Drought in Context:
Rethinking Indices, Resilience, and Impacts.

Sarra Kchouk

Propositions

1. Drought indices are hammers that make all droughts look like a nail.
   (this thesis)
2. In hydrological modelling, the debate over food or water security disregards local communities' primary concern: livelihood security.
   (this thesis)
3. Knowing when to stop a manuscript is harder than knowing how to start.
4. Rather than serving society, fieldwork researchers' pursuit of discomfort is a self-serving act to showcase their own resilience and empathy.
5. Academia reproduces formal and informal traditional systems of social stratification.
6. Encouragement for interdisciplinary PhD research is out of sync with the job market's scarcity of positions in interdisciplinary fields.
7. Authority figures set evaluation criteria that place people with different strengths at a systematic disadvantage.
8. The undervaluation of diversity in formal settings suppresses individual essences, much like straightening one's hair until its natural texture is forgotten.

Propositions belonging to the thesis, entitled

Drought in Context: Rethinking Indices, Resilience and Impacts

Sarra Kchouk
Wageningen, 14 May 2024

Drought in Context

Rethinking Indices, Resilience, and Impacts.

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The book cover, featuring artwork by the *Acidum Project*, blends elements and symbolism relevant to the themes of this thesis. Appearing first is a character from the series '*Propheticos*', from '*prophetic*', which also opens Chapter 1. The rain prophets of Northeast Brazil (*Profetas da chuva*) are rural individuals who forecast weather and climate, typically before and during the rainy season, using traditional methods like observing ecosystem changes and celestial phenomena, sometimes incorporating religious rituals. These practices, passed down orally through generations, blend empirical knowledge and personal experiences with nature. This highlights the tradition and necessity of rural populations to utilise local and contextual indicators, a central theme of Chapter 1. Next, a sunbeam trajectory contrasts existing elements, unveiling a new perspective. This contrast acts as an analogy for how the local context in drought monitoring either highlights or conceals crucial elements. It symbolises a chosen perspective in drought monitoring, a core theme of Chapter 2. This sunbeam is borrowed from the art piece '*Voltar*', which opens Chapter 2. The prophet stands at the centre of a spiral or a multi-layered basin. This depiction evokes the concept of a basin of attraction, which explains how the resilience - of rural populations to drought impacts in the context of this thesis, is highly dynamic and variable. This concept is at the core of Chapter 3, which is introduced by the artwork '*A Gota*', painting a psychedelic basin of attraction. The prophet's action of opening a gap in their gown reveals their heart, depicting a green landscape untouched and unaffected by the sun. This green gap symbolises the resilient strategies implemented by rural populations to cope with drought; strategies yet overlooked by conventional monitoring, thus creating a gap between what is and what should be monitored. This theme is the central focus of Chapter 4, which is opened with a magnification of this element from the artwork '*Propheticos*'. In Chapter 5, these thematic elements, both within the thesis and the artwork, are assembled to demonstrate the importance and implications of the local context for drought monitoring and for rural communities.

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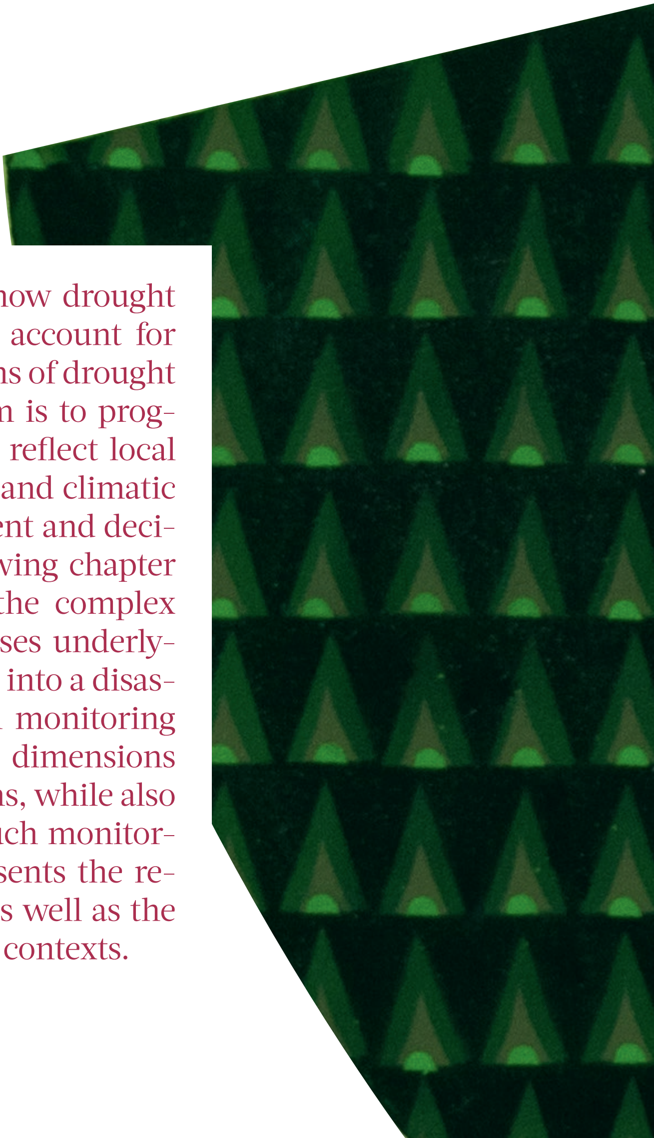
01

Introduction

Abstract. This thesis investigates how drought monitoring can comprehensively account for the impacts and human dimensions of drought in relevant local contexts. The aim is to progress towards drought indices that reflect local realities and include both human and climatic dimensions in drought management and decision-making processes. The following chapter first provides a background on the complex nature of drought and the processes underlying a meteorological event turning into a disaster. It examines the challenges in monitoring droughts, including the human dimensions and impacts on human populations, while also emphasising the importance of such monitoring. Additionally, the chapter presents the research questions and objectives, as well as the research area and the researcher's contexts.



1

"I arrive and leave without clear signs, unlike the stark devastation of hurricanes or floods. My presence is slow and subtle, a creeping change that often remains unnoticed until my ravages become evident. My damages are intangible and elusive to capture in numbers or words, spanning from small villages to vast continents, with consequences that may emerge either now or in the future. Historically, my pervasive influence has contributed to the downfall of powerful civilisations. I do not discriminate in what or whom I affect; age, wealth, gender, or political beliefs do not stop me. However, contending with me does; reflecting in the course, disparities in priorities and resources…
What am I?"

In an attempt to define this phenomenon that is subtle and elusive, drought can end up being portrayed in a grand, almost mythical manner, likening it to a creature of legend or a biblical test of faith, depicting it akin to a sneaky but invisible evil.

In this riddle, I caricatured the threat posed by drought, by exaggeratedly combining words often used in studies, including my own, to translate the complexity of characterising drought, which adds an epic dimension to this phenomenon. This invisible threat hovering over us yet affected an estimated 90 million people monthly between 2008 and 2017, with drastic projected increases (Smirnov et al., 2016), and has contributed to some of the world's most severe famines (FAO, 2018).

"It has no clear onset or demise, it is elusive, subtle, and creeping": Such words employed to describe drought originate from its physical processes. These processes are non-linear and involve feedback mechanisms; drought propagates through multiple space and time levels unequally, making it difficult to objectively determine the extent of its damages, let alone quantify them. Consequently, it is impossible to have a universal definition of drought. Drought can successfully be employed, metaphorically, in (popular) culture to symbolise the poetically sad absence of something that only an intervention beyond human control, like rain, can amend. However, from a more technical perspective, poetic conceptualisations of such phenomena do not help us address them; what does, is their clear characterisation in their relevant context.

1.1 Drought in context

The hazard posed by drought is constituted by abnormally dry weather or an exceptional lack of water compared to normal conditions (UNDRR, 2021). To elaborate, the term hazard refers to a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation (Sendai Framework; UNDRR, 2024). Drought, from a hydrometeorological perspective, has a natural origin, and other than climate change mitigation, little can be done to prevent its occurrence (Solh and Van Ginkel, 2014). A drought hazard is more than a local shortfall in precipitation. It is a failure of whatever is the system that drives the hydrological balance (UNDRR, 2021). This can include reduced rainfall over a certain period, inadequate timing or ineffectiveness of precipitation, and/or a negative water balance due to increased atmospheric water demand following high temperatures or strong winds (Figure 1.1). Causes or exacerbating factors of drought include a lack of snow- or glacier-melt or increased temperatures (UNDRR, 2021).

Drought poses a level of risk, or in other words, potential for adverse consequences (IPCC, 2021). This drought risk varies spatially and temporally and occurs with varying degrees of intensity and severity. It is widely acknowledged that risk is more than just the likelihood and severity of hazardous events and potential impacts. Rather, drought risk is complex, multifaceted, and dynamic, resulting from the complex and non-linear interactions of drought events with the exposure of humans, infrastructure, and ecosystems, to systems' vulnerabilities across multiple scales, sectors, and systems (UNDRR, 2021).

Drought risk is the product of hazard, exposure, and vulnerability (UNDRR, 2021; Carrão et al., 2016; Figure 1.1). Exposure is generally defined as the elements of a system that could be adversely affected by the drought hazard (UNDRR, 2024; Carrão et al., 2016). It comprises all assets, sectors, infrastructure, species or ecosystems, and people located in a drought-prone area. In addition to directly exposed elements, there are indirectly exposed elements such as trade and financial systems (UNDRR, 2021). Vulnerability can be defined as the conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards; here: drought (UNDRR, 2024; IPCC, 2014; UNDRR, 2021). Furthermore, (the lack of) coping and adaptive capacities are central to determining vulnerability (IPCC, 2014; UNDRR, 2021).

Due to its multidimensional nature, vulnerability to droughts is challenging to measure quantitatively and is best assessed by considering relevant and context-specific drivers of vulnerability (UNDRR, 2021). These factors can be social (e.g. demographic characteristics, community awareness and preparedness), linked to governance (e.g. effective drought management policies, strength of institutional frameworks and coordination among agencies), economic (e.g. gross domestic product (GDP) per capita, dependence on agriculture), physical/infrastructural (e.g. roads, dependence on hydropower, water storage and distribution infrastructure), and environmental (e.g. land and soil degradation, deforestation and loss of vegetation, See Figure 1.1). For example, during the 2018 drought in Cape Town, the wealthiest population, who were already the highest water consumers before the crisis (Enqvist and Ziervogel, 2019), had the financial means to install private groundwater wells (Simpson et al., 2019). This reduced their vulnerability to drought impacts, compared to before the crisis. However, this led to a decrease in water availability for those unable to afford similar solutions, increasing their vulnerability.

Another example is in the Jaguaribe basin in Northeast Brazil (Van Oel et al., 2009), where people in different locations within a river basin experience different water availability situations, especially during droughts. In the Horn of Africa, political instability has led pastoralist communities to concentrate, either forcibly or voluntarily, in drought-prone areas. This relocation resulted in land degradation due to intensified overgrazing, in turn exacerbating the effects of drought. The resulting decrease in agricultural productivity led to livelihood losses, thereby compelling people to migrate again out of affected areas, therefore creating a feedback loop where the drivers of drought, land degradation and migration, reinforce each other (Walker et al., 2022; Mengisteab, 2012; Hermans and Mcleman, 2021).

Resilience and vulnerability are interlinked concepts in disaster risk management. Resilience can be summarised as the ability of a system to efficiently minimise both the magnitude and duration of its performance deviation from the designed level when disturbed by a disruptive event and to return to its usual targeted performance levels (Proag, 2014; see Figure 1.1). This involves the system's inherent capacities to absorb, adapt to, and recover from disruptions. Resilience can be enhanced in four ways (Proag, 2014; Fiksel, 2003): (i) diversity, or "existence of multiple forms and behaviours"; (ii) efficiency, or "performance with modest resource consumption"; (iii) adaptability, or the "flexibility to change in response to new pressures"; and (iv) cohesion, or the "existence of unifying forces or linkages". Enhancing resilience (through inbuilt system features and capabilities) leads to a decrease in vulnerability, thereby reducing the potential damage from disruptive events (Proag, 2014). In that sense, not all droughts become a risk or a disaster.

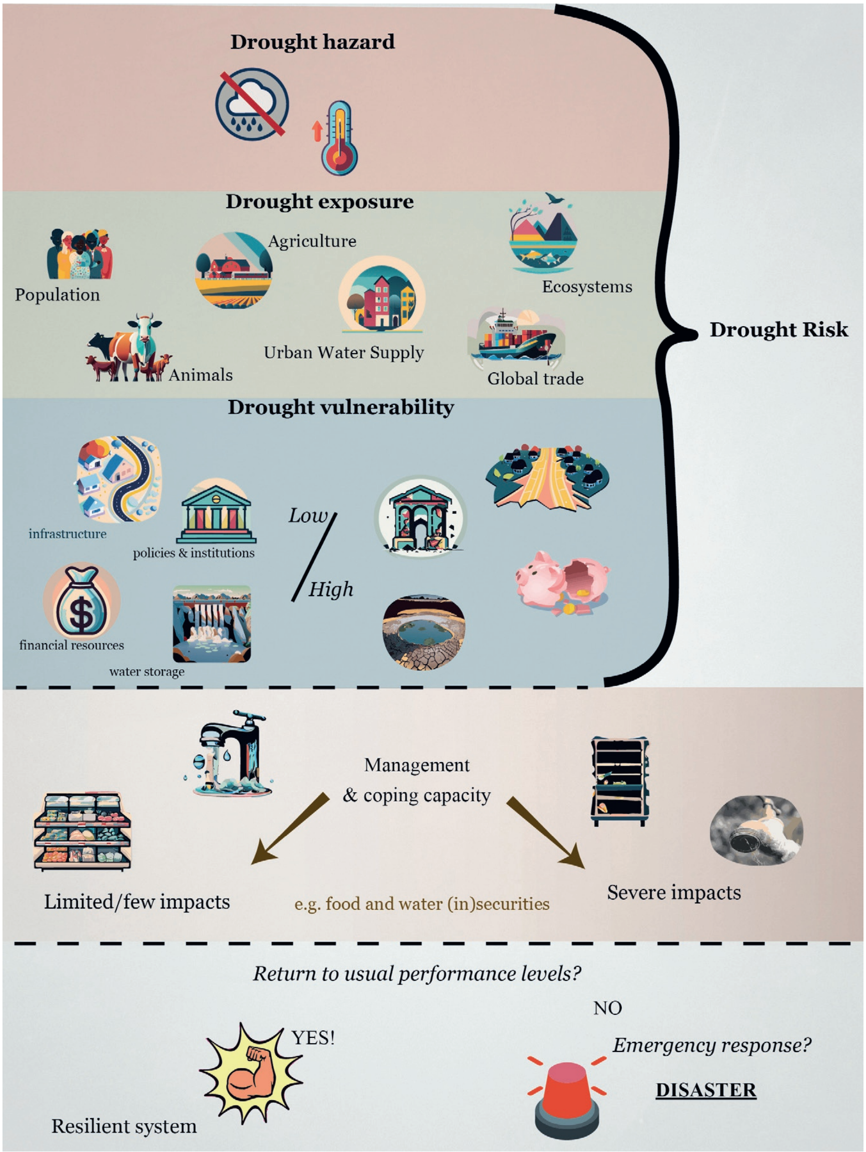


Figure 1.1: Overview of key concepts used in this thesis: drought-risk components (hazard, exposure, vulnerability), and their connection to drought impacts, drought management, and resilience with regard to drought as a disaster (based on UNDRR, 2021).

A drought becomes a risk when the drought hazard affects exposed and vulnerable societies and ecosystems with inadequate capacity to cope with the lack of water (UNDRR, 2021). Drought results in a disaster when the caused harm justifies an emergency response, varying from local to international scale (Proag, 2014; see Figure 1.1). As a matter of fact, the World Bank and United Nations (2010) contrast *"natural hazards and unnatural disasters"*.

Failure to manage drought risk and/or cope with the lack of water can result in negative consequences for lives, livelihoods, the economy, and ecosystems (UNDRR, 2021). These consequences are termed drought impacts (Figure 1.1). Drivers of drought hazards, risks, and impacts can be natural, human-induced, or a combination of both (UNDRR, 2024). Such underlying factors and processes, which are commonly referred to as 'drought drivers' can influence the frequency, duration, intensity, and spatial extent of droughts and their impacts (UNDRR, 2021).

Therefore, the central elements of adequate drought management, to minimise drought impacts, are characterising and understanding drought risk so it can be better addressed. This requires a proactive approach to predict, prevent, prepare for, mitigate, and respond to drought risk to minimise potential impacts (UNDRR, 2021). One of the ways to do this is to monitor drought, to follow its development. Monitoring drought involves characterising its risk. The proportion of the risk, and thus the extent of drought impacts, are dependent on the levels of the hazard, the exposure, and the vulnerability. Particularly since the exposure and the vulnerability are highly dependent on local circumstances (UNDRR, 2021), this implies that the assessment and monitoring of drought risk require to be context-sensitive.

1.2 Rethinking indices, resilience, and impacts

Context-sensitive assessment of drought is a crucial component in managing drought risks. This involves taking into account the unique characteristics, circumstances, and conditions of what is at risk, be they humans, ecosystems, or infrastructure. A proactive approach to drought risk management includes appropriate measures being designed in advance, with related planning tools and stakeholder participation. The proactive approach is based on short- and long-term measures and includes monitoring systems for a timely warning of drought conditions, identification of the most vulnerable part of the population, and tailored measures to mitigate drought risk and improve preparedness (UNDRR, 2021).

Drought monitoring and early warning systems (DEWSs) typically aim to track, assess, and deliver relevant information concerning climatic, hydrologic, and water supply conditions and trends (UNCCD, 2024). Two examples are the U.S. Drought Monitor and the Brazilian Drought Monitor. The U.S. Drought Monitor (https://droughtmonitor.unl.edu/; 2024) releases a weekly map displaying drought-affected areas in the U.S. using five classifications: abnormally dry (D0), indicating potential or recovering drought, and four drought levels: moderate (D1), severe (D2), extreme (D3), and exceptional (D4). The indices used to categorise the drought severity rely on precipitation, temperature, soil moisture, and stream flow.

The Brazilian Drought Monitor (http://monitordesecas.ana.gov.br/; 2024), directly related to the two case studies in Northeast Brazil in this thesis, provides monthly maps. The drought severity categories range from 'no drought' to 'weak drought', signalling the onset or end of dryness, 'moderate', 'severe', 'extreme', to 'exceptional drought', indicating widespread agricultural losses and critical water shortages. The indices used to categorise the drought severity rely on the available data for precipitation, evaporation, and runoff.

It is not evident whether drought monitoring can provide a context-sensitive drought risk assessment. Currently, the majority of drought monitoring and early warning systems, including the Brazilian and US Drought Monitors, is still very much focused solely on the physical processes underlying drought propagation (Bachmair et al., 2016; UNCCD, 2024), therefore largely overlooking the human drivers of drought and its impacts on human populations.

One of the root causes is the "creeping phenomenon" aspect of drought, or the challenge of not being able to identify and thus monitor a change that occurs slowly over a long period of time. This is where, as mentioned before, conceptual definitions of drought make drought early warning, impact assessment, and response, difficult for scientists, natural resources managers, and policymakers. Indeed, the lack of a universal definition often leads to confusion and inaction on the part of decision-makers, since scientists may disagree on the existence and severity of drought conditions (Wilhite and Pulwarty, 2017). However, it is important to define discrete drought events for the purposes of estimating losses and damages from extreme events and for implementing policies (UNDRR, 2021). And this is where operational definitions of drought are useful. Such definitions highlight practical implications in an attempt to identify the onset, severity, and cessation of drought periods (Mishra and Singh, 2010).

Operational definitions of drought highlight specific criteria based on the use of hydrometeorological and land-surface variables as indices (Bachmair et al., 2016). Such indices are sector-specific and are typically derived from variables such as, but not limited to, precipitation, climatic water balance, soil moisture, streamflow, and groundwater levels. Based on the numerical value of these hydro-climatic-based indicators, droughts are then usually termed meteorological, soil moisture (i.e. agricultural and/or ecological), or hydrological drought (Zargar et al., 2011). However, these are all progressive manifestations of the same drought propagating through the hydrological cycle (UNDRR, 2021). Furthermore, drought is depicted as a sequence occurring in an almost linear order (Wilhite and Glantz, 1985; Zargar et al., 2011) which suggests the lack of direct human influence. This is rather a simplification of a complex process, in which it is considered that an anomaly (e.g. lower precipitation, higher temperature than average) of the values of those physical drivers will lead to a cascade reaction influencing the magnitude of other physical variables and leading in turn to the subsequent type of drought. The difference between the values of the drought indices and the threshold used to define the level of dryness is considered to depict the severity of a drought (Vogt et al., 2018).

Drought indices are developed either for drought monitoring and awareness-raising or for water management (UNDRR, 2021). They are central to triggering water conservation measures and determining whether (and how much) drought assistance will be provided to affected regions (Quiring, 2009). They are also useful for drought forecasting (Dutra et al., 2014), climate change studies (Naumann et al., 2018; Cook et al., 2020), and as input for drought impact modelling (Stagge et al., 2015) and drought risk assessments (Carrão et al., 2016).

However, two components pivotal for such purposes are lacking: indices or variables accounting for (i) the human influences (on drought) and (ii) human impacts (of drought). Thus, in the current configuration of most existing DEWSs, the presumed likelihood of experiencing impacts is mainly linked to the severity of climatic features only (e.g. Brazilian Drought Monitor, 2024; African Flood and Drought Monitor, 2024; U.S. Drought Monitor, 2024).

The exclusion of anthropogenic drivers of drought, including vulnerability and exposure, from drought monitoring systems can be attributed to the historical focus on climatic factors in drought monitoring. The first conceptualisations of drought focused primarily on understanding and assessing key attributes of the hazard, such as frequency, intensity, duration, or area affected. The prevalent use of the term “natural disasters” reflects the perception of disasters as purely natural phenomena, which are therefore addressed as such (Hewitt, 1983; Ward et al., 2022; UNDRR, 2021). The consideration of holistic risk concepts, considering social, economic, political, and environmental drivers, coexists with the historical climatic focus; however, it has not yet been implemented operationally in DEWSs.

Another reason for the sole focus on climatic factors in drought monitoring is that physical and anthropogenic aspects are completely intertwined with drought risk (Aghakouchak et al., 2021), leading to practical challenges in quantifying and attributing anthropogenic contributions precisely. Anthropogenic drivers introduce complexity and variability as they are dynamic and non-static, which is challenging to incorporate into standard monitoring systems. Drought can trigger failures in one or multiple parts of the system, leading to cascading impacts on other sectors or systems, both in the same region and in areas far from the drought-affected zone (De Brito, 2021). The three risk components (drought hazards, exposure, and system vulnerabilities) are not static, but subject to constant spatial-temporal dynamics. Key factors driving these dynamics encompass, among others, population growth, tourism, mobility, and alterations in agricultural land and ecosystems due to human activities, such as the growing need for land for housing and food production, along with political priorities and economic development (UNDRR, 2021). Consequently, it is complex and challenging to consider all the sectors and stakeholders exacerbating and impacted by droughts, nested at different levels of spatial, temporal, and decisional scales. However, these dynamic factors are pivotal in understanding how drought-related disturbances develop into drought impacts and in proactively anticipating their occurrence.

Drought impacts on human populations, such as livelihood, water, and food securities are also rarely consistently monitored or even included in DEWSs. This is understandable as there is already a plethora of definitions for drought and drought types, and there are at least as many possibilities for defining impacts (Mishra and Singh, 2010; Wilhite, 2000; Santos Pereira et al., 2009). Therefore, due to their local complexities, not only are exposure and vulnerability often overlooked in drought monitoring, but the actual impacts of drought, characterised by their complex spatial and temporal variations, are also typically not monitored.

Amidst these considerations, a pivotal concept for drought risk management, if not its equivalent, is drought resilience. In a broader sense, drought resilience encompasses the ability of people, the economy, and the ecosystem to be minimally impacted by drought, recover quickly, and adapt (Crossman, 2018). Understanding various adaptations and coping strategies to deal with shocks and disasters, such as droughts, is particularly valuable. Monitoring these drivers of resilience to drought and drought impacts is crucial in anticipating the erosion of adaptive capacity and, consequently, the occurrence of impacts.

The need to understand, assess, and monitor the drivers and complexities of current and future drought risks, as well as their spatiotemporal dynamics, is highlighted by recent initiatives (Sendai Framework and GAR Special Report on Drought, 2015, 2021). Nevertheless, regarding current common practices for monitoring drought through DEWS, there appears to be a gap in fully achieving their objective of facilitating proactive, well-informed decision-making and empowering vulnerable groups with timely, reliable data and indicators (Pulwarty and Verdin, 2013; UNDRR, 2021). Consequently, this shortfall can complicate the ability of drought managers to make well-informed decisions and take appropriate action, especially if the effects of anomalies in the hydrological cycle, as indicated by drought indices, remain unknown outside the affected area.

This endeavour of monitoring drivers, complexities, and spatiotemporal dynamics of drought risk for informed decision-making is confronted with another challenge: the specificity of the local context. Understanding, assessing, and monitoring these characteristics are inherently complex, and as mentioned earlier, they are highly context-specific. Therefore, there is a need to not only rethink drought indices to better capture the impacts of drought but also to tailor them to fit the specific contexts in which they are applied. This is the focus of this thesis: to understand how drought monitoring can comprehensively account for the human dimensions of drought in the relevant local context.

1.3 Research questions and objective

This central question spans the entire thesis:

How can drought monitoring comprehensively account for drought impacts in the relevant local context?

It is the guiding question in each of the chapters. The objective is to enhance our understanding and progress towards the development of indicators that can allow drought managers to make more comprehensive decisions, using indicators that accurately reflect local drought impacts. To address this central research question, the thesis is structured around three sub-questions, each exploring a different facet of the overarching question.

RQ1: How is drought currently monitored and how are drivers and impacts aligned?

This first sub-question focuses on understanding current methods of drought monitoring and investigation, examining what are commonly used indices in scientific drought studies and the most frequently reported impacts of drought worldwide. The aim is to determine the relative attention for physical drivers of drought, being the drought indices, and the impacts on food and water securities. The research particularly seeks to identify the main variables used to characterise drought. Additionally, it seeks to explore whether there is a geographical distribution for both drivers and impacts, and any potential (mis-)alignment between them. In cases where such (mis-)alignment or specific patterns are observed, the research aims to explore why the physical drivers of droughts, or their impacts on food and water security, are studied differently across various regions of the world. It is also explored if regional discrepancies in indices and impacts can be attributed to local factors.

RQ2: How does drought cause local impacts?

The second sub-question is designed to unravel the dynamics that drive the transformation of drought disturbances into impacts across various spatial levels and through different periods of time, particularly emphasising how actions taken in the past can have lasting effects on future impacts. It investigates the extent to which the human and physical dimensions of drought are distinguishable. Most importantly, the study theorises the factors that drive the coping capacities of stakeholders at the local level, ultimately determining their resilience and adaptability in the face of drought. It explores the rationale behind the decisions made by local actors and examines how these decisions have ripple effects or interact with other decisions made at different spatial levels, both in the present and the past. This is exemplified through one case study in Northeast Brazil

RQ3:To what extent does current drought monitoring capture impacts experienced by local communities?

The final specific research question focuses on evaluating whether drought monitoring accurately reflects the impacts historically felt by local populations during past drought events. This investigation is important for pinpointing where drought monitoring may fail to capture local impacts, which is crucial for practitioners to make well-informed, proactive, prospective, or responsive decisions regarding specific drought assistance. As established in Chapter 2, there exists a fundamental difference between the methods of drought monitoring and the impacts that actually occur. Chapter 3, also based on one case study in Northeast Brazil, further emphasises this by highlighting the specificity of local impacts as a result of local dynamics. Using these findings, it is aimed to identify shortfalls in current drought monitoring practices to provide recommendations for improvements. These improvements aim to ensure that drought monitoring considers both the human drivers of drought and the impacts on human populations. Ultimately, this converges towards answering the main research question of how to comprehensively account for drought impacts in the local and relevant context.

1.4 Scientific context

The research conducted is grounded in three pillars of knowledge, aiming not only to draw from but also to contribute to the existing literature in (i) socio-hydrology, (ii) social-ecological systems, in the context of (iii) drought management. Through its findings, the thesis seeks to enhance and expand the current understanding of these interrelated fields.

Socio-hydrology (SH) is a field that integrates hydrology with social, economic, and environmental sciences to study the interplay between human societies and water systems. It focuses on how human activities and hydrological processes coevolve and influence each other over time (Müller et al., 2024).

Social-Ecological Systems (SES) and SH are closely related fields. SES explores the interactions between human and ecological systems, emphasising the interconnectedness of people and nature. This field looks at how societal (social, economic, cultural) and ecological (biological, physical) components interact and impact each other (Ostrom, 2009; Partelow, 2018). While SES has a broader focus on ecological and human systems interactions, socio-hydrology zooms in on the aspect of water within these interactions.

Many developments in the field of SES are relevant to SH. Elsawah et al. (2019), for example, identified priority research areas in SES modelling to address barriers that limit support of decision-making. The areas are largely around: multi-faceted uncertainty assessment and management; leveraging new data types and sources; dealing with scales and scaling issues; combining qualitative and quantitative methods and data; capturing structural changes; and representing human dimensions in SES. Whereas the last two items, in particular, are primary concerns of SH, all of the mentioned items are relevant for disaster risk management, which includes drought management.

Socio-hydrology (SH) and Social-Ecological Systems (SES) significantly enhance drought management by offering a multidimensional perspective. SES broadens the scope by considering the ecological impacts of droughts on ecosystems, biodiversity, and dependent communities, advocating for strategies that incorporate ecological resilience and socio-economic factors. SH, on the other hand, focuses on human-water dynamics, with both disciplines aiding in the development of sustainable, equitable, and responsive policies. Through their focus on feedback loops and interactions between different system components, SH and SES encourage adaptive management approaches, emphasising the importance of learning and adjusting strategies based on ongoing monitoring and emerging information. This approach supports the resilience of communities and ecosystems against future droughts. Furthermore, SH and SES advocate for multi- and trans- disciplinary stakeholder engagement (Brandt et al., 2013; Müller et al., 2024), ensuring that drought management strategies are comprehensive, diverse in perspective, and tailored to specific contexts. The following three subsections focus on how these bodies of knowledge contribute to the aim, scope, and answering the overarching question of this thesis.

1.4.1 Socio-hydrology

While socio-hydrology aims at combining both social and hydrological components and their interaction and co-evolution (Müller et al., 2024), there is also a historical bias centred around having a prevalence of the hydrological over the social (Vanelli et al., 2022). In fact, at conferences such as the Delft 1st Conference on Sociohydrology (https://delft2021sh.org/), debates on placing 'socio' before 'hydrological', 'socio' rather than 'social-' and whether it should be 'socio-hydrology' rather than 'hydro-sociology' were used to justify this focus on the sole hydrological aspect. Furthermore, leading figures in the discipline argue for an approach whose outcomes should remain mainly quantitative or directed towards modelling (Sivapalan et al., 2012; Montanari et al., 2013; Blöschl et al., 2019). However, there is another school in socio-hydrology that aims for a more egalitarian consideration of both components (De Brito et al., 2018; De Ruiter and Van Loon, 2022; Van Oel et al., 2009), and I believe that my research falls into this category. In the era of the Anthropocene, it is impossible to minimise the human influence on the hydrological cycle, or else, detach it as an additional component. There has already been an update of the diagram of the water cycle from the time I studied it at university to now, where human activities are added and that emphasises how such exclusion made no sense (Abbott et al., 2019). Another interesting argument mentioned at that same conference is that, unlike 'socio-hydrology and hydrology', socio-hydrogeology and hydrogeology are interchangeable terms as it is unlikely that water in subterranean aquifers will extract itself, therefore, recognising the inherent interwoven water and human components.

This research positions itself within this vision of socio-hydrology, with equal consideration to both components. As extensively discussed in the previous parts of the introduction, drought mobilises, or rather, shows this entanglement between the anthropogenic and purely hydrological components. This thesis can be seen as socio-hydrological, basing itself on the combination of the analysis of quantitative data and the application of social theories.

1.4.2 Social-Ecological Systems (SES) Research

This study builds on insights from the field of Social-Ecological Systems, with its use being twofold: addressing the complex spatial and temporal dynamics of droughts, and examining the factors contributing to resilience and vulnerability to drought, both of which lead to drought impacts.

