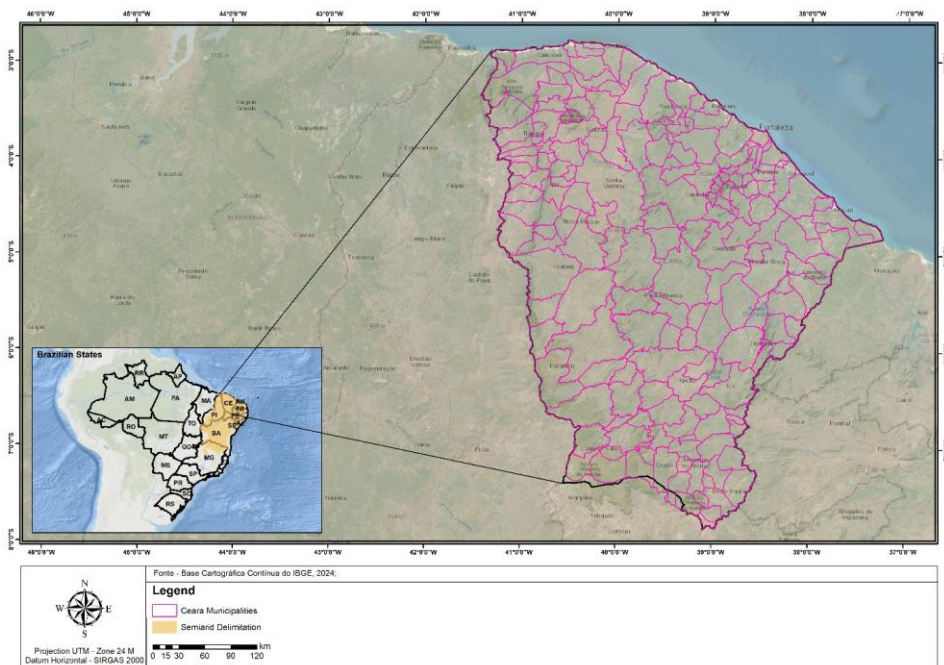
Figure 1: Geographic overview of Ceará State, Brazil.

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.

189 Although the research had a weakness in starting monitoring during a non-drought period, it still
190 provided insightful findings on the effects of drought in the area, even in years that were not
191 considered statistically dry.

192 **2.2 Study data**

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

197 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 April 2022	Household level
Policy documents data	Not applicable	National level and State level

198

199 The data collection process for this study was designed to capture the multifaceted impacts of
200 drought in the region. We employed a comprehensive approach by triangulating multiple data
201 sources and methodologies to capture a holistic understanding of the phenomenon. Figure 2
202 presents a workflow outlining the sequential steps involved, each corresponding to a specific
203 dataset. For a more comprehensive overview with steps and codes, we refer readers to the
204 supplement materials section S.1., and to another study using the drought monitoring data set
205 (Walker et al., 2024).

