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It's not all about drought: What “drought impacts” monitoring can reveal

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ABSTRACT

Drought impacts monitoring has been called the missing piece in drought assessment. The potential to improve drought management is high but uncertain due to rare analyses of impacts datasets, predominantly because there are few impacts monitoring programmes to generate the datasets. Drought impacts monitoring is conducted on the ground in much of Brazil by local observers at monthly and municipality scale to support the Brazilian Drought Monitor. In Ceará state, within drought-prone semiarid northeast Brazil, over 3600 drought impacts reports were completed by agricultural extension officers from 2019 to 2022. We investigated, through manual coding and observer interviews, the reported drought impacts and impact drivers. Analysis provided a catalogue of the experienced impacts and showed that impacts still occur, and are often normalised, during non-drought periods, sometimes as lingering effects of previous droughts. The impact drivers were predominantly non-extreme hydrometeorological conditions or a result of socio-technical vulnerabilities such as insufficient water infrastructure. The normalisation of “impacts” included, in particular: a generally accepted high level of crop losses and consistently low reservoir levels around which the agricultural and domestic systems are adapted. Conventional drought indices often did not align with experienced impact severity, highlighting the limitations of relying solely on these indices for emergency response. Continual impacts monitoring could be extremely valuable anywhere in the world for identifying vulnerabilities and informing proactive measures to reduce drought and other hazard risk, in addition to guiding targeted mitigation efforts.

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1. Introduction

Many, if not most, scientific drought publications commence with a paragraph that details the worldwide impacts of drought. We hear about the millions of people affected, the US$ billions of damage to economies, and the extent of food shortages. Similarly, news media about drought generally leads with images of starving livestock, people having to collect water from scarce and unsafe sources, or destructive wildfires. It is inferred that these impacts all relate to severe drought. Yet, drought severity, at least to natural, or physical, scientists, is usually measured using hydrometeorological drought indices rather than the experience from the ground, and how impacts relate to drought severity is uncertain due to various factors of vulnerability. These impacts are almost always confounded by other intertwined factors, such as conflict, poverty, political decisions or over-exploitation of resources [1–4]. The contribution of non-climatic drivers to "drought impacts", and the relationship between drought severity and impacts, are difficult to evaluate because drought impacts are not routinely monitored [5,6].

A drought impact can be defined as "… a specific effect of drought on the economy, society, and/or the environment, which is a symptom of vulnerability" [7]. Commonly visible drought impacts are on agriculture and water resources, which can affect livelihoods, health, ecosystems, energy and industrial production, and transportation. These negative socioeconomic effects may eventually trigger or exacerbate political instability, conflict and migration [5]. But at what point these impacts start to be felt by populations, and what the specific impacts are in different regions, are not well understood. Therefore, the planning of drought adaptation and mitigation measures is problematic when both the baseline situation and the commonly experienced impacts are uncertain [5,6,8].

Drought impacts monitoring has been referred to as the missing piece in drought monitoring and forecasting [9]. Drought hazard is monitored by quantitative indices like standardised precipitation index (SPI) or similar that show anomalies in, for example, rainfall, river flow or reservoir level [10]. However, when these indices show that a drought is occurring, what effect the low rainfall or lack of water resources are having, where, and on whom or what, are rarely known outside of the affected area [6]. By monitoring the impacts of drought, timely and relevant assistance can be provided. Furthermore, the increased scientific understanding could increase resilience to future drought by revealing underlying vulnerabilities that need to be acted on.

Yet some drought impacts monitoring is already occurring with various objectives. Often it is unintentional where data are collected for different purposes that reveal drought impacts, such as government statistics on crop yield, hydropower generation or river navigation. Intentional drought impacts monitoring is less common and exists in several forms. Databases such as the Emergency Event Database (EM-DAT)[1] and the European Drought Impact Report Inventory (EDII)[2] involve the submission of reports by professionals that detail the occurrence and effects of disasters, but only post-event. EDII reports were analysed by Stephan et al. [11] and Tijdeman et al. [12] to assess drought and impact propagation and relationships with hydrometeorological indices. Crowdsourcing programmes such as the US National Drought Mitigation Center (NDMC)'s Condition Monitoring Observer Reports (CMOR)[3] and the Community Collaborative Rain, Hail and Snow (CoCoRaHS)[4] network collect observations from members of the public who complete online questionnaires then see their reports uploaded to an online dashboard. Focusing on North and South Carolina, USA, Lackstrom et al. [13] analysed volunteers' qualitative observations from CoCoRaHS to identify impacts and assess relationships with the US Drought Monitor.[5] Such programmes experience surges in reporting during times of drought; the baseline situation is seldom reported [14]. Most useful would be drought impacts information collected at regular spatial and temporal scale. A potential source of such datasets are drought monitors that produce maps of drought condition based on conventional drought indices and which often have a ground-truthing aspect. Where trained observers collect drought impact information at regular spatiotemporal frequency, the resulting datasets may offer more than just on-the-ground validation for the drought monitor.

The aim of this study was to determine what could be learnt from such a drought impacts monitoring dataset: What drought impacts were reported and when, were there other impact drivers in addition to drought, and how did the occurrence of impacts compare to conventional drought indices? Such studies are sparse because data collected by the people on-the-ground who are actually experiencing impacts are so scarce. A drought impacts monitoring dataset from northeast Brazil, acquired as part of the Brazilian Drought Monitor[6], was the subject of this study. The overarching purpose of the analysis was to contribute to improved management of both drought and potentially other natural hazards in the region.

2. Case study

2.1. Northeast Brazil

The *Sertão* semiarid region of northeast Brazil makes up 13% (1.1 million km^2) of the country (Fig. 1) and is home to around 27 million people [15]. Even though rainfall is relatively high for a semiarid region, with an annual average around 750 mm, high temperatures and low humidity produce annual potential evapotranspiration levels exceeding 2000 mm [16]. Rainfall is concentrated into the months of February to May with high spatial and interannual variability. The state of Ceará is the focus of this study and is considered representative of the wider northeast region. The coastal zone is significantly wetter than the hot dry interior, which is reflected in the land cover; the interior is predominantly *caatinga* (xeric shrubland and thorny forest) and agricultural land comprising

[1] https://www.emdat.be/.
[2] https://www.geo.uio.no/edc/droughtdb/index.php.
[3] https://droughtimpacts.unl.edu/Tools/ConditionMonitoringObservations.aspx.
[4] https://www.cocorahs.org/Maps/conditionmonitoring/.
[5] https://droughtmonitor.unl.edu.
[6] https://monitordesecas.ana.gov.br.