The complexities of managing droughts are characterised by varying spatial, temporal, and decisional scales, involving a wide range of societal actions and stakeholders. Actions range from local innovations like micro-irrigation (Grafton et al., 2018) to larger-scale projects such as building reservoirs (Boelens et al., 2019). These actions, indicative of complex human-environmental interactions, involve stakeholders within and outside the water sector, spanning multiple governance levels - from individual water users to international policymakers (Hoekstra et al., 2019) Interventions are nested across these levels, affecting various stages of the supply chain from production to household management (Van Oel et al., 2019). The GAR Special Report on Drought 2021 (UNDRR, 2021) highlights three main aspects of droughts: spatiotemporal variation, multidimensionality, and indirectness, emphasising their cross-sectoral and cascading impacts. Social-Ecological Systems (SES) theory, which has been applied in various fields, aids in understanding the unpredictable changes and legacy effects in these systems (Delgado-Serrano et al., 2015; Gunderson and Holling, 2002). However, its application to understand the spatiotemporal complexities of droughts is not widely prevalent yet.

Addressing the risks and impacts of droughts requires a systemic, holistic approach that recognises the complex interdependencies and feedback mechanisms between human societies and ecological systems. Central to this is the concept of SES resilience, which emphasises adaptability and the capacity of systems to adjust to changes and disturbances. Effective drought management should involve cross-sectoral, transdisciplinary collaboration and multi-level governance, acknowledging the non-linear, dynamic nature of social-ecological interactions. This comprehensive approach underscores the importance of considering entire systems in environmental management, rather than focusing on isolated components, to maintain functionality and resilience in the face of external stressors (Hagenlocher et al., 2023). A SES perspective, strong by encompassing multiple sectors, levels and consideration of coping, adaptive, and transformative capacities of drought-affected systems is highly valuable for drought management, as further explained below.

1.4.3 Drought management and decision-making

In many countries, drought management has historically been reactive (UNDRR, 2021). This might have to do with drought often being considered a purely stochastic phenomenon beyond human control. However, there is a gradual shift towards a proactive risk approach, based on the Integrated Drought Management Program (IDMP)'s three-pillar method: (I) monitoring and early warning systems, (II) vulnerability and impact assessment, and (III) mitigation and response. These three pillars are not meant to be isolated; they are interconnected and involve feedbacks between them (IDMP, 2024).

The interaction among IDMP's three pillars suggests that each is informed and influenced by the others, breaking down silos and creating a cohesive approach to drought management. However, many studies on drought-risk management position themselves in one or more of these pillars, but do not focus on the feedbacks between them. In fact, also the IDMP itself does not emphasise these connections in its working documents. Yet, the interconnectedness of these pillars is of major importance, as feedbacks between them can inform their adjustments, supporting the refinement of drought policies and enhancing their effectiveness.

This thesis is inserted in that context, specifically focusing on the interconnectedness between monitoring and early-warning systems and vulnerability and impact assessment. This thesis cuts across all three pillars with an emphasis on pillar I through its research on indices. It draws significantly from pillar II as it aims to investigate how human dimensions affect drought risk and how impacts affect human populations. The objective is to integrate them into drought monitoring and early warning systems, ultimately aiming at informing mitigation and responses (pillar III). Thus, this thesis is at the intersection of the two first pillars and intends to inform the third.

Furthermore, while proactive in nature, the three-pillar approach does not yet pursue prospective risk management, where action seeks to avoid the development of new or increased risks (UNDRR, 2021). Prospective risk management goes further than proactive approaches by seeking to prevent new or increased risks before they are realised. Proactive management is about immediate readiness for known risks, while prospective management aims to prevent potential future risks from developing (United Nations General Assembly, 2016). Prospective approaches ensure more effective and integrated drought management because of their focus on holistic, long-term prevention and aim for resilience-focused strategies to anticipate and mitigate evolving risks and complexities. Prospective approaches to drought management refer to understanding and addressing the interconnected factors that contribute to drought risk, influenced by a complex network of ecological, social, economic, and climatic factors.

Research on drought as a complex systemic risk fits a prospective drought-management approach that is being advanced (UNDRR, 2021), and this thesis positions itself within this effort. As mentioned in the previous subsection, adopting a social-ecological perspective, which is the focus of Chapter 3, notably in terms of the resilience of drought-affected systems and multiple levels of drivers and impacts, fits this prospective approach.

Finally, improved early-warning systems are pivotal in supporting a prospective and proactive approach to drought management, enabling collaborative analyses that lead to the development of targeted indices for effective policy interventions, specifically tailored to geographic and stakeholder needs (Pulwarty and Verdin, 2013). They play an integral role in both formal and informal decision-making processes, empowering vulnerable sectors and social groups to effectively assess and mitigate potential losses and damages (Pulwarty and Verdin, 2013). Furthermore, historical and institutional analyses within these frameworks are key to identifying processes and entry points for reducing vulnerability to drought impacts (UNDRR, 2021). Prospective and proactive drought risk management relies on the active involvement and support from all stakeholders, including national and local governments, and citizens. Integrating local knowledge and practices with modern methods fosters mutual trust, acceptability, shared understanding, and a sense of ownership and self-confidence within the community (Bohensky and Maru, 2011; Nyong et al., 2007). This approach directly relates to the research in this thesis, especially in bridging the gap between conventional drought-monitoring approaches and the actual impacts experienced by rural communities (Chapter 4).

1.5 Research setup

This thesis is by essence interdisciplinary as it combines the physical and human dimensions intertwined in drought, as extensively discussed in this introduction. Consequently, both social and natural compartments were the object of study and mixed-methods, combining quantitative and qualitative analysis, were integrated.

1.5.1 Research approach

Table 1.1 provides a concise summary of the objectives and methods of each chapter, providing insight into how they contribute to the overall picture.

I started my thesis research with a bibliographic review to grasp how drought is monitored globally. As mentioned in Section 1.2, drought indices are not only an important part of DEWSs; they are also useful for climate-change studies. Therefore, my interest included understanding what dimension of drought the studies in different countries focused on and what was the reason underlying such specific focus. Dimension refers to which aspect of the physical or human components of drought risk. This led to compiling an inventory of these indices, delving into their specifics and identifying the most prevalent ones geographically. Following this, I conducted a bibliometric analysis using Scopus-sourced articles related to droughts' physical drivers and food and water securities impacts (Chapter 2).

I then explored historical drought events and their impacts, to see how theoretical understanding aligns with real-world experiences and what are the dynamics underlying drought drivers resulting in impacts. Fieldwork conducted from November 2021 to July 2022, took place in the Jaguaribe River Basin in Northeast Brazil's state of Ceará, which is further detailed in the next subsection. I undertook a 'drought diagnosis', developed as part of our '3DDD project,' which provided guidelines for metaphorically diagnosing areas affected by drought (Walker et al., 2022). This involved historical analysis of drought events and impacts using mixed methods, validated through discussions with both academic and non-academic actors. The methodology of this diagnosis is detailed in Chapter 3 (Section 3.2.1).

Table 1.1: Overview of scientific methods utilised in this thesis

Chapter	Research Question	Aim	Methods
Thesis	**How can drought monitoring comprehensively account for drought impacts in the relevant context?**	Enhance our understanding towards the development of indices that accurately reflect local drought impacts and allow drought managers to make more comprehensive decisions.	
1	How is drought currently monitored and how are drivers and impacts aligned?	Compare the global scientific focus on physical drought drivers and drought-related impacts on water and food securities	Bibliometric analysis on scientific peer-reviewed articles retrieved from Scopus
2	How does drought cause local impacts?	Conduct a historical analysis of previous drought events	Drought Diagnosis, including grounded theory and interviews
		Analyse the spatial and temporal dynamics of drivers of drought risk and impacts	(Included in the Drought Diagnosis) Literature from Social-Ecological Systems Concepts
3	To what extent does current drought monitoring capture impacts experienced by local communities?	Compare available drought indices with the real impacts experienced by a rural community	Quantitative and qualitative data analysis

Finally, I focused on determining whether drought monitoring accurately reflects actual local drought impacts, and if any gaps between the two can be effectively addressed. To achieve this, I combined quantitative and qualitative data, sourced from conventional agro-hydro-climatic databases as well as from my fieldwork campaign, focusing on one rural community (Chapter 4).

1.5.2 The local context of Northeast Brazil

The semi-arid region of Northeast Brazil, commonly known as "Sertão" in Brazilian Portuguese and also referred to as the "Drought Polygon," encompasses (parts of) ten states (Figure 1.2): Alagoas, Bahia, Pernambuco, Minas Gerais, Paraíba, Rio Grande do Norte, Ceará, Piauí, Sergipe (ANA, 2017). The Northeast Region of Brazil is one of the five official and political regions of the country.

It includes the aforementioned states except Minas Gerais, which is part of the Southeast Region. In this thesis, the term 'Northeast Brazil' refers exclusively to the semi-arid areas within these states of the Northeast region.

The Sertão is semi-arid (ratio rainfall/potential evapotranspiration between 0.2 and 0.5; Lal, 2004) and averages around 800 mm of rainfall annually (Marengo and Bernasconi, 2015), mostly concentrated within the four-month 'wet season' from February to May. This rainfall is highly heterogeneous spatially and temporally, characterised by intense rainfall events and high interannual variability (Martins and Reis Junior, 2021). The region is also characterised by high temperatures and low humidity, leading to over 2000 mm of annual potential evapotranspiration. The region's poor shallow soils over crystalline geology results in a lack of large aquifers and only intermittent rivers (Magalhães, 2016).

Chapters 3 and 4 focus on case studies from drought-impacted rural communities in the state of Ceará (Figure 1.2). These chapters highlight the importance of local context in monitoring drought and assessing its impacts. The context relevant to these communities is detailed in each of the chapters. To fully grasp the interplay of hazards and policies, it is crucial to understand the role and origin of small-scale and subsistence farming in Brazil, which ultimately shaped the drivers of the vulnerability and exposure of populations and their assets to drought and today's *'local context'.*

Figure 1.2: Northeast Brazil. The two communities used as case studies in this thesis are represented by the red stars (Based on ANA, 2017)

1.5.2.1 Family farming legacy

In Brazil, the Northeast region has long been stigmatised as “a problem region, the poorest in the country, the most disadvantaged” (Théry, 2012). To explain the situation, drought is often invoked. However, the rainfall of 800 mm in most of the Northeast (Marengo and Bernasconi, 2015) challenges the notion that drought is the sole explanation for the region’s disadvantage. In addition to drought, the poverty and social vulnerability of the Northeast region are mostly linked to the original latifundia system. The family farming system, representing nowadays 80% of the agriculture in Northeast Brazil but detaining only 37% of the agricultural lands (De Aquino et al., 2020), originates from a colonial law in 1850 (Sabourin and Caron, 2001). This law was enacted under the pressure of some latifundists (large landowners) whose concern was to limit the increasingly frequent illegal occupations of land. It actually resulted in the settlement of numerous families by regularising the situation of the occupants, the cattle herders of the *fazendeiros*’ (large farm owners), by enabling them to purchase land and legally establish themselves with their herds. These herds were accumulated through a compensation system implemented by the landowners, where herders were remunerated with one calf for every four born, selected by the owner. This law resulted in the division of large farms into small rural communities, representing the origin of family farming in Northeast Brazil.

In addition, latifundists restricted equal access to water by maintaining the reservoirs on their own lands. Successive divisions by inheritance led to the fragmentation of farms into strips, where plots are in length and aligned, to guarantee access, even limited, to water and the most fertile soils of the lowlands. This configuration turns collective management at the lowland or watershed scale particularly difficult and complicates the construction of water use infrastructure (e.g. irrigation, access for herds, fences; Sabourin and Caron, 2001). The start and then the increase of a small farming economy remained however limited to meeting consumption needs, as the climatic uncertainty also made agricultural production uncertain.

Irrigation, which can address this form of vulnerability, appeared very late in the Northeast of Brazil. From the end of the 19th century to the 1970s, water policies gave priority to populations and herds’ water supply through the construction of large dams. Irrigated agriculture represented a stage of intensification of agriculture that had no place in a society that had been oriented, since the beginnings of colonisation, towards extensive livestock farming (Sabourin and Caron, 2001). Molle (1991) added that agriculture remained despised, assigned first to indigenous populations and persons of mixed-race, then to agricultural workers and sharecroppers. The settlement of these populations and their clustering in communities near water points, represent the origin of family farming in Northeast Brazil; until now, members of these communities are the descendants of the first occupants or purchasers of these old large farms.

While past droughts coupled with its colonial history have shaped Northeast Brazil's current context, future projections provide strong evidence that climate change will increase the risk and severity of droughts (Castellanos et al., 2022).

1.5.2.2 Current and predicted drought risks and impacts in Northeast Brazil

In the Northeast region, an increase in dryness is projected due to the combination of increased temperatures, less rainfall, and lower atmospheric humidity (5 to 15% relative humidity reduction). These conditions create water deficits, projected for the entire region after 2041 (reduction of 3–4 mm per day) over the semiarid region (Marengo and Bernasconi, 2015; Marengo et al., 2017).

This means that 28 million people are exposed to this projected increased dryness, encompassing 13% of the Brazilian territory (SUDENE, 2017), and is heightened due to the region's high poverty levels both in rural and urban areas. About 45% of the population in capital cities live in poverty, often in slums with inadequate water and health infrastructure. Rainfed agricultural systems account for 95% of the farmed lands in Northeast Brazil (Marengo et al., 2022).

Government responses to drought in the region have historically been reactive, focusing more on infrastructure development rather than on proactive preparedness. This reactive approach resulted in two decades of reservoir building, strongly supported by the state (Da Silva, 2003). This fostered a safe development paradox with rural populations overly relying on reservoir storage for their income and livelihood (Campos, 2015).

The impacts of intense droughts in Northeast Brazil have historically led to significant agricultural losses, livestock deaths, and increased food prices. The most recent drought lasted from 2012 to 2018 and was both the most prolonged and most severe in terms of rainfall deficit since rainfall monitoring began around 110 years ago (Pontes Filho et al., 2020; Walker et al., 2022). It proved devastating to many agricultural, livestock, and industrial producers (Gutiérrez et al., 2014; Walker et al., 2022). Smallholder farmers were hit hardest due to their reliance on rainfed agriculture for their livelihoods. Crop losses were estimated at 70%–80% and economic losses at over US$3 billion (Brito et al., 2018). As reservoirs collapsed, towns and cities suffered from a lack of domestic water supply and an increase in water-related disease due to poor water quality, in addition to food insecurity (Eakin et al., 2014).

Predicted increases in drought frequency, coupled with inadequate soil management practices, are likely to exacerbate desertification risks, affecting rural livelihoods and prompting migrations to urban centres. The implications of climate change on human health, particularly diseases linked to food and water insecurities, are increasingly concerning. Despite agriculture's modest contribution to Northeast Brazil's economy, it faces significant negative impacts from climate change, which could severely affect the poorest rural populations (Vieira et al., 2020; Tomasella et al., 2018).

Therefore, Northeast Brazil, marked by its semi-arid climate and history of droughts, represents a relevant case study to explore specific vulnerability and exposure drivers such as limited water resources, socio-economic challenges, and agricultural reliance. It is also relevant to highlight how these factors critically shape local drought impacts, and how current monitoring may fail to capture the full scope of local impacts, directly addressing the thesis's core research question.

1.5.3 Drought within my context: Positionality and field-based research

Before progressing into the empirical content of this thesis, it is helpful to discuss positionality and its influence on my fieldwork. Chapters 3 and 4 are empirically based and dependent on interviews conducted with local stakeholders, making it important to consider how my identity and personal values may have influenced the research and its results. One of my chosen methods of field-based research, closely tied to my positionality, also brings up important considerations for conducting ethical and sound scientific research.

Positionality in research refers to an individual's worldview and approach to a research task within its social and political context (Foote and Gau Bartell, 2011; Savin-Baden and Major, 2023). It encompasses an individual's ontologies: an individual's beliefs about the nature of social reality and what can be understood or learned from the world; epistemologies: an individual's beliefs on what knowledge is and how we learn or understand information; and assumptions about human nature and agency: individual's assumptions about the way we interact with our environment and relate to it (Sikes, 2004; Bahari, 2010; Ritchie et al., 2013). These concepts shape how research is conducted, influencing its outcomes and results, and also affect the choice of research topics (Malterud, 2001; Grix, 2018). Positionality is often defined by a researcher's relationship with the subject, research participants, and the context of the research with its process (Reich, 2021). While some aspects of positionality, such as gender, nationality and skin-color are regarded as fixed, others like political views, personal life-history, and experiences are regarded as more fluid, subjective and contextual (Chiseri-Strater, 1996). These aspects influence but do not determine automatically a researcher's perspective (Reich, 2021).

Positionality in research is therefore context-specific in two key ways: the context of the research and the context of the researcher, without necessarily being intertwined; my research field existed well before my involvement. My research began within the established academic environment of Wageningen University and the context of Northeast Brazil. Within these two contexts, my experiences, viewpoints on the research, and my intersectional identity and personal values all significantly influenced the key stages of my thesis research: developing the initial research proposal, formulating and adapting the research questions, selecting methods, carrying out the fieldwork, analysing the data, and formulating conclusions and policy recommendations.

I have an agricultural engineering background from my studies in Tunisia. Already unsatisfied with its purely technical lens, I sought and added experiences with mixed methods, including grounded theory, interviews, and focus groups, and engaged in processes of co-creation. One such experience was in the same study area as this thesis, in Northeast Brazil, focused on the topic of drought impacts, and lasted three years. Therefore, since the early stage of my scientific career, I have had an inclination for co-creation processes, usually with rural communities vulnerable economically and to climate change. This was evident right from the interview for this PhD-position, as it aimed to provide insight into how each candidate would conduct research on local and contextual drought indices. Some individuals with a modelling background might think about local and contextual physical-based drought indices, where the local and contextual part involves adapting current indices and conducting local modelling. And it can still be addressed this way! But when I started my PhD, I directed it towards exploring how subsistence farming is affected by drought and how this can be better captured by drought indices.

My prior field experiences in the area, albeit limited to a minority of the communities involved in this research, have been an asset and an additional source of confirmation bias, in shaping the study. I spent nearly four years living in Fortaleza, working at the Meteorology and Water Management Institute of the State of Ceará (Funceme), which has been a key partner in this thesis research, providing both knowledge and logistical support. During the thesis fieldwork, I conducted interviews in Portuguese, a language I learnt and became fluent in, still with a noticeable accent. My familiarity with the local Brazilian accent from Ceará accent and ‘slang’ was an asset. Having a deeper understanding of the area, I made conscious efforts to respect the local customs and practices. This included choosing appropriate times for visiting farmers, carefully avoiding the busy cropping seasons, and scheduling visits to align for example with the end of market days or at the communities’ gatherings. Such considerations aimed to ensure respectful engagement with the communities.

While I was aware of my positionality, I remained open to various perspectives and unpredicted outcomes. The publications resulting from this research were always guided by integrity, well-supported conclusions, and a clear acknowledgement of any uncertainties or discrepancies. But of course, the way I conducted my fieldwork held traces of my positionality and led me to raise many more reflections about field-based research, further developed in the Synthesis Section (5.3.3).

Finally, this thesis was conducted as part of the 3DDD project, which stands for Diagnosing Drought for Better Dealing with Drought in 3D: (human) Dimensions, (socio-hydrological) Dynamics, and Dialogues. My thesis represented the first 'D', focusing on the human dimensions of droughts. This research was intricately linked with the work of two other PhD candidates: Germano Ribeiro Neto and Louise Cavalcante. Germano's research centred on the socio-hydrological dynamics of droughts, by incorporating human activities into drought modelling. Louise focused on the dialogues around drought, examining the evolution and implementation of drought policies and their interaction with society in Northeast Brazil. Both Germano and Louise, who are co-authors of Chapters 3 and 4, significantly influenced the direction of my research. Their insights helped me iteratively formulate my ideas and structure my knowledge. Furthermore, the interaction among our respective 'D's critically shaped my approach to addressing the main question of this thesis and the recommendations I provided, both in the Synthesis (Chapter 5).

02

Local Context in Drought Monitoring

Abstract. Drought monitoring and Early Warning Systems (DEWSs) are seen as helpful tools to tackle drought at an early stage and reduce the possibility of harm or loss. They usually include indices attributed to meteorological, agricultural and/or hydrological drought: physically based drought drivers. These indices are used to determine the onset, end and severity of a drought event. Drought impacts, like water and food securities, are less monitored or even not included in DEWSs. Therefore, the likelihood of experiencing these impacts is often simply linearly linked to drivers of drought. This chapter aims to evaluate the validity of the assumed direct linkage between drivers of drought and water and food insecurities impacts of drought. Scientific literature on both drivers and impacts of drought is reviewed through a bibliometric analysis based on 5000+ scientific studies in which selected drought indices (drivers) and drought-related water and food insecurities (impacts) were mentioned in relation to a geographic area. The review shows that there is a tendency in scientific literature to focus on drivers of drought, with the preferred use of meteorological and remotely sensed drought indices. Studies reporting drought impacts are more localised, with relatively many studies focusing on Sub-Saharan Africa and Australasia for impacts with regard to food security and water security, respectively. Such results further suggest that studies of food and water insecurities impacts related to drought are dependent on both the physical and human processes occurring in the geographic area, i.e. the local context. With the aim of increasing the relevance and utility of the information provided by DEWSs, it is argued in favour of additional consideration of drought impact indices oriented towards sustainable development and human welfare.

Slightly modified from the publication: Kchouk, S., Melsen, L. A., Walker, D. W., & van Oel, P. R. (2022). A geography of drought indices: mismatch between indicators of drought and its impacts on water and food securities. Nat. Hazards Earth Syst. Sci., 22(2), 323-344. doi: 10.5194/nhess-22-323-2022

2.1 Introduction

Drought is a threat to a wide range of human activities in virtually all climate zones and countries (Van Loon et al., 2016a; Bachmair et al., 2016; Van Lanen et al., 2017). It is an elusive phenomenon without a clear onset and demise. In contrast to other hazards such as floods, landslides or earthquakes, drought has a creeping nature causing impacts to persist for many years (Kim et al., 2019). Consequently, impacts can be cumulative for consecutive periods of droughts, devastating both ecosystems and societies (Bachmair et al., 2016; Van Lanen et al., 2017).

Many concepts exist for defining a drought (Santos Pereira et al., 2009; Lloyd-Hughes, 2014). Definitions of drought are either conceptual or operational. Conceptual definitions of drought are descriptive and highlight the natural hazard element: for example, precipitation below what is expected or normal (Knutson et al., 1998). Operational definitions of drought highlight practical implications in an attempt to identify the onset, severity, and cessation of drought periods (Mishra and Singh, 2010). For example, the UN Convention to Combat Drought and Desertification (UNCC, 1994) defines drought as "*when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems*".

The numerical value of hydro-climatic variables is associated to three main types of drought: meteorological, agricultural (or soil moisture) and hydrological droughts. These variables are in fact the physical drivers of droughts, which refer to the hydrometeorological contributing or counteracting factors that affect the development of droughts (Seneviratne, 2012). Those physical drivers are used by many drought studies as the framework to represent drought propagation. In the literature, the temporal propagation of drought is often considered to be a sequence occurring in an almost linear order (Wilhite and Glantz, 1985; Zargar et al., 2011; Bachmair et al., 2016), and in which humans have no direct influence. This is a simplification of a complex process, where it is considered that an anomaly (e.g. lower precipitation, higher temperature than average) of the values of those drivers will lead to a cascade reaction influencing the magnitude of other physical variables and leading in turn to the subsequent type of drought. As such, hydrological drought is inaccurately simplified as a result of the persistence in duration of agricultural (or soil moisture) drought, which itself is simplistically attributed to the persistence of meteorological drought.

Drought monitoring and Early Warning Systems (DEWSs) aim to monitor the physical drivers of drought to predict drought. They aim to tackle drought at an early stage to reduce the possibility of harm or loss. For assessing the severity of a drought, physical variables are usually translated into indices of drought. The difference between their values and the threshold used to define the level of dryness is considered to depict the severity of a drought (Vogt et al., 2018). Drought impacts, such as water- and food security, are rarely continuously monitored or even included in DEWSs. This is understandable as there is already a plethora of definitions for drought and drought types, and there are at least as many possibilities for defining impacts (Mishra and Singh, 2010; Wilhite, 2000; Santos Pereira et al., 2009). Drought impacts are nonstructural, difficult to quantify or monetise, and can be direct or indirect due to the extended nature, in time and area, of drought (Wilhite et al., 2007; Logar and Van Den Bergh, 2011; Bachmair et al., 2016). In addition, most the of DEWSs do not take the underlying vulnerabilities of the drought-affected or monitored areas into account. Thus, in the current configuration of most DEWSs, the presumed likelihood of experiencing impacts is mainly linked to the severity of climatic features only (e.g. Princeton Flood and Drought Monitors; U.S. Drought Monitor; Brazilian Drought Monitor).

This study aims to review scientific reporting on physical drought drivers and drought impacts, related to water and food securities, for affected countries and analyse how these two compare. Improving our understanding of the linkage and separation between drought drivers and drought impacts enables us to provide directions to further improve the accuracy of the information provided by DEWSs. We retrieved scientific studies from countries in which selected physical drivers of drought and food and water securities impacts of drought are mentioned. The components of drought drivers and impacts on which the literature focused were explored and compared for different areas of the world.

2.2 Data and Methods

2.2.1 Methodological approach

The methodological approach comprises three steps:

Step 1. Exploring which physical drought drivers are the most recurrent in the scientific literature. We investigated which indices of physical drought drivers are most frequently used in scientific drought-related studies and to what drought type they were linked. For each of these scientific studies, we also retrieved the country of focus. This allowed us to identify: the most frequently mentioned type of drought for different geographic regions, and the prevalent drought indices used in scientific studies.

Step 2. Exploring which drought impacts are the most recurrent in the scientific literature. In contrast with drought drivers, for drought impacts, there are no established indices commonly used in DEWSs and in scientific studies. We thus retrieved from scientific articles, keywords associated to drought impacts related to water security and food security. This allowed the identification of the most frequently mentioned water- and food-related drought impacts.

Step 3. Comparing the findings of Steps 1 and 2. This enabled the evaluation of the alignment between reported drought types and impacts, with regard to the number of publications and differences in geographic focus.

2.2.2 Data

We considered the number of studies about drought indices and drought impacts, respectively, and their geographical distribution as our units. Our list of drought indices is based on two prominent studies in the field of drought indices: indices commonly used operationally to depict different types of drought (Svoboda and Fuchs, 2016) and the indices commonly used by water managers (Bachmair et al., 2016). Our list will, however, inherently be incomplete because many other indicators exist beyond the ones mentioned in these two studies. This resulted in 32 indices that we linked to three main drought types (Table 2.1): meteorological (9 indices), soil moisture/agricultural (15), and hydrological (8) drought.

We opted for Scopus to retrieve the scientific publications of interest as it is the database covering the largest range of both, peer-reviewed literature types (scientific journals, books and conference proceedings), and disciplinary fields (science, technology, medicine, social sciences, and arts and humanities; Scopus, 2021). We then searched in the Scopus database for queries strictly including “drought” AND “[the indicator]” in the title, abstract and authors’ keywords of the studies. We repeated the queries for each indicator individually as we were interested in knowing country-based preferences. The sum of the individual indices linked to drought queries returned 4137 articles for the “meteorological” drought type of indices, 2799 articles linked to “agricultural” drought and 393 articles linked to “hydrological” drought. The title, authors, author’s keywords, year of publication, journal name and abstract were retrieved using the Bibliometrix package (Aria and Cuccurullo, 2017) executed on R (version 4.0.0) following Addor and Melsen (2019). In the title, keywords and abstract of each paper, names of countries were identified, corresponding to the area of application of the study. The same approach was followed for the drought impacts. We grouped drought impacts into two focus categories: food security and water security. Their keywords are indicated in Table 2.1. The queries included “drought” AND selected “[drought impact]”. This resulted in 4764 articles linking drought to food security and 805 articles linking drought to water security.

All articles were published between 1960 and March 2021 and the exact queries for both drought indices and impacts are included in Table A1 in the appendix. Even though we recognise drought can impact ecosystems, this topic was excluded from the analysis for reasons of brevity. The dataset and the script used for its analysis are both available for consultation (Kchouk et al., 2021).

Many scientific studies are methodological; their goal can be the validation, calibration or improvement of the indices, thus, not all studies have a focus country. We only considered studies mentioning a country in their title, abstract and keywords; this being the only criteria for inclusion or rejection of papers in our analysis. This reduced the number of studies including the name of a country in their title, abstract and keywords by 28% for drought indices and by 44% for drought impacts. We also did a manual verification on some of the scientific studies to see if the association with a country was valid. This allowed us to bring some corrections to the metadata to avoid incorrect associations (e.g. removing mentions of the “Indian Ocean” that led to the incorrect association of the studies to India; removing the copyrights, generally at the end of the abstract, referring to another country than the one of the study).

Table 2.1: Drought indices and impacts sought in studies retrieved from Scopus. Their acronym, input data when applicable, total number of studies, number of studies mentioning a country, and the three main scientific fields these articles cover are detailed.

Meteorological drought indices studies	**Total number of studies of drought indices : 5567**		**Total number of studies mentioning a country: 4023**		**Studies not mentioning a country : 27.7%**	**Top 3 subject area retrieved from Scopus[1]**
“Meteorological drought” indices mentioned in the study	Acronym	Input data	Number of studies	Studies mentioning a country	Portion of studies not mentioning a country (%)	1) ES 2) EPS 3) ABS
Standardized Precipitation Index	SPI	Precipitation	2451	1812	26.1	1) ES 2) EPS 3) ABS
Standardized Precipitation Evapotranspiration Index	SPEI	Precipitation, temperature	1059	751	29	1) ES 2) EPS 3) ABS
Aridity Index	AI	Precipitation, temperature	247	182	26.3	1) EPS 2) ES 3) Eng
Precipitation Deciles	Deciles	Precipitation	12	9	25	1) ES 2)ABS 3) EPS
Keetch-Byram Drought Index	KBDI	Precipitation, temperature	84	66	21.4	1) ES 2) EPS 3) ABS

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[1] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

Palmer Drought Severity Index	PDSI	precipitation, temperature, available water content	1279	867	32.2	1) ES 2) EPS 3) ABS
Percent of Normal Precipitation (Index)	PNPI	Precipitation	23	18	21.7	1) ES 2) EPS 3) ABS
Rainfall Anomaly Index	RAI	Precipitation	304	244	19.7	1) EPS 2) ES 3) ABS
Self-Calibrated Palmer Drought Severity Index	scPDSI	Precipitation, temperature, available water content	108	74	31.5	1) EPS 2) ES 3) ABS
Agricultural and Soil Moisture drought indices studies	**Total number of studies of drought indices : 5085**		**Total number of studies mentioning a country: 3137**		**Studies not mentioning a country : 38.3%**	**Top 3 subject area retrieved from Scopus**[2]
“Agricultural drought” indices mentioned in the study	Acronym	Input data	Number of studies	Studies mentioning a country	Portion of studies not mentioning a country (%)	
Crop Moisture Index	CMI	Precipitation, temperature	43	20	53.5	1) EPS 2) ABS 3) ES
Evaporative Stress Index	ESI	Remotely sensed potential evapotranspiration	88	42	53.3	1) ABS 2) EPS 3) ES
Evapotranspiration Deficit Index	ETDI	Soil water in the root zone on a weekly basis, which is computed from SWAT model	17	13	23.5	1) ES 2) EPS 3) ABS

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[2] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

Enhanced Vegetation Index	EVI	NIR/red/blue surface reflectances, canopy background adjustment, coefficients of the aerosol resistance for correction for aerosol influences in the red band.	305	206	32.2	1) EPS[3] 2) ES 3) ABS
Normalized Difference Vegetation Index	NDVI	Spectral reflectance measurements acquired in the red and near-infrared regions	2041	1288	36.9	1) EPS 2) ES 3) ABS
Leaf Area Index	LAI	Leaf and ground area	1152	583	49.4	1) ABS 2) ES 3) EPS
Palmer Moisture Anomaly Index – known as the Palmer Z index	PZI	Derivative of the PDSI calculation, precipitation, temperature, available water content	47	30	36.2	1) EPS 2) ES 3) ABS
Soil Adjusted Vegetation Index	SAVI	Spectral reflectance measurements acquired in the red and near-infrared regions, with the addition of a soil brightness correction factor	68	37	45.6	1) ABS 2) ES 3) EPS

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[3] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

Soil Moisture Anomaly	SMA	Precipitation, temperature, available water content	138	87	37.0	1) EPS[4] 2) ES 3) ABS
Soil Moisture Deficit Index	SMDI	soil water in the root zone on a weekly basis, which is computed from SWAT model	13	10	23.1	1) ES 2) EPS 3) ABS
Soil Water Deficit Index	SWDI		33	26	21.2	1) EPS 2) ES 3) ABS
Soil Water Storage	SWS	available water content, reservoir, soil type, soil water deficit	717	494	31.1	1) ABS 2) ES 3) EPS
Vegetation Condition Index	VCI	(same as) NDVI	271	187	30.1	1) EPS 2) ES 3) CS
Vegetation Drought Response Index	VegDRI	SPI, PDSI, percentage annual seasonal greenness, start of season anomaly, land cover, soil available water capacity, irrigated agriculture and defined ecological regions	14	13	7.1	1) EPS 2) ES 3) ABS
Vegetation Health Index	VHI	NDVI and brightness temperature, both from thermal bands	138	101	26.8	1) EPS 2) ES 3) CS

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[4] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

Hydrological drought indices studies	**Total number of studies of drought indices : 550**		**Total number of studies mentioning a country: 344**		**Studies not mentioning a country : 37.5%**	**Top 3 subject area retrieved from Scopus**[5]
"Hydrological drought" indices mentioned in the study	Acronym	Input data	Number of studies	Studies mentioning a country	Portion of studies not mentioning a country (%)	
Reservoir Level		Water levels in reservoirs	72	35	51.4	1) ES 2) Eng 3) EPS
Palmer Hydrological Drought Index (PHDI)	PHDI	precipitation, temperature, available water content	58	34	41.4	1) ES 2) EPS 3) ABS
Streamflow Drought Index	SDI	Streamflow values	180	117	35	1) ES 2) ABS 3) EPS
Standardized Runoff Index	SRI	"Runoff"	106	69	34.9	1) ES 2) EPS 3) Eng
Standardized Streamflow Index	SSFI	Streamflow data	85	56	34.1	1) ES 2) EPS 3) ABS
Streamflow anomaly		Streamflow data	9	8	11.1	1) ES 2) EPS 3) ABS
Standardized Water-level Index	SWI	Groundwater well levels	17	13	23.5	1) ES 2) EPS 3) SS
Surface Water Supply Index	SWSI	Reservoir storage, streamflow, snowpack and precipitation	23	12	47.8	1) ES 2) Eng 3) SS

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[5] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

Drought impacts studies	Input data	Number of studies	Studies mentioning a country	Portion of studies not mentioning a country (%)	Top 3 subject area retrieved from Scopus[6]
Food security	Food security, famine, hunger, malnourishment, malnutrition, agricultural loss.	4764	2601	45.4	1) ABS 2) ES 3) SS
Water security	Water security, water access, water availability, water crisis	805	506	37.1	1) ES 2) SS 3) EPS

2.3 Results

2.3.1 Drought types and indices

The indices mentioned in the drought-related studies were classified according to the categories used in Table 2.1; their frequency of occurrence is shown in Figure 2.1. Meteorological drought indices are reported most frequently, followed by agricultural or soil moisture drought indices, and hydrological drought indices. The most frequently mentioned indicator is the Standardised Precipitation Index (SPI), followed by the Normalised Difference Vegetation Index (NDVI). Hydrological drought indices are less frequently utilised in comparison to the two other categories.