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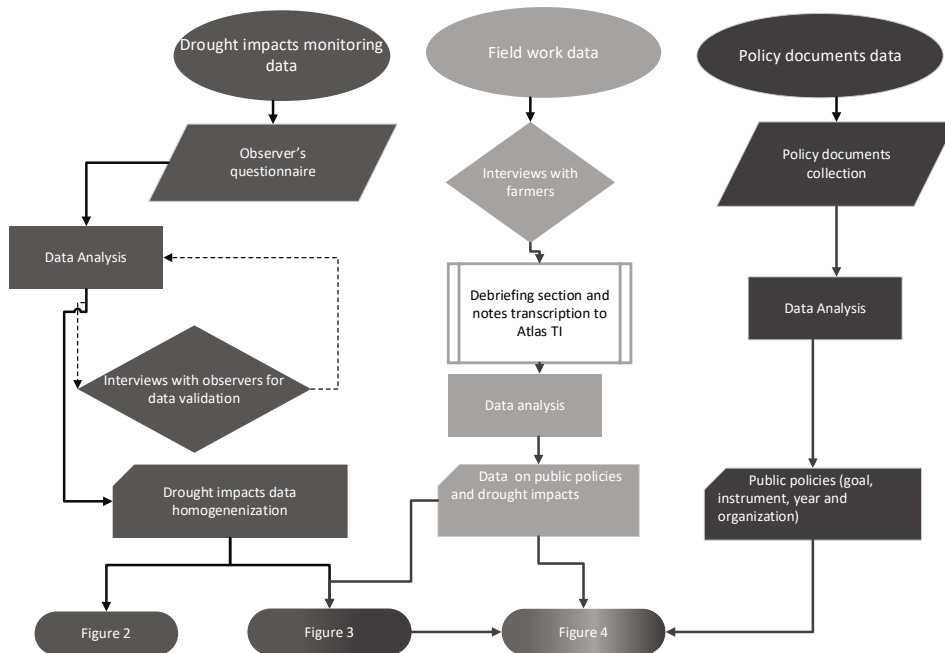
207 Figure 2: Summary of data collection and analysis methodology

2.2.1. Drought impacts monitoring data

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

218 In the homogenization step, we were interested in finding a common terminology to unify the
219 understanding of local impacts observations, to achieve simplicity and manageability of data, to
220 add clarity and focus on the most common patterns, and to increase readability. The outcome of
221 this effort was the identification of 14 distinct impact types (Table 3 in the Supplementary
222 material), which were then classified into impacts due to drought impacts classification, i.e.
223 hydrological, agricultural, and socio-environmental-economic impacts of drought.

2.2.2. Fieldwork data

225 Interviews and/or casual conversations were conducted with 60 smallholder farmers across
226 multiple visits to the study area. Questions were formulated to encourage participants to describe
227 the drought risks, impacts, and factors increasing or decreasing the likelihood of impactful drought
228 over time in the study area. The interviewees were randomly chosen. Some were more in-depth
229 interviews that lasted an hour, in other cases a short conversation, depending on the person's
230 availability. All the interviewees provided consent before being interviewed. The interviews were
231 not recorded, but fieldwork notes were either written up while the interview was ongoing or written
232 up immediately afterwards. Fieldwork notes were transcribed and analyzed using Atlas.ti software
233 to identify key themes and patterns related to drought impacts and public policies.

234 **2.2.3. Policy documents data**

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

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

244 **2.2.4. Analysis and synthesis**

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

250 # 3. Results

251 Figure 3 presents 1,933 reported impacts*, categorized into three main types: hydrological,
252 agricultural, and socio-environmental-economic impacts of drought. These impacts were reported
253 in a open question, where observers were given the freedom to express what they considered
254 relevant during that period. Consequently, the reported impacts were not limited to drought alone,
255 for instance, impacts related to pests and socioeconomic impacts were reported, that may or not
256 have been aggravated (or alleviated) by drought.

257 The bars reveals that most impacts are linked to hydrological drought (N =1.187), with agricultural
258 drought (N = 718) being the next most common. In contrast, socio-environmental-economic
259 impacts of drought (N = 28) exhibit the lowest frequency. Due to scale considerations, this bar has

260 its details unclear. These impacts include: wildfires (8), high production costs (9), and
261 socioeconomic impacts* (11).