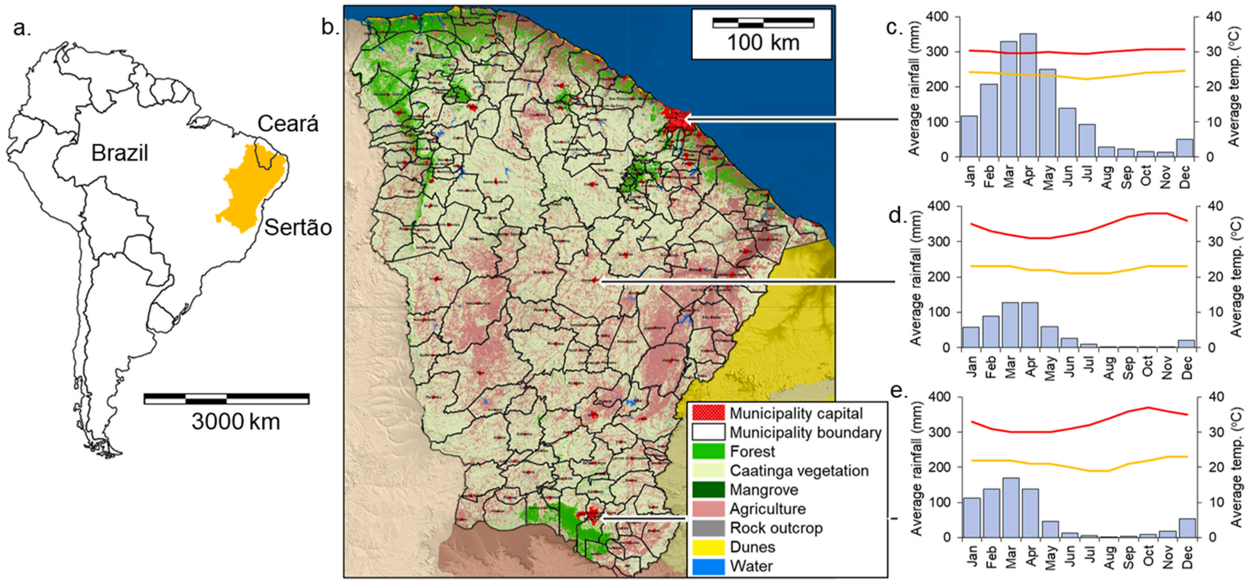

Fig. 1. Location map showing Ceará state within the Sertão semiarid region of northeast Brazil (a), and a landcover map of Ceará (b). The climate charts are representative of the wetter coastal zone (c), the dry interior (d) and the slightly less dry highlands in the far south (d). Landcover and climate data from MapBiomas[7] and FUNCEME.[8]

mixed pasture and cultivation (Fig. 1). Rainfed agriculture dominates with smallholder farmers constituting a significant proportion of the population and the majority of the agricultural sector. Soils are poor and shallow above crystalline geology creating a lack of aquifers and only ephemeral rivers. Northeast Brazil is consequently drought-prone. Historically, famine and mass migration afflicted 100,000s of people and the most recent drought from 2012 to 2018 devastated livestock and crop producers, damaged regional economies and led to widespread water scarcity [3].

2.2. Brazilian drought monitor

As part of efforts to switch from reactive to proactive drought management, the Brazilian Drought Monitor[6] was established in 2014 by Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) and Agência Nacional de Águas e Saneamento Básico (ANA), based on and in collaboration with the US Drought Monitor.[5] The aim was to produce a single monthly map of drought condition (Fig. 2). The Drought Monitor commenced with the northeast region and has since incrementally expanded to cover 25 of Brazil's 26 states. The mapping process involves integration of relevant regional meteorological databases and remote sensing analyses to compute drought indices. The developers stress that the map is produced manually – rather than automatically based on thresholds of numerical observations – considering conventional drought indices at multiple computation periods from one to twenty-four months: standardised precipitation index (SPI), standardised precipitation evapotranspiration index (SPEI), standardised runoff indicator (SRI), and normalised difference vegetation index (NDVI) (see https://monitordesecas.ana.gov.br/perguntas-frequentes and [17]). This is followed by validation by regional offices that consider ground observations from networks of observers [17]. The resulting categories on the Drought Monitor range from 'no drought' to 'weak drought', referring to onset or cessation of dry conditions, through 'moderate, severe and extreme drought', to 'exceptional drought', referring to widespread crop/pasture losses and water shortage at emergency level [18]. The creators of the Drought Monitor stress that the monthly maps highlight *relative drought*, that is, the situation in a particular location is assessed relative to its historical record and not necessarily in relation to drought perception, which is subjective. Relatedly, drought severity reflects the natural conditions induced by physical phenomena and does not incorporate drought management processes (such as reservoir levels).

The Drought Monitor aims to be a key tool to support dialogue between states and the federal government about addressing drought risks and conditions as well as for drought preparedness planning [18]. The Drought Monitor is a political decision-making instrument. Emergency responses, such as provision of water tanker trucks and payout of index-based insurance, can be triggered when a municipality reaches a certain level of severity on the Drought Monitor (despite the creators stating this is not its purpose).

3. Methodology

3.1. Drought impacts monitoring

A ground-truthing programme was established by the Drought Monitor developers to validate the monthly outputs. Each state covered by the Drought Monitor has a network of observers that completes a monthly questionnaire per municipality; the reports

[7] https://mapbiomas.org.
[8] http://funceme.br.

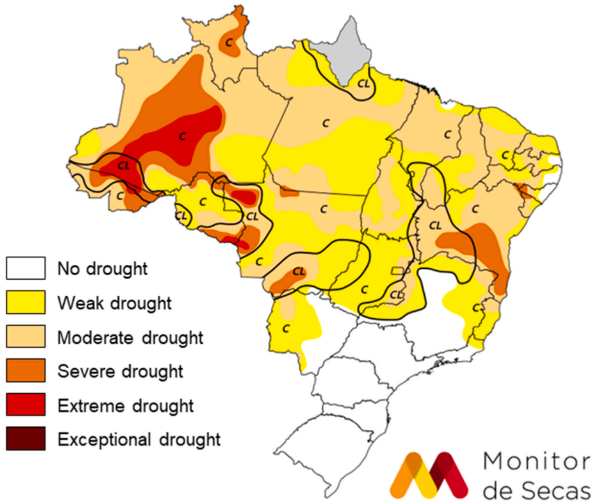

Fig. 2. An example output (from November 2023) of the Brazilian Drought Monitor.[6] The letters refer to impact types: C = short term (e.g. agriculture), L = long term (e.g. hydrology). The northern state of Amapá is coloured grey because it is not yet incorporated.

should then be utilised by the validators when they approve and recommend adjustments to the drought categories in their region of the centrally-produced drought map. The questionnaire consists of four multichoice questions related to drought condition, rainfall, crop production and water availability (each state may add its own additional locally-relevant questions), and one final open question as follows (translated from Portuguese):

> "If you wish, use the space below to specify what type of water access problems the municipality has registered and/or report other drought-related impacts that are currently observed in your area of operation:"

The nature of the questionnaire, especially the open question 5, means the programme is a globally rare and consequently valuable example of drought impacts monitoring by the people "on-the-ground" who experience the impacts. Crucially, this type of regular spatially distributed monitoring should provide both baseline conditions and the effects of any disturbances.

In Ceará, the network of observers are technicians employed by Empresa de Assistência Técnica e Extensão Rural do Ceará (EMATERCE), the state government rural/agricultural extension service. Ceará state consists of 184 municipalities and EMATERCE has offices throughout the state, most with responsibility for two or three municipalities. Technicians consist of older personnel from the municipality (thus with high local knowledge) who are generally paired with younger staff who are often on internships as part of university study. Interviews and discussions with technicians revealed that the questionnaires are completed based on observations and discussions with farmers and other communities. Their day-to-day work involves visiting a wide area of the municipalities and their offices are also visited by farmers from across the municipalities. Consequently, the technicians consider their reports to be summaries of the conditions and impacts from the whole month and the entire municipality.

Fig. 3 shows that when monitoring commenced in February 2019 the drought category was much improved for most of Ceará (i.e. from severe and extreme to moderate, weak or no drought). Consequently, it would not be expected to find the severest drought impacts within the dataset. The monitored period has clearly seen relatively benign drought conditions, based on the physical indices utilised by the Drought Monitor, though with obvious spatial and temporal variability.

While the programme is designed to provide one report per municipality per month, that has never been achieved. The average number of municipalities reporting per month is 80 (out of 182) within a range of 27–150. The monthly distribution is shown in Fig. 4 with a peak in the wet season, suggested by EMATERCE to be because this is the time when rainfed farmers are impacted by drought; the dry season is expected to be dry. The months of September and October that appear not to fit the pattern are due to very high reporting rates for those months in 2022. This uptick in reporting is through the authors working more closely with EMATERCE to promote the value of the drought impacts monitoring programme [19]; the success of which can be seen by the increased monthly average reporting rate in 2022 over previous years (Fig. 4). The map in Fig. 4 shows that, while the number of municipalities reporting per month was generally fewer than half, reports are distributed around the state, that is, all areas of the state, and all climate and landcover zones shown in Fig. 1, are covered.