For the regions of Australia-Oceania, Middle-East and North Africa (MENA) and Sub-Saharan Africa (SSA), there are fewer studies utilising hydrological drought indices than for the other regions (Figure 2.2). Further geographical differences are observed in Figure 2.2. Most areas resemble the overall pattern shown in Figure 2.1; exceptions are Australia-Oceania and Sub-Saharan Africa, where agricultural drought indices are most frequently reported.

In addition, not only are meteorological drought indices the most investigated, they are also the most associated with a country in studies, in comparison to agricultural drought, hydrological drought and impacts (Table 2.1). Meteorological drought indices represent 53 % of the scientific studies while agricultural drought represents 42 % and hydrological drought, only 5 %.

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[6] ES: Environmental Science ; EPS: Earth and Planetary Sciences; ABS: Agricultural and Biological Sciences; Eng: Engineering; CS: Computer Science; SS: Social Sciences

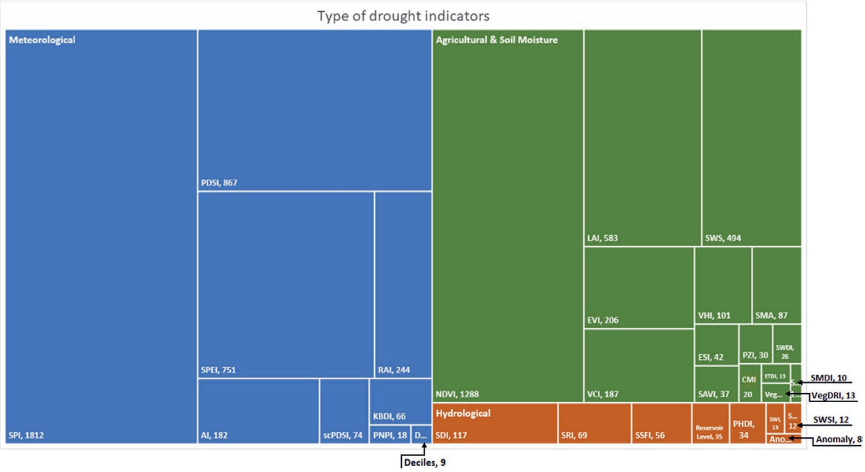

Figure 2.1: Treemap showing the proportion of indices for different drought types (blue is meteorological, green is agricultural and soil moisture drought, and orange is hydrological drought) employed in the title, abstract and keywords of drought related studies on Scopus. The number indicates the number of studies including a country in their title, abstract or authors' keywords.

This indicates that in most of the studies, rainfall and temperature are the dominant criteria utilised to report the occurrence of drought. Such a result is expected because of the ease of use of meteorological drought indices. We further develop this point in Sect. 2.4.3.

During the preliminary research that led to the results mentioned in our study, we conducted a time analysis. We visualised and compared the evolution of the usage of drought indices and drought impacts in the literature in order to analyse and link it to factors such as improved data availability, scientific progress or a change in the societal view on droughts (not shown). However, we did not find any remarkable pattern, peak or correlation. Therefore, we decided to not include this part in our study.

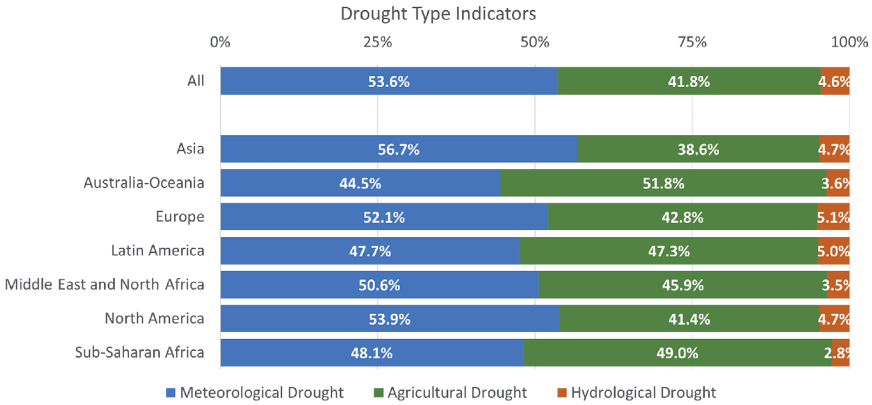

Figure 2.2: Barplot showing the proportion of drought type studies per region of the world, according to the drought indices referred to in the title, abstract and keywords of droughtrelated studies on Scopus.

2.3.2 Drought-related impacts: food security and water security

Globally, there were five times more studies linking drought to food-security than drought to water-security (Figure 2.3). This pattern is the same for most areas of the world. For Sub-Saharan Africa the predominance of food security indices is most pronounced (93%), followed by Asia and Europe (84%). Australia-Oceania is the only region where drought-related water security studies predominate over food security studies (52%), while Sub-Saharan Africa is the region where it is reported the least (6.6%).

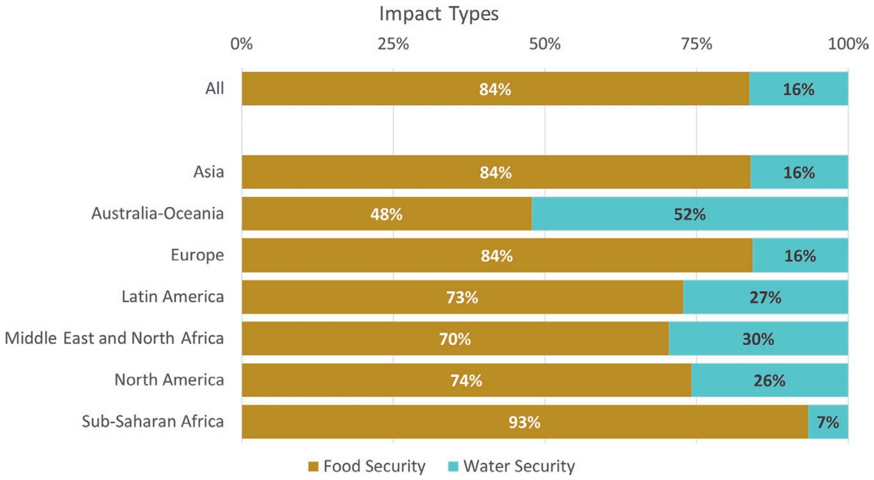

Figure 2.3: Barplot showing the proportion of food and water security studies related to drought per region of the world on Scopus.

2.3.3 Geographic patterns for indices of drivers and impacts

Figure 2.4 shows that drought-drivers studies are quite evenly distributed across the regions except for SSA. The height of the dark blue boxes is substantially smaller than the others, suggesting that the share of SSA in drought-drivers studies is minor.

In the same way, two geographical patterns appear in the share of drought-related impacts studies. The height of the boxes of SSA and Australia-Oceania for food and water securities, respectively, related to drought is significantly larger than those of the other regions for the same indicator category. This means that food security related to drought is most frequently reported for SSA and that water security related to drought is most frequently reported for Australia-Oceania. Similarly, drought-related water security is the least reported for Europe.

The geographical pattern of drought drivers and impact studies seen in Figure 2.4 is also present in the cartogram representations in Figure 2.5. In this cartogram representation, each country has been rescaled in proportion to the number of studies on Scopus related to drought indices or water and food security impacts. First, the three drought driver categories appear to have the same pattern of investigation, all mostly focused on northern high-income countries. The United States and Mexico, North-Mediterranean countries and Australia-Oceania are strongly focusing on drivers in drought-related studies. Middle-income countries with high demographic and economic growth such as China, India and Iran also see a focus on drought-related drivers. They stand out from their geographic neighbours that are almost disappearing from the map.

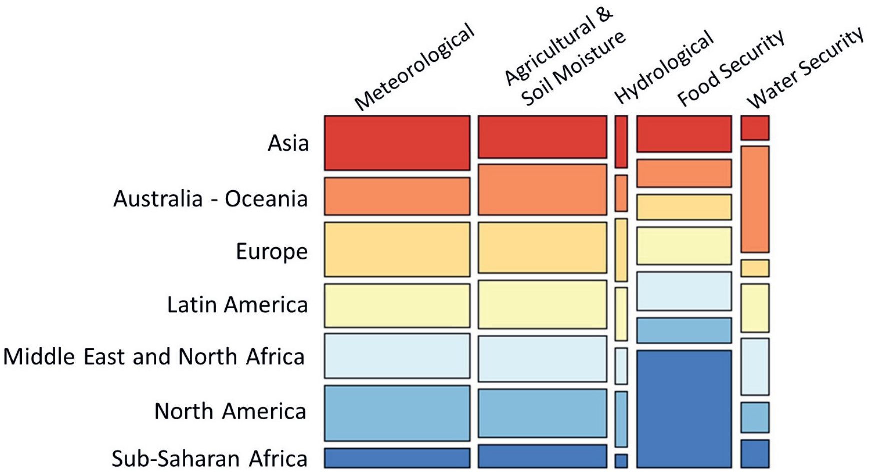

Figure 2.4: Mosaic plot showing how frequently keywords, being the types of drought and impacts, were mentioned in the titles, abstracts, and keywords in droughtrelated studies on Scopus. The height (vertical) of each box indicates how frequently the keyword is used for each region (the frequency was scaled by the number of papers for each region, that is, the plots show the keyword frequency if all the regions had an equal number of papers). The width (horizontal) of each box indicates the relative frequency of each keyword.

In contrast, the African continent is strongly under-represented in terms of drought drivers studies, particularly with regard to meteorological and hydrological drought indices, with notable exceptions for Ethiopia, Kenya and South Africa. However, the distribution of agricultural and soil moisture drought studies appears to be more even in African countries, and higher in Sahelian countries.

Looking at the geographical repartition of drought-related impact studies (Figure 2.5d and e), two main observations are notable. First, the repartition of the impacts studies differs from the drivers studies. Second, both impacts, food and water security, show a different geographic pattern. Water security related to drought is most frequently investigated for Australia, the USA Mexico, Brazil, the Middle East and South Africa. In contrast, food security is most commonly investigated for India, Ethiopia, Kenya and other African countries.

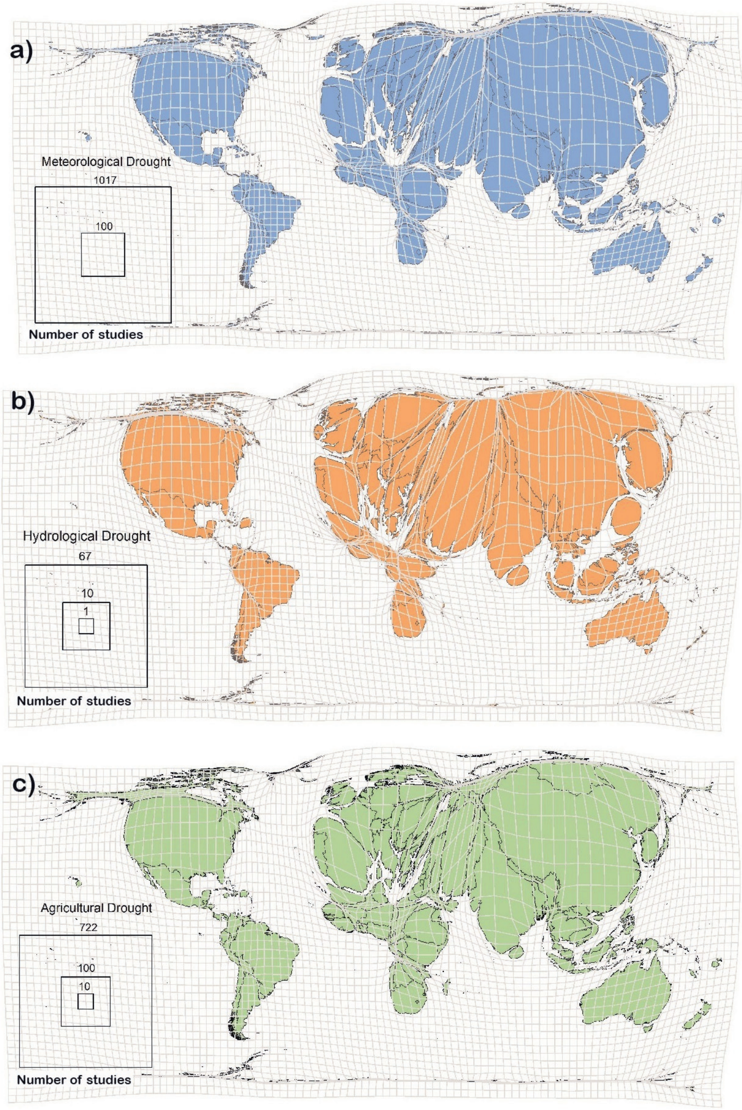

Figure 2.5: Contiguous cartograms (Gastner-Newman) of the world with each country rescaled in proportion to the number of studies on Scopus related to drought and a) Meteorological drought indices b) Hydrological drought indices c) Agricultural and Soil Moisture drought indices

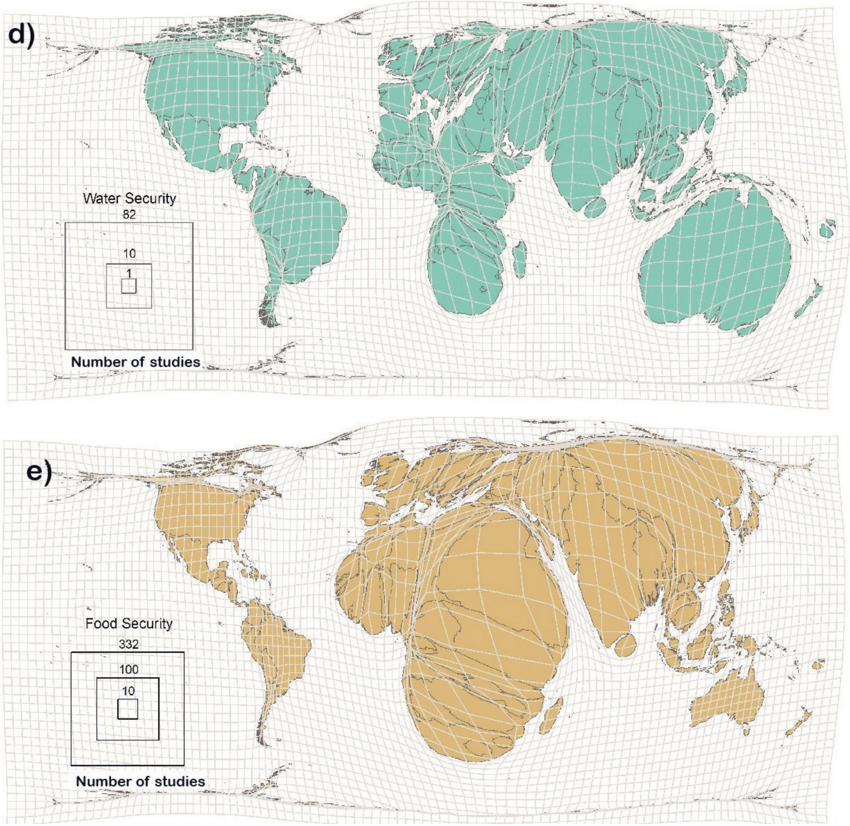

Figure 2.5 (continuation): d) Food security e) Water security. The size of the square relates to the size of the countries and indicates the number of studies.

2.4 Discussion

This bibliometric study shows that unbalanced attention is given to physical drought drivers and impacts across the world. In this discussion section, we start by raising four hypotheses to explain why some features of drought are more frequently reported for some regions or countries than for others. The four hypotheses relate to: physical conditions (Sect. 2.4.1), socio-economic conditions (Sect. 2.4.2), data availability (Sect. 2.4.3), and scientific interests and orientation (Sect. 2.4.4). We continue by discussing potential limitations in our methodological approach (Sect. 2.4.5). We posit that these four hypotheses are also the four dimensions that are inherent to the local context of a geographic area. Drought monitoring is influenced by these to accurately predict droughts, their severity and impacts. In that sense, we end by formulating recommendations (Sect. 2.4.6) about shifting the scope of drought metrics to match the local context of a specific drought event.

2.4.1 Physical conditions

The most notable result from Section 2.3 is the more abundant investigation of meteorological drought over agricultural drought and hydrological drought (except in SSA and Australia-Oceania), with the SPI being the most used indicator in drought-related studies.

By focusing on meteorological drought, it is mainly the deficit of precipitation that is investigated. In humid areas, tropical, continental or temperate climates, a deficit of precipitation is less likely to affect the overall physical water scarcity and cause water shortage. In that sense, the occurrence of drought is only statistically-based and not reflecting a true water deficit for the demand, only a below-average situation (which is, however, in line with formal definitions of drought). In arid and semi-arid climates with lower levels of precipitation, it is recommended to use SPI cautiously because it can fail to indicate drought occurrence (Wu et al., 2007) and opt instead for indices that include evapotranspiration like the SPEI (Salimi et al., 2021). In such areas where evapotranspiration plays a larger role with regard to evaporative demand, water shortage is more common. For arid and semi-arid areas with low average rainfall and a higher risk of water scarcity, it may be more appropriate to determine water deficit at the crop, field or farm scale. This could explain the more frequent use of agricultural drought indices in the more arid Australian-Oceanian and Sub-Saharan regions (Figure 2.2 and Figure 2.4) that mainly monitor vegetation (NDVI, LAI) and soil water content (SWS; Figure 2.1).

For some agricultural drought indices, there is both an upper and a lower limit that is independent of whether the climate of the area is arid or humid: vegetation health or soil water content are or are not frequently deteriorated or in deficit, respectively. In that sense, agricultural drought indices are relevant for any type of climate. However, SPI and most meteorological and hydrological drought indices, are statistical values showing a deviation from the average and are standardised for all climates. Even if they remain meaningful, drought is more challenging in dry climates rather than wet climates. This key point is dismissed because of the statistical and standardising propensity of meteorological drought and hydrological drought indices, in contrast to the values of agricultural drought indices that are a practical interpretation of hydro-climatic features (e.g. of the reflectance, in the case of NDVI and LAI).

2.4.2 Socio-economic conditions

SSA combines the lowest number of studies about drought indices with the highest proportion in terms of drought impacts (Figure 2.4). Even though SSA is known to experience a rise in temperatures and an increase of aridity in the past, present and future by observation and model projections (Niang et al., 2014; Serdeczny et al., 2017) the reported impacts in the Emergency Database (EM-DAT) are scarce (Harrington and Otto, 2020). Yet, the International Disaster Database (EM-DAT) run by the Centre for Research on the Epidemiology of Disasters (CRED), has the most complete and global records of past natural and human-made disaster events (Guha-Sapir et al., 2012).

Most of SSA is in a situation of economic water scarcity (Molden, 2013), implying a lack of human, institutional and financial capital to satisfy the demand for water, even in areas where the physical availability of water is not limited. The symptoms described by Molden (2013) associated with economic water scarcity include scant infrastructure development, either small or large scale, meaning that populations experience difficulties obtaining sufficient water to meet agricultural or domestic needs. Applying the same reasoning, drought mitigation or monitoring bodies and scientific publications are a product of human, institutional and financial capital. Thus, it is likely that drought drivers are under-investigated in SSA, leading to the same effects of economic water scarcity: water and food insecurities. Also, the report of impacts of extreme weather in SSA to disaster databases as EM-DATA is predominantly conducted by non-governmental organisations rather than governments, often as a side product of their main task to identify the location with the greatest need for humanitarian aid (Harrington and Otto, 2020).

In some areas, food insecurity can be a cumulative result of a dry climate and high pressure on natural resources enhanced by rapid demographic growth. Countries such as Bangladesh, China, Ethiopia, India, Indonesia and Pakistan, have some of the highest numbers of drought-related food security publications (Figure 2.5). Most of these countries have high fertility rates and rapid population growth (United Nations, 2019; Vollset et al., 2020). According to the Food and Agriculture Organization (FAO, 2010), the majority of the world's undernourished people live in these six countries and over 40% live in China and India alone. The same applies to the countries of SSA, presenting the highest population growth rate in the world (World Bank, 2019), the highest number of drought-related food security publications (Figure 2.5), and 22% of the population being undernourished (FAO et al., 2019). Rapid population growth increases the challenge of adequately meeting nutritional needs as food production depends on croplands and water supply, which are under strain as human populations increase. This suggests that countries with arid climates and a high population growth are more exposed to food security impacts.

Moreover, populations of low-income countries are the most exposed to drought-related food insecurity. In the world's poorest countries, around 30 percent of GDP comes from agriculture; those countries are mostly concentrated around the Sahelian region: Mali (37.4% of GDP), Niger (35.4%), Chad (46.1%), Central African Republic (31.9%), Sudan (31.2%), Kenya (31.1%) and Ethiopia (34.7%) according to the World Bank (2016). As we can see from Figure

2.5, those countries are most commonly reporting food security impacts related to drought. In contrast, in OECD economies – regarded as developed and high-income countries – agriculture accounts for less than 1.5 percent of GDP (World Bank, 2016). In the same way, we note the fewest amount of publications related to food security in those OECD countries. Also, in these Sahelian countries, agriculture accounts for more than 80% of the livelihoods (FAO, 2021). As more people rely on agriculture for their livelihood, they are more exposed to hazards like drought and thus vulnerable to food-insecurity and the poverty trap.

It is also important to mention the link between food security and governance. Food security is dependent on a complex interplay of factors. Some are outside the direct control of governments, like hydrometeorological extremes. But institutions, rules and political processes do play an important role in reaching increased food security. According to the Food and Agriculture Organization (FAO, 2011), *"food security is unlikely to develop where there is not an organised, politically active and mobilised constituency pushing the issue higher on the public and political agenda"*. Thus, good governance is crucial for reaching food security. Corruption is one of the pervasive aspects of bad governance. It can affect food security by creating inefficiencies in the use of natural resources and food distribution (Economist Intelligence Unit, 2015). Practices of corruption are spread in low- middle-, and high-income countries to different degrees (Transparency International, 2021) and in different levels of the food production and distribution chain (Transparency Int'l, 2019). Low-income countries are indeed the ones struggling the most to tackle corruption (Transparency International, 2021) contributing to their already prominent exposure to food insecurity. The addition of corruption, an indication of misallocation of resources and incapacity to successfully implement change and development, increases the risk of stagnation of food availability and indicates those countries as less suitable prospects for successful intervention (Economist Intelligence Unit, 2015).

In other words, focusing on physical drivers of drought is an advantage more apt to be of interest in areas where more basic and essential needs, such as food security, have been met.

2.4.3 Data availability

The SPI is the most widely used index in drought-related studies (Table 2.1 and Figure 2.1). This can be explained by its ease of use: First, it only requires (monthly) precipitation data, easy to monitor by use of rainfall gauge networks or satellite estimation. Second, SPI reference values exist so they can be compared and are applicable in all climate regimes. Finally, SPI can be computed for different periods of time including periods of record containing missing-data, even though it ideally needs at least 30 years of monthly precipitation data (WMO, 2012).

However, all these strengths are at the same time weaknesses. The SPI will provide in all cases an output of whatever inputs are used (Svoboda and Fuchs, 2016). As an example, a significant quantity of zero precipitation values at short time scales may lead to biased values of the SPI, because the rainfall might not fit for the recommended gamma distribution, which is a fundamental first step of the SPI calculation (Wu et al., 2007). This scenario is applicable to dry climates with a distinct dry season when calculated for periods shorter than 12 months. As mentioned in section 2.4.1, an index including an additional temperature parameter to account for evapotranspiration is more suitable for such areas. As we can see in Figure 2.6, many countries with dry climates (Iran, Australia and Pakistan) commonly use the SPI in their drought-related studies. In those dry contexts, it has been proposed to focus on the duration of the drought rather than only its severity (Wu et al., 2007). However, even short-lived dry spells often combined with heatwaves of a few days, characteristic of dry climates, when occurring during the reproductive stage of crop development can be enough to ravage an entire harvest leading to food insecurity (Hatfield and Prueger, 2015).

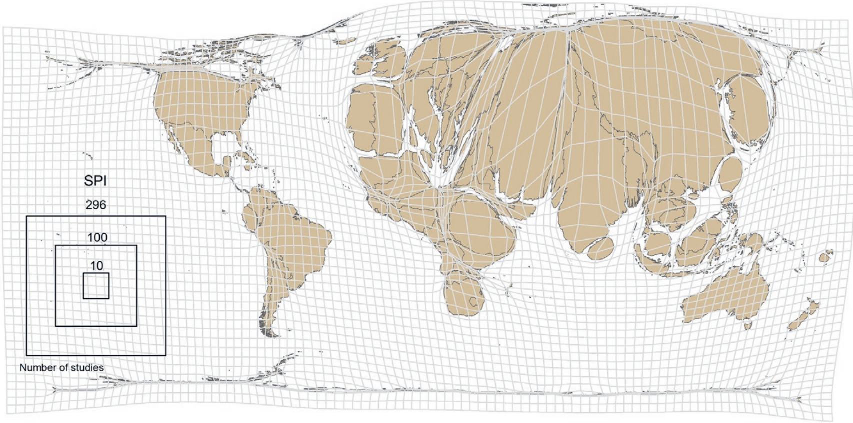

Figure 2.6: Contiguous cartograms (Gastner-Newman) of the world with each country rescaled in proportion to the number of studies on Scopus related to drought and the SPI

Most of the meteorological drought indices, beyond the SPI, are sensitive to the quantity and reliability of the data to fit the distribution. Their calibration requires a recommended 30 to 50 years of data. However, only very few regions of the world possess such an abundant historical hydrometeorological database. This is particularly challenging for developing countries. According to the World Bank (2018), two-thirds of the hydrological observation networks in developing countries are reported to be in poor or declining condition. The distribution of rain gauges across SSA is eight times lower than the WMO minimum recommended level, and while coastal West and Southern Africa, and the East Africa Highlands of Kenya and Uganda are relatively well represented, areas of greater aridity are severely underrepresented (Walker et al., 2016). Consequently, reanalysis rainfall products are also less reliable for these more arid regions due to a lack of ground truthing data (Walker et al., 2016). The availability of data seems to be closely tied to the socio-economic condition of a country. As mentioned in Section 4.2, countries exposed to economic water scarcity generally experience a lack of capital to satisfy the demand for water and a lack of an extensive and well-maintained hydro-climatic monitoring network. Therefore, most of the countries of SSA are underrepresented or absent from publications related to drought indices, while high-income countries commonly report them (Figure 2.5).

The same applies to hydrological drought indices studies that are under-reported in SSA (Figure 2.2, Figure 2.4, and Figure 2.5). River flow monitoring networks in SSA are experiencing a similar decline to meteorological monitoring networks (Walker et al., 2016). However, globally, little attention seems to be given to the monitoring of hydrological drought indices (Figure 2.1 and Figure 2.2). Long-term and regular hydrological monitoring is dependent on equipment and installations, their management and maintenance and the engagement of technical personnel. Not only hydrological monitoring is local and conditional by directly being related to the water supplies, but it requires high costs of implementation not always accessible for low and middle-income countries. In Europe, the lack of hydrological indices has been attributed more to a lack of wide access and exchange of hydrometric data at regional, national and international scales due to economic, legal and practical barriers rather than a complete lack of related observations (Viglione et al., 2010; Bachmair et al., 2016).

In the Global North, data sharing is incentivised by funding bodies as an ongoing task alongside research activities. However, as Bezuidenhout and Chakauya (2018) highlight, funders operating in low and middle-income countries are not fully exploiting this power yet. But the main limitation goes beyond looser requirements or a lack of incentive by funders operating in low and middle-income countries concerning data sharing. In most African universities, promotion criteria are closely linked to publications of peer-reviewed journal articles (Bezuidenhout et al., 2017). Bezuidenhout and Chakauya (2018) stated that the main, if not only, incentive, of researchers at many African universities to disseminate data is to publish it in peer-reviewed journals, which slows down its release rate. In the African continent, these limitations are compounded by questions of network density, data accessibility, temporal continuity, spatial representativeness, and tedious bureaucratic processes. These reasons led researchers investigating water resources dynamics in Africa to rely increasingly on modelled and satellite data (Hasan et al., 2019).

As Table 2.1 shows, NDVI – a remotely sensed index – is the most commonly used in agricultural drought-related studies. Only 3 out of the 15 agricultural drought indices are not remotely sensed. Just like the hydrological drought indices, this can reflect (i) the lack of hydrometric (field) observations or (ii) if they exist, a lack of sharing and access to them (Bachmair et al., 2016). Bachmair et al. (2016) highlight how *"the scarcity of water status observations, especially for groundwater, reflects the common focus on drought seen through the lens of rainfall and soil moisture that can be easily (remotely) monitored and/*

or modelled". Indeed, the data needed to calculate agricultural drought indices seem more accessible. The most used index is the NDVI and requires land surface imagery containing both red and infrared bands and processing software; global NDVI datasets are available open source at relatively high spatiotemporal distributions. As there are no requirements for historical data for calibration or a monitoring network, this could explain why the African continent more prominently reports agricultural drought than meteorological drought and hydrological drought (Figure 2.5).

It is important to realise that data availability may be closely tied to the year of implementation of the drought indices. Indeed, hydro-climatic databases have different ages and dataset quality according to the country, but it can also be possible that the implementation of drought indices is a precursor of hydro-climatic data monitoring.