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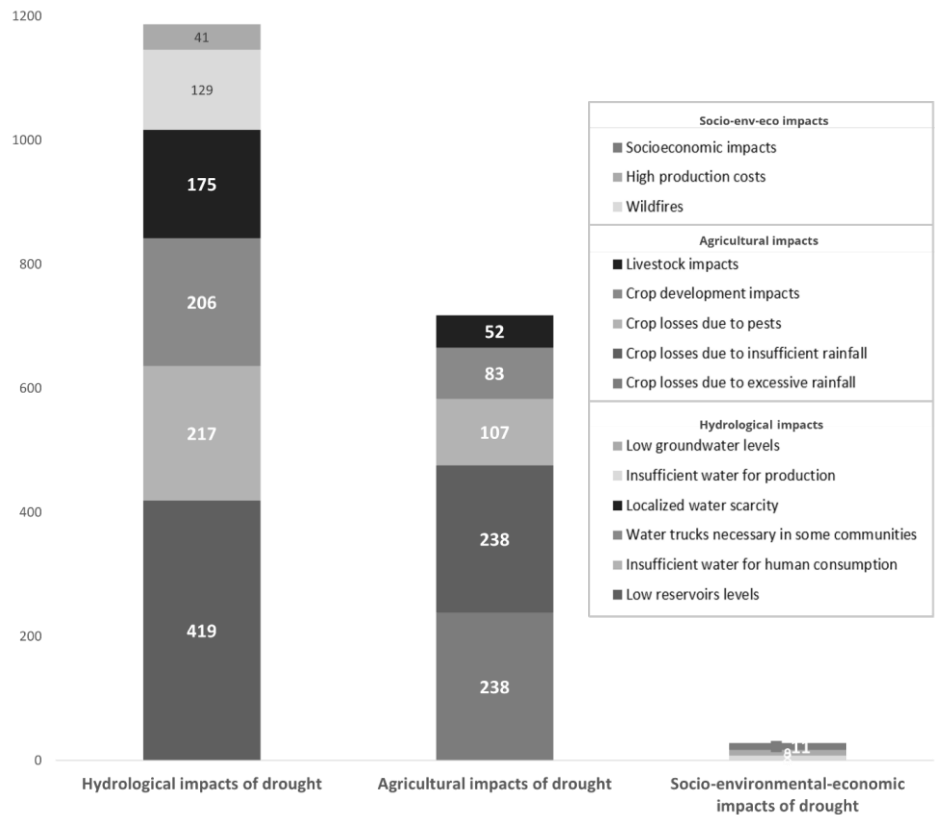
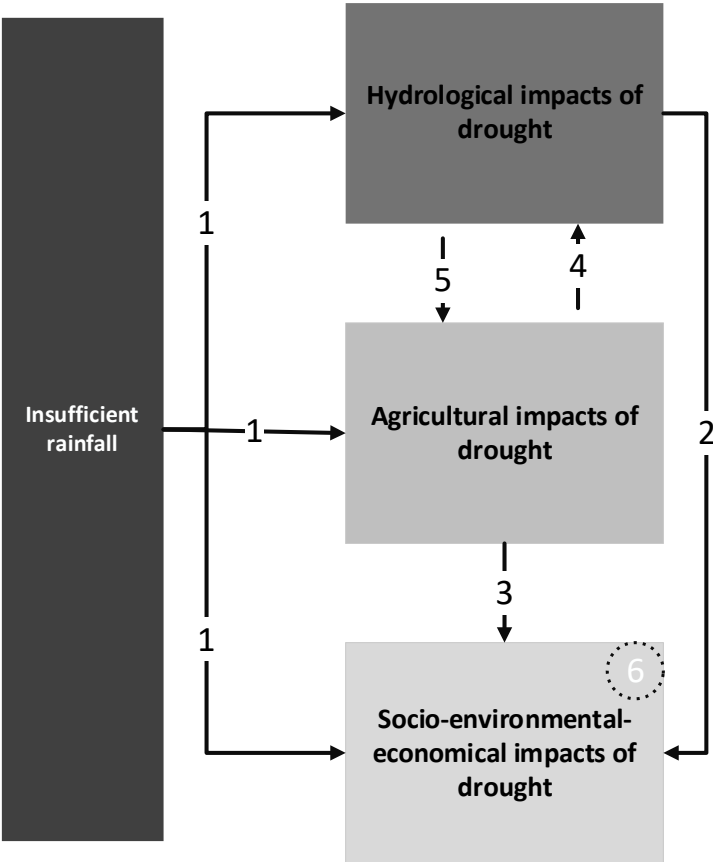