3.2. Data analysis

The dataset spans three years and nine months, therefore four wet seasons, and consists of 3641 reports. Preliminary assessment of the dataset confirmed that responses to the open question 5 were the most useful. That is because observers were free to record anything that was notable and prevalent in their municipality rather than being steered by the multichoice answers. Reports ranged from a few words to several lengthy sentences. Preliminary assessment also revealed that some form of machine analysis could be problematic due to inconsistencies in language, such as the use of colloquial expressions, and mostly the importance of context in understanding the meaning, especially whether the report was describing a negative or positive situation. This latter point is discussed in detail

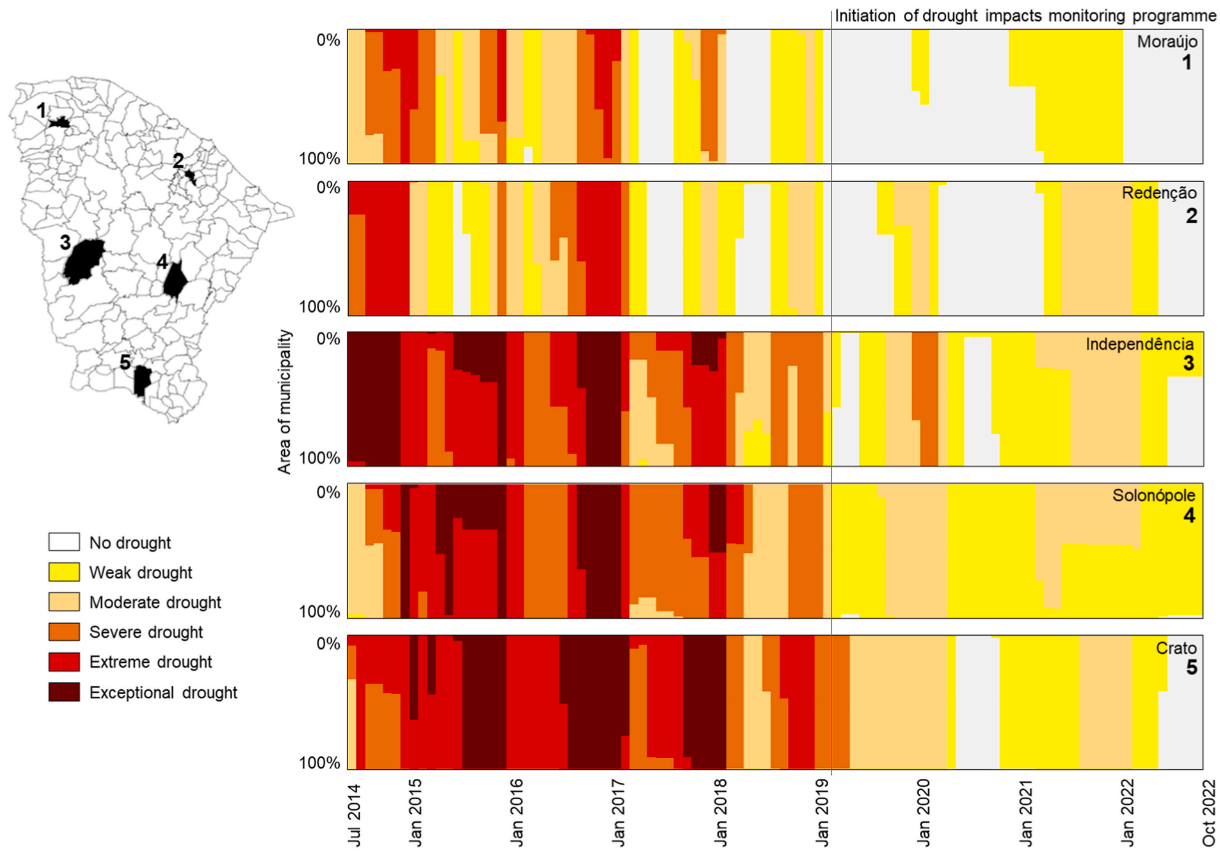

Fig. 3. Example Drought Monitor[6] outputs (right) show the percentage area of selected municipalities within each drought category at monthly scale since its creation. Drought impacts monitoring initiated in February 2019 (blue line). The municipalities' locations within Ceará are shown on the map (left).

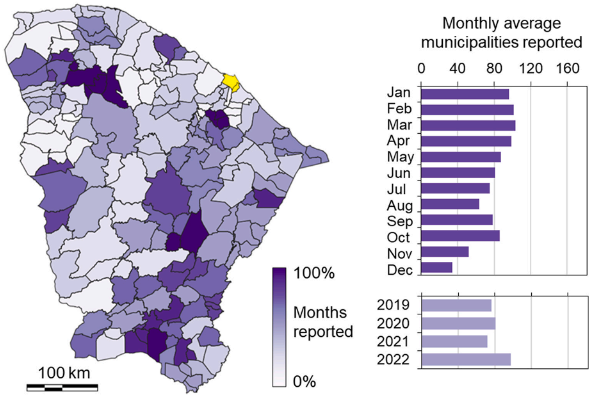

Fig. 4. Map of Ceará showing the percentage of months that each municipality provided a drought impacts report since data collection began in February 2019 to October 2022 (inclusive). The plots show the average number of municipalities that reported per month (upper), and the monthly average per year (lower). There are 182 participating municipalities; Fortaleza and Eusébio, coloured yellow, are excluded being almost entirely urban.

later. Therefore, the observers' reports were manually analysed through inductive coding using the qualitative analysis program Atlas.ti (version 22). Codes were developed for impacts as they were identified within the reports. To reduce subjectivity in the designation of codes, samples of the data were coded individually by four of the authors, initially with no guidance from the lead coder to ensure grounded theory was followed. Any discrepancies in coding were subsequently discussed. Multiple such rounds were completed with any newly agreed upon codes or amended codes then deductively searched for within the entire already coded dataset for inclusion or editing. The coding and analysis benefited from field experience in the area by the team collectively totalling 10+ years, including conducting interviews with smallholder farmers regarding experiences of drought (e.g. Kchouk et al. [20]; Ribeiro Neto et al. [21]). Therefore, there was pre-existing appreciation of the local conditions, water resources, agriculture, and other livelihoods that were described in the reports facilitating their comprehension and interpretation.

The first objective of the analysis was to identify what drought impacts occurred in Ceará during 2019–2022. Of the 3399 reports that could be coded (242 from the total of 3641 were blank or a dash or number), there were 6537 occurrences of codes. When the codes were categorised, it was clear that much more than only drought impacts were reported. There were five categories of codes: (1) *negative impacts*, specific negative effects on society, the economy or environment, which were not all necessarily due to drought; (2) *positives*, where positive information, such as the cessation of an impact, was provided; (3) *impact drivers*, the causes of and factors that contribute to impacts; (4) *responses*, efforts to mitigate impacts, and; (5) *extra information*, any additional and potentially useful information that did not fit the other categories. Two typical examples are provided below of longer and shorter reports with their coding and categorisation (note that some codes were later combined and renamed):

1. Translated from Portuguese: *The impacts related to drought are those that are causing lack of water in some locations and shortage of food for animals. For water supply, water trucks are being used and wells are being drilled where it is possible*.

Report 2644, Forquilha, December 2021

Underlined codes: localised water scarcity (*negative impact*), food shortage for livestock (*negative impact*), water trucks needed (*response*), boreholes drilled (*response*).

2. Translated from Portuguese: *None*

Report 2633, Trairi, November 2021

Underlined codes: no problems due to drought (*positive*).