2.4.4 Scientific interest and orientation

As mentioned previously, in DEWSs, the indices linked to the three categories of drought are seen as physical drivers as they are used to determine the occurrence and severity of a drought. However, as shown in Sections 2.3 and 2.4.3, the distinction between drought drivers and impacts, based on hydro-climatic variables, is context-dependent. First, the linear representation of drought implies that agricultural drought and hydrological drought are an impact of meteorological drought. Yet the indices used for meteorological drought have a different scope to those used for agricultural drought and hydrological drought. Taking the example of the most used indices, the SPI has a temporal focus with a strong statistical perspective on drought. Whereas for agricultural drought, the NDVI has a "spatial distribution" focus as it uses remote sensing to indirectly determine water-limitation in the vegetation at a specific time, like a snapshot of the vegetation's health. In that sense, the NDVI measures a drought impact.

Moreover, water security is often confounded with hydrological drought. However, as we can see from Figure 2.5d and e, the areas where each hydrological drought and water security are reported in scientific studies are not the same, suggesting that the occurrence of the first does not imply the other. In that sense, the literature seemingly indicates that hydrological drought is not the only driver of water security. It is well-established that human-driven demand affects water security, along with the hydrologic system (Van Loon et al., 2016a; Van Loon et al., 2016b).

The scientific reporting about drought suggests its risk of occurrence in an area and potentially an initiative of preparation for related damages. Though for each country, it is likely that drought is investigated according to: (i) a determined scientific approach, more physical or social; (ii) a purpose, in the sense of what is at greatest risk of being impacted by drought.

As shown in Table 2.1, most of the drought-drivers indices are investigated under the domain of environmental, Earth and agricultural sciences, suggesting a more physically-based approach. Food and water securities related to drought, respectively more reported in SSA and in Australia-Oceania (Figure 2.5), are also studied through the scope of physical sciences but unlike the drivers, also through the lens of social sciences (Table 2.1).

Institutional incentives in many western countries may favour research that falls into well-defined silos. Research that meaningfully incorporates both physical and social science may not be sufficiently interesting to merit ground-breaking publications on both fronts; it may instead require one or the other discipline serving in a more consultative role.

Food security is a complex concept that requires a holistic approach. Food systems underpin food security and they are the result of the production, processing, distribution, preparation and consumption of food. These steps are themselves the results of dynamic interactions between and within the bio-geophysical and human environments (Gregory et al., 2005). Thus, its study requires the intervention of different specialists. Food systems encompass three main components: "*(i) food availability (with elements related to production, distribution and exchange); (ii) food access (with elements related to affordability, allocation and preference) and (iii) food utilisation (with elements related to nutritional value, social value and food safety)*" (Gregory et al., 2005). Hence, when food systems are stressed, food security is affected. As food security depends on many components, it stands vulnerable to the disturbance of any of them. These components can be disturbed by a range of factors that can be environmental, like droughts, but also circumstantial like conflict, changes in international trade agreements and policies, HIV/AIDS (Gregory et al., 2005). Food insecurity can be enhanced when these factors are combined. SSA is an area particularly prone to extreme heat-related impacts, as we mentioned in Sect. 2.4.1, but also to these circumstances. SSA holds: (i) more than 95% of farmed land relying on rainfed agriculture (Wani et al., 2009); (ii) about 75% of the world HIV/AIDS prevalence as of 2016 (Odugbesan and Rjoub, 2019); (iii) 19 of the 43 economies with the highest poverty rate, all classified as in fragile and conflict-affected situations (Corral et al., 2020). This indicates that in drought-related studies focused on Sub-Saharan Africa, food security and the occurrence of these social processes are closely related.

Australia, known to be the driest inhabited continent (Hill, 2004), has a "National Plan for Water Security"(Government of Australia, 2007) that comprises a variety of mechanisms addressed by national and state governments (Cook and Bakker, 2012). Water security is also aimed to be addressed in an integrative and multi-scale way by "taking action on climate change, using water wisely, securing water supplies and supporting healthy rivers and wetlands"(Government of Australia, 2007).

Besides Australia, the fact that water security is reported for countries that are socio-economically very different, such as countries in the Sahel and the USA (Figure 2.5), suggests the experience of different types of water security. The definition of “water security” by Un Water (2013) is quite holistic. A population’s access to adequate quantities of acceptable quality water has the goal of sustaining three areas: livelihoods, human well-being, and socio-economic development (Montanari et al., 2013). Countries at different stages of development are more likely to focus on one of those three areas. Human well-being related to water-security can have many different understandings (Jepson et al., 2017; Hoekstra et al., 2018). Those can vary from one extreme to the other, as enough water for sanitary purposes, e.g. sanitation and showers, to indulgent leisure (e.g. swimming pools and gardens (Savelli et al., 2021; Bradley and Bartram, 2013; Willis et al., 2010). In South Africa, experiences of Cape Town Day Zero’s water crisis were diametrically different amongst the wealthy elite and the township dwellers. The first went through restrictions to water their garden and fill up their swimming pools while the second had insufficient water to take showers and go to the toilet (Savelli et al., 2021). Livelihoods and socio-economic development can also be understood and applied in different ways: from subsistence farming (Makurira et al., 2011) to agrobusiness and irrigation of crops meant for export (e.g. California; Morris and Bucini, 2016). The same can apply to food security: from malnutrition (Belesova et al., 2019) to the genetic adaptation of fruits and vegetable strains to droughts (Belesova et al., 2019; Basu et al., 2016).

Therefore, not only can areas be exposed to food and/or water insecurities, but they can be exposed to different declinations and severity within each. Water and food insecurities are very context-specific, not even attributable to the country scale but to smaller areas. They are the result of complex and multi-disciplinary mechanisms, including social processes in addition to the physical processes. Thus, to be accurately monitored, drought-related water and food insecurities also need multi-disciplinary metrics. This comes in contradiction with drought indices that measure drought severity by looking only at the hydro-climatic component. Consequently, by eluding (the monitoring of) social processes that can trigger and enhance drought impacts while solely focusing on their hydroclimatic component, DEWSs seem to be formulating an incomplete assessment of the severity of droughts.

2.4.5 Limitations

The inability to deduce a cause-and-effect relationship between two variables, solely on the basis of an observed association or correlation between them is common to all disciplines. The same applies to drought drivers and drought impacts even in drought-prone areas. Drought and a related variable such as food security, may be directly related, or drought may be one of many stressors in a complex food system. Aligning a drought index and some type of impact variable is a good start but given the complexity of the systems in question, it is unlikely that drought would have sufficient explanatory or predictive power on its own. Without continuous and widespread monitoring of drought impacts, the societal pattern enabling understanding of how drought is experienced differently and why, will not be identified. Therefore, the attempt to explain the geographical repartition of drought-related impact studies by linking some features of drought to one or many of the four hypotheses detailed above, as per this study, remains then purely hypothetical.

Our approach separated studies by geography, principally at a sub-continental scale. Other divisions on which to base our analysis could have been applied, like climatic or income levels, and may have led to additional insights. However, separating studies by geographical region allowed highlighting of: (i) both physical and socio-economic similarities expected in homogenous; (ii) countries standing out. This enabled the investigation of potential justifications. Also, certain studies might be missing because they focus on regions rather than countries. We assume that this effect is fairly evenly distributed across the globe and consequently, we do not expect this to introduce a bias. Besides, for the majority of studies, the country (or countries) that (partly) coincide with the focus region is also mentioned in the title or abstract.

Disparities exist inside countries, particularly larger countries such as the United States, China, Brazil and India, where physical, socio-economic, data availability and interest disparities occur. However, because our drought indices and impacts investigation and analysis are at the country level, our discussion is also generalised to that scale. Getting rid of that aggregative propensity and grasping those regional disparities would have required an investigation at the scale of within-country regions (e.g.: California Central Valley, Brazilian semi-arid, the city of Cape Town). Yet, it is mostly the name of the countries that are used in publications on Scopus. Moreover, that level of detail and analysis would be more appropriate for comparative studies between chosen semi-arid regions of the world rather than a broader study, like this one, where a similar focus on drought and drought impacts indices are examined.

This study focuses on two types of drought-related impacts: food and water insecurities. Clearly, the impacts of droughts are not limited to these two categories. For instance, text mining approaches conducted in Europe, based on media reports, showed that droughts lead to impacts related to forestry, fires, recreation, energy and transport sectors in addition to agriculture and water supply (Stahl et al., 2016; De Brito et al., 2020). The geographic distribution of the impact studies would be different if we also had considered impacts on, for instance, energy security, forestry, transport and tourism. Countries with predominant activities related to these sectors may have a high number of related drought impact studies, resulting in a different geographic repartition than the one shown in this present study. Our results are therefore only valid for the impact we evaluated: water and food securities.

The studies we obtained and analysed were a result of using Scopus, rather than another abstract and citation database, and of how we formulated our queries. Our search was constrained to articles having their title, abstract and keywords in English, potentially excluding important articles written in other languages. Additionally, the queries of the drought drivers were per indices, individually, while the queries of the impacts were regrouped by two themes. We justified the approach of grouping drought impact keywords due to the lack of metrics existing for water and food insecurities related to drought, as it is the case for drought indices.

Also, working with word frequencies, as we did, could have led to the consideration of a drought index or impact that was only mentioned in the abstract as an example but that was not an object of the study. To verify this, we manually evaluated a random sample of 50 studies retrieved from Scopus. We did not identify any study mentioning a drought index while not using or investigating it. Concerning the impacts, we indeed found that sometimes, terms like “water security” (or other impacts or the key-words used in the related query detailed in Table A1) were utilised without being investigated in the study. However, for the cases that we encountered in our sample, the studies were global and had a more bibliographical scope. This means that no country was mentioned in the title, abstract or keywords. As mentioned in our methods section (2.3.1), we only considered studies mentioning a country in their title, abstract and keywords. This means that there is only a small chance that studies mentioning an impact without further investigating it were included in our analysis. They were generally discarded at an earlier stage because they did not mention any country.

Finally, we chose in our study to focus on how drought drivers and impacts were reflected in the scientific literature. However, disparities between topics of academic research and policy initiatives may exist. In addition, academic research may or may not align with other operational and ground-truthed initiatives, such as efforts conducted by agencies and organisations working toward drought impact relief, sustainable development and human welfare.

2.4.6 Recommendations

It has to be recognised and highlighted that DEWSs have achieved the goal of providing timely and reliable information to decision-makers for drought management and mitigation. As we aimed in our study to put drought-related variables in the appropriate context and appropriate relation to one another, we also acknowledge that the indices that DEWSs rely on are mostly conceptual and descriptive which contradicts DEWSs operational purposes. The value of this study is to increase the relevance and utility of DEWSs, which leads us to posit that their structure tends to exclude the human influence on drought and drought influence on humans. The emphasis is on the natural effects on the hydrological system. Subsequently, the accuracy and efficiency of drought mitigation measures can be sub-optimal, based only on information lacking consideration of observed (local) drought impacts.

Several studies have promoted a shift of paradigm, aiming to define drought by its impacts and considering that if a system is impacted by a drought, this means that it was already vulnerable to drought (Blauhut et al., 2015; Blauhut et al., 2016). Analysing observed and inventoried past drought impacts across European countries was used as a proxy to determine specific vulnerabilities. Dealing with drought may benefit from a diagnostic process that starts by analysing drought impacts rather than merely focusing on drivers (Walker et al., 2022).

We recommend to also consider the human welfare aspects (e.g. food and water securities) that drought is affecting, rather than focusing on deficits of water volumes and flows only. In humanitarian approaches, a human welfare approach makes sense as the damages caused by a hazard and that aim to be addressed, can adversely affect, in the short and long-term, basic human safety through malnutrition, displacement, livestock or even human mortality. This approach is also applicable in drought management. Indeed, there is a lack of consensus in defining drought and its impacts, resulting in difficulty in agreeing on coherent and accurate drought metrics. Therefore, shifting the focus of drought mitigation to observable, graspable and quantifiable goals, such as human welfare, could overcome the uncertainty around drought and drought impacts definitions.

The human welfare proxy could be considered as an optimal situation without water shortage, e.g. zero hunger, poverty, conflicts and water insecurity. Thus, it could be aligned with the Sustainable Development Goals (SDG) as they (i) represent the development priorities of both low- or high- income countries; (ii) benefit from existing and improvable metrics. Also, similarly to drought indices, SDGs have a global nature inclined to overlook the local context. By taking into account local particularities, the SDGs could be reached at the local level even if it is through a drought mitigation scope. Instead of the linear and still conceptual driver-focused “meteorological-agricultural-hydrological” droughts, the disaster scope could shift to more societally relevant goals linked to “poverty, water security, and food security”. Thus, operational approaches to drought management would be the equivalent of determining the extent to which drought is hampering the achievement of one or many of these defined goals. Therefore, our study calls for additional research analysing the role of drought in research on the Sustainable Development Goals, and more precisely about whether or not the DEWSs are incorporated into development efforts by researchers.

Some studies have already been arguing in favour of considering other approaches than the two main top-down and bottom-up approaches for climate change adaptation strategies (Ludwig et al., 2014; Conway et al., 2019). Both approaches come with their strengths and weaknesses and conciliating them represents a challenge and many complexities, often unsuitable for integrating into water management (Ludwig et al., 2014). The issues complicating the decision-making are well known: the top-down approach is too broad and presents too much uncertainty; the bottom-up approach focuses too much on socio-economic vulnerability and too little on developing (technical) solutions (Ludwig et al., 2014). Thus, a risk-oriented approach that focuses more on “systems of receptors rather than conventional sectors”(Warren et al., 2018), where research identifies vulnerability to different extreme events rather than only analysing their probabilities of occurrence (Bliss and Bowe, 2011), is an alternative.

2.5 Conclusions

We conducted a bibliometric analysis on 5000+ scientific studies in which drought was associated to an index and water and food securities, with the aim of comparing how drought drivers (e.g. precipitation, temperature, evaporative demand) and drought impacts (food and water insecurities) were reflected in the literature. Our results revealed that drought is mainly depicted through a focus on precipitation-based and remotely sensed indices. It is the SPI, a single-variable index, that is the most broadly used in different climatic and geographic contexts, despite being the one including the least local contextual information. Drought is regularly approached merely as a rainfall statistical anomaly and equated to meteorological drought.

Drought driver studies tend to focus on particular geographical regions, especially northern countries, whereas studies reporting impacts related to food and water securities are more commonly located in Sub-Saharan Africa and Australia-Oceania respectively. Moreover, the areas where drought drivers are reported in scientific studies are different from the drought impacts ones. There is also a difference in the geographic repartition of drought-related food security and water security scientific studies. This suggests that drought impact studies are certainly dependent on both the physical and human processes occurring in the geographic area, i.e. the local context.

Because “local context” can have different meanings, we raised four hypotheses that can be attributed to local context and that can contribute to drought drivers resulting in drought impacts. First, the physical availability of water; drought drivers indices measure the water deficit in one or several of the components of the hydrological cycle, implying that the severity of drought is the same in arid or humid climates. Second, the socio-economic conditions in the countries, as the income per capita and the demography that affect, respectively, the capital involved in research and the vulnerability to hazards. Third, the data availability, related to the second point concerning socio-economic conditions, affects the selection and accuracy of an index, especially if the chosen index is unsuitable for the particular climate. Fourth, the scientific approach and the interest in the country that determines from which physical and/or social sciences scope drought will be looked at and for what purpose. It seems that drought impacts are considered more through social sciences lenses than drought drivers. Drought driver indices seem to remain conceptual metrics depicting climate features and do not seem to be linked to human-centred solutions. Also, both water and food securities are scientific concerns mostly in arid and semi-arid regions, from high to low income and whether drought drivers are investigated or not. This suggests many variants of the same type of impact according to what or who is likely to be most impacted by drought in the area.

Thus, more research is needed where the scope of drought mitigation is widened to the vulnerability to drought events rather than only their probability of occurrence. DEWSs would then more accurately predict the severity of drought by also including drought indices that are people-centred. In this way, drought metrics would also better align with SDSs. These drought metrics could become more useful in monitoring the negative role of drought in achieving human welfare, and with that, the SDGs.

03

Drought Impacts on Social-Ecological Systems

Abstract. This study applies 'Social-Ecological Systems (SES)' concepts with the aim of analysing why and how events happening across spatial, jurisdictional, and temporal scales influence droughts and their impacts in rural communities. To trace the evolution of droughts and their impacts on the livelihood system, we conducted a drought diagnosis in the rural community of Riacho da Cruz in the Banabuiú basin in the semi-arid Northeast of Brazil. We analysed how the livelihood of this community reacted differently to drought events and why the impacts of previous drought events either contributed to the adaptation of the livelihood system or its collapse. SES theory helped us posit that it is the collective capacity of stakeholders (nested across the levels of the different spatial, temporal and decisional scales of drought management) to manage their resilience to drought, that determines whether the considered system adapts, collapses or shifts into a new stable state, in response to drought. Monitoring these factors that influence drought resilience could enable the development of drought(-impact) indices that account for the spatial-temporal complexities of drought. Such results can aid in improving the targeting of policies toward drought-affected communities and ensuring they receive the necessary resources

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3.1 Introduction

Droughts are multi-dimensional phenomena as they involve multiple processes located across different spatial, time and decision scales that interact with each other. If a strict definition of drought roots from a lack of rain, this abnormally low rainfall can have large (e.g. El Niño/Southern Oscillation (ENSO); Dai, 2013), intermediate (e.g. land-surface feedbacks that can exacerbate droughts; Miralles et al., 2019) and local (e.g. cumulative precipitation heterogeneity; Liu et al., 2016) scale drivers. The time scale is also key when considering what aspect of drought is to be investigated. As each water use has its time scale, the period over which precipitation deficit accumulates is one of the components that separate different types of drought. Agricultural (soil moisture) droughts usually operate on shorter time scales, like the 2012 US flash drought with an onset of a matter of weeks that led to billions of US dollars of losses in agricultural production (NOAA, 2023; Qing et al., 2022). Hydrological drought, reflected in reservoir and groundwater storage, is often evaluated at the monthly or yearly time scale (Lorenzo-Lacruz et al., 2017). Frequency, duration, and intensity of drought all become functions depending on the implicitly or explicitly established time scales.

The same applies to the dichotomy between drought drivers and impacts. A categorisation between drivers and impacts of drought is not straightforward. A good example to illustrate this is irrigation, which can indicate a need to overcome drought-induced water scarcity (Mancosu et al., 2015) and for which excessive water abstraction can also be a driver of hydrological drought (Taye et al., 2021; Kustu et al., 2010). As such, the impacts of previous drought events can turn into future drivers of drought.

Societal actions and contributions to the drought phenomenon can occur at different spatial, temporal, and decisional scales. These can consist of, for example, increasing the water supply from local innovations to bigger structures, from promoting micro-irrigation (Grafton et al., 2018) to building dams to create reservoirs (Ribeiro Neto et al., 2022). These societal actions involve complex human-environmental interactions that are not straightforward (Hoekstra et al., 2019). Drought stakeholders can be inside or outside the water sector. They can be at different governance levels: from the individual water user (e.g. farmer or factory manager) to irrigation scheme and river basin committees, governmental policymakers, and international agreements. They can also be located at different stages of the supply chain: from stockholders, investors, producers, processors, and traders to retailers and consumers (Hoekstra et al., 2019). Consequently, their interventions are also nested across these levels of analysis. Looking at it from a spatial-scale perspective, those interventions can be made from the production-line level to the factory level, the river basin level, the country level, and the international level. Looking at it from a supply-chain perspective: from production, trade, processing, international markets and auctions to distribution, sale and household management (Van Oel et al., 2019). Such examples are characteristic and specific to droughts, which the GAR Special Report on Drought 2021 (UNDRR, 2021) summarises into three main aspects: spatiotemporal variation, multidimensionality, and indirectness. Droughts can manifest over various timescales, ranging from a few months to decades, and can affect small watersheds or entire continental regions. The impacts of droughts are cross-sectoral and cascading. Additionally, drought impacts may not be immediately visible, often displaying limited direct effects.

These are what we call, in this study, the spatiotemporal complexities of drought. It is difficult to take into account all the sectors and stakeholders exacerbating and impacted by droughts, nested in different levels of spatial, time and decisional scales. Social-Ecological Systems (SES) theory has proven useful for addressing unpredictably changing behaviours in space and time of the considered systems and to understand how some outcomes are in fact legacy behavioural effects from past events (Delgado-Serrano et al., 2015; Gunderson and Holling, 2002). SES theory has been employed to study a broad range of topics, from economics (Simmie and Martin, 2010; Torres et al., 2019), transportation systems (Hayes et al., 2019), healthcare (Wilcox et al., 2019) and of course natural resources adaptation to climate change (Fedele et al., 2020), yet studies using this theory to understand the spatiotemporal complexities of droughts remain scarce.

In this study, we aim to answer the following question: why and how do drought-related disturbances occurring at different levels of time, space, and decision scales create impacts at the focal scales and levels considered? We address this question building on the case study of a rural community located in the semi-arid drought-prone Northeast Brazil. We conducted a drought diagnosis (Walker et al., 2022) which allowed us to assess the trajectory of the community (Section 3.3.1) and further analyse this trajectory through the lens of SES theory (Section 3.3.2). Concepts of adaptive cycle, panarchy, resilience, and basins of attraction (Walker et al., 2004; Gunderson and Holling, 2002) allowed us to represent the multi-scale and level drought-related disturbances impacting the focal scale and understand the reasons behind their resulting drought-related impacts. Based on our results, we developed a framework for identifying the multiscale disturbances for the considered case and for explaining how these disturbances can lead to the system adapting or collapsing in response to drought. We posit that this framework provides a basis for the development of drought-impact indices, that can be adapted to the local context so that they account for the spatiotemporal complexities of drought in any area considered.

3.2 Data and Methods

We conducted a three-step drought diagnosis (Walker et al., 2022) detailed in Section 3.2.1, complemented by interviews (Section 3.2.2). The first step allowed us to assess the context of our drought-affected study area which was analysed in the second and third steps through the lens of SES theory(Section 3.2.3), whose principles are explained in Section 3.2.4.

3.2.1 Three-step drought diagnosis

Our methodological approach is based on the first three steps of the five-step drought diagnosis approach elaborated in Walker et al. (2022). This approach borrows from the diagnostic process of the medical sciences to better assess and treat droughts, where the disease is the drought and the patient is the drought-affected area. We chose to use this methodology because it emphasises that the drought diagnosis and treatments should be “patient-specific, or in other words, contextualised to a drought-affected region and its vulnerabilities, rather than a generic solution”. To implement this approach, we conducted interviews with 40+ different stakeholders at the study site and municipality- and state-level organisations between November 2021 and July 2022. More information about the interview approaches, the interviewees and the data collected is detailed in Section 3.2.2.

-**Step 1. Initial diagnostic assessment (anamnesis)**–Evaluation and history of symptoms, patient history, physical examination.

• Evaluation and history of symptoms = Evaluation and history of impacts: the drought impacts.

During this first step, we gathered available data on drought events and affected areas, keeping in mind that the complexity of drought and its impacts means that some facts might be overlooked. Beyond a clear separation between direct and indirect impacts, we investigated the incidence of drought impacts holistically in consultation with the local stakeholders. In this step, it was possible to identify which social, economic, and environmental sectors were the most affected by drought over time and what were the drivers. A few of the interviewees recollected these drought events and impacts from the 1970s, whether they lived those drought events themselves or heard them narrated by parents. We started our historical reconstruction from the 1970s but have more data from the 2000s. This is because it is from the 2000s that drought policies and approaches shifted from an approach of fighting drought through large dam construction and water transfer channels to strategies of coping and adaptation to drought (Cavalcante et al., 2022); it is also the active working years of most of the interviewees.

• Patient history = Drought history: the history of drought risk in the region.

In this step, we analysed past drought events to assess the evolution of the drought hazard over time. For the state of Ceará, we assessed drought event occurrence, severity, duration and geographic extent (Table 3.1).

• Physical examination = Physical characterisation: physical characteristics that increase the likelihood of impactful droughts.

Most of the physical characteristics within a drought management plan are fixed, like the regional climate or the soil map which were hence easier to include in our assessment.

Table 3.1: Data used for the drought diagnosis

Data source	Information extracted	Time Range
National Company of Water Resources (Cogerh)	Reservoir volumes Water allocation Type of water supply and infrastructure Occurrences of social conflicts Water management decision-making	2004-2022
Meteorology and Water Management Institute of the State of Ceará (Funceme)	Reservoir locations Reservoir volumes Water truck routes Vulnerable rural communities Hydroclimatic drought maps and indices	2004-2022
Brazilian Institute of Geography and Statistics (IBGE)	Total agricultural production per municipality Market price of agricultural products	1977-2022
Agricultural Defence Agency of Ceará (Adagri)	Livestock vaccination	2012-2022
Agricultural secretaries of Quixeramobim and Piquet Carneiro municipalities	Local agricultural policies, auxiliaries and credits Beneficiaries of social programs Vulnerable rural communities Crops and agricultural products market prices	2019-2022

What is more likely to change are agricultural strategies, drought and water management policies and governance structures (Cavalcante et al., 2022), and human-modifications to the hydrology. Through data collection from COGERH, FUNCEME, the agricultural secretary of

Quixeramobim and interviews with decision-makers and farmers, we traced the evolution of the water sources supplying the different uses in the study area (small/big/private/public reservoirs, shallow wells or aquifers, water trucks, piped water supply), the evolution of the water allocation, and the agricultural and livelihood strategies (see Table 3.1).

At the end of this first step, corresponding to two months of field-based research, we observed emerging patterns of multi-scales (space, time and policies) and levels of drought processes and legacy behaviours that concepts of the Social-Ecological Systems address. From our interviews with farmers and decision-makers, we understood that the livelihood system was the most important component of human welfare for the rural population and the most impacted by drought or drought-related events. As previous studies recommended looking at droughts from the perspective of how the welfare of the affected populations is impacted (Blauhut et al., 2015; Blauhut et al., 2016; Walker et al., 2022; Chapter 2), we analysed the collected data from the perspective of drought-related impacts on livelihood security.

Our initial diagnosis was thus directed towards understanding how and why drought affected the livelihood systems in the studied areas with concepts from SES theory. The two subsequent steps were conducted accordingly with this approach.

-Step 2. Diagnostic testing–Further analyses to confirm the diagnosis

Diagnostic testing aims to verify the initial diagnosis and determine what needs to be further investigated. It requires the input of specialists from a range of disciplines to limit tunnel vision and confirmation bias. This could also involve the reconsideration of impacts previously omitted or attributed to inexact origins. In addition to supplementary iterative rounds of collection of rural populations' narratives, we approached this second step through the lens of SES theory which we detail in Section 3.2.4.

-Step 3. Consultation–Obtaining a second opinion from specialists

This third step stems from the recognition that alternative expertise needs to be brought into a diagnosis. Cross-disciplinary advice was considered to test if the identified SES concepts of panarchy, adaptive cycle, resilience and basins of attraction had sufficient explanatory power. We shared our theory and submitted it for feedback with different stakeholders. Climate, social and soil scientists, hydrologists, agricultural engineers and technicians took part in the feedback rounds. Our diagnosis was updated each time new information was learned. The three steps were conducted as a cycle of information gathering, integration, interpretation, and identification of what further assessment was necessary (Walker et al., 2022).

3.2.2 The interview approach and data collection

The drought diagnosis was coupled with the grounded theory research method (Strauss and Corbin, 1994), where the hypotheses and theories constructed are "grounded" in the collected and analysed data. Forty-one unstructured and semi-structured interviews were conducted with farmers and actors from water and agricultural organisations (Table 3.2). The selection of the forty-one interviewees and the investigated study site was progressive as the first interviews were conducted with state-level decision-makers who recommended contacting other actors and so on (i.e. snowball sampling; Parker et al., 2019). Furthermore, after conducting forty-one interviews, a saturation of information was observed, as no new insights were obtained from additional interviews. From November 2021 to June 2022, the interviews and field research were conducted in 12 rural communities in the Jaguaribe River basins (Figure 3.1). Although the data analysis was coherent with the theories developed in this study, we chose to focus this article on one case study, located in the Banabuiú basin, in the municipality of Quixeramobim (Section 3.2.3). This was for reasons of brevity and because this case study represents sufficient different aspects of resilience to drought impacts, which are further developed in Section 3.3.2.

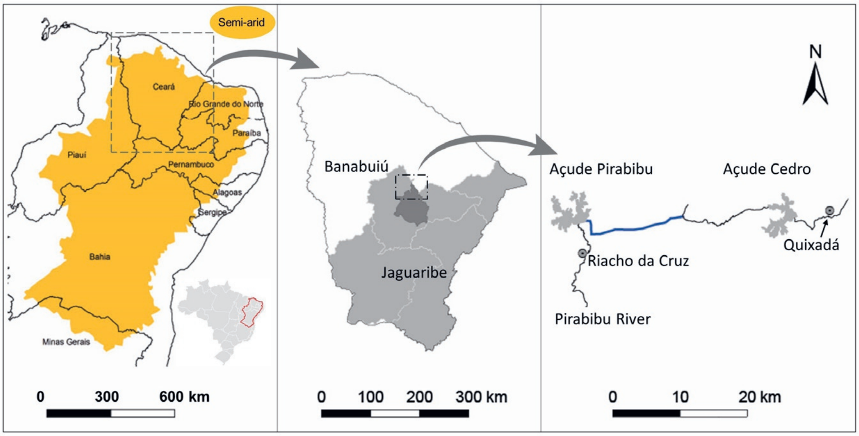


Figure 3.1: Map of the case study showing: the semi-arid Northeast of Brazil (left); the state of Ceará, the Banabuiú sub-basin as part of the Jaguaribe River Basins, and the municipality of Quixeramobim in dark grey (centre); and the rural community of Riacho da Cruz, the city of Quixadá and the Açude Pirabibu connected to a tributary stream of the Açude Cedro through a water canal (in blue; right).

All the interviewees provided consent before being interviewed. The interviews were not recorded but were written up immediately afterwards in order that the interviewees, who were in majority smallholders, would feel more at ease. Of the solicited actors, none refused to be interviewed. Questions were formulated to encourage the participants to describe what they considered to be the drought risks, impacts and factors increasing or decreasing the likelihood of impactful drought over time in the study area. Table 3.2 shows how the interviews were conducted. Step 3 of the drought diagnosis consisted of rounds of feedback that were achieved through scientific seminars with researchers from different disciplines working in the same region and with interviews with technicians, farmers and decision-makers.

Table 3.2: Summary of the semi-interviews and outputs detailing the stakeholders, their associated institutions, interview topics, and the time range of the data

Stakeholder	Institution, if applicable	Question type	Category of queries	Time range of the data
Decision-makers Researchers Technicians	Water management institutes	Semi-structured	Vulnerable groups Water availability and access Water-related conflicts Drought severity and impacts	1990s-2022
Decision-makers Technicians	Agricultural secretaries	Semi-structured	Vulnerable groups Water access Agricultural practices Markets existence and prices Drought impacts Social and agricultural programs and policies	1970s-2022
Decision-maker	Municipality of Piquet Carneiro	Semi-structured	Vulnerable groups Drought impacts Hydraulic infrastructure Drought emergency state	1970s-2022
Farmers and rural inhabitants		Unstructured and semi-structured interviews	Daily life and family Agricultural and livelihood strategies Droughts in the distant and recent past	1956-2022
Researchers	Funceme Cirad Embrapa	Semi-structured	SES concepts Agricultural production Drought impacts Drought aggravating factors	

3.2.3 Case study site

The area of study is the rural community of Riacho da Cruz, located inside the Banabuiú river basin, within the state of Ceará (Figure 3.1). Ceará has a notable drought history, being one of the ten states in the Sertão, the semi-arid Northeast of Brazil (Figure 3.1), or infamously within the "Drought Polygon".

Crises due to drought-associated water scarcity marked Ceará's development cycles (UNDRR, 2021). The average rainfall of 750 mm is relatively high for a semi-arid region, but it is mostly concentrated in the 4 months of January to April and is spatially heterogeneous in addition to being highly variable interannually (Martins and Reis Junior, 2021). Annual evapotranspiration exceeding 2000 mm and the poor shallow soils above crystalline geology do not promote aquifer storage and permanent rivers, but only intermittent streams (De Nys et al., 2016). To fight the state's low water availability due to the combination of irregular precipitation, high evaporation, and the unfavourable hydrogeological context, government approaches focused mainly on solutions aiming to increase water supply. In the 1990s and 2000s especially, heavy investments in hydraulic infrastructure like reservoirs, wells, water supply systems, and irrigation projects were made with the rationale that increasing the water supply would reduce the vulnerability to drought and consequently prevent water shortage (Cavalcante et al., 2022; Gasmi et al., 2022). Next to public investments in infrastructure for water supply, rural populations started unrestrictedly building private reservoirs, which ultimately modified the way that hydrological drought evolved during the most recent drought of 2012 (Ribeiro Neto et al., 2022). This drought lasted from 2012 to 2018 and was both the most severe and prolonged in terms of rainfall deficit in the 110-year monitoring history in the area (Pontes Filho et al., 2020). This multi-annual drought severely impacted the agricultural and livestock sectors, composed of 95% smallholder farmers who were the hardest hit due to their reliance on rainfed agriculture for their livelihoods. Crop losses were estimated at 70%–80% and economic losses at over US$3 billion (Brito et al., 2018). Food and water security, and water quality were impacted as reservoir volumes collapsed (Eakin et al., 2014).