263 Figure 3: Number of impacts reported by observers in relation to categories of drought

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

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

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

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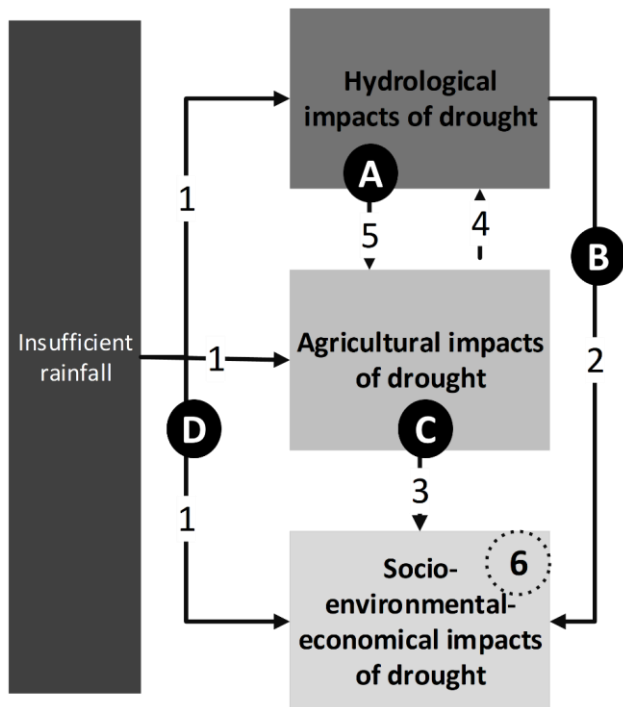
278 Figure 4: Schematic illustration depicting various directions for the cascading of drought impacts.
279 **Cascade direction number 1, insufficient rainfall causing hydrological, agricultural or socio-**
280 **environmental-economical impacts of drought.** This direction can follow various paths, directly
281 extending from the primary driver to others. Insufficient rainfall can lead to localized water
282 scarcity, crop development impacts, and increased risk of wildfires. e.g. Municipalities have
283 indicated that the absence of rainfall, coupled with low air humidity and elevated temperatures, has
284 led to fires in certain regions.

285 **Cascade direction number 2, hydrological impacts of drought to socio-environmental-**
286 **economical impacts of drought.** Low water availability for human consumption may have
287 socioeconomic consequences, necessitating expenses on water trucks to fulfill household
288 requirements. e.g. In cases of reduced rainwater cistern levels designated for human consumption
289 or low reservoir levels, households turn to buying water from water trucks to replenish their
290 cisterns.

291 **Cascade direction number 3, agricultural impacts of drought to socio-environmental-**
292 **economical impacts of drought.** Deficiency in soil moisture can adversely affect the cultivation
293 of crops intended for feeding livestock, leading to the purchase of expensive animal feed. e.g. The
294 decrease of soil-moisture in the allocated floodplain area designated for the cultivation of grass and
295 sorghum for silage provision during dry periods has led to a consequential shift in agricultural
296 practices. Consequently, some farmers have decided to sell a portion of their livestock, thereby
297 reducing the size of their herds, enabling farmers to buy extra complements like soybeans to feed
298 their animals.

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

305 **Cascade direction number 5, hydrological impacts of drought leading to agricultural impacts**
306 **of drought.** The hydrological impacts of low reservoir levels (resulting in reduced stream flow and
307 low groundwater levels) and soil-moisture drought can affect the growth of crops and insufficient
308 water available for irrigation.e.g. Such conditions are applicable to maize cultivation, where
309 insufficient soil moisture hinders fruit development, leading to a deceleration in the growth of the
310 plant.