The second objective was to evaluate the principal drivers of the impacts, based on contextual information provided within the reports, on information gleaned from interviews, and on comparisons with conventional drought indices.

3.3. Observer interviews

A series of interviews were conducted with EMATERCE technicians. Interviews were initially in groups, followed by individual interviews of selected technicians to achieve coverage of a wide area of the state and of different types of impacts reported. In total, 29 technicians were interviewed, representing over 40 municipalities.

The first aim of the interviews was to establish the comprehensiveness of the data collection, in terms of impacts and different affected groups. Notably, there was insistence that all types of drought impacts were reported. Similarly, interviewees claimed that all parts and populations of their municipalities were covered, including the more remote and consequently poorer and more vulnerable subsistence farmers, if not by visiting in-person then by telephone. However, municipalities of Ceará range in area from 73 to 4261 km^2, and in population from 4800 to 274,000 (excluding Fortaleza). Therefore, it is unrealistic to expect the data to be all-encompassing.

Additional interview aims were: a) to relate the qualitative with the quantitative reports, for example, understanding what percentages of water resource availability and crop losses were considered high, satisfactory or low; b) to query uncertain reports, and; c) to test hypotheses resulting from analysis of the codes.

3.4. Comparison of reported drought impacts with conventional drought indices

For this comparison, we utilised Drought Monitor outputs because they are an integration of several hydrometeorological and remote sensing drought indices. Drought Monitor outputs were obtained in the form of the monthly percentage area of each municipality within each drought category (as used to create Fig. 3). The proportionally dominant drought category provided the municipality's classification each month. The drought impacts monitoring data were reduced to binary yes/no monthly time series per municipality of whether or not drought impacts were reported. Impacts clearly caused by excessive rainfall and all types of non-impact information meant classification of “not reported”. Confusion matrices comparing drought impact observations to Drought Monitor outputs were used to assess the relationship between the two datasets (Fig. 5).

The number of true/false positives/negatives was used to derive two statistical measures:

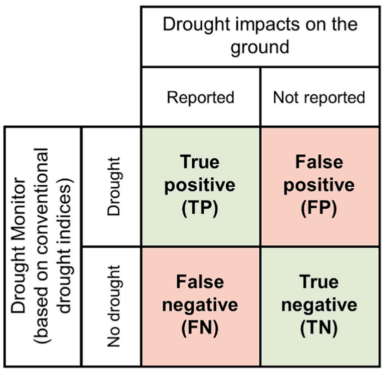

Fig. 5. Confusion matrix applied each month to each municipality.

- Precision is a measure of the accuracy of the positive predictions made by a model or system. In this case, we are not evaluating the "accuracy" of the Drought Monitor at predicting observed impacts; we are merely using these measures to compare the Drought Monitor outputs with the impacts reports. Precision calculates the proportion of true positive predictions (correctly predicted positive instances) out of all positive predictions made by the model (the Drought Monitor), regardless of the actual number of positive instances in the dataset. It is a measure of the ability to avoid false positives. TP/(TP + FP)
- Recall, also known as sensitivity or true positive rate, is a measure of how well a model or system is able to identify all the positive instances in a dataset. It calculates the proportion of true positive predictions out of all actual positive instances in the dataset. It is a measure of the ability to avoid false negatives. TP/(TP + FN)

4. Results

4.1. What the observers' reported

The relative abundance of each code category is shown in Fig. 6. Even though such information was not explicitly requested on the questionnaire, perhaps it should not be surprising that codes categorised as *positive* were most abundant given that the dataset spans a period of no or relatively mild drought, especially in comparison to the 2012–2018 drought that people had so recently experienced. It is more unexpected that such a quantity of *negative impacts* was still reported. However, incorporated in the *negative impacts* category are impacts both due to drought and to other drivers. Despite not being requested, it was extremely useful in achieving our second objective of evaluating the principal drivers of impacts to find that the *impact drivers* were regularly explicitly stated. A catalogue of the reported *impact drivers*, *negative impacts* and *responses* is presented in Fig. 7.

Grouping into categories and sub-categories occasionally required interpretation because some codes could be alternatively categorised. For example, "water trucks provisioned …" was categorised as a *response* because a decision had been made to provide supplemental water. However, this code represents a *negative impact* because the water trucks were obviously necessary due to a lack of water access and that corresponding impact was not always simultaneously stated (as per the example in the "Data analysis" section). The nature of natural hazards means the distinction between drivers and impacts is often blurred as one impact leads to another, which leads to another in a cascade. Thus certain impacts can be both drivers and impacts, such as (in extreme cases rather than in this dataset) when crop losses lead to food insecurity which leads to famine and/or migration. Similarly, because agriculture is the dominant livelihood activity, many of the agricultural impacts were probably associated with socioeconomic impacts, though this was unstated. Likewise, "insufficient water for irrigation" and "low water reserves for animal use" fit both the "water accessibility and availability" and "agriculture" impact sub-categories.

The absolute quantities of impacts and their quantitative relative abundance should not be over-analysed due to some ambiguities. The reported impact drivers, impacts and responses are rarely mutually exclusive, many may be part of a cascade, and some may be synonymous. For instance, "localised rainfall" may have led to "low reservoir levels" causing "low water reserves for human use" precipitating "water trucks provisioned in some communities". Some reports may have listed that entire cascade, or a similar such cascade of driver–impacts–response, while the majority only reported the more serious impacts or response, such as regarding water trucks, even though the other impacts were necessarily occurring too. In some cases, "low reservoir levels", "low water levels" and "low water reserves for animal [and/or human] use" may be synonymous, but the heterogeneity in water sources and their different uses (uncovered during fieldwork) indicates that these listed impacts are often disparate.

First considering the agricultural impacts: Despite the uncertainties, it remains extremely notable in famously drought-prone semiarid Ceará that the most frequently reported impact is "crop losses due to excessive rainfall". This code referred to both waterlogging of low-lying areas and untimely rains during harvest (i.e. high intensity rainfall or too much rain at the "wrong time" rather than high volumes). In contrast, despite the period of no or relatively mild drought, "crop losses due to drought", was still a frequent impact. Reports of impacts on livestock production were infrequent, despite the prevalence of such agriculture; livestock production represented 50.8% of Ceará's agricultural economy in 2021, compared to 42.4% for crops [22]. Socioeconomic and environmental impacts were also rarely reported.

Regarding water accessibility and availability, the most commonly reported impacts of water scarcity, low water reserves for human use, and the frequently reported response of water trucks, are troubling, especially given relative lack of drought over the studied period. What's more, while impacts driven by irregular rainfall were commonly reported, often the rain was sufficiently heavy to damage crops, but clearly it did not always contribute to safeguarding water access (i.e. high intensity but low volume).

4.2. Normalisation of impacts

Observer interviews revealed the normalisation of what would be considered in other areas to be significant drought impacts. Crop losses of up to 50% were considered usual and acceptable. Therefore, the reports mentioning, for example, "*There was a loss of*

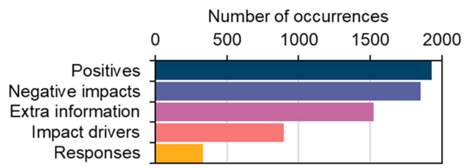

Fig. 6. The relative abundance of each code category from the observers' reports.