The rural community of Riacho da Cruz is located within the municipality of Quixeramobim. Municipalities are the smallest political and administrative divisions in Brazil. Other smaller subdivisions exist inside the municipalities as districts and rural communities, but they remain under the jurisdiction of the municipality. We chose to focus on the informal jurisdictional level of the (rural) community for the following reasons: the objective of this study is to provide a comprehensive understanding of the human dimensions influencing resilience to drought impacts. This resilience can manifest at many levels such as individual, household, community, country or climatic region. We chose to focus on the community level as it underscores the capacity for collective action to manage resilience and its four aspects (Frankenberger et al., 2013; Walker et al., 2004) that are detailed in Sections 3.2.4 and 3.3.2.

3.2.4 SES theory: adaptive cycles, panarchy, resilience and basins of attraction

Social-Ecological Systems, according to (Delgado-Serrano et al., 2015), are "complex adaptive systems characterised by: (1) integrated biophysical and socio-cultural processes, (2) self-organization, (3) nonlinear and unpredictable dynamics, (4) feedback between social and ecological processes, (5) changing behaviour in space and time, (6) legacy behavioural effects with outcomes at very different time scales, (7) emergent properties, and (8) the impossibility to extrapolate the information from one SES to another". Complex adaptive systems (CAS) comprise a dynamic network of interacting agents, capable of learning (Ahmed et al., 2005; Miller and Page, 2007). System behaviour may not be directly explained by the behaviour of its components. Understanding these systems therefore requires holistic rather than reductionist approaches. CAS examples are the brain, the economy, the immune system and SES (Ahmed et al., 2005). As such, SES are complex adaptive systems, but not all complex adaptive systems are SES.

Social-Ecological Systems theory (SES theory) examines how SES respond to stressors and disturbances. SES theory emphasises the importance of understanding and adapting to non-linearity. It explains the human use of different adaptation and coping strategies to deal with shocks or disasters such as hurricanes (Hasnain et al., 2023), floods (Cheng, 2019), droughts, heat waves or wildfires (Thonicke et al., 2020). SES theory builds on the adaptive cycle, the panarchy and the resilience approach that we employed in this study.

3.2.4.1 Adaptive cycles

Adaptive cycles show how SES respond to disturbances and changes (Gunderson and Holling, 2002; Holling, 1986; Scheffer, 2009). Adaptive cycles can be represented as infinity loops or "lazy-eights" in which dynamics are powered by three drivers, each represented on an x, y and z dimension (Figure 3.2). The y dimension is the 'potential' (or "wealth"), representing stored or accessible resources (financial or natural). The x dimension is the 'connectedness', representing the flexibility of the system in response to external variations. The z dimension represents 'resilience'; the system's capacity to absorb or withstand perturbations and other stressors while still retaining essentially the same function, structure, identity, and feedbacks (we will later sharpen this definition). Together, these three dimensions determine system dynamics and shape future responses to disturbances. Combinations of high or low potential, connectedness and/or resilience can lead to changing states of the system. Dimensions' levels vary along four distinct phases together composing the "adaptive cycle" (Figure 3.2): growth and exploitation (r), conservation (K), collapse or release (Ω) and reorganisation (α). A forward loop connects ‘r’ to ‘K’, representing a slow and incremental phase of capital accumulation and growth. A backward loop connects ‘Ω’ to ‘α’ representing the system restarting the cycle or transforming into a new configuration with different properties (symbolised as the exit arrow in Figure 3.2A). In this way, system behaviour is characterised by dynamic fluctuations of potential, connectedness, and resilience, which affect the transition process from one phase to the next when confronted with a disturbance.

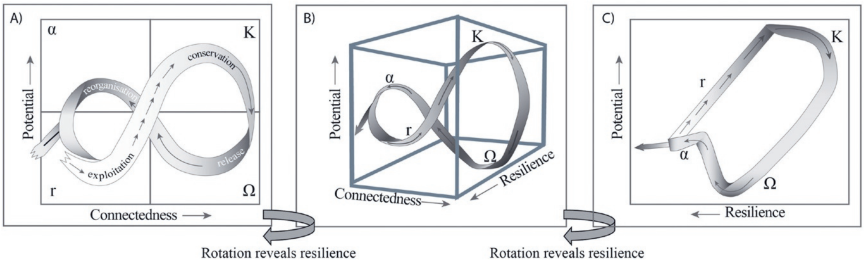


Figure 3.2: Adaptive cycles can be represented as a “lazy-eight ” showing a 2D projection of a 3D object (Figure 3.2A), emphasising fluctuations and different combinations of potential and connectedness, while ‘hiding’ the resilience component that a rotation of the view reveals (Figure 3.2B). Resilience decreases as the cycle moves towards K, as intensified connectedness and inflexibility make it increasingly difficult for new entrants to step in and create new pathways, turning the system brittle. Events that would have previously been overcome without causing any structural change are now destabilising events leading to crises and transformations. As the cycle shifts rapidly into its “back loop”, the resilience expands as the accumulated resources are reorganising for a new initiation of a cycle. In Figure 3.2C we represent the variations of resilience through the four phases of the adaptive cycle (r, K, Ω and α) in relation to the potential. Figure 3.2A, 3.2B and 3.2C reveal resilience and how it shrinks and expands throughout the adaptive cycle. The arrows represent the speed of the phases of the cycle, where short and closely spaced arrows represent a slowly changing situation and long arrows represent a rapidly changing situation (Adapted from Gunderson and Holling, 2002).

3.2.4.2 Panarchy

The panarchy framework connects adaptive cycles in a nested hierarchy. It refers to the influence that events located at different levels have on the focal and considered level. In a SES, at least three levels each representing an adaptive cycle can be considered: (i) the intermediate size and speed that generally represents the focal level, e.g. the catchment or community level; (ii) the small-and-fast cycle, located below the intermediate cycle, e.g., the field or household level; (iii) the large-and-slow cycle, located above the intermediate cycle, e.g. the national level (Figure 3.3). Multiple connections exist between the phases of the adaptive cycles of these three levels. Two of these connections are better explored and labelled “revolt” and “remember”. The “revolt” dynamics occur from smaller to larger levels as small-and-fast cycles accumulate and overwhelm larger-and-slower cycles (Holling et al., 2002). The “revolt”-label stems from the process that structures and processes at smaller scales can overthrow those at larger scales, creating new processes and structures that will replace the previous processes and structures. This particularly occurs when the larger cycles are in their “K” (conservation) phase. In that phase, the system is most vulnerable because it is at its most rigid and less resilient state (Figure 3.2). On the contrary, the “remember” dynamic occurs from larger to smaller scales. The label “remember” refers to slow-moving larger scales that retain an institutional memory of previous structures and processes. Smaller scales are influenced by this memory to (re)create systems that are similar to those that existed at this same scale in the past, particularly in the reorganisation (α) phase after a collapse (Ω).

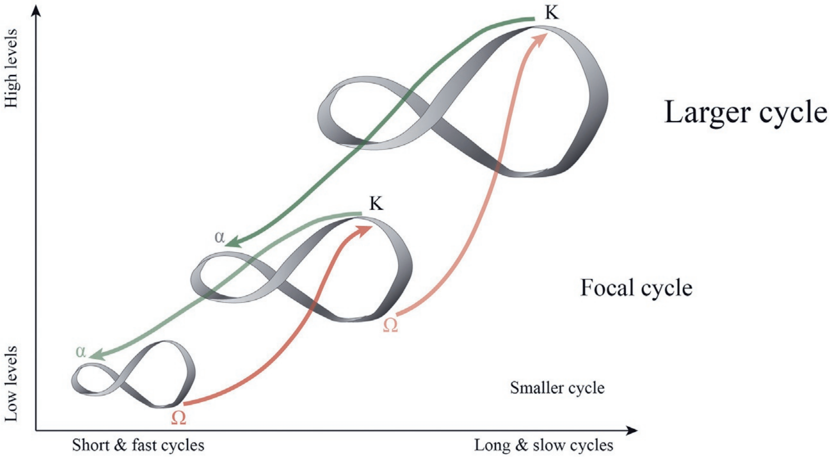


Figure 3.3: Representation of the “panarchy” with three selected levels of a panarchy emphasising two main connections. The “revolt” connection represents a critical change in the cycle at a smaller level that will cascade up to a larger level when it is the most rigid and the least resilient. The “remember” connection draws the potential accumulated and stored at a larger scale, back to the smaller scale to facilitate its renewal. Cycles at smaller levels are short and fast while they are long and slow when they are at larger levels (adapted from Redman and Kinzig, 2003).

The smaller and faster-nested levels invent, experiment and test by going through frequent periods of reorganisation (Redman and Kinzig, 2003), but their functioning remains constrained and defined by the slower-and-larger levels that conserve and keep a memory of the SES dynamic. The slower and larger levels set the functioning conditions of the small-and-fast levels. Panarchy is one of the aspects of resilience that makes the SES at the considered level keep its identity and thus its adaptive cycle. Therefore, when a system collapses and reorganises under a new structure and identity, three additional critical aspects of resilience drive the transformation of the past system into a new one: latitude, resistance and precariousness. These aspects are worked out in more detail in the concept of basins of attraction and stability landscapes, developed in Section 3.2.4.3.

3.2.4.3 Resilience and basins of attraction

In basins of attraction, an attractor is a set of states towards which a system tends to evolve in the absence of disturbances (Walker et al., 2004). When a system tends toward this attractor, it is in an "equilibrium state". This can be illustrated with a marble rolling in a smooth rounded bowl that will come to rest motionless in the lowest bottom centre point of the bowl (American Heritage Dictionary, 2005). However, all SES continuously undergo disturbances that move them away from the attractor within a stability domain or "basin of attraction". The considered system thus evolves within the virtual boundaries of this basin. A system can have multiple attractors and can therefore have multiple basins of attraction separated by thresholds within a stability landscape (better represented in Figure 3.8a, in the Results Section 3.3.2.3). When a system undergoes disturbances, it may escape from the basin and reach another basin of attraction, resulting in a new and different set of controlling processes. The loss of resilience in response to disturbances can lead to the SES structure being altered until losing its identity and consequently reorganising. If a system is resilient, it will remain within the boundaries of the basin. Thus, a more specific definition of resilience than that mentioned earlier can stem from the concepts of basins of attraction. Indeed, resilience is the magnitude of disturbance that a system can tolerate before it shifts into a different basin of attraction (or stability domain), with different controls on structure and function. Resilience is thus the main component of the basins of attraction that provides its identity to a system.

The basins of attraction can be represented as commonly described "basins" which are a three-dimensional topographic structure. In this representation, resilience can be schematised and represented as the size of one basin within a stability landscape. Each three-dimensional basin is modulated by four components that describe the resilience (Figure 3.8a). The Latitude (L) is the width of the basin circled by its boundaries, which means that it represents the maximum amount of disturbance a system can withstand without losing its ability to recover by shifting into another basin. In other words, L represents the capacity of change of a system before losing its identity. The resistance (R) is the depth of the basin, which corresponds to how tied to the attractor the system is, and thus how easy or difficult it is to change it. In other words, the resistance represents the factors and feedbacks limiting the propagation of disturbances that cause the system to move away from the attractor. The precariousness (Pr) is defined as the trajectory of the system and its current position in the basin in relation to the threshold. By considering the position of the system in a basin of attraction, the precariousness thus represents the persistence of that system under a defined scenario. When considering its trajectory, this corresponds to the system moving to a less resilient state and potentially towards a new basin of attraction. Thus, the precariousness equals the minimum amount of perturbation needed to drive a system at a stable state outside of its basin of attraction. The panarchy (Pa), previously detailed, refers to all external disturbances at smaller or higher levels than the focal level, influencing the three other aspects. These four components are essential as the alteration of one of them leads to the alteration of the resilience of the system and consequently, of the stability landscape. A change of resilience of the state of a system corresponds in fact to the change of shape of the basin of attraction in which the system finds itself. The disturbances leading to a change in the stability landscape can be endogenous, meaning that these changes come from the variables controlling the system: the number of basins of attraction can change, just as the position of the thresholds between basins (L) or the depths (R). A system can thus find itself within a different stability domain because the stability landscape changed (Walker et al., 2004). Logically, a combination of endogenous and exogenous factors can also lead to changes in the stability landscape.

Finally, whether they are caused by endogenous or exogenous factors, the drivers of these changes can be of natural or human origin and in SES, human actions are dominant (Walker et al., 2004). This means that actors have the capacity to manage resilience (which is in fact the definition of adaptability (Walker et al., 2004) and consequently, the system. (Un) intentionally, decisions of actors can determine whether their system stays in its current stability domain or crosses into, or back to, a desirable, or undesirable, domain. As humans can influence resilience, they can do so by altering its four components: Pa, L, R and Pr.

In Section 3.3.2, I will use this theory to examine the influence of humans on managing their resilience to drought in the community of Riacho da Cruz.

3.3 Results: The diagnosis of the Riacho da Cruz human-water system

A livelihood consists of the capabilities, assets (including both material and social resources), and activities required to support a living (IRP and UNDP, 2010). Livelihood strategies are the combination of activities that people choose or have to undertake to achieve their livelihood goals (Alinovi et al., 2010). Naturally, these strategies transform as opportunities, risks and limitations change. In the community of Riacho da Cruz, the livelihoods strategies changed trying to fit the conditions imposed by drought. These strategies were as dynamic as were the droughts and the fluctuation of their socioeconomic environment. In our study areas, livelihood is a human dimension strongly affected by drought and in which related decisions, strongly affect the development of drought. In the next sections, we describe the trajectory of the livelihood system in the community of Riacho da Cruz and the underlying factors to secure this livelihood under drought and other disturbances.

3.3.1 Initial diagnostic assessment

The development of the rural population of the community of Riacho da Cruz can be divided into three time periods: before 2001, from 2001 to 2017, and from 2017 onwards.

Before 2001, the community of the Riacho da Cruz mainly consisted of an agricultural workforce for the two main livestock farms in the area, Canafístula and São José, both belonging to the farm-owner (*fazendeiro*) Damião Carneiro after which the district is named. The livelihood of the community was mainly based on farm labour in addition to the sporadic sale of surplus from subsistence farming production, providing basic food security to the community. The rural population did not have access to piped water and the subsistence farming system to ensure basic food security was rainfed.

In 2001, the construction of a dam in the community was finalised. Officially named Açude (dam) “Margarida de Morais Queiroz”, its popular designation was “Pirabibu dam” after the eponymous downstream river (Figure 3.1). Its construction was initiated in 1999 by national- and state-level organisations: the National Department of Works to Combat Drought (DNOCS) and COGERH, respectively. The main objectives of the dam were to supply water to the downstream and strategic Cedro dam through a water canal (Figure 3.1), to turn tens of kilometres of the Pirabibu river from intermittent into perennial, and to irrigate approximately 100 hectares along the Pirabibu river (Figure 3.1). The Cedro dam provides the water supply to the city of Quixadá. This supply was at risk in 1999 when the water level of the Cedro dam was decreasing after three successive years of abnormally low rainfall – which led to the decision to construct the Pirabibu dam. In 2001, a satisfactory rainy season raised the water level of the Cedro dam and with it, decreased the threat of Quixadá running out of water. In a joint decision, DNOCS and COGERH reattributed the use of the Pirabibu dam water to the needs of the downstream communities. The water of the Pirabibu dam was prioritised to be piped into the houses of the community and, secondly, available and used for new irrigation practices.

From 2001, community members started practising livestock farming with on-farm forage cultivated using irrigation from the dam. The first households that converted to livestock farming were those that received financial compensation for ceding a part of their land where the Pirabibu dam was built. The other households that did not benefit from the compensation requested a line of micro-credit specifically intended for investment in infrastructure in rural communities (Pronaf - Programa Nacional de Fortalecimento da Agricultura Familiar, grupo “B”). Such a transition was motivated by several factors. First, livestock farming was considered an adequate practice for a semi-arid area, as underlined by the municipality's target to turn Quixeramobim into "the largest milk basin (*a maior bacia leiteira*)". Secondly, the community benefited from its livestock-farming tradition. Already present livestock farmers had the required knowledge and could also benefit from technical assistance for livestock farming (forage seeds, veterinary assistance, pest and disease control). Thirdly, a stable market for meat and milk with limited price fluctuation provided a steady income. Finally, and most importantly, cattle provide a financial asset as animals can always be sold at a fair price. All interviewed farmers referred to the cattle as a "savings account" (*poupança*). Therefore, from 2001 to 2005, farmers progressively converted to livestock farming by acquiring animals and irrigation equipment for forage production. Their income increased accordingly, providing means to intensify farming with more animals and increased forage production. Therefore, by 2005, virtually the entire community was dedicated to livestock farming for meat and milk production.

From 2005 to 2014, forage production was further increased to provide cattle feed to increase milk production. This water-use pattern remained unchanged even when the Pirabibu reservoir reached critical water levels and close-to-zero volumes in 2004, 2008 and 2009. Critical water levels were each time followed by a sudden recharge after a satisfactory rainy season. The wet season of 2004 recharged the reservoir up to 60% of its capacity and the wet season of 2009 up to 77%. From 2009 onwards, the water level of the Pirabibu reservoir was no longer substantially recharged and even dropped to zero in 2015 (Figure 3.4).

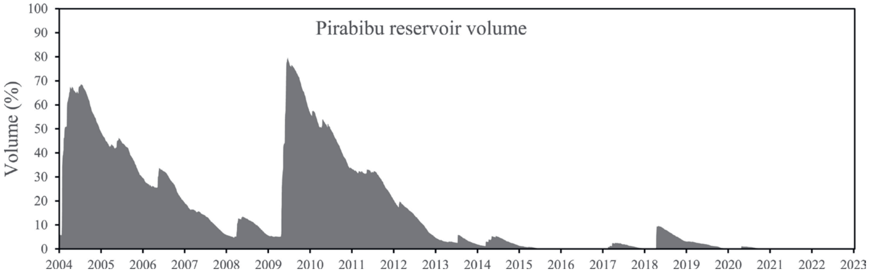


Figure 3.4: Evolution of the volume (in percentage of capacity) in the Pirabibu reservoir from 2004 to 2022 (Funceme and Cogerh, 2023)

In the dry season of 2014, with no water in the Pirabibu reservoir, irrigating and producing forage onsite was impossible. The first decision of farmers was to maintain the size of the livestock and buy the forage that could not be produced on-site. This decision was motivated by the belief that each year of low rainfall would be the last, and that after a wet year with dam water recovery, old practices could be continued. This belief was reinforced by the Pirabibu reservoir being recharged twice in the past by a satisfactory rainy season after years of low rainfall. Even if they kept their assets, their livelihood was negatively impacted as their costs increased. Moreover, the market price of forage increased with suppliers profiting from the 2012-2019 drought and the generalised high demand, triggering a so-called "pork cycle" (or cattle cycle; Rosen et al., 1994) characterised by cyclical fluctuations of supply and prices in livestock markets. Discouraged by the high prices, buying forage was a strategy only used during the dry season of 2014. Another year of meteorological drought during the wet season of 2015 did not recharge the Pirabibu reservoir as hoped, nor contributed to the production of enough forage for the year. This was a trigger for most of the farmers to decrease their livestock by progressively selling their animals. Some farmers still believed in the filling of the Pirabibu reservoir and intensive livestock farming and decided to keep their animals, which resulted in cattle death. The number of animals, being the financial assets, decreased and led to decreased milk production and lower income. The "savings account" money from selling cattle was used to cope with the decreased income and became the standard coping strategy in the community of Riacho da Cruz from 2017 until 2022.

From 2017, livestock farming remained oriented to meat and milk production and became merely extensive (5 cows per household maximum, as opposed to an average of 20 per household in 2014), with its capacity fluctuating and adjusted to the forage produced during the rainy season. In years of a satisfactory rainy season, more forage was produced, encouraging farmers to buy more cows and to increase their milk production and thus their income. In years of low rainfall, with less forage able to be produced on-site, farmers sold their animals to restock their "savings account" and cope until the next satisfactory rainy season.

3.3.2 Diagnostic testing and consultation

3.3.2.1 Multi-scale and level influences on the livelihood system of Riacho da Cruz

The three periods that characterise a different orientation of the type of livelihood of the community of Riacho da Cruz can be represented and understood with the adaptive cycles of SES theory described in Section 3.2.4.

Our considered system is the livelihood system predominant in the community of Riacho da Cruz. Over time, this system had three different orientations: manual workforce until 2001, intensive livestock farming from 2001 to 2018, and extensive livestock farming since 2018. Each orientation of the livelihood system represents a different adaptive cycle. The transition from one orientation of livelihood to another represents the beginning of a new adaptive cycle, with new feedbacks and identity. The potential, connectedness and resilience of the livelihood system fluctuate through the four phases of the adaptive cycles as follows (Figure 3.5).

From α to r: The first transition (reorganisation) from manual workforce to intensive livestock farming (growth and exploitation) is triggered by the construction of the Pirabibu dam and the opportunity of available surface water in the dry season in the community. The recent water availability, the financial compensation for the land and the knowledge of livestock by working as employees in the main farms, represent the potential inherited from the (reorganisation- α and the last phase of the) first adaptive cycle that is available to be invested into a new cycle.

From r to K: This first r (growth and exploitation) phase of the second cycle is dominated by farmers (the agents) who take advantage of the opportunities from transitioning from the previous cycle, and the resources adapted to the current cycle.

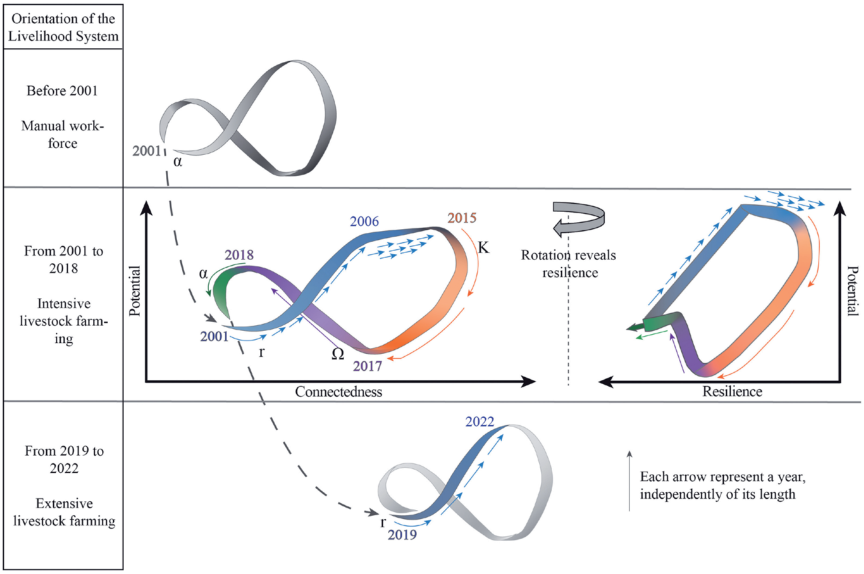


Figure 3.5: Adaptive cycle applied to the livelihood system of the community of Riacho da Cruz. On the left, the emphasis is on the potential and connectedness. On the right, the rotation of the view emphasises the resilience and potential dimensions.

In an experimental phase, farmers tested combinations of irrigation, all-year forage production, livestock buying and market opportunities, to find the right balance of these elements to contribute to their livelihoods. Because the farmers are adapted to deal with their new environment, the resistance to the system is high. In that sense, no definitive connections are yet established and the connectedness of the livelihood system remains low. It is a slow and incremental phase of capital accumulation and growth as assets, in the form of livestock, are being acquired and are starting to provide an income.

The farmers who had not yet converted from manual workforce to intensive livestock farming were those who did not receive financial compensation. After perceiving the return on investments in livestock farming, they decided to contract micro-credit to support their transition. At community level, the livestock increases and with it, the assets, the income and thus, the potential of the livelihood. After the experimentation phase, the farmers of the community learned the successful sequence of decisions that would maximise their livelihoods. The produced milk is sold to local milk companies. Calves and cows that no longer produce milk are sold for meat. Cows that are not lactating at that moment are kept for further insemination. The forage to feed the cattle is produced on-site all year long, rainfed in the wet season and irrigated from the Pirabibu dam the rest of the year. As the optimal connections between the available water in the dam, irrigated forage production and livestock farming are being established to constitute the skeleton of the livelihood of the community, the connectedness grows as well. This means the livelihood system is strongly dependent on enough water in the dam, to guarantee the rest of the production chain (Figure 3.6). For instance, the share of rainfed forage depends on a satisfactory rainy season, increasing the pressure on the Pirabibu dam in years of low precipitation. The system reached its K stage in 2006 and remained in a high potential- high connectedness-low resilience plateau, until 2014. At this stage, the system is very rigid and poorly open to new opportunities. Its resilience is minimal and the system is not pliant to unexpected and uncontrolled events, such as a multi-year meteorological drought, that could have been overcome more easily in the past, earlier in the r-phase.

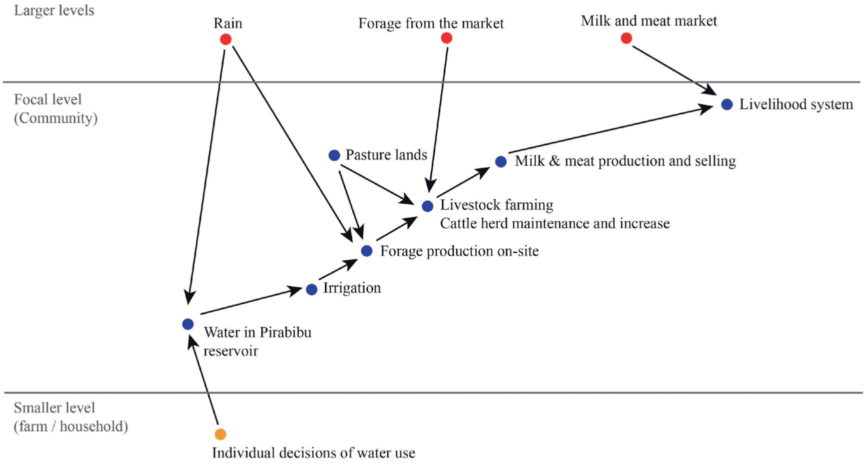


Figure 3.6: Gradation of connectedness between the elements, at focal, smaller and larger levels affecting the livelihood system of the Riacho da Cruz community.

Ω to α: As the livelihood cannot be based on intensive livestock farming alone anymore, it is temporarily maintained by the income provided by selling livestock. The existing connections between livelihood, milk and meat production, forage production onsite, irrigation and availability of water are undone. The connectedness decreases again. The livelihood, even if at its lowest potential, cannot be based on intensive livestock anymore and the economic agricultural activities can only be rainfed. It has thus become resilient to what caused its collapse, namely the drying of the Pirabibu dam. Resilience increases again.

α to r: The livelihood orientation is converted to another type of activity as farmers adapted to the idea of the Pirabibu dam never recovering. Their livelihoods are reorganised to be based on the selling and buying of animals, completed by a low income from milk or meat production when it is possible. The potential, being the financial means and/or the animals remaining from the previous cycle, is reinvested into the next cycle. Adapted to these new circumstances, the resilience of the new livelihood system is high.

3.3.2.2 Cross-scale interactions affecting the livelihood system of Riacho da Cruz

As we previously mentioned, our system is the livelihood at the jurisdictional level of the community. The successive shifts of the orientation of the system are a consequence of actions undertaken at that same level but also of decisions and phenomena that happened at higher or lower levels. We adopt a panarchy representation to better understand the influence of other temporal and spatial scales on the livelihood system of the community of Riacho da Cruz (Figure 3.7).

At the smaller level are the farming systems as a decision-making unit (Fresco and Westphal, 1988), comprising the farm household, cropping and livestock managed by the farmers to sustain their livelihoods. Their adaptive cycles are like the cycles at the focal scale, only shorter and faster, typically at a temporal resolution of one wet or dry season or one agricultural year. Their potential is likewise composed of the income and assets gathered at the farm level, with the main driver of the fluctuation of this potential being the individual decisions made by the farm holders. On a short time scale, the farmers decide the strategies that balance different combinations of rainfed and irrigated production, herd size and the sale of animal products, that the farming business grows, maintains itself, declines or reorganises. These strategies can be maintained or changed by the farmers, for example, from one agricultural year to another, according to their contexts and influencing events happening at larger scales and levels. In the case of the community of Riacho da Cruz, these larger-level events are droughts, the fluctuations of the market, and the agricultural and water management policies conducted by the DNOCS, Cogerh and the agricultural secretary of the municipality of Quixeramobim.

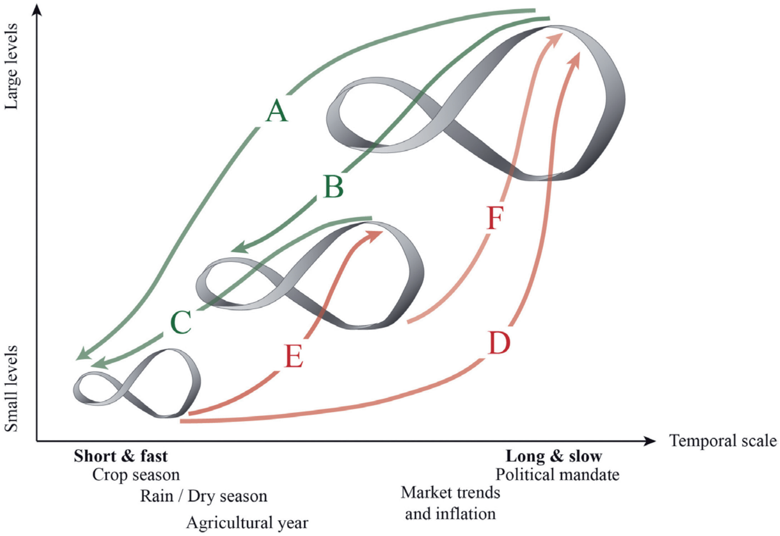
There are continuous feedbacks between smaller and larger levels, with events influencing each other. These feedbacks happen through the revolt and remember connections. The remember connections (connection A in Figure 3.7) influencing the decisions of the farmers of Riacho da Cruz are the encouragements provided by the agricultural office to invest in livestock farming as an economic activity adequate for dry and drought-prone areas.

In that same line, (agricultural) water management policies in the state of Ceará have an institutional tradition to “fight against drought” (Cavalcante et al., 2022) which manifested as the expansion of the water infrastructure network and an over-reliance on water resources to conduct economic and agricultural activities. This is the case with the decision to build the Pirabibu dam and allow its water use for irrigation. Finally, the market prices of forage were the main driver of the farmers’ profit being negatively impacted first and ultimately, by the farmers’ decision to reduce the size of their cattle herds and shift to extensive livestock farming.

From the larger levels, the main remember connection (connection B in Figure 3.7) affecting the focal scale is the decision from Cogerh and DNOCS to build the Pirabibu dam which triggered intensive and irrigated livestock farming as the main source of livelihood in the community of Riacho da Cruz.

The connection from the focal to the smallest level (connection C) is mainly the tradition of livestock farming in the area, both in terms of existing farms in the area and the agricultural and livestock knowledge. These keep the farmers tied to base their livelihood on this activity, whether it is by working at a *fazendeiro*’s main farm, practising intensive livestock farming or buying and selling cows.

The revolt connections are events that lead to the collapse of systems at a larger level when they are the most fragile. The individual decisions of farmers to continue to irrigate during a multi-annual drought led to the Pirabibu reservoir drying, which led to the collapse of the intensive livestock farming system in the community of Riacho da Cruz (connection E). These individual decisions of water withdrawal at the farm level are also one of the main drivers of strategic state reservoirs drying leading to a hydrological drought (connection D) as shown by Ribeiro Neto et al. (2022) in a study conducted in the Jaguaribe River basin. The pork cycle effect is the inflation of forage prices at a higher level due to its simultaneous purchase by farmers. Finally, it is the drying of the reservoirs at the community level that leads water management policies to persist in “fighting against drought” (connection F) and building continuously more dams (Cavalcante et al., 2022; Walker et al., 2022), even if these dams are the first link in the drought chain (back to connection A).