311 **Cascade direction number 6, whithin the socio-environmental-economic impacts of drought**.
312 These impacts are interconnected with the livelihoods and well-being of farmers and households.
313 e.g. Agricultural losses, which result in less feed for animals, cascading into an extra expense by
314 having to buy feed in the market, consequently there is a reduced margin and loss of income.
315 Therefore, farmers will sell their assets - the livestock -, resulting in more loss of income.
316
317 Figure 4 demonstrates how policy responses intervene to alleviate the ongoing drought impacts
318 cascade. To enhance readability and comprehension, policies are represented with pictures taken
319 during fieldwork. Table 3 provides a comprehensive overview of these policies, detailing the
320 specific issues addressed by them, and the type of instruments employed to address each problem,
321 the year of enactment, and the managing organization.

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

325 **Policy response path A**, from hydrological drought impacts to agricultural impacts of drought,
326 two policies are implemented: One is the *production cistern* (A1), 52m^3 rainwater harvest
327 reservoirs to water livestock and provide small-scale irrigation to guarantee food security for the
328 household. Another is *Hora de Plantar* (A2), the distribution of beans and maize seeds with high
329 genetic potential for drought resistance to smallholder farmers prior to the rainy season. This is the
330 only policy specific to Ceará state; all others are Nacional policies.

331 **Policy response path B**, from hydrological to socio-environmental-economical impacts of
332 drought, two policies are represented: One is the *cistern* (B1) with 16m^3 rainwater harvest
333 reservoirs for domestic purposes. Second is *water trucks* (B2) for distributing water for domestic
334 uses, coordinated by the federal government in collaboration with the Ministry of National
335 Integration and the Ministry of Defense.

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

343 **Policy response path D**, from insufficient rainfall to socio-environmental-economic impacts of
344 drought. One policy is *Bolsa Família* (D2), a conditional cash transfer (~ $120) for families.
345 Conditionalities are ensuring that children attend school and receive necessary vaccinations.
346 Second, are the Food Acquisition Program (PAA) and the National School Feeding Program
347 (PNAE) (D1), are public procurement policies that promote social inclusion and poverty reduction
348 by connecting small-scale farmers with government institutions that procure food. Regarding PAA,
349 one farmer mentioned, "*the [PAA]... during the dry season is helpful because it is guaranteed, and
350 you can already count on the resources*." Third is the National Program for Strengthening Family
351 Agriculture (PRONAF) (D3). Access to rural credit enables farmers to obtain financing under
352 favorable conditions tailored to their needs and interests.

353 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
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 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's important to acknowledge that the low frequency of reported socio-economic impacts may not necessarily indicate a reduction in these impacts. Instead, it could reflect the way the data was collected or what people chose to focus on. Tangible impacts, such as reduced crop yields, are often easier to notice and report 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 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

373 eating a local bird, a low nutritious food they'd never eat if it wasn't an emergency. There was no
374 assistance from the government, she said "*with money, one could buy everything*". This drought's
375 main impacts were on food, water, and later finances. In contrast, she mentioned that during the
376 2012-2018 drought, fish died in the mud, and only one water truck (16 m^3) would come per month
377 for 20 families. This scarcity led to conflicts, albeit minor. They received crop insurance, and the
378 impacts were primarily related to water scarcity. Despite the 2012-2018 drought being statistically
379 more severe than the 1993 drought, the support of social programs made the impacts less severe.