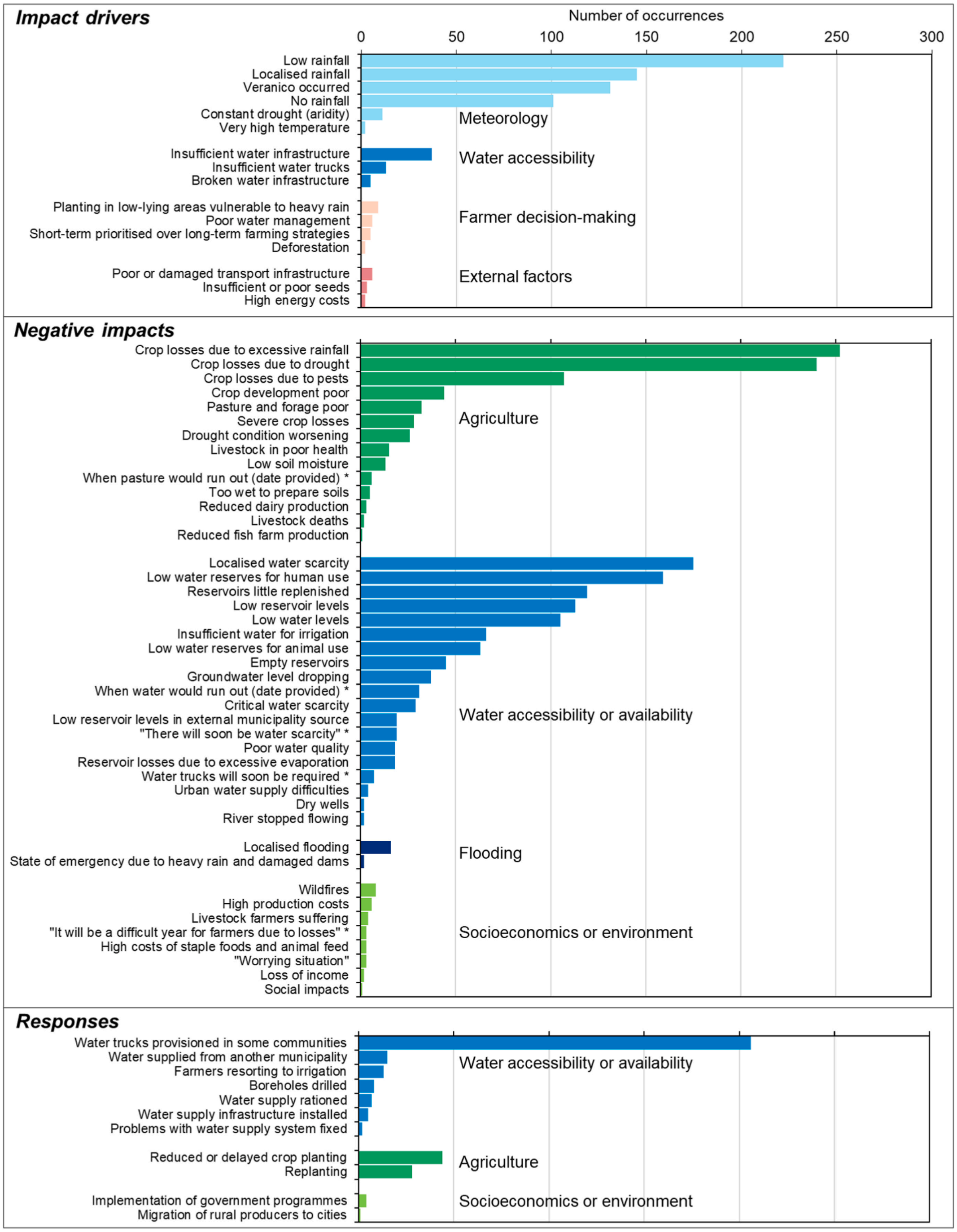

Fig. 7. The relative abundance of the identified *impact drivers*, *negative impacts* and *responses* from the observers' reports, colour-coded by sub-category. Impacts marked with * relate to a prediction provided by the observer. *Veranico* is the local name for a short duration flash drought.

around 20% for beans and 15% for maize" (*Report 3341, Acarape, August 2022*) perhaps should not be considered a *negative impact*. Only when crop losses were greater than 50% would the observer state "high" or "significant" crop losses occurred. However, because we are reluctant to categorise any sort of loss as a *positive*, Fig. 7 presents "crop losses" as a *negative impact*, but separately shows "severe crop losses" indicating losses that were worse than usual. A similar finding was revealed over water levels. During the 2012–2018 drought, reservoir levels dropped to a few percent of capacity. The length of the drought meant that the socio-agricultural systems adapted to this low water availability. Therefore, a statement like "*the level of the dam today is at 26.66% of its capacity*" (*Report 2473, Orós, August 2021*), rather than being a drought impact was a cause for celebration and is synonymous with reports stating that reservoir levels were "good" or "satisfactory". This is exemplified in statements like "*The Lima Campos reservoir that supplies the* *municipality of Icó has 18.11% of its capacity, which can guarantee supply during the year 2020*" (*Report 1292, Icó, May 2020*) and very commonly "*Levels are low, but there is no problem with access to water*" (*Report 1655, Coreaú, October 2020*). Interviewees pointed out that sufficient water to last through the dry season, be it only 15% of capacity or 75% depending on the reservoir and the system it supports, would lead to such positive statements. Only when there was insufficient water to last through the dry season would reports state, for example, "*water reserves for both human and animal consumption are low*" (*Report 71, Nova Olinda, February 2018*). Relatedly, we observed during fieldwork, and it was reported both in interviews and the observers' reports, that water trucks are a ubiquitous part of the water supply system. It's true that more are required during times of drought, but in Ceará their use is normalised rather than necessarily being a negative impact or drought response. With crops the threshold between acceptable and unacceptable losses was 50% (of a target set at the beginning of the season by a committee with consideration of seasonal forecasts), whereas with reservoirs this value varies by location. Interviewees mentioned that this figure of 50% crop losses relates to the *Garantia Safra* criteria. In this index-based income guarantee programme, farmers with low monthly income are eligible to receive monthly payments when their production losses exceed 50% [23]. In summary, many of the "negative impacts" in this context are actually the baseline, which shifted as a result of the previous prolonged drought.

4.3. Relationship between reported impacts and drought indices

There are five categories of drought on the Drought Monitor, from "weak" to "exceptional" (see Fig. 2). Only the mildest three categories occurred during the period of the reports, therefore, a confusion matrix can be produced comparing reported drought impacts with each of these three drought categories declared by the Drought Monitor (Table 1).

Table 1 shows that, according to conventional drought indices used by the Drought Monitor, there were only 66 instances of severe drought and only 772 instances of moderate drought (TP + FP on Fig. 5), yet there were 1211 instances of drought impacts being reported (TP + FN). This indicates that milder drought index values can be present when drought impacts occur. The precision scores show that the more severe drought categories better coincided with reported drought impacts. In other words, as conventional drought indices indicated presence of more severe levels of drought, the number of false positives decreased, such that, to give a hypothetical example, if drought responses were launched in particular municipalities when the "severe drought" category was reached, drought impacts were indeed being experienced there on almost 70% of instances. The recall scores show that a large proportion of reported drought impacts did not coincide with drought as categorised by the drought indices used by the Drought Monitor; the number of false negatives increased as drought category became more severe. While 36% of reported impacts occurred simultaneously with declared "moderate drought", less than 4% of reported impacts occurred during "severe drought". Therefore, continuing the hypothetical example, emergency response triggered when "severe drought" was declared in particular municipalities would not have been triggered in more than 96% of instances when impacts were being experienced. This analysis essentially shows that the drivers of reported impacts are more complex than what is represented by conventional drought indices.

There are several caveats to this assessment of relationship between reported impacts and drought indices. The Drought Monitor is produced at national scale (see Fig. 2) and is not designed for such precise assessment of individual municipalities. Another spatiotemporal scale issue is apparent from the reports that mention both negative impacts and positives, which may have occurred at different times during the month or in different parts of the municipality. In our methodology, any mention of a drought impact meant that month in that municipality was classified as "drought impact reported". Additionally, because we did not apply a level of severity to the drought impacts, some of what we recorded as drought impacts may not have been, in the opinion of the observer, impacts at all and are actually a "normal" situation that arose since the 2012–2018 drought. However, despite the caveats, it is clear that "drought impacts" are occurring even when conventional drought indices suggest they should not be. Therefore, there are factors that create vulnerability even to mild drought and/or the impacts have other drivers; there may also be lingering direct or indirect effects of historic droughts.