Remember connections (from larger to smaller levels)	A **From largest to smallest**	B **Larger to focal**	C **Focal to smallest**
	Encouragement to practice livestock farming Over-reliance on water availability (Cavalcante et al., 2022) Forage is too expensive	Construction of the Pirabibu reservoir	Livestock selling and buying
Revolt connections (from smaller to larger levels)	F **Focal to largest**	E **Smallest to focal**	D **Smallest to largest**
	Increase of hydraulic infrastructures (Walker et al., 2022)	Dry Pirabibu reservoir	Pork-cycle Hydrological drought (Ribeiro Neto et al., 2022)

Figure 3.7: Panarchial connections between three selected hierarchical levels, their respective spatial and time scales and the “revolt” and “remember” connections between them. The focal level, which is the livelihood system in the community of Riacho da Cruz, the smaller level is represented by the individual farming system and the larger levels consider the climate, the market and the agricultural and water management policies.

3.3.2.3 Understanding livelihood system shifts in the community of Riacho da Cruz

The influence of the panarchial connections is important in understanding the multi-scale and -level events that contribute to the shift of the livelihood system at the considered focal level. Panarchy Pa, latitude L, the resistance R and the precariousness Pr, drive the change of the resilience of the livelihood system of the community of Riacho da Cruz, from a stable state and its transition to another.

In Table 3.3 below, we clarify and summarise how these four parameters affect the overall resilience of a system to its stable state. We illustrate with examples from the Pirabibu-Riacho da Cruz human-water system.

Table 3.3: Characterising four resilience components (L, R, Pr and Pa) of the livelihood system in Riacho da Cruz

Focal system → *e.g. The Riacho da Cruz Livelihood system*	Attractor 1, 2,..., n: What is the dominant equilibrium state of the system? *e.g. from 2001 to 2016, the livelihood system tends to intensive livestock farming*
Components of the resilience ⤵	
Latitude (L)	How much disturbance leads to a non-reversible loss of ability to recover? *e.g. How much disturbance (shortage of water, feed and income) can the intensive livestock farming system withstand before collapsing?*
Resistance (R)	What limiting factors keep the system in a stable state? *e.g. What disturbance-limiting factors (water storage, money savings, loans, insurance, government subsidies) limit negative measurable impacts of drought?*
Precariousness (Pr)	How close is the system to a shift to an alternative equilibrium state? • How many agents of the system persist in the stability domain? *e.g. What share of households continue livestock farming rather than converting to another livelihood?*
Panarchy (Pa)	What are the influences from larger and smaller levels that influence L, R and Pr?

In Table 3.4 are summarised the variables corresponding to the four parameters determining the resilience of the livelihood system types.

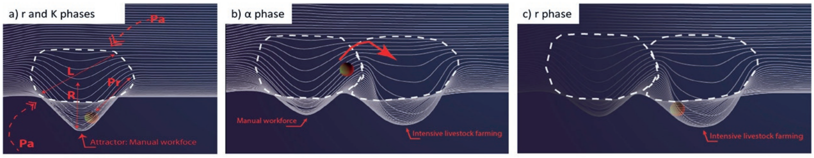
Before 2001, the livelihood of the community of Riacho da Cruz is based on the income provided by working at the two local livestock farms in the area. This constitutes the attractor to which the system tends in its stable state (Figure 3.8a). The system is stable and in its growth and conservation stages. The latitude of that system depends on the employment opportunities at local livestock farms. These were so far fixed and safe and rather than the community, disturbances were controlled by the managerial team of the farms. The system is also resistant, as the lack of opportunities and natural resources in the area limit other types of activities on which to base livelihoods. The precariousness is low, as all the farmers of the community of Riacho da Cruz work for the farms. This corresponds to a wide and deep basin of attraction with the ball very close to the attractor: the livelihood system is resilient to the state of manual workforce and the force needed to destabilise it should be important.

Table 3.4: Evolution of the four resilience components (L, R, Pr and Pa) according to the type of livelihood system in Riacho da Cruz

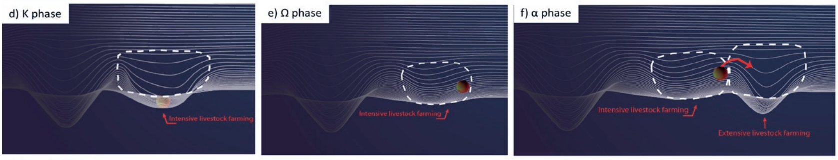
Livelihood system type (Attractor) →	**Manual labour at livestock farms (Before 2001)**	**Intensive livestock (2001-2018)**	**Extensive livestock for subsistence (2019 onwards)**
Components of the resilience ⤵			
Latitude (L)	• Employment at the livestock farms • (Lack of) rain for rainfed and subsistence agriculture	• (Lack of) rain, • Water in the Pirabibu dam, • Irrigation equipment, pastures for grazing, forage	• (Lack of) rain, • Pastures for grazing
Resistance (R)	• Lack of natural and financial resources to practice a self-owned type of farming	• High market prices of milk, meat and forage • Incentives from agricultural centres to practice livestock • Available loans for irrigated forage production	• Animals as a “savings account” mentality: livestock perceived as goods to resell if needed • Only knowledge of livestock farming • Incentives from agricultural centres to practice livestock farming
Precariousness (Pr)	• The households that are employed at the farm and practice subsistence farming	• The households that converted to intensive livestock farming exclusively	• The households that converted to extensive livestock and/or subsistence farming
Panarchy (Pa)	• Cedro reservoir dry, • Construction of the Pirabibu dam	• Drought of 2012-2019 • Inflation of forage market prices • Over-reliance on irrigation • Individual decisions of water management	• Hydrological drought

This important force is the panarchy, materialised by the construction of the Pirabibu dam. With water available for new activities, the resistance of the system decreases. More farmers convert to a new activity as a base for their livelihoods and the precariousness increases. The ball gets closer to the edge of the basin and the livelihood system previously based on manual workforce reorganises to livestock farming (Figure 3.8b) until intensive livestock farming becomes the new attractor of the livelihood system (Figure 3.8c).

Before 2001:



Between 2001 and 2019:



After 2019:

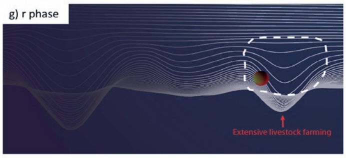


Figure 3.8: Time course of the livelihood system evolution of the Riacho da Cruz community as represented by the shifts of stability domains resulting from the successive iterations of the phases of the adaptive cycle. The stability landscape is composed of one to three stability domains or basins of attraction. The boundaries of the basins are symbolised by the dashed lines. The ball represents a chosen focal scale of the considered SES. The ball is inside the basin of attraction tending towards one attractor. In Figure 3.8a, L represents the width of the basin of attraction and R represents its depth. Pr is the distance of the system from the limit of its current basin of attraction. Pa is represented by the dashed arrows, which are disturbances coming from lower or higher levels than that considered level, but affecting the L, R and Pr of the focal level.

From 2001, with this new attractor, the parameters of the resilience of the livelihood system to this stable state oriented at intensive livestock farming, change as well. As mentioned in Table 3.3 and Table 3.4, the latitude corresponds to how much disturbance the livestock farming system can withstand before it collapses. This translates in terms of shortages of resources that the livestock system can handle. These resources are the rain, the water available for irrigation, and the forage produced and bought at the market. The resistance parameters are the factors limiting the propagation of disturbances and holding the system close to its stable state. In this case, this corresponds to the market prices of the meat, milk and forage, the incentives from the municipality to practice livestock farming and the existence of loans to fund such activities. The precariousness corresponds to the share of farm holdings that persist in intensive livestock farming or are converted to another type of livelihood. The panarchy parameter corresponds to the influences of other smaller and larger levels on the La, R and Pr of the livelihood system. These influences are the multi-annual drought of 2012-2019, the over-reliance on hydraulic infrastructure and irrigation and the inflation of the forage market.

The resources needed for intensive livestock farming are entirely connected (as mentioned in Section 3.3.2.1 and Figure 3.6) and mostly dependent on the water available in the reservoir. Consequently, little disturbance can be withstood by the system, even less when it is at its most rigid conservation phase (Figure 3.8d). The L is thus relatively low and the Basin of attraction to this stable state is narrow. Similarly, the R is moderate, represented by a shallow basin of attraction. The price of milk and meat is stable and satisfying for a regular income. The incentives to practice livestock farming are strong in terms of encouraged activity by the municipality's agricultural centre and due to the agricultural knowledge of the community. However, once loans have been solicited for irrigation installation, additional credit lines are non-existent. At the peak of the K phase, all farm holdings are oriented towards intensive livestock farming thus the precariousness is null. The ball is close to the attractor. Pa affects, mostly through the revolt connections the three other La, R and Pr parameters. The multi-annual drought coupled with the decisions of farmers to irrigate at full livestock capacity affects L which decreases – the basin shrinks. The inflation of forage prices affects R – the basin flattens. Farmers start losing income and cattle, the precariousness increases and the ball starts rolling closer to the edge of the basin. This is the release phase (Figure 3.8e). As more farm holdings lose more of their cattle, the precariousness increases until the livelihood system cannot be maintained on intensive livestock farming. The system shifts to another stability domain, with a different attractor, in a rapid reorganisation phase (Figure 3.8f). In 2019, the livelihood system in the community of Riacho da Cruz shifted its orientation to extensive livestock farming and the sale and buying of animals (r phase, Figure 3.8g).

3.4 Discussion

The results presented in this study are based on the case of the drought-affected rural community of Riacho da Cruz, located in the semi-arid drought-prone Northeast of Brazil, which was thoroughly detailed and linked to theories of Social-Ecological Systems (SES). Results of similar but less detailed drought diagnoses in the same area are of a similar nature as those for the community of Riacho da Cruz. The results of this study are therefore likely relevant to other cases of drought-affected rural communities as well.

Knowledge from the field of SES may be useful in identifying linkages between drought-related disturbances and impacts when they occur at different time-, space- and decision-scales and -levels. The applicability of concepts of adaptive cycles, panarchial revolt and remember connections, and basins of attraction for the community of Riacho da Cruz, suggests these are useful approaches for drought-impact studies in general. These approaches together provide a generic analytical framework comprising three elements: i) the degree of connectedness between the intrinsic elements of the system; ii) the type of scales and levels; and iii) the parameters composing the resilience of the system being impacted by disturbances. These elements vary for different communities or basins and should be analysed using relevant corresponding data for those cases.

Our data were collected through surveys and grounded-theory methods to ensure that the SES concepts used to address drought and drought impacts spatial-temporal complexities are adapted to the observed experiences of drought-affected populations and of drought managers. This also ensures that the outcomes of the application of such SES-based frameworks are local and contextual. More specifically, applying this framework can provide a basis for the development of drought-impacts indices. The contraction or expansion of the basin of attraction and the trajectory of the system from one basin to another, determined by the parameters L, R, Pr and Pa (Section 3.3.2.3 and Figure 3.8), are impacts of the disturbances on the considered system. In the case of the community of Riacho da Cruz, this corresponds to the impacts of drought-related disturbances on the livelihood system. The four resilience parameters (L, R, Pr and Pa) are categories of dynamic and interlinked variables, determining whether the considered system is stable or progressing towards a collapse. Our SES-based drought-diagnosis approach and results are coherent with recommendations of other drought studies as well. It has been proposed that impacts should also be accounted for when defining a drought, considering that a system impacted by drought was already vulnerable to it (Blauhut et al., 2015, 2016). Similarly, in tackling drought, it may be beneficial to begin by analysing drought impacts instead of focusing on drivers (Walker et al., 2022). Rather than focusing on water volumes, the human welfare components affected by drought (e.g. food-, water-, and livelihood-securities), should also be accounted for in determining the severity of drought and considered in the elaboration of drought indices (Chapter 2).

Limitations of our study include several potential sources of bias that relate to interviews conducted, which focused on past drought events and their impacts. Firstly, interviewees can have a skewed perception of the past, where they may overestimate the frequency or intensity of positive experiences and underestimate negative experiences (positive memory bias, (Adler and Pansky, 2020). Secondly, interviewees' memories of past events may be affected by their current circumstances, emotions, or other factors (memory bias; Grant et al., 2020). Thirdly, interviewees may be self-selected and may not be representative of the entire population affected by or knowledgeable about drought (selection bias; Catalogue of Bias Collaboration, 2017). Fourthly, interviewees may be inclined to give socially desirable responses, particularly if the interviewer is perceived as having power or authority (social desirability bias, (Bergen and Labonté, 2020). Finally, interviewers may unconsciously influence interviewees' responses or interpretation of the data (observer bias; Mahtani et al., 2018). To minimise these biases, a broader variety of methods to gather data could have been used, in addition to interviews and a grounded-theory approach. These methods could include collective interviews and secondary sources, serious gaming (Madani et al., 2017) or participatory GIS (Cinderby et al., 2011). Further research accounting for these biases could benefit from robust sampling techniques and interview protocols to ensure that data is collected in a consistent and unbiased manner.

Data availability is critical for the extent to which relevant processes can be observed and patterns of livelihood strategies can be conceptualised. The availability of mostly qualitative and quantitative data was limited for our study area. Here, conducting a focused drought diagnosis was thus particularly necessary to collect and analyse information about the history of drought impacts, drought risks and drought-severity aggravating factors. Our results could be strengthened with insights from more detailed information on agricultural production at the scale of the community, yearly or seasonally, which would allow the quantification of the potential of the livelihood system and its fluctuation when adapting or collapsing. What is more, such fluctuations could have been quantified economically, hydrologically, or in terms of quality of life of the rural population, allowing a better grasp of drought impacts. However, such quantitative data remain non-existent and the municipal agricultural data provided by the IBGE can only inform us about general trends rather than detailed quantification of production. Further research in this direction, combining a SES framework and detailed quantitative data (water balance, economic trends, and human well-being) could contribute to the provision of local contextual numerical drought impacts indices. Alternatively, the framework characterising the four resilience components (L, R, Pr and Pa) to drought impacts on the considered system in Table 3.3 can serve as a basis for co-created drought impact indices. The variables corresponding to these four parameters were deduced as a result of our drought diagnosis (Table 3.4). Co-determination, together with drought-affected populations, of the variables composing these four categories is another potential step towards the development of more accurate drought impact indices.

Our SES-based drought-diagnosis approach could also benefit Drought Early Warning Systems (DEWSs). DEWSs aim to monitor and tackle drought at early stages to reduce possibilities of harm or loss. However, most configurations of DEWSs do not take into account drought impact indices or social drivers of droughts. They mainly deduce the likelihood of experiencing impacts from the severity of hydroclimatic features (Chapter 2). Indices based on resilience parameters (L, R, Pr, Pa) do not make a distinction between physical and social drivers of drought. Instead, they reflect variables that are important for maintaining a livelihood, or any other component of human welfare; the absence of which leads to further impacts that lower the livelihood resilience to droughts. Such indices complement previous and current efforts of including vulnerability components to assess drought risk, under the condition of being always adapted to the specific context in which drought risk is assessed (Meza et al., 2019). What's more, the drought diagnosis highlighted how the human influences on drought and drought impacts are dynamic: not only do these influences vary over space, time, and decision levels, but they also interact with each other and are intertwined with the physical components of droughts. Ultimately, these always-evolving human influences steer the considered system, which is the livelihood system in our case, toward new conditions or new "states" of the system.

Additional practical implications in line with our results can be developing interventions and policies that are system-oriented, adaptable, contextually appropriate, and geared toward long-term resilience. Indeed, drought management in Northeast Brazil has historically adhered to a fight-against-drought paradigm (Cavalcante et al., 2022). While this approach has been overly focused on the physical aspect of drought, with efforts to amplify hydraulic structures, it ultimately proved to be maladaptive in some contexts, as evidenced by the case of the community of Riacho da Cruz. Our findings underscore the necessity of accounting for the ever-changing human influences on drought and its impacts, which are specific to the considered context, and determine the occurrence and severity of drought impacts in the long run. Applied to our case study, such dynamic human-induced factors include the lack of diversity of economic and productive activities, largely incentivised by municipality-level policies or the lack thereof, and the volatility of agricultural input prices on a drought-shocked market. Decision-makers can benefit from our perspective by meaningfully reflecting on what drove the past strategies that communities chose or had to implement to secure their livelihood under drought and other disturbances. This emphasizes the value of learning from past experiences to inform future policies and interventions.

This study adds an application for a drought-affected rural community in the Northeast of Brazil to the SES literature. Studies of SES involving water resources have been largely focused on lake and coastal dynamics, fisheries, and agriculture (Partelow, 2018). The novelty of our study lies in its exploration of in-depth concepts of SES specifically in the context of drought, which has not been previously addressed in existing literature. Additionally, studies that simultaneously explore drought and SES only tend to focus on the general definition of SES as a system with strong interlinkages between social and ecological components. Thus, the findings of this study can also be used to better interpret findings from other local communities in contexts of droughts and water scarcity. We analysed primary qualitative data to understand the evolution of the orientation of the livelihood system on a twenty-year timespan. This matches the recommendations of future research by Partelow (2018) of integrating new data for analysis and looking at temporal changes within cases, which is currently missing in the SES literature.

3.5 Conclusions

We conducted a drought diagnosis for the rural municipality of Riacho da Cruz in semi-arid Ceará, Northeast Brazil, linking hydroclimatic time series and data from 40+ interviews. We applied grounded theory to understand and conceptualise how drought impacts are shaped by processes at different temporal, spatial, and decisional scales. Social-Ecological Systems (SES) theory was found to well-explain the human influence on drought impacts, beyond only the physical aspects. Applying the concept of adaptive cycles was useful to understand and represent how the livelihood system of the community becomes less pliant to drought-related disturbances and opportune to collapse. Applying the panarchy concept was helpful to understand how events occurring at different scales and levels shape the drought impacts on the livelihood of the community of Riacho da Cruz. Applying the SES resilience concept enabled the identification of the variables determining whether the livelihood system adapts, collapses, and shifts towards a new configuration.

This study is one of the very few that explores SES concepts of the adaptive cycle, panarchy, resilience, and basin of attraction in-depth to drought-affected communities and their livelihoods. In addition to enriching the SES literature and its applicability for drought-impacted communities, the theoretical implications of this study include: (i) providing empirical evidence and insights into the adaptive cycles of the livelihood of drought-impacted communities, and how communities navigate and respond to drought-related disturbances; (ii) showcasing how interactions and feedback between local and regional levels influence the resilience, adaptation, and transformation of these communities; and (iii) highlighting the conditions that may lead to either sustainable adaptation or undesirable shifts of the communities. Our results can contribute to the understanding of community resilience in the face of drought by identifying the factors that enhance or undermine this resilience, including adaptive capacities, governance systems, and resource availability.

The practical implications of our study build on these theoretical implications. Identifying the factors underlying the resilience of drought-affected communities to drought impacts can help policy-makers develop interventions that are better informed, contextually appropriate, and oriented toward long-term resilience. These factors can be identified through the proposed conceptual framework of parameters of resilience to drought impacts.

Such a framework can be a basis for the development of local and contextual drought-impact indices and thus support the further development of Drought Early Warning Systems to increase their societal relevance and equip them to monitor drought severity more appropriately.

04

Bridging Monitoring and Realities

Abstract. Despite recent studies emphasising the dual human and physical nature of droughts, there is a lag in advancing this insight in drought monitoring and early warning systems (DEWS). These systems mainly depend on physical indices and often overlook the experiences of affected communities, resulting in a drought-monitoring gap. This study introduces the Monitoring Efficacy Matrix (MEM) to assess the alignment between officially monitored data, relevant to drought impacts, and the actual experiences of a rural community in Northeast Brazil, which we investigated through interviews. The MEM revealed 'drought-monitoring challenges', composed of mismatches and blindspots between the official data and local experiences. Mismatches stem from varying spatial and temporal levels; blindspots arise from the diversity of local resilience strategies, or vulnerabilities, influencing drought impacts. What we define as a 'drought-monitoring gap' results from the tendency to prioritise specific indices and pragmatic spatial and temporal levels over a comprehensive drought-monitoring approach. We posit that a first step to bridge this gap can draw inspiration from recent drought-impact-monitoring initiatives, which are focused on the continuous monitoring of non-extreme events by municipal technical extension officers. However, ultimately bridging the drought-monitoring gap remains conditional on the adaptation of DEWSs frameworks to accommodate the integration of qualitative and local data representing the relevant drought-related local context.

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4.1 Introduction

More and more studies highlight the human influence on droughts, demonstrating that drought results from both natural and anthropogenic drivers (Aghakouchak et al., 2021; Van Loon et al., 2016a; Walker et al., 2022; Di Baldassarre et al., 2019) and affects both the hydrological cycle and human populations (Savelli et al., 2021; Ribeiro Neto et al., 2022; Chapter 3). Despite this acknowledgement in the literature, there has been limited advancement in incorporating this knowledge in drought monitoring and early warning systems (DEWSs). DEWSs still predominantly depend on physical indices, overlooking equally-important human drivers, and not comprehensively accounting for the experiences of drought-affected populations (Bachmair et al., 2016; UNDRR, 2021; Chapter 2). Monitoring drought impacts is challenging because they are non-structural, difficult to quantify or monetise, and can be direct or indirect (Bachmair et al., 2016; Logar and Van Den Bergh, 2013; Chapter 3; Wilhite et al., 2007). Although there are encouraging drought-impact-monitoring initiatives (EM-DAT; EDII, 2023; Smith et al., in press), these have largely served only to increase the understanding of drought (Lackstrom et al., 2022; Stephan et al., 2021; Tijdeman et al., 2022).

The lack of accounting for the human drivers of droughts and drought impacts in DEWSs results in what we call a drought-monitoring gap: a gap between drought-relevant data that is monitored and the drought conditions experienced by human populations. While DEWSs aim to facilitate proactive, well-informed decision-making and empower vulnerable groups with timely, reliable data and indicators (Pulwarty and Verdin, 2013; UNDRR, 2021), they are currently not fully meeting this objective. This can, in turn, complicate the ability of drought managers to make well-informed decisions and take appropriate action if the effects of the anomaly in the hydrological cycle, as indicated by drought indices, are unknown outside the affected area and by the affected populations.

Therefore, there is a necessity to address the drought-monitoring gap from both ends: the relevance of monitoring human drivers of drought, and of the drought impacts as experienced by populations. Firstly, monitoring human drivers of drought is important because human actions can significantly influence exposure and vulnerability to drought, impacting both its severity and the effectiveness of mitigation efforts (Van Loon et al., 2016b; Meza et al., 2020; Carrão et al., 2016; Aghakouchak et al., 2021; Haile et al., 2020). Walker et al. (2022) detail numerous examples of water and drought mismanagement that led to inadequately addressing or even aggravating drought impacts. This mismanagement generally resulted from a narrow understanding of the drought threat limited to hydrometeorology. Guidance literature from the Integrated Drought Management Program (IDMP) and others has for many years urged a shift from crisis management to risk management, from costly, ineffective, poorly coordinated, poorly targeted reactive “solutions” to investment in building resilience by addressing the root causes of vulnerability to drought impacts (e.g. IDMP, 2014, 2017; Wilhite, 2000). Secondly, it is important to consider drought impacts and their integration in early-warning or monitoring systems because impact data improves understanding of vulnerabilities, aids in developing mitigation strategies, supports targeted relief allocation, informs policy, and reflects actual conditions better than hydrometeorological data alone (Walker et al., 2024). This enhanced understanding is crucial for accurate decision-making and resource management in diverse local systems and sectors affected by drought (Hayes et al., 2011; Lackstrom et al., 2013; Wilhite et al., 2007). These reasons have led to drought impact monitoring being referred to as the "missing piece" in drought monitoring and forecasting (Lackstrom et al., 2013; Walker et al., 2024).

In this study, we seek to answer the following question: how can we bridge the existing drought-monitoring gap between the available drought-relevant data that are formally monitored and actual drought impacts, as experienced and reported by local populations? We address this question by focusing on the case study of a rural community in semi-arid, drought-prone Northeast Brazil. Our study aims to compare the drought impacts experienced over time by this rural community with the drought-relevant data formally monitored, covering that same area and also available at different spatial and temporal levels. This comparison was made using our newly developed Monitoring Efficacy Matrix (MEM), a conceptual tool designed to evaluate the efficacy of drought indices in tracking drought impacts. The MEM allowed us to identify instances where the two datasets – rural experiences and official data – did not align. We termed these instances 'drought-monitoring challenges'. By examining these drought monitoring challenges and understanding the reasons underlying the drought-monitoring gap, we reflect on whether drought-impact indices –local, contextual, yet replicable and useful for drought (impact) monitoring – are a realistic goal.

4.2 Data and Methods

4.2.1 Methodological approach and framework

Our methodological approach comprised three steps.

- *Step 1:* We explored the drought conditions and impacts experienced over time by the rural population. We focused on the community of Olho d'Água located within the municipality of Piquet Carneiro (Figure 4.1). For this purpose, we conducted interviews; this approach is detailed further in Section 4.2.2.
- *Step 2:* We examined the conventional drought indices and officially monitored data relevant to drought impacts that could characterise drought conditions in the area of focus. "Conventional indices" refer to the commonly used indices to quantify and characterise drought conditions. To achieve this, we chose to examine time series characterising rainfall and meteorological drought (SPIs, Brazilian Drought Monitor Map), agriculture (cropped and harvested areas, crop yields, agricultural output), and

hydrology (reservoir volumes and water surface area). These drought indices and official data are among the most used and agreed-upon to monitor and characterise drought severity (Bachmair et al., 2016; Chapter 2), and also fit the impacts on livelihood, food, and water securities we aimed to explore. These datasets have specific spatial and temporal levels of monitoring, which are not necessarily homogenous across the different datasets, nor with the levels at which impacts are experienced by populations. Specific information about the data series and data collection is provided in Section 4.2.3.

- *Step 3:* We compared the findings of Steps 1 and 2 using a newly developed Monitoring Efficacy Matrix (MEM). The MEM is a conceptual framework that aids in identifying monitoring challenges, which include mismatches and blindspots. This framework was designed to examine the alignment of a drought index with reported impacts. The application of the MEM allowed for the evaluation of the alignment between experiences of drought impacts by the population at the community level, and the conventional indices which are also available for different spatial and temporal levels. The specifics of the MEM, along with the definitions of monitoring challenges are elaborated on in Section 4.2.4.

4.2.2 Case study and data collection

The study focuses on the Olho d'Água community in Piquet Carneiro, situated in the Banabuiú river basin of the state of Ceará (Figure 4.1). This rural community comprises fifteen households, with members working either within the agricultural sector or in other sectors, such as public service. At the time of the interviews (from November 2021 to June 2022), productive activities relied on the water from a relatively small reservoir, officially unmonitored, with a maximum water-surface area reaching 14 hectares. The Brazilian state of Ceará, located in the semi-arid region known as Sertão, has faced consistent drought challenges (UNDRR, 2021). The latest multiannual drought (2012 – 2019), noted for its intensity, deeply affected the region's agriculture. Most impacted were smallholder farmers reliant on rainfed agriculture, who experienced significant crop losses and economic setbacks (Brito et al., 2018; Pontes Filho et al., 2020) as well as compromised water availability and quality (Eakin et al., 2014). The region's annual rainfall averaging 750 mm, predominantly occurring from January to April and its annual evapotranspiration exceeding 2000 mm, hinder surface water storage (Martins and Reis Junior, 2021). In response to these challenges, the government invested heavily in water infrastructure during the 1990s and 2000s (Cavalcante et al., 2022). Additionally, private unmonitored small reservoirs became widespread, sometimes limiting the recharge of larger strategic reservoirs, especially during the severe 2012-2019 drought (Ribeiro Neto et al., 2022). The distinction between what are colloquially labelled as monitored and unmonitored, non-strategic and strategic reservoirs is crucial for understanding the local context and the monitoring challenges involved. Strategic reservoirs comprise large public infrastructure projects, promoted and continually monitored by state water agencies. They are mostly “strategic” at the state level because these large reservoirs in priority serve the population in urban areas while not reaching rural communities. Therefore, smaller reservoirs (under 1 million cubic meters, Rabelo et al., 2022) are typically constructed by rural populations to ensure their water access. These are, in contrast to the first type, non-strategic, as they are not specifically positioned on the reservoir grid planned by state water agencies. However, they informally remain strategic at the local level since most of the productive activities of rural communities depend on water from these small reservoirs. Since they are locally built, they are also locally managed, thus eluding the control, maintenance, and monitoring of official agencies. In the municipality of Piquet Carneiro, the ‘São José II dam’ is the only formal strategic reservoir (Figure 3.1).

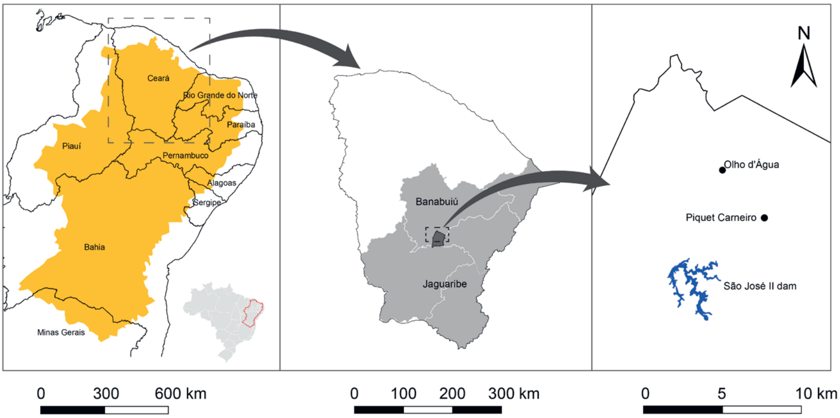

Figure 4.1: Map of the case study showing: the semi-arid Northeast of Brazil (left); the state of Ceará, the Banabuiú sub-basin as part of the Jaguaribe River Basin, and the municipality of Piquet Carneiro in dark grey (centre); the city of Piquet Carneiro, the community of Olho d’Água, and the São José II dam in dark blue (right).

In Piquet Carneiro, fifteen interviews were conducted: eleven with members of the Olho d’Água community and four with practitioners (Table 4.1). The interviewees and study site were selected through a snowball sampling method, where initial participants recommended other potential interviewees (Parker et al., 2019). After these interviews, no new information emerged, indicating information saturation. These fifteen interviews were part of a more elaborate fieldwork campaign, from November 2021 to June 2022, comprising 41 interviews with farmers and individuals from water and agricultural organizations and covering 12 rural communities in the Jaguaribe River basin (Figure 4.1).

All the interviewees provided consent before being interviewed. The interviews were not recorded but were written up immediately afterwards so that the interviewees, who were in majority smallholders, would feel more at ease. Of the solicited actors, none refused to be interviewed. Questions were formulated to encourage the participants to describe what they considered to be the drought risks, impacts, and factors increasing or decreasing the likelihood of impactful drought over time in the study area. Table 3.2 shows how the interviews were conducted.

Table 4.1: Interviews Summary

Actor	Organisation	Interview type	Query category	Time period referred to
• Practitioners • Rural extension technicians	Agricultural secretaries of Piquet Carneiro	Semi-structured	Vulnerable groups Water access Agricultural practices Markets existence and prices Drought impacts Social and agricultural programs and policies	1970s-2022
• Local government	Municipality of Piquet Carneiro	Semi-structured	Vulnerable groups Drought impacts Hydraulic infrastructure Drought emergency state	1970s-2022
• Farmers and rural inhabitants	Not applicable	Unstructured and semi-structured interviews	Daily life and family Agricultural and livelihood strategies Droughts in the distant and recent past	1956-2022

4.2.3 Drought-relevant data

We extracted data from different international and Brazilian databases (Table 4.2). These data provide information on climatology, reservoir storage, and agricultural production. We used the rainfall data to calculate different SPIs, with each indicating a different purpose: SPI-3 indicates short-term soil moisture, relevant for crops; SPI-6 provides a mid-term view, affecting agriculture and early signs of water storage changes; SPI-12 monitors long-term trends in water storage and streamflow (WMO, 2012).