4. Discussion

381 Our research findings indicate that policy responses play a crucial role in alleviating the cascade of
382 drought impacts, leading to variations in the distribution of these impacts depending on the extent
383 of local implementation. The reduction in the frequency and severity of impacts, particularly on
384 livelihoods, reflects the positive effects of development policies in fostering economic dynamism
385 within the region. Programs such as Bolsa Família, Garantia Safra, the Food Acquisition Program
386 (PAA), and the National School Feeding Program (PNAE) have been instrumental in 'breaking' the
387 cascade into socioeconomic impacts by providing crucial financial resources to vulnerable
388 populations, thus giving them the means to cope with drought. Stakeholders, including farmers and
389 observers, noted that recent drought periods (2012–2018) were more manageable compared to the
390 past (80s and 90s) when such governmental programs were absent. Today, droughts no longer
391 result in hunger and mass migration in the rural communities of the Brazilian semiarid region as
392 they once did. However, it is important to recognize that while these welfare programs have
393 significantly mitigated the immediate impacts of drought, they may have done so more by
394 providing temporary relief rather than by promoting long-term adaptation strategies. This suggests
395 that while the population is better equipped to manage droughts, they are not fully adapted to the
396 phenomenon, highlighting the need for a continued focus on sustainable adaptation measures
397 (Mancal et al., 2016).

398 However, while these programs have significantly contributed to 'breaking' the cascade of
399 socioeconomic impacts by fostering long-term resilience, their effectiveness is contingent on
400 integration with broader strategies aimed at sustainable development and climate adaptation. This
401 concern is particularly relevant as climate change continues to transform the risks faced by
402 individuals and households, potentially exacerbating poverty, inequality, and social instability.
403 Therefore, while the population is better equipped to manage droughts, they are not fully adapted
404 to the phenomenon, highlighting the need for an integrated approach where social protection is
405 aligned with climate policy to strategically contribute to long-term resilience and well-being
406 (Bedran-Martins et al., 2018). Although these programs have succeeded in improving material
407 quality of life and increasing the Human Development Index, they do not fully address the
408 multifaceted nature of vulnerability in the context of climate change. For example, despite the
409 improvements in material conditions, the subjective well-being of households continues to be
410 influenced by factors beyond economic security, such as health status and safety (Costella et al.,
411 2023).

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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 and Milhorance, 2019).

Many reports emphasize ongoing water supply challenges, indicating that despite the construction of reservoirs, the hydrological drought continues to pose significant challenges in 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 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 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 regardless of the formal classification of the period as a severe (or weak or no) 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 it afftects biodiversity, allowing for a better understanding of how these impacts are distributed on 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 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 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

490 ecosystem services, such as soil conservation and water retention through agroforestry practices,
491 to further alleviate residual drought impacts in the semiarid region.

492 In response to Michel Jarraud's claim, our investigation revealed that policy responses have been
493 somewhat effective in alleviating the socioeconomic impacts due to the development policies in
494 place. However, drought-related policies still tend to be reactive, such as implementing crop
495 insurance only after drought impacts have occurred. This reactive approach presents an opportunity
496 for improvement. For instance, moving towards proactive policies, such as utilizing cash transfers
497 based on forecasted impacts rather than responding to those that have already happened, could
498 enhance the effectiveness of drought management. This shift emphasizes the importance of
499 forecasting and associated proactive measures. After several years of research and discussion on
500 drought, we advocate that drought should be managed as a cross-cutting issue that impacts multiple
501 sectors simultaneously, necessitating a comprehensive and interconnected approach. Drought's far-
502 reaching impacts go beyond water scarcity, influencing agricultural production, socio-economics,
503 and increasing the risk of fires. Therefore, we highlight the significant role that public policies can
504 play in mitigating the cascading effects of drought, particularly those impacts not directly related
505 to increasing water availability.

506 This analysis opens space for further research in other regions of the world where drought impacts
507 are also monitored, for instance the USA[1] and Central and Eastern Europe[2]. This type of analysis
508 should be conducted to assess policy effectiveness to deal with drought impacts, and that can only
509 be done with continual drought impacts monitoring, which is unfortunately lacking in most of the
510 world (Smith et al., 2023). Another avenue for further investigation lies in longitudinal studies
511 covering extended periods, encompassing periods characterized by both drought and rainfall
512 occurrences, thereby comprehensively addressing diverse hydrological circumstances. This aspect,
513 which was not explicitly delineated in the present study, represents a crucial limitation that requires
514 attention in future research.

5. Conclusion

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

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

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

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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