4.4. Drivers of impacts

The assessment of impact drivers led to the choice of title for this manuscript: "It's not all about drought". While the reported impact drivers shown in Fig. 7 do most commonly relate to irregular rainfall, consideration of Figs. 3 and 6 shows the large number of reported negative impacts that occurred during a period of relatively mild drought and often no drought. This is confirmed by Table 1, which shows that the reported drought impacts do not always track anomalous drought index values. It is obvious in Fig. 7 that not all negative impacts are caused by drought, but even those impacts classified as "drought impact reported" for the statistical comparison with conventional drought indices appear, upon closer scrutiny, to commonly have non-drought drivers or at least non-drought-related aggravating factors. These non-drought drivers of impacts are described in the following sub-sections.

Table 1
Confusion matrix of reported on-the-ground drought impacts and drought category according to the Drought Monitor. "n" represents the total number of reports for all months and municipalities that could be classified as either "drought impact reported" or "not reported".

n = 3396	True positive	True negative	False positive	False negative	Precision	Recall
Weak drought	827 (24.4%)	1107 (32.6%)	1078 (31.7%)	384 (11.3%)	43.4%	68.3%
Moderate drought	440 (13.0%)	1853 (54.6%)	332 (9.8%)	771 (22.7%)	57.0%	36.3%
Severe drought	46 (1.4%)	2165 (63.8%)	20 (0.6%)	1165 (34.3%)	69.7%	3.8%

4.4.1. Non-extreme hydroclimatic drivers

Notwithstanding the aforementioned caveats, there is a climatological explanation for the mismatch between reported drought impacts and drought indices related to the non-identification of *veranicos* by conventional drought indices. A *veranico* is a short duration (days to weeks) dry spell, or flash drought, occurring within the growing season that is characteristic of the region and can be extremely detrimental to crop production depending on its timing; it is most impactful at the flowering/pollination stage of maize – the dominant rainfed crop in the region [24–26]. The short duration means hydrometeorological indices, operating on minimum monthly timesteps, rarely detect *veranicos* and remote sensing indices assessing vegetation greenness (e.g. NDVI) have no change to detect because the plants may remain green even though the fruits poorly develop, so called *seca verde* or "green drought" [26]. The significance of *veranicos* is highlighted in Fig. 7 where "*veranico* occurred" is seen to be one of the most commonly reported impact drivers; the even more commonly reported "localised rainfall" may also allude to *veranico* occurrence.

At the opposite end of the non-extreme hydroclimatic event spectrum from a dry spell is high-intensity rainfall. Droughts rarely occurred during the period of observed impacts, likewise floods (Fig. 7). However, the most commonly reported impact was "crop losses due to excessive rainfall", relating to waterlogged fields or unseasonal rains during the usually dry harvest period, both causing crops to rot in the field.

4.4.2. Socio-technical drivers

Some impacts in Fig. 7 could be considered both impacts and socio-technical drivers of further impacts. For example, impacts relating to higher costs, triggered by shortages, would likely lead to reduced agricultural production and earnings. Similarly, declining availability of some water sources or forage may lead to reduction of livestock herds through sale or deaths. Many of the water accessibility and availability drivers, impacts and responses in Fig. 7 are socio-technical failings, mainly related to insufficient water infrastructure (for storage and/or transfer), that generate water scarcity – this likely leads to further socio-technical failings in a vicious cycle.

Factors which aggravate, or may entirely drive, "drought impacts" are shown as *impact drivers* in Fig. 7. Most common were those affecting water access, often mentioning communities that were beyond water supply networks and in remote areas. This remoteness was often exacerbated by poor road infrastructure that led to problems in farmers accessing markets, an issue that is aggravated further during particularly wet periods when roads become impassable. Some aggravating factors were considered by the observers to be related to farmer decision-making, in particular the planting of crops in floodplains. This decision harks back to the 2012–2018 drought when it was a valid agricultural strategy to take advantage of latent soil moisture, whereas post-drought, planting in those low-lying areas increases the risk of crops succumbing to heavy rainfall. Therefore, it could be argued that this decision-making, likewise the impact drivers referring to water management and prioritisation of short-term strategies, are drought impacts relating to the shifting baseline.

Low budgets for the responsible institutions may drive the infrastructural failings, while low farm level income excludes investment in pest control that contributes to the third highest agricultural impact in Fig. 7 of "crop losses due to pests".

Poor water management is another impact driver identified by the observers. This may refer to the paucity of local governance that coordinates water infrastructure installation as well as the organisation of emergency responses. In Ceará, such local management committees are rare; the water management system focuses on large strategic reservoirs and water supply for urban areas. Rural water supply systems were implemented through development programmes mainly financed by the World Bank (Sao José I–IV programmes), but fieldwork revealed that the associations created in order to access these programmes were not always sustainable nor had capacity to maintain the infrastructure.

Even though our experience in the area suggests the impact drivers in Fig. 7 capture the most important socio-technical factors generating impacts, because the information was not specifically requested and only occasionally provided in the reports, there are likely to be more factors and all are likely occurring more widely.

5. Discussion

5.1. What this analysis reveals about northeast Brazil

The impacts dataset arose from Ceará though is considered to be representative of the wider *Sertão* region (Fig. 1) due to the similar semiarid climate, predominance of mixed *caatinga* vegetation and rainfed agriculture, and being economically poor (the nine northeast states are in the bottom eleven of Brazil's twenty-six states for GDP per capita[9]). Because the dataset derives from a period of no or mild drought, it can be considered to be providing the baseline situation, albeit a shifted baseline following the prolonged drought. This is a significant advantage of this continuous spatially distributed monitoring over event-based databases. What we saw are that "impacts" are the norm.

The identified impacts suggest the regional policy focus on "living with drought" [27] ought to concurrently consider non-extreme hydroclimate events. High-intensity rainfall events and *veranicos* occur much more frequently than "normal" droughts – several times per year – and cause notable impacts to local populations. Therefore, initiatives like seasonal forecasting and the Drought Monitor that contribute to adaptive agricultural and water resources policy-making [28] could better factor in these events, which may require development of improved indices and forecasting tools [26]. Such action would be timely because, even though climate change projections show decreased rainfall for northeast Brazil and thus longer droughts [29], the projected higher temperatures will also generate higher intensity rainfall while the quantity and frequency of *veranicos* are likely to increase [30]. Whereas the frequency was

[9] https://ibge.gov.br/.

unexpected, the finding regarding impacts of excessive rainfall is not new. Sun et al. [25] showed that crop yield in Ceará negatively correlated with both dry spell and wet spell frequency. De Oliveira et al. [31] showed that 23% of disasters in Ceará were due to excessive rainfall, vs 76% for drought, though with similar per capita losses, R$58 due to floods and R$67 due to droughts.

Importantly, many of the observed impacts have socio-technical rather than climatic drivers, therefore, they should be "easier" to solve than the climate crisis. People are currently experiencing water access, agricultural and socioeconomic impacts due to insufficient or damaged infrastructure and due to sub-optimal management or planning. These impacts will only become worse when the next drought inevitably arrives and proactive fixes are known to be more cost-effective than crisis management [32]. The cited report by the Integrated Drought Management Programme (IDMP) recommends that, since drought already puts a huge burden on national budgets, the required shift to risk management approaches should start with recommendations of "low-hanging fruit". This refers to "mitigating actions that have immediate co-benefits beyond drought risk management and that would be beneficial with or without droughts" [32], which perfectly describes the socio-technical issues identified here.