Since 2016, the Brazilian Drought Monitor has produced a monthly map of drought conditions, based on SPI, SPEI, Standardized Runoff and Dry Spell Indicators, and remote-sensing indices, validated by regional offices that consider ground observations from networks of observers (De Nys et al., 2016). The Drought Monitor categorises conditions starting from 'no drought' to 'weak drought', which indicates the beginning or end of dry conditions. Categories of 'moderate', 'severe', 'extreme', and culminating in 'exceptional drought', indicate widespread losses in crops and pastures and water shortage at an emergency level. We retrieved data relevant to large and strategic, and small and non-strategic reservoirs. Finally, we obtained agricultural data encompassing the relevant crops in the community of Olho d'Água.

All the utilised datasets, with access links, are available for consultation (Kchouk et al., 2023).

Table 4.2: Step 2 data – conventional drought indices

Data source	Information extracted	Time Range
CHIRPS	Rainfall time series	1980-2023
Meteorology and Water Management Institute of the State of Ceará (Funceme)	Small reservoir locations and surface area	2004-2022
National Company of Water Resources (Cogerh) and Funceme	Sao José II Reservoir volumes	2004-2022
National Water and Sanitation Agency (ANA) and Funceme	Brazilian Drought Monitor	2014-2022
Brazilian Institute of Geography and Statistics (IBGE)	Total agricultural production per municipality Quantity Produced Crop yield per hectare Livestock population Milk and honey production	1977-2022

4.2.4 Monitoring efficacy matrix and drought-monitoring challenges

Monitoring efficacy refers to the effectiveness with which a monitoring system detects, tracks, and reports on specific parameters or events it is designed to make visible. It encompasses the accuracy, reliability, timeliness, and comprehensiveness of the monitoring system in providing relevant and actionable information to stakeholders. This can all be applied to drought, drought monitoring systems, and the metrics they rely on, which are the drought indices. Drought-monitoring efficacy then refers to the effectiveness of a drought-monitoring system to detect, track, and report drought conditions, comprised by drought severity and impacts. Such systems or indices can sometimes fail to accurately, reliably, timely, and/or comprehensively capture drought conditions in different ways: this is what we call the drought monitoring challenges. We posit that a drought-monitoring efficacy matrix can help to detect, identify and describe what these drought-monitoring challenges are.

The Monitoring Efficacy Matrix (MEM) is a conceptual tool designed to evaluate the efficacy of conventional drought indices in tracking various types of drought impacts. It features columns representing conventional drought indices, which are the standardised methods or metrics used to measure and characterise droughts and their conditions. The rows of the MEM classify different drought impacts, organised within and across various distinct levels that subsequently influence the selected impacts (Table 4.3). By juxtaposing drought indices with these impacts, the MEM provides a comprehensive perspective on how effectively these indices capture the multifaceted impacts of droughts.

Table 4.3: Example of an empty monitoring efficacy matrix

Scale: *e.g. Jurisdictional*	Drought indices	Index 1 e.g. *SPI*	Index 2 e.g. *Reservoir Volume*	...	Index n
Level:	Drought impact on e.g.				
Small *e.g. Household*	*Livelihood*				
	Food security				
	Water security				
Middle *e.g. Community*	*Livelihood*				
	Food security				
	Water security				
Large *e.g. Municipality*	*Livelihood*				
	Food security				
	Water security				

Scale refers to the dimensions used to measure and study phenomena, whether they are spatial, temporal, or analytical. Within these scales, levels represent specific units of analysis (Gibson et al., 2000). Spatial levels can for example range from the plot to the basin and time levels can range from seconds to decades; it all depends on the studied phenomena. For example, on a spatial scale, events can range from cellular processes to global climate changes, while on a temporal scale, they can cover rapid events like hurricanes and long-term societal shifts (Cash et al., 2006). Drought and its impacts cover several levels, both at spatial and temporal scales (Chapter 3). Furthermore, it is not only the physical aspect of drought that determines the severity of droughts. Anthropogenic factors, even if indirectly related to drought, can amplify the impacts. For instance, the likelihood of drought affecting the livelihood, water, or food systems also depends on how diversified the considered system is. The more the considered system is reliant on one source, the more likely it is to be impacted by drought and collapse; the more diversified it is, the more resilient to drought impacts, and the less likely it is to face severe impacts (Chapter 3). Thus, adequate drought monitoring should be comprehensive of all the levels within the spatial and temporal scales where the system might be impacted, and also of all the elements within the system that determine its resilience to drought impacts.

Monitoring challenges arise when the drought indices do not comprehensively and accurately capture the impact at the selected level of analysis. Such monitoring challenges fall into two types: mismatches and blindspots. A mismatch occurs when the level at which monitoring takes place (be it the level defined by official data or of a drought index) does not align with the spatial or temporal reach of the impact aimed to be monitored. Blindspots result from not monitoring all the elements that contribute to the resilience or vulnerability of the considered system to drought impacts.

When filling in our MEMs, mismatches and blindspots emerged when real-world experienced impacts were compared with the official data. In our case, these monitoring challenges appeared when we could not find impacts mentioned by the population of Olho d’Água in the official monitoring data. In our study, mismatches and blindspots occur in the following instances:

(i) Mismatches occur when impacts, or signals of these impacts, mentioned by the rural populations cannot be found in the official data because the official data level is too broad or too narrow, either in space or time, to capture the extent of the experienced impact. For example, a spatial-scale mismatch might arise if official livestock data are available at municipality level, counting tens of thousands of cows, while in reality, each household within a specific community only owns about five cows. Such data, because of its broad scale, might not accurately depict the experiences of every community within the municipality. A temporal-scale mismatch might emerge for example if a drought indicator's timeframe is too extended to capture shorter, yet impactful, events within its range. An example is the SPI-1, the shortest SPI, which sometimes overlooks impactful flash droughts; because it is based on monthly data, it cannot detect dry spells shorter than a month (Walker et al., 2023).

(ii) Blindspots occur when the official data only capture the range of elements composing the considered system in an incomplete or limited manner. This could either lead to an underestimation or overestimation of vulnerability. For example, a blindspot can occur when small reservoirs, pivotal in many communities' water systems, have only their count monitored and not their volumes. Overlooking volumes might lead to overestimating the physical water availability and therefore, underestimating the vulnerability to drought impacts. Another example can be when the livelihood system of a community relies on the sale of very specific cash crops while agricultural monitoring focuses on subsistence crops. Such crucial elements can be overlooked by official data because the monitoring level is too broad to accurately capture them, as these elements are too specific to a limited area or a limited period of time; in other words, blindspots can sometimes be caused by mismatches.

Confronting conventional drought indices with the impacts experienced by rural populations provides insights into what is needed for local and context-specific drought impact indices. Identifying mismatches and blindspots allows us to identify the missing information essential for a comprehensive understanding of drought impacts tailored to particular systems, levels, and local contexts. While our exploration is specific to our case study area (Section 4.2.2), this study serves as a foundation for assessing the effectiveness of broader-scale monitoring. This study inherently poses the questions of up to what level can we effectively monitor drought and its impacts and if drought impacts indices that are generic and replicable, yet specific to the area, are possible to develop.

4.3 Results

4.3.1 Drought impacts experienced by rural populations of Olho d'Água, Piquet Carneiro

This section offers a summary of the trajectory of the Olho d'Água community to aid understanding of Section 4.3.3 in which we develop the MEMs. Detailed narratives are in the supplementary material (Kchouk et al., 2023).

The earliest recollection of droughts we gathered in Olho d'Água community starts in 1958. Until 2003, the livelihood, water and food systems were highly dependent on rainfall (Table 4.4). Household food consisted of subsistence rainfed maize and beans and milk from two cows maximum per household. The rare surplus would be sold for cash. Some households in the community also had small patches of cotton for selling.

The drinking-water system was reliant on a shallow well for the whole community. Until 2003, droughts severely impacted the water, food, and livelihood securities, also aggravated by a lack of alternatives and governmental interventions. Notably, the droughts of 1958 and 1970 led to food and income insecurities, made worse by rising staple prices and depleted community finances.

The government's "Workfronts" initiative (Costa, 1974; Rocha, 2001) during this period offered employment but inconsistent payments. Later droughts, spanning 1983 to 2003, affected household and community water security, with the only community well drying up. The community also suffered food insecurity from crop failure and livestock deaths

However, from 2003, there was a significant shift in the community's experience of drought impacts due to improved water management and governmental policies. Agriculture diversified from traditional livestock and subsistence crops to beekeeping, fruit production and their onsite processing (Table 4). These three activities have become the main source of agricultural income in the community. Several government programs, like a local beekeeping educational project introduced in 2007 through the Sustainable Development Program for Rural Territories (Programa de Desenvolvimento Sustentável de Territórios Rurais- PRONAT), the Food Acquisition Program (Programa de Aquisição de Alimentos-PAA) and the National School Feeding Program (Programa Nacional de Alimentação Escolar - PNAE), both introduced around 2003, greatly assisted this diversification, enabling greater resilience against drought impacts. These programs supported local agricultural initiatives, encouraging crop and income diversification, and facilitated income stability during the 2012-2019 drought. In addition, more community members sought employment outside of the agricultural sector. The diversification of the agricultural system was also made possible through the community's small reservoir (constructed between 2003 and 2012, though the exact year is not recalled by anyone) and the introduction of cisterns, with each household benefiting from two. Cisterns allow the harvesting of rainwater but can also be filled by water trucks, subsidised by the national government, during periods officially declared as 'emergency situations'. In 2005, households in the community received their first cistern, installed as part of a national government program to provide drinking water security. In 2007, a second, larger cistern was provided to each household, enabling them to use water also for irrigation. Farmers also dug shallow wells in their plots for irrigation.

Table 4.4: Overview of the main elements composing the livelihood, food, and water systems in the community of Olho d'Água over time

Period	Pre-2003	2003-2012	2012-2019
System			
Livelihood System	• Rainfed subsistence crops: pastures for livestock, small areas of cotton (max. 1 ha per household). Surplus of beans and maize was sold.	• Honey production • Irrigated and diverse onsite food production (sold at the local market, door-to-door, through the governmental program) • Food processing (sold at the local market, door-to-door, through the governmental program)	• Food processing (from food bought elsewhere) – sold at the local Piquet Carneiro Market and through governmental programs • Honey production • Cash transfers programs
Food System	• Rainfed subsistence crops (beans and maize) • Milk from livestock (2 cows max. per household)	• Buying from supermarkets • Food produced onsite • Milk from livestock (max. 5 cows per household)	• Buying from supermarkets • Food produced onsite • Milk from livestock (max. 5 cows per household)
Water System	• One community shallow well (for drinking)	The community shallow well was replaced by: • Individual shallow and deep wells (for irrigation) • Cisterns (2 per household, for drinking and irrigation) • Community's small unmonitored reservoir (for irrigation)	• Cisterns (only for drinking – no more irrigation) • Water trucks (only for drinking) • Wells and small reservoirs dried up

.

During the 2012-2019 drought, the community's diversified income sources and proactive interventions, in addition to governmental measures, buffered impacts on the livelihood, food and water systems, avoiding their collapse like in the pre-2003 period. Cattle were still affected, crop yields declined, and all water sources dried up. Livelihoods were maintained from food processing, with food not necessarily produced onsite but bought elsewhere, and with the sale assured through the PAA and PNAE. Honey production, albeit affected, was maintained. Livelihood was also maintained by income from other jobs, receiving crop insurance (Garantia Safra; Kühne, 2020), and benefiting from a cash transfer programme (Bolsa Família; Soares et al., 2010). As their livelihood was stable, people could afford to buy food. The local water sources dried up but water trucks were deployed, even though quantities were below what was needed (Table 4.4). By 2020, the community experienced a recovery in agricultural production due to the replenishment of their reservoir during the rainy season. This recovery triggered farmers to invest in innovative farming techniques, such as hydroponic systems and greenhouses.

A notable challenge to the livelihood system, not related to drought, is the ageing population of Piquet Carneiro and their purchasing power. Specifically, retirees, who predominantly purchase farmers' products in local markets, determine the sales pattern. Sales tend to fluctuate, largely because the majority of buyers are retirees, whose purchasing power depends on the timing of their pension payments. Sales generally dip towards the end of the month, coinciding with the period just before pensions are paid. The availability of cash in banks also significantly influences the purchase of farm products. Piquet Carneiro's banks frequently experience cash shortages as retirees withdraw their full pensions concurrently. Some buyers resort to travelling to other cities to withdraw their pensions, capitalising on this trip to buy products from the local markets. The farmers interviewed noted that while some other farmers prefer to sell in these other cities, they choose to remain in Piquet Carneiro. Failing to make sales in Piquet Carneiro, they don't incur any financial setbacks. However, travelling to another location brings the risk of being at a loss, by incurring fuel expenses without any return if no sales are made.

4.3.2 Conventional, global and official drought data

We gathered data related to the physical drivers of drought, as well as the most common direct impacts on reservoir storage, and agricultural production, from various sources for Northeast Brazil (Table 4.2).

Our figures representing agricultural data focus on the most produced crops (Figure 4.2a), those covering the largest harvested areas, and those yielding the most (Figure 4.2b). For most crops shown, the areas harvested and cropped are identical. Therefore, we have combined both types of areas into a single axis in Figure 4.2b and c. Comprehensive graphs, encompassing all crops cultivated within the municipality, can be found in the supplementary material. We also highlight agricultural products that are significant in the farmers' experiences (mentioned in Table 4.4), such as bananas (Figure 4.2c), livestock, honey and milk production (Figure 4.2d). Bananas serve as cash crops, and their sale contributes to income. On the other hand, staple crops like beans and maize are primarily produced for family consumption, with any surplus being sold. Some crops which appear to be pivotal for contextualising the farmers' narratives are not available in the official agricultural data, perhaps due to their limited scale (e.g. cassava, soursop and guava). The absence of such local key crops is addressed in the subsequent section to highlight a blindspot.

The lower part of Figure 4.2 depicts the timeseries of SPIs 3, 6, and 12, highlighting periods with below-average rainfall that might result in droughts. Additionally, starting from 2014–the year the Brazilian Drought Monitor started monthly reporting of drought severity–these figures also show the portion of the municipality impacted by each drought severity level. Figure 4.3 displays the change in the number of reservoirs larger than 0.5 hectares for the period 2008-2020. Only their counts and locations, through detecting their water surface, are officially monitored and not their volumes.

The quality of the datasets varied depending on their sources (see Table 4.1 in the Methods Section). Our primary intention was to visually represent and juxtapose the data with the experiences of the community of Olho d'Água. Our aim is not to evaluate the data quality or identify correlations among meteorological, agricultural, and hydrological data. However, certain discrepancies and contradictions are evident. For instance, the cotton area declines without any apparent replacement (Figure 4.2b), which is also later addressed to highlight monitoring challenges.

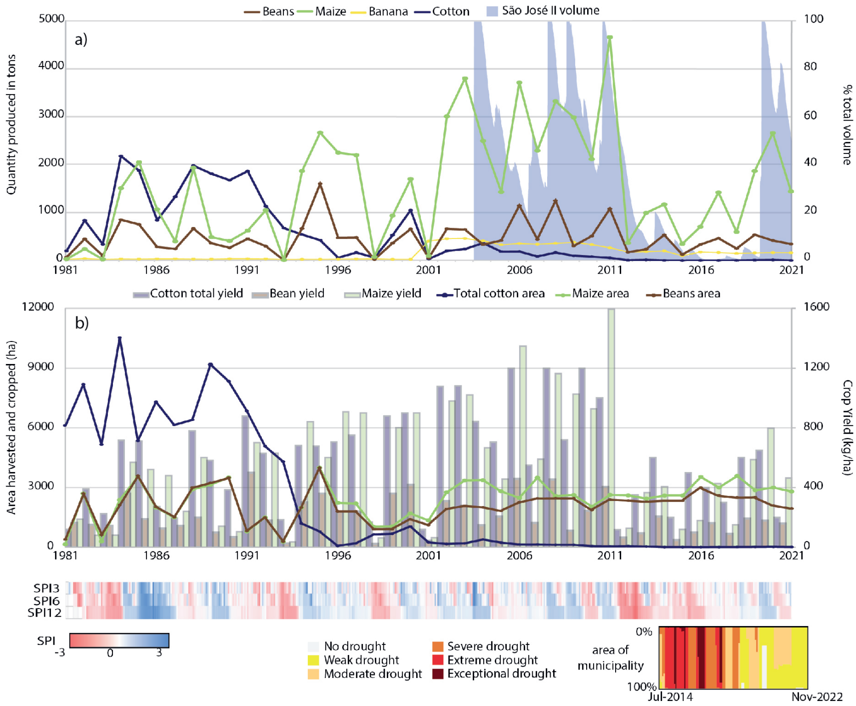

Figure 4.2: (a) Annual crop quantity produced in tons in the municipality of Piquet Carneiro from 1974 to 2019 (lines). Daily evolution of the percentage of total volume of the Sao José II dam, which is the only monitored dam in the municipality of Piquet Carneiro (blue shaded area); (b) Annual equal cropped and harvested area in Piquet Carneiro from 1981 to 2021 (lines). The columns represent the annual crop yield per hectare (Source: IBGE, PAM)

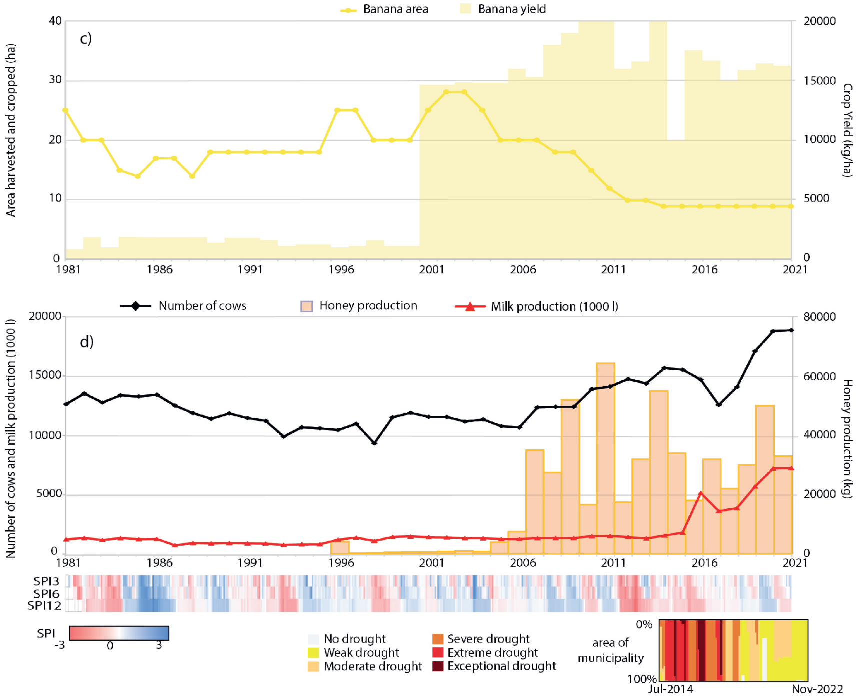

Figure 4.2 (continuation): (c) Annual equal cropped and harvested area of banana in Piquet Carneiro from 1981 to 2021 (lines). The columns represent the annual crop yield per hectare of banana. (Source: IBGE, PAM); (d) Annual livestock population and production in Piquet Carneiro with the number of cows' head (black line), the annual milk production (in thousands of litres, red line), and the annual honey production (in kg, orange columns; Sources, IBGE and Conab). Below are the colour bars of the monthly values of the SPIs 3, 6, and 12. At the bottom are the monthly percentages of the municipality under different categories of drought severity, from July 2014 to November 2022 (Sources: Cogerh/Funceme, Brazilian Drought Monitor, CHIRPS)

The Standardised Precipitation Indices (SPIs) highlight various meteorological drought events (Figure 4.2). Between 2003 and 2012, no severe meteorological drought events were indicated, especially when contrasted with the preceding and succeeding decades. From 1981 to 2003, four multiannual meteorological drought events occurred. From 2012 onwards, a multi-annual drought persisted until 2019. During this period, monthly drought maps produced by the Brazilian Drought Monitor began to be elaborated, categorising the percentage of the municipality affected by different severities of drought.

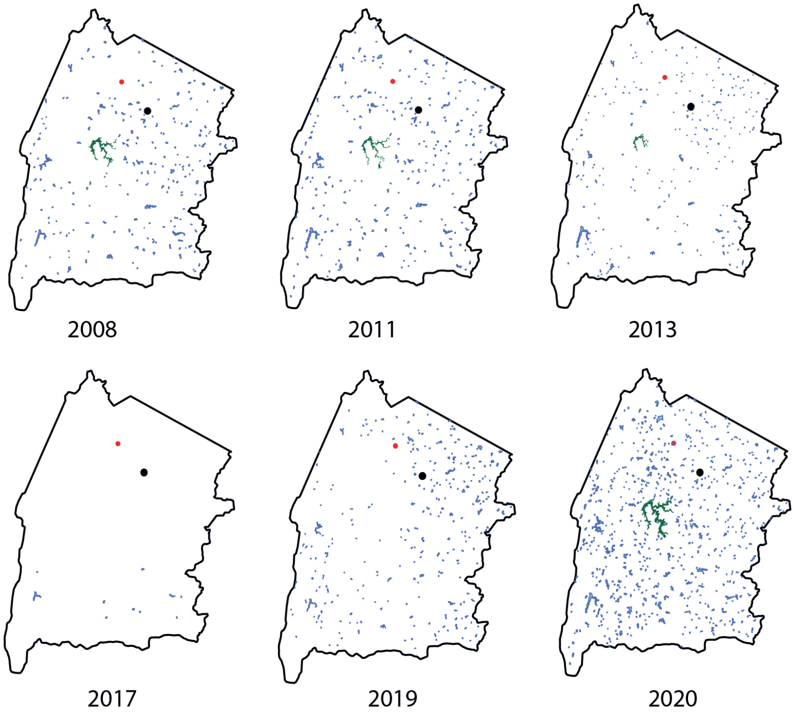

Figure 4.3: Maps of the non-strategic reservoirs with an area >0.5 hectares in the municipality of Piquet Carneiro from 2008 to 2020 and between July and November. The only officially monitored and strategic dam, Sao José II, is in dark green. The capital Piquet Carneiro is the red circle and the community Olho d'Água is the black circle (Funceme, 2020).

Before 2003, surface water data were quite limited, with neither strategic nor non-strategic reservoirs being closely monitored. Monitoring data for the Sao José II dam began in 2004 and for small "non-strategic" reservoirs in 2008. From 2004 to 2012, Sao José II dam monitoring showed significant volume dips that did not consistently align with drought periods. Notably, the Sao José II reservoir dried up entirely in 2017 but regained its maximum capacity by 2020 (Figure 4.3a). As for non-strategic reservoirs, data are available every one to two years and inform us about their location and water area, as long as it exceeds 0.5 hectares. From 2008 to 2011, the count of small reservoirs increased. Then, from 2012 to 2019, their number began to decline, hitting a low point in 2017 before rebounding in 2019 to numbers higher than before the drought (Figure 4.3).

Agricultural data up to 2003 highlight cotton as the dominant crop in both quantity and area within the municipality (Figure 4.2b and c). This dominance saw a sharp decline around 1995, coinciding with periods of low rainfall. Interestingly, the agricultural data show that cotton yield continued to increase until 2012, even though its cropped area and produced quantity were nil. Starting in the early 2000s, maize production saw a significant increase, but its occupied area remained constant. Between 2003 and 2012, yields of both maize and bananas increased, despite no corresponding growth in their cropped areas. From 2012 to 2019, the area allocated to staples like beans and maize stayed the same, yet their yields and quantities declined.

Regarding livestock data (Figure 4.2d), there was a consistent decline in cattle numbers prior to 2003. From 2003 to 2012, the number of livestock steadily increased, although milk production remained stable. Starting in 2008, honey production began to rise in the municipality, experiencing fluctuations with some years showing up to three times more honey production than others. After 2012, cattle numbers continued to increase until experiencing a decline in 2017. Milk production, however, remained relatively stable during this time. Starting in 2018, cattle numbers began to rise again, reaching their highest levels ever by 2022. Interestingly, milk production saw a five-fold increase from 2015 to 2016, dipped slightly in 2016 and 2017, and then surged to its highest levels from 2018 onward, following the pattern of livestock numbers.

4.3.3 Confronting experienced impacts and conventional drought indices in the Monitoring Efficacy Matrix

We completed three MEMs for three different periods: pre-2003 (Table 4.5A), 2003 to 2012 (Table 4.5B), and 2012 onwards (Table 4.5A); the three periods were selected due to their differing contexts. What changed were management practices introduced in the meantime that later alleviated or worsened drought impacts. By examining the MEM, we aim to understand the reasons underlying the potential monitoring challenges. By comparing the three MEMs, and the monitoring challenges, we aim to understand what information is still lacking for well-informed drought management. We identified a multiplicity of mismatches

Table 4.5: Monitoring efficiency matrices over the three different periods: Pre-2003 (A), 2003 to 2012 (B), and 2012 to 2019 (C); and monitoring challenges overview (D). Monitoring challenges include 'mismatches' (indicated by the letter M) and 'blindspots' (indicated by the letter B). 'Matches' correspond to instances where the impacts observed by the population of Olho d'Água were also reflected in the official monitoring data. We have ranked mismatches and blindspots based on our assessment of their relevance.

Table 5A: Pre-2003

Index (spatial level; temporal level) Impact on	SPI (0.05°, monthly, values below -1)	% of municipality in each drought severity category	Water area >0.5 ha	Reservoir level	Quantity produced (municipality, annual)	Area harvested (municipality, annual)	Crop yield/ha (municipality, annual)	Livestock (municipality, annual)	Milk (municipality, annual)	Honey (municipality, annual)
Livelihood security (LS)	Match. Livelihoods based on rainfed agriculture	**Blindspot as not monitored**			M1			M1		N/A
		B8								
Food security (FS)	Match. FS extremely dependent on rainfed subsistence crop		B8			Match, with the overfocus on beans and maize. Crashes of the staples in years of drought.				
Water security (WS)	Match. Shallow wells extremely dependent on rainfall		M7							

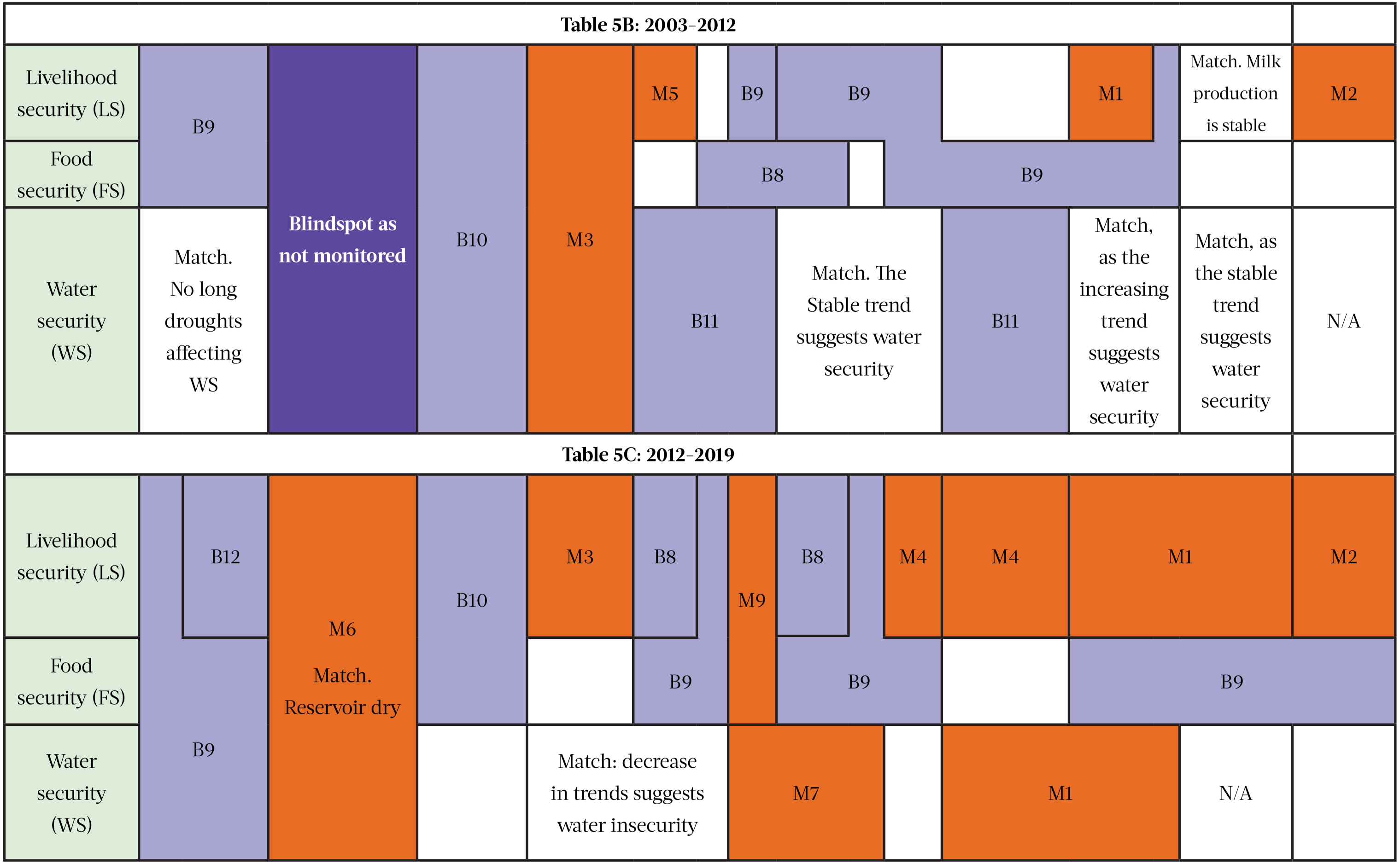

Table 5B: 2003–2012

Livelihood security (LS)	B9	**Blindspot as not monitored**	B10	M3	M5 B9	B9		M1	Match. Milk production is stable	M2
Food security (FS)					B8		B9			
Water security (WS)	Match. No long droughts affecting WS				B11	Match. The Stable trend suggests water security	B11	Match, as the increasing trend suggests water security	Match, as the stable trend suggests water security	N/A

Table 5C: 2012–2019

Livelihood security (LS)	B12	M6 Match. Reservoir dry	B10	M3	B8 M9	B8 M4	M4	M1		M2
Food security (FS)	B9				B9	B9		B9		
Water security (WS)				Match: decrease in trends suggests water insecurity	M7		M1		N/A	

Table 5D: Monitoring Challenges Overview
Mismatches: the spatial or temporal level of the official monitored data masks locally experienced drought impacts
M1: Mismatch in terms of whether larger-scale livestock data can be accurately applied to small-scale cattle farming in the community.
M2: Mismatch in terms of whether larger-scale honey production data can be accurately applied to the honey production in the community.
M3: The reservoir is not used by the community of Olho d'Água. It is not the appropriate indicator for livelihood, food, or water security at the community level.
M4: High yields paired with limited cropped area in the data at the municipality level actually suggest a focus on a single farm, challenging its generalisability across the entire municipality.
M5: A temporal mismatch emerges when the chosen time scale for monitoring does not capture the actual duration over which events or impacts unfold, making it difficult to accurately assess their influence on LS, FS, or WS within that specific time frame.
M6: Since the monthly drought map is produced at almost national scale and refined to sub-state scale, there is a mismatch: the Drought Monitor was not designed to show the drought severity classification at even municipality scale, never mind for individual communities. When there is variation within the state, we cannot be sure which communities fall under which drought category and how this concretely affects their LS, FS, and WS.
M7: Data stable or upward trend suggests irrigation, which was not the case as the community declared water insecurity and the impossibility of irrigating.
Blindspots: not all the elements of resilience or vulnerability of the systems to drought impacts are monitored
B8: Blindspot on the full scope of agricultural practices that support livelihood and food security in the community.
B9: Blindspot on the full scope of alternatives to rainfed agriculture, or alternatives to the variable monitored by the index, that prevent the collapse of the LS, FS, and WS.
B10: Blindspot emerging from important components of the indicator, the water volume not being accounted for.
B11: Blindspots related to the practices of irrigation. The trend of the monitored variable suggests irrigation, for which there is a blindspot as we do not have any official monitoring data in that regard.
B12: A blindspot emerges because the crucial information regarding cash shortages, which affect market sales and consequently livelihoods, is not considered at all.

and blindspots, varying per time period. Despite these variations, there are similarities in these monitoring challenges, and patterns do emerge. All these challenges are compiled in an overview table (Table 4.5D), which summarises the main types of monitoring challenges. These challenges are further elaborated on following Table 4.5.

Before 2003: Low community resilience to drought, with unreliable and incomplete monitoring data.