In addition to learning from the most reported impacts, what was seldom reported by the observers is revealing. Impacts concerning livestock, such as health of animals and dairy production, were rarely reported. Interviewees insisted such information was elicited from farmers, therefore, the livestock industry appears resilient to the climatic and anthropogenic drivers that affected water accessibility and cultivation. Similarly, there were relatively few reports of socioeconomic and environmental impacts, which may partly be due to the previously discussed normalisation of impacts, but may also be a sign that policies, programmes and adaptive management have been effective, as we were informed by older technicians who had lived through many droughts. This point was also made by de Aquino et al. [33] regarding the 2012–2018 drought, which, despite being the worst on record, did not have the severe socioeconomic impacts of historic droughts due to diversification of the economy, social welfare programmes, and improvements in infrastructure.

5.2. Further useful information provided by drought impacts monitoring

Drought impacts monitoring not only identifies the most significant impacts experienced by those on the ground, but also where and when they are occurring. A commonly discussed complexity when it comes to identifying, forecasting and managing drought, is the uncertainty and inconsistency of determining when a drought starts and ends [32,34]. Monitoring drought impacts unveils drought onset and cessation in different areas and in different economic sectors. Consequently, developing droughts can be identified early enough for mitigating actions and those actions can be better targeted. This is particularly important for rapid onset flash droughts that are becoming more prevalent as the world warms [35,36], though monthly reporting may be too coarse. Whereas the information collated in Fig. 7 would show at the time of collection where and what interventions are required, the positive observations presented in Fig. 8 show when they are no longer needed (confirmation over and above relying on impacts no longer being reported). This is especially useful for costly and logistically challenging interventions such as provision of water trucks or, in more extreme cases, provision of humanitarian aid. The positive observations additionally provide monitoring and evaluation of responses and adaptation measures.

Planning drought interventions is most cost-effective when lengthy advance warning can be provided. Required funding and resources can then be sought and directed prior to potential drought-induced shortages and price hikes. Observers often provided predictions within their reports that would enable these preparatory actions. Predictions were both negative and positive (see Figs. 7 and 8), including when particular water resources and pasture would run out and where there will be sufficient supplies to last through

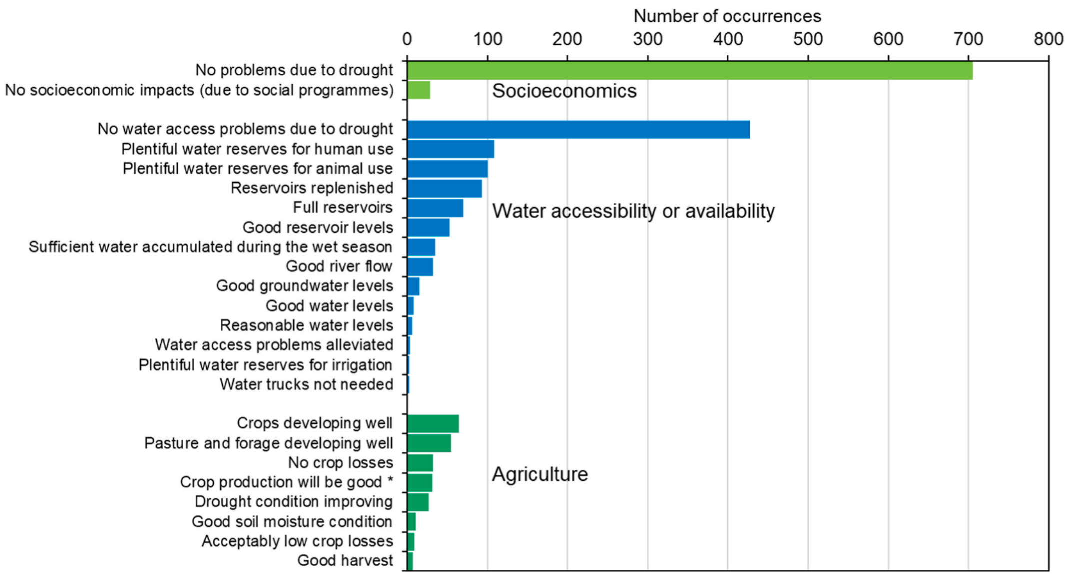

Fig. 8. The relative abundance of the different positive observations. Observations marked with * relate to a prediction provided by the observer.

the dry season, and where farmers would likely experience losses or would be celebrating high production. Such information could inform decision-making on areas where water trucks should be made ready and where they could be diverted from, where insurance/cash payments may soon be required, and where livestock feed may need to be stockpiled.

The information on *responses* in Fig. 7 is valuable for policymakers because it reveals the adaptation and management decisions that are considered to be the most beneficial by the affected people (assuming that less beneficial actions would go unmentioned or would be mentioned negatively). Common responses related to: agricultural decision-making, like adjusting planting timing, and; water infrastructure, such as water supply from external municipalities, drilling boreholes, and installing or repairing pipework. Reported effective responses could be transferred to other areas.

The final category of information provided in the reports is the *extra information* (Fig. 9), which could be useful to different organisations involved in drought management. Some of this information is collected officially – such as rainfall measurements, reservoir levels, and planted areas of different crops – and can be found in openly available government statistics.[8,9] Other information, like quantified losses of different crops, is less available, likewise, the use of different water sources for different purposes and particular communities that are currently experiencing impacts.

It is important to remind that any information other than drought impacts was not requested on the questionnaire. Further observations were simply deemed worthy of note by the observers. Therefore, the total numbers of occurrences in Figs. 6–9 are likely substantial underestimates and there will undoubtedly be additional impact drivers, responses, positive observations, and extra information that went unreported. If any of these information types are particularly useful to interested actors, they could be elicited within the questionnaire. That may mean training the observers to look for such information and potentially adding additional questions.

5.3. Reflections on the analysis and recommendations for drought impacts monitoring

The manual analysis method of the drought impacts dataset was time-consuming and labour-intensive. However, the method allowed for appreciation of the heterogeneity of context within reports and revealed the need for further investigation through interviews. Therefore, we would always recommend some manual analysis prior to machine analysis of drought impacts monitoring data. The analysed dataset could be a training dataset for machine learning analysis of subsequently collected data and for the datasets from neighbouring states. Natural language processing approaches have been applied to newspaper articles [37] and social media [38] to spatiotemporally evaluate drought impacts, noting decreased workload and reduced subjectivity at the expense of some inaccuracies over impact identification. Joint efforts have been underway since March 2022 to harmonise how drought impacts information is collected and reported by EMATERCE technicians across Ceará [19], coinciding with training of several hundred new technicians [39], which would give greater confidence in machine analysis. The aim of this harmonisation is to reduce potential heterogeneous biases regarding what impacts are focussed on, whether they are widespread or localised and all areas are considered, and to encourage reporting of impact drivers and responses. These joint efforts also aimed to emphasise the value of the monitoring programme in order to increase the level of detail provided and increase the spatial and temporal coverage of the reports. The uptick in reports towards the end of 2022 suggests this has been successful (Fig. 4).

To harmonise data collection and simplify analysis, the number of closed questions on the questionnaire could be increased. This would enable immediate data presentation as reports are uploaded to a central system with automatic flagging of extreme impacts. Such systems are in place in the USA through the NDMC's CMOR-Drought programme[3] and the CoCoRaHS Condition Monitoring.[4] Formulation of multichoice and Likert scale questions could be based on the most common impacts reported in Fig. 7 (along with other information deemed useful from Figs. 7–9) with automated mapping of reports onto a real-time GIS-based dashboard for use by any interested actors. However, a questionnaire is often successful when, and because, it is concise. Lengthening the questionnaire may be beneficial for analysis but off-putting for the people gathering and providing the information. We are definitely not advocating for removal of an open question, which allows for reporting of new unexpected impacts and other useful information.

Several drought monitors around the world crowdsource impact information from a broader range of the population, including the USA,[3] India[10] and an alternative drought monitor in Brazil.[11] Though achieving public awareness of these programmes and consistent participation requires substantial effort due to a diverse range of motivations for involvement [40,41]. Citizen science and crowdsourcing of impact information shows potential, but there is a risk of reports not being submitted completely objectively, such as when something could be gained from an increase in the classified drought severity like payout of index-based insurance [42]. Trained observers ensure, to a greater extent, that protocols on data collection are followed and that the impacts reports consider the whole required area and time-span, various groups and sectors, and even non-drought periods [13].

5.4. Improving utilisation of drought impacts monitoring data

This study indicates that drought impacts monitoring combined with a drought monitor have the potential to reduce impacts experienced by affected populations, sectors and ecosystems. As shown in the graphical abstract, the current communication pathways are quite passive, though they are successful at increasing awareness of drought events and bringing together policymakers from different groups. These pathways could be made more proactive by: a) better integrating impacts reports into drought monitors to truly reflect the on-the-ground experience, leading to improved mitigation, and b) directly utilising the impacts reports to uncover existing vulnerabilities for targeted action. Continued monitoring and reporting would then provide feedback on how well the interventions are working.

[10] https://indiadroughtmonitor.in/.
[11] https://www.gov.br/cemaden/pt-br/assuntos/monitoramento/monitoramento-de-seca-para-o-brasil.

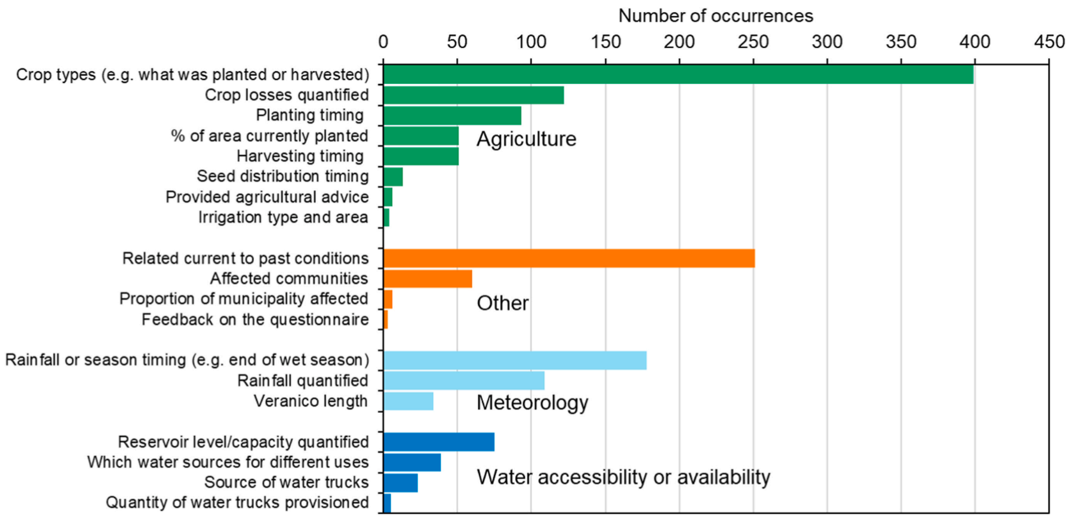

Fig. 9. Extra information from the drought impact reports that did not fit the other categories in Fig. 6. "Related current to past conditions" was a qualitative or quantitative comparison between the current rainfall or drought situation and the average or recent past conditions.

The abundance and severity of impacts caused by intensive rainfall and *veranicos* suggest a need for a multi-hazard monitor. This appears particularly relevant at the time of writing in early-2023 as northeast Brazil is currently experiencing deadly floods and landslides [43]. Lackstrom et al. [13] similarly uncovered impacts resulting from a range of hazards when assessing CoCoRaHS condition reports in the USA. Emergency response is often triggered when a municipality reaches a particular level of drought severity on the Drought Monitor. Yet, a significant proportion of the experienced impacts occurred at lower levels of drought severity (Table 1) and were not necessarily caused by drought (Fig. 7). Therefore, for triggered emergency response to be relevant and timely, the controllers could focus more on on-the-ground impacts observations, which could be enabled with integration into a multi-hazard monitor. Examples of such monitors include various countries in southern Africa[12] with maps displaying precipitation, soil moisture and streamflow indices, and the near global DisasterAWARE system providing alerts and information on 18 hazards.[13] However, many of the reported agricultural impacts in our study that subsequently affected livelihoods related to just not enough or just too much rain at the wrong time. These are not extreme hydrometeorological events and would be difficult to pick up with hazard indices confirming the requirement to utilise and integrate observations from local populations. Climate change studies commonly predict increasing climate variability and unpredictability that would increase the frequency of these low-level but impactful events [29,44].

6. Conclusions

Drought impacts monitoring is increasingly recognised as the missing piece in drought monitoring. Beyond only a few well monitored variables in certain areas (such as crop yield in some countries or hydropower output), we do not know how people, the environment, and different economic sectors are affected by drought at different levels of severity. Few deliberate continual spatially-distributed drought impacts monitoring programmes exist globally, thus there has been little opportunity to test the value of these datasets and compare them to the traditional ways of monitoring drought, with conventional drought indices. Our study was one of the first to conduct such research.

Analysis of a "drought impacts" monitoring dataset from Ceará, in semiarid northeast Brazil, showed that impacts still occur, and are often normalised, during mild or non-drought periods, which describes the 2019–2022 period of the dataset. Essentially, the reported impacts are not "drought impacts", though this normalisation of impacts could be considered a legacy of the severe 2012–2018 drought. The impact drivers were either: a) non-extreme hydrometeorological conditions, such as intensive rainfall and *veranicos* (short duration flash droughts characteristic of the region); or b) socio-technical vulnerability, such as a lack of water infrastructure. The normalisation of "impacts" included, in particular: a level of crop losses that is considered usual, consistently low reservoir levels around which the agricultural and domestic systems are adapted, and regular water supply through water tanker trucks. Understanding the context of the reports was critical in determining if a reported impact was indeed an impact or was the normal situation or even a positive observation.

Drought monitors similar to Brazil's are an increasingly common early step in drought management. Most aim for integration/validation of conventional drought indices with on-the-ground observations, and as such, should have datasets of drought impacts monitoring, whether they are crowdsourced or from official observers. Our analysis of the Ceará data shows that these datasets are more valuable and useful than just for validating drought maps and we encourage drought monitor developers to make this information openly available to researchers and interested actors. Greater integration of impacts monitoring with drought, or multi-hazard, moni-

[12] http://hydrology.soton.ac.uk/apps/.
[13] https://www.pdc.org/disasteraware/.

tors would improve the capability of triggering relevant and timely emergency response. Furthermore, expansion and analysis of impacts monitoring programmes enables identification of vulnerable areas and sectors, and reveals which impacts have non-climatic drivers that are potentially easier to pre-emptively fix.

CRediT authorship contribution statement

David W. Walker: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Juliana Lima Oliveira:** Data curation, Investigation, Validation. **Louise Cavalcante:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Sarra Kchouk:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Germano Ribeiro Neto:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Lieke A. Melsen:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Francisco Bergson P. Fernandes:** Data curation, Validation. **Veronica Mitroi:** Conceptualization, Validation, Writing – review & editing. **Rubens S. Gondim:** Validation, Writing – review & editing. **Eduardo Sávio Passos Rodrigues Martins:** Funding acquisition, Validation. **Pieter R. van Oel:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

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

Data availability

The drought impacts reports are available at https://bit.ly/3Lc462R and drought monitor data are available at https://monitordesecas.ana.gov.br/.

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