The community's resilience to drought impacts is low due to heavy reliance on rain for livelihood, food, and water. This results in severe impacts during droughts, and the SPI matches these drought periods as described by rural populations. During this time, there are no available hydrological data, creating a blindspot. Agricultural monitoring omits pastures crucial for the community (Blindspot 8). Contrastingly, one interviewee who lived in the community during the peak of cotton production in Ceará in the 1960s and 1970s, mentioned that cotton production was not prominent in the community. Thus, the agricultural data (Figure 4.2a and b) may inaccurately emphasise cotton's prominence in the area (Mismatch 1) and its high yield contrasts with its scant production in the community before stopping.

The stable trend in cotton during droughts also suggests irrigation, in contrast to the community's water scarcity experiences reporting full loss (Blindspot 11). Municipality-level livestock data, ranging from 9000 to 13500 cows, is not comparable to the community's owning not more than two cows per household, nor applicable to the milk production within the community (Mismatch 1).

Between 2004 and 2011: Increased diversification in livelihood and food systems, with partial but still inadequate drought monitoring.

During this period, no multi-annual droughts occurred. As previously stated, livelihood, food, and water systems have diversified. Consequently, while rainfall previously exerted a strong influence on each of these systems, rainfall alone cannot explain current impacts anymore because the resilience of the system to drought impacts has increased. This is also true for the other indicators. The community's livelihood is not exclusively dependent on onsite food production or agriculture anymore, given that more individuals now work outside this sector. Thus, the SPIs only offer a partial view of the resilience of the livelihood system (Blindspot 9). Moreover, stable incomes ensure food security, which is no longer solely linked to subsistence farming as in the past (Blindspot 8). The reservoir level is not representative for the community that does not utilise it (Mismatch 3). Small reservoirs are crucial, hinting at usage patterns in communities. Yet, monitoring of these reservoirs is incomplete as their volumes or levels are not officially monitored or available (Blindspot 10). The stable trend of cropped areas, coupled with increased production, especially of banana and maize, suggests irrigation practices. However, we lack data on irrigation, which is a crucial element of water security (Blindspot 11). The rising livestock trend in the official data, ranging from 12000 to

15000 cows, does not reflect community patterns, with households owning no more than five animals (Mismatch 1). Similarly, honey production remains predominantly a household activity, even though it is the primary source of agricultural income in the community. While the data show fluctuation in honey production, the community reported only increases. Therefore, it is also challenging to apply such data to the community level (Mismatch 2). Also, looking at the agricultural production of one year is not conclusive to evaluate whether the community was livelihood or food (in)secure during that year. Families generally store part of a year's production, for consumption, processing, or sale in other years when the production falls short (Mismatch 5).

From 2012 onwards: Greater resilience to drought due to alternative measures, yet continued monitoring challenges

This period is marked by the 2012–2019 multi-annual drought. However, the prior decade allowed the development of capacities that were not eroded in the absence of any severe droughts. Although the 2012–2019 drought affected the livelihood, food, and water systems, they were not as severely impacted as they were before 2003, because of alternative governmental measures like *Bolsa Família*, *Garantia Safra*, PAA, PNAE, and water trucks. These alternatives are not accounted for or officially monitored (Blindspot 9). During the drought, the Brazilian Drought Monitor produced monthly maps from which the percentage of the municipality under different categories of drought severity can be extracted. However, it remained unclear under which categories the rural communities fell or what these categories implied in terms of impacts on water, food and livelihood securities (Mismatch 6). The stable cropping area suggests ongoing irrigation, but this is not the case as the community reduced its cropped area, or even eliminated the banana production, and had to stop irrigation (Mismatch 17).

Furthermore, the reported high yield of bananas, considering the limited cultivated area, raises questions about its accuracy and its generalisability to other communities (Mismatch 4). The quantity of basic staples such as beans and maize decreased during the drought (Figure 4.2a), leading to the surplus from previous years being fully consumed in the initial years of the drought. The food security of the community did not depend on these staples anymore as they were income-secure and could afford to buy food produced elsewhere, but this shows how some impacts can manifest long after the time they are monitored (Mismatch 5). The fluctuating honey production, shown in Figure 4.2d, might not accurately reflect the community's situation. Honey production, the main source of agricultural income, declined significantly during this period in the community and recovered only in 2020. This suggests a mismatch in the applicability of larger-scale data to the honey production trend in the community (Mismatch 2). The same mismatch is present for livestock data, which trend of 12000 to 20000 cows, is too broad to reflect the local average of five cows per household (Mismatch 1). Additionally, factors like cash shortages in local banks, which are not related to drought but affect farmers' income, are not being monitored (Blindspot 12).

4.4 Discussion

4.4.1 Implications for drought monitoring at community level in Northeast Brazil

The focus of our research on a small rural community in Northeast Brazil is useful to underscore a crucial point for drought monitoring: it is imperative to understand how the focus system is impacted by drought in order to monitor drought impacts efficaciously. We have previously advocated for a system-oriented and contextualised perspective in drought monitoring (Chapters 2 & 3), where the considered systems represent components of human welfare that are affected by drought. In this study, we have taken livelihood, food and water securities as focal systems, and examined how they have been impacted at the community level differently over time by different drought events, as the local context changed. We have assessed if drought impacts were effectively captured by conventional drought indices and official data. Such comparison was made using a newly developed Monitoring Efficacy Matrix (MEM) and aimed to detect drought monitoring challenges, consisting of mismatches and blindspots. Mismatches draw attention to the misalignment between levels of monitoring and the experienced drought-impacts, while blindspots point to the absence of monitoring of all elements composing the considered system, that can be impacted by drought or mitigate drought impacts on the system. As systems undergo transitions, like the transition from substantial to more diversified agriculture, these elements also change. Therefore, what needs to be monitored evolves as well, reinforcing the necessity for a systems perspective in drought monitoring, rather than the current hydroclimatic-oriented approach.

Our findings support this always-evolving system perspective. The three MEMs revealed monitoring challenges that were different for the three different time periods. Over these three distinct and consecutive periods, the efficacy of drought monitoring appears to decrease as the community's livelihood, food and water systems diversified and became more resilient. In the first period, rainfall monitoring largely aligned with experienced drought impacts due to the community's dependence on rainfall, although the monitoring remained incomplete. In the following periods, as the community diversified its livelihood, food, and water sources, the monitoring gap also increased. This indicates that as systems became more complex and resilient, conventional indices and data became less capable of capturing the entire range of nuances of that resilience to drought impacts. Some blindspots can be caused by monitoring systems not accounting for all or some aspects of the resilience to drought impacts. Some examples include overlooking alternative income sources, community reservoirs' volumes, the influence of government programmes, or cash shortages caused by a population mainly comprising retirees. Such blindspots occur due to the plurality of perspectives on what constitutes the livelihood, food, and water systems and what constitutes their resilience to drought impacts, or in simple terms “what should be monitored and how?” This plurality of perspectives is discussed further in the next section.

Additionally, mismatches can also arise from the misalignment between the scales and levels at which conventional drought indices are available and the scales and levels at which impacts are actually experienced. Such mismatches can be temporal, occurring when the chosen timeframe for monitoring does not align with the duration or frequency of impacts or mitigation strategies. They can be spatial when aggregated, large-scale data do not accurately reflect smaller-scale, local conditions. Spatial mismatches can also occur the other way around, when data is too specific and mostly skewed by outliers, reducing its applicability at a larger level. Such mismatches occur due to the plurality of scales and levels at which drought drivers and impacts can or should be monitored. This plurality of monitoring scales and levels is also further discussed in the next section.

4.4.2 Reflections on what this analysis reveals about drought monitoring

The term “plurality” is commonly used in the literature on scales and levels (Cash et al., 2006; Wiegant et al., 2020; Poteete, 2012). Plurality refers to the failure to recognise heterogeneity in the way that scales are perceived and valued by different actors, even at the same level. This challenge surfaces when there is an assumption of a single, universally suitable characterisation of scale and level for the entire system or all actors. In this present study, this plurality of scales is characterised by the different mismatches, highlighting the impossibility of detecting locally experienced impacts, mentioned by the population, as the monitoring data does not cover the spatial or temporal reach of these impacts.

We believe that the concept of ‘plurality’ can be broadened to cover the heterogeneity of perspectives on livelihood, water, food security, or any other component of human welfare and what characterises this component. The challenge can emerge from assuming that a specific system holds higher importance or priority unanimously for all involved actors. For instance, one might assume that for everyone involved in drought management, water security is the primary concern. Another assumption might be that the elements that make up a system are consistent for all spatial, temporal and jurisdictional scales. For example, assuming that all rural communities in a municipality rely mainly on rainfed subsistence agriculture. Drought monitoring faces this challenge of plurality as it often standardises both scales and perspectives of impacts. Yet, this study and others in the literature highlight the varied spatial and temporal reach of drought impacts, as well as the varied nature of these impacts, the range of people they affect, and how these impacts also vary according to the actors impacted (Van Oel et al., 2019; Savelli et al., 2021; Chapter 3).

The reasons behind the oversimplification of scales and perspectives in drought monitoring can be traced back to its purpose: to inform and guide decision-making. Three interconnected reasons can explain this standardisation: (i) stakeholders' varied interests; (ii) control; and (iii) simplification (Cash et al., 2006). (i) The way issues are defined in terms of scale often aligns with varied stakeholders' goals and interests. This is because defining the scale of a problem determines who makes decisions and who benefits from them, with the risk of sometimes resulting in unequal outcomes. For instance, (Van Oel et al., 2019) pointed out that water-for-food governance encompasses multi-level actors, each with different perspectives and impacted differently by drought, therefore necessitating different indices of drought impacts. This leads to (ii) control, through governments framing problems (Van Lieshout et al., 2011), including droughts, to fit within their jurisdiction in their bid to manage issues within their reach and mandate. For example, a government or authority might use a specific indicator to assess drought severity across a jurisdiction, even when the severity can differ considerably within that area. This approach allows governments to standardise their responses and resource allocation according to predefined administrative boundaries. A perfect example to illustrate this case is the *Garantia Sáfra* – the Index-Based insurance mentioned earlier in this study (Section 4.3.1). In case of droughts or heavy rains, agriculture extension officers visit selected fields and assess whether crop losses exceed fifty percent. Pay-outs to the whole region occur if the 'Water Requirement Satisfaction Index', in the respective municipality is reached (Kühne, 2020). Drought monitoring can be reduced to a particular scale, level, or perspective for (iii) simplifying drought management. This is why drought management tends to be siloed across different ministries, departments, or authorities (Wilhite, 2019), due to its different effects on virtually all aspects of society (Bressers et al., 2016). This siloing can, in turn, complicate drought governance by fragmenting the responsibilities of drought management (Bressers et al., 2016; Edelenbos and Teisman, 2011), which is why there is a growing demand for more unified and collaborative management approaches (Pulwarty and Sivakumar, 2014; UNDRR, 2021). This is what the Brazilian Drought Monitor succeeds to do. As previously mentioned in this study (Section 4.2.3), even though the monthly drought severity map relies on broad and non-contextual indices, its function is more as a collaborative tool through the generated monthly discussions on localised drought conditions which ultimately improves institutional and operational capacities to respond to a drought event (Cavalcante De Souza Cabral et al., 2023).

Therefore, a drought impact index that is both localised and replicable is challenging, if not unachievable. This is due to the inherent challenge of "plurality" in scales and perspectives. There is no "best" combination of scale, level, or perspective for drought monitoring because of the complexity and varied impacts of droughts across different scales and stakeholders. The monitoring gap arises from this imbalance between 'broad and easy' monitoring and capturing the local context. It results from the necessity to select specific scales, levels, and variables due to the impossibility of encompassing all relevant perspectives and scales in monitoring. However, what might help bridge this monitoring gap is a focus on monitoring systems' resilience through non-extreme events, and stakeholder consultations, as we discuss below.

4.4.3 Practical implications and recommendations for monitoring drought and drought impacts

While our study identifies the mismatches and blindspots in existing drought monitoring indices, it does not provide alternative indicators that could better address these monitoring challenges. In that sense, our work provides an analytical overview. Our research introduces a methodology for evaluating the suitability of existing indices for monitoring drought impacts on specific systems, scales, and levels.

As this study and the identified monitoring challenges are based on comparing two datasets, official and based on interviews, one notable limitation lies in the quality of such data. While we have frequently pointed out inconsistencies and shortcomings in the official data, we have also built our argument about monitoring challenges on that same data and its quality. However, this does not undermine our study's findings as this official data, with its inconsistencies and shortcomings, is precisely what decision-makers have to work with. The interview process is also subject to several forms of bias. These include positive memory bias (Adler and Pansky, 2020), where participants might emphasise positive memories over negative ones; memory bias (Grant et al., 2020), where current circumstances can influence past recollections; selection bias (Catalogue of Bias Collaboration, 2017), where interviewees may not fully represent the community; social desirability bias (Bergen and Labonté, 2020), where respondents might give answers they think are expected; and observer bias (Mahtani et al., 2018), where the interviewer could inadvertently influence responses. However, some of these biases are negligible as consistent conversations in other communities were independently conducted by other researchers and corroborated the findings.

These limitations serve as a blueprint for future research and improvements in drought monitoring. We advocate for the continuous and official monitoring of drought impact data by technical extension officers, whether agricultural or social, at the local municipality level. As we will develop later in the text, drawing from existing initiatives (Walker et al., 2024), such continuous monitoring would allow for a more accurate and reliable assessment of drought impacts, thereby improving the quality of drought interventions.

To date, no drought impact index covers both physical and human drivers. Notable initiatives include the Water Poverty Index (WPI; Sullivan, 2002), which gauges 'water poverty' across scales but faces challenges of plurality (Sullivan et al., 2006). The recently introduced Days to

Day Zero (DDZ) Index (Lankford et al., 2023) assesses the resilience of irrigated agriculture in semi-arid regions. The DDZ, although tailored for irrigation, underscores the need to also monitor non-extreme events and actions with both the WPI and DDZ tracking the escalation towards extremes rather than just the extremes themselves.

Monitoring non-extreme drought events can prompt anticipatory measures. By tracking these events, drought managers can begin to implement medium- and long-term strategies, ensuring they are better prepared when a severe drought does occur. Currently, this proactive approach is hindered by drought monitoring systems and official data, which focus on extreme events. They often detect an anomaly or a deviation from the average when corrective action is already more challenging, as the impacts already occurred. This need is highlighted in a recent study by Walker et al. (2024) also in the Brazilian semi-arid region. Their analysis of a drought impacts monitoring dataset from Ceará, showed that impacts still occur but are often normalised during mild or non-drought periods. The main drivers of these impacts were either non-extreme hydrometeorological conditions or socio-technical vulnerabilities.

In Walker et al. (2024), monitoring non-extreme drought impacts is delegated to agricultural technicians within the municipality, possessing rich local knowledge from past drought experiences and from operating in the communities within the municipality on the daily basis of their work outside of the monitoring. Though the reporting is at the municipal level, the nuances regarding how and why different communities are affected by drought in various ways can still be discerned, provided the technicians report it. This type of monitoring is a good compromise between what is logistically feasible in terms of monitoring and capturing the local nuances of (resilience to) drought impacts before they escalate to extreme levels, thereby helping bridge the monitoring gap.

Finally, it is important to note that another significant factor in the monitoring gap is that, even when human drivers of resilience to drought impacts are investigated, the challenge remains of how to integrate them into drought monitoring or early warning systems which are currently predominantly based on physical drivers. Many human drivers of resilience and vulnerability to drought impacts are qualitative, as shown in this study (e.g. adherence to programs, diversification of the water, food, or livelihood system), or the Brazilian drought monitoring impact study (e.g. high costs of energy, planting in low-lying areas; Walker et al., 2024). Current drought monitoring systems often have a strict framework that does not easily accommodate qualitative data. Yet, qualitative observations play a pivotal role in local decision-making at household and community levels, which can have ripple effects at higher spatial levels or further in time (Ribeiro Neto et al., 2023; Chapter 3). Therefore, an important challenge for drought monitoring lies in developing frameworks that allow the integration of such crucial qualitative data.

4.5 Conclusions

We developed a Monitoring Efficacy Matrix (MEM) to assess how well official data relevant to drought impacts align with community-level drought experiences, especially regarding impacts on water, food, and livelihood systems. By applying the MEM to the case of the rural community of Olho d'Água in Northeast Brazil, we identified monitoring challenges, consisting of mismatches and blindspots. At the community level, mismatches were caused by discrepancies between broad-scale data and specific local conditions, such as using municipal-level livestock and honey production data for small-scale farming, and drought data time-resolution not aligning with drought impacts duration or lag time. Blindspots emerged from important components of the indices not being accounted for, such as small reservoirs water volume, or from entirely missing the community's evolving resilience factors, such as irrigation and alternative crops. Our findings reveal that as the community's livelihood, food, and water systems diversified and became more resilient, the efficacy of drought monitoring decreased.

These mismatches and blindspots stem from the plurality of spatial and temporal levels pertinent to drought actors and impacts, as well as actions and strategies that determine a system's resilience to drought impacts. Given the challenge of considering all relevant scales and perspectives, drought monitoring often standardises or selects specific scales, levels, and variables to monitor. This approach, while aiming for simplification in drought governance and management, creates a monitoring gap by favouring 'broad and easy' monitoring at the cost of losing the local nuances of drought impacts.

A first step to bridge this drought monitoring gap is focusing on tracking systems' resilience by continuously monitoring non-extreme events and delegating this task to municipal technical extension officers. This type of monitoring offers a better balance between logistical feasibility at the municipality level and capturing local nuances of resilience to drought impacts at the community level. A second step, towards fully addressing this monitoring gap, would still require adaptations in drought monitoring and early warning systems, as current frameworks do not accommodate the integration of the qualitative nature of data associated with human drivers to drought impacts.

05

Synthesis

Abstract. This chapter synthesises the findings of the thesis on drought monitoring, local impacts, and human dimensions. It revisits the research questions through the lens of the results presented in the empirical chapters (Chapters 2, 3, and 4) and how they collectively address the central research question. Key aspects covered include the disparity between current drought monitoring methods and the actual impacts experienced at the local community level. This disparity reveals a "drought-monitoring gap," characterised by an overemphasis on broad-scale physical indices and an underrepresentation of nuanced human experiences and resilience dynamics in rural areas. Furthermore, this chapter proposes strategies for bridging the monitoring gap. It advocates for integrating local contexts by incorporating qualitative data into drought monitoring and highlights the importance of decentralised monitoring approaches to capture a fuller spectrum of drought impacts. The research's scientific contributions are discussed, particularly in relation to socio-hydrology, social-ecological systems, and drought management. The findings' relevance to other drought-affected areas and their implications for the Sustainable Development Goals are also explored. Finally, the chapter concludes with a critical reflection on the limitations of drought monitoring and indices and underscores the necessity of ethical considerations and a deeper understanding of the local context.

5.1 Overview of thesis results with research questions

The research reported in Chapters 2, 3, and 4 primarily provides answers to research questions 1, 2, and 3 respectively. On top of this, they also provide important additional evidence related to the other questions. As such the combined information from Chapters 2, 3, and 4 synergistically results in comprehensive insights that allow me to now answer the central research question. Figure 5.1 reflects this.

After having identified the most used indices and their applications in Chapter 2, I explored historical drought events and their impacts in Chapters 3 and 4, to see how theoretical understanding aligns with real-world experiences. This was supported by the constatation from Chapter 2 that physical drivers of drought are more studied, therefore maybe better understood, and sometimes can be remotely monitored. Conversely, human-related drivers of droughts and impacts are less intensely studied and remain less well understood. The fieldwork, involving the 'drought diagnosis', revealed patterns in the dynamics of drought disturbances and impacts, leading to the main theory presented in Chapter 3: drought-impacted communities in social-ecological systems. This concept also supports Chapter 4, an empirical study that bridges the scope of Chapters 2 and 3.

After an in-depth study of the dynamics underlying drought drivers resulting in impacts and how drought monitoring is conducted, the gaps between conventional monitoring and impacts experienced by local communities became clearer. This led to the scope of Chapter 4, focusing on the reasons for these gaps, and whether it can actually be addressed. This involved conducting an empirical case study. I however selected a different rural community than the one studied for Chapter 3. This allowed me to introduce a contrast between two different livelihood systems at the community level, at two different states of resilience, and highlight the reasons for such a difference, and how local relevant context can be very local, between two small farming communities located in the same river basin, in the same semi-arid area, in the same state. Chapters 3 and 4 both engage with the concept of resilience. Chapter 3 demonstrated how the loss of resilience can lead to drought-related impacts or even the collapse of the system under study. In contrast, Chapter 4 focuses on a community resilient to drought impacts. This study revealed that surprisingly, resilient communities – although desirable in drought management – pose challenges for conventional drought monitoring and indices. The SDGs addressed are elaborated further upon in Section 5.2.3.

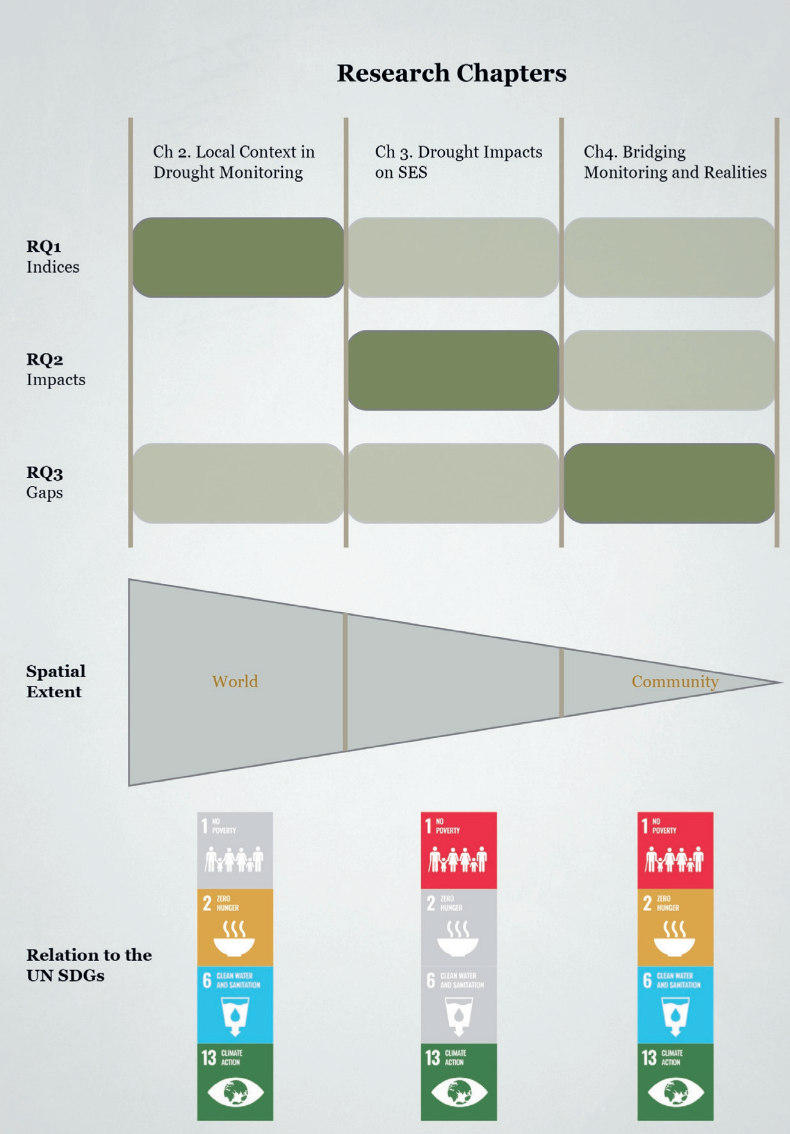

Figure 5.1: Overview of the contribution of each research chapter to the three specific research sub-questions that together address the overarching main research question of this thesis. The darker-coloured bars indicate a stronger contribution, whereas the lighter colour indicates a lower contribution. In addition, the spatial extent of each research chapter and the SDGs the chapter addresses, are indicated (Adapted from Smolenaars, 2023).

5.1.1 How is drought currently monitored and how are drivers and impacts aligned?

Drought monitoring is often implemented using Drought Monitoring and Early Warning Systems, which currently use various indices to assess onset, severity, and length. These indices are typically attributed to meteorological, agricultural, and hydrological droughts, representing physically-based drought drivers. Drought is mainly depicted through a focus on precipitation-based and remote-sensing-based. It is the Standardized Precipitation Index (SPI), a single-variable index indicating a meteorological drought, based on a rainfall anomaly, that is the most broadly-used index in different climatic and geographic contexts. This widespread use occurs despite being the index that includes the least local contextual information and is known for its limitations in arid and semi-arid climates (Wu et al., 2007).

There is a misalignment between studies on drought's physical drivers and those on impacts related to food and water securities, both in quantitative and geographical foci. There are notably more studies on meteorological and agricultural drought indices than on impacts related to food and water securities and a geographical skew exists towards Global-North countries for physical drivers, and sub-Saharan Africa and Australia-Oceania for impacts. There is also a difference in the geographic partitioning of scientific studies focusing on drought-related food security and those focusing on water security. The observed misalignments indicate that the emphasis of studies on a certain aspect is influenced by the specific characteristics and needs of the geographic area, or the 'local context'.

Four main categories help understand this local context: physical conditions, socio-economic conditions, data availability, and scientific interests. These factors shape how drought is experienced and managed in different regions, influencing the focus of research, whether on physical drivers or socio-economic impacts and human dimensions.

5.1.2 How does drought cause local impacts?

Different people could answer this question differently. In my case, I argue that local drought impacts stem from a loss of resilience. However, it is important to be more specific. It is not the community *per se* that is resilient or vulnerable. It is rather a specific aspect of the social-ecological system (like food, water or livelihood security) within that spatial level (the state, the community) and at a determined period of time, to a disturbance and its impacts, such as drought. This is because resilience is dynamic. To illustrate the dynamics behind this fluctuation of resilience, and get beyond concepts that only make it difficult to understand, I exemplified such resilience dynamics with the case of the community of Riacho da Cruz, reconstructing the historical trajectory of its livelihood over time. Therefore, when discussing local drought impacts and resilience, the focus is on the resilience or vulnerability of the Riacho da Cruz livelihood system to drought impacts from 1970 to 2022. The successful application of SES concepts to drought for the community of Riacho da Cruz suggests that they could also be relevant to other cases.

Local drought impacts in Riacho da Cruz are intricately tied to the dynamics of resilience, potential (stored or accessible resources), and connectedness within the community's livelihood system. Changes in these factors, influenced by decisions and environmental conditions, determine the community's vulnerability to drought impacts. The case study shows how shifts in livelihood strategies, like moving from manual labour to intensive and then to subsistence farming, reflect adaptations to changing conditions and resilience levels. Each shift reflects a response to varying conditions, such as the construction of the Pirabibu dam and subsequent droughts, which affected water availability and altered the community's dependence on resources.

Resilience is highly dynamic; today it might be far from collapse, and tomorrow very close. This 'distance' refers to the concept of precariousness. Precariousness refers to how close a system is to collapse, which in this case is determined by the community's resilience to drought. The community's dependence on the Pirabibu dam made their livelihood vulnerable, and consecutive droughts pushed the system to a point where it had to adjust or collapse. A collapse, which is the forced shift from intensive to subsistence livestock farming, while lowering economic potential, increased resilience by terminating dependence on the dam. Thus, precariousness in Riacho da Cruz is influenced both by local decisions and external factors, showing how closely a community's livelihood system can teeter on the edge of viability in the face of environmental changes.

5.1.3 To what extent does current drought monitoring capture impacts experienced by local communities?

Current drought monitoring struggles to accurately capture the full range of impacts on local communities, creating a "drought-monitoring gap". This gap arises from a mismatch between conventional drought data and the actual conditions experienced, especially in rural areas. It is characterised by an overemphasis on physical indices rather than human experiences, leading to a limited understanding of drought effects on community livelihoods, food, and water security. This gap was already highlighted in the scientific literature (Chapter 2) but also empirically demonstrated, showing that the monitoring gap stems from more than just a focus on physical drought drivers.

Firstly, mismatches within and across spatial and temporal scales exist as conventional drought indices often operate at broader spatial and temporal scales than the impacts experienced by local communities. For instance, broad-level data on livestock may not accurately represent the realities of small-scale cattle farming in rural communities. Similarly, the timeframes used in drought monitoring may not effectively capture the real duration or delayed impacts of drought at the local level. For example, a meteorological drought in a particular year may only manifest its impact on food security at the community level when household reserves of dry food, stored during more prosperous years, are depleted. Additionally, there are blindspots in current monitoring methods, where crucial elements of community resilience or vulnerability to drought are overlooked.

Such mismatches and blindspots in drought monitoring stem from the plurality of spatial, and temporal levels, and perspectives relevant to different drought actors and impacts. There is no universally "best" combination of scale, level, or perspective for drought monitoring because of the complexity and varied impacts of droughts across different scales and stakeholders. For instance, what is important for water security in one area may not have the same importance in another region. Assumptions about uniformity across different spatial, temporal, and jurisdictional scales are also inaccurate, such as presuming all rural communities rely mainly on rainfed subsistence agriculture. Therefore, given the challenge of considering all relevant scales and perspectives, drought monitoring often standardises or selects specific scales, levels, and variables to monitor. This approach, while aiming for simplification in drought governance and management, creates a monitoring gap by favouring 'broad and easy' monitoring at the cost of losing the local nuances of drought impacts. A way of bridging this monitoring gap is a focus on monitoring systems' resilience through non-extreme events, and stakeholder consultations, as we discuss in the next sub-section.

5.1.4 How can drought monitoring comprehensively account for drought impacts in the local context?

To comprehensively account for local drought impacts, this thesis suggests integrating relevant local contexts into drought monitoring, thus enhancing accuracy and aiding decision-making from practitioners to rural households. The following key findings (1-4), and supporting recommendations (5 and 6), together answer the central research question:

1. **Broader socio-economic challenges:** Drought impacts extend beyond water and agriculture to broader socio-economic aspects at the community level. Current approaches often overlook the human dimensions of drought risks.

2. **Livelihood security as a primary driver:** Individual decisions driven by livelihood security collectively exacerbate drought conditions. Communities' alignment with resilient approaches depends on their potential to enhance their livelihoods. A sentiment frequently expressed by farmers in many communities, and especially echoed in Riacho da Cruz where inhabitants lacked access to piped water before the introduction of the Pirabibu dam, was revealing. When asked why they prioritised water use for irrigation and livestock over preserving it for drinking or cultivating food for their families, their response was straightforward and pragmatic: "*With money, you buy water and you buy food*".

3. **Diversification and institutional mechanisms:** The resilience of communities like Olho d'Água, which diversified their livelihood system, contrasts with Riacho da Cruz, where over-reliance on intensive farming and one single water source led to vulnerability. Institutional support, such as cash transfers and small farming support programs, have likely promoted this diversification and therefore, resilience.

4. **Mismatch between local context, indices, and governmental representation, leading to challenges in policy and implementation.** This is a key outcome of the interaction of the three different PhD projects that were part of the larger 3DDD project: the lack of accurate local indices and local governmental representation to inform and prospectively or proactively address the impacts experienced, leading to predominantly individual decision-making that exacerbates drought conditions, like the unrestricted building of small reservoirs. Drought policies currently lack mechanisms to address immediate local-level shocks, leading to (rural) household-level decisions with broader consequences.

For both Olho d'Água and Riacho da Cruz communities, their respective municipal agricultural extensions have played pivotal roles, but their political capabilities are inherently limited. They function as technical assistance rather than authorities equipped to address shocks, which are sometimes induced by municipal, state, or governmental actions and incentives. For instance, the initiative to make Quixeramobim, home to the Riacho da Cruz community, the region's largest milk producer, was strongly promoted by municipal political authorities, but lacked support such as the establishment of safety nets for potential shocks, like the increased forage prices and cattle death. The coping capacities remain limited at the very local level, which is the household level, as farmers had to sell their assets, making it incredibly difficult to return to high-potential or high-yield activities. This illustrates a broader issue where policies are enacted at higher levels without corresponding safety or control mechanisms at the local level to face shocks like droughts, which is surprising in drought-prone areas. This situation creates a solitary experience for individuals at the local level leaving farmers having to independently face the challenges of droughts. The burden of coping, therefore, becomes an individual struggle at the household level, disconnected from broader policy initiatives. Consequently, decision-making remains highly individual, leading to broader consequences, such as the unregulated construction of small reservoirs and the unsustainable use of water, as highlighted by Cavalcante et al. (2022), Ribeiro Neto et al. (2022), and Ribeiro Neto et al. (under consideration), and discussed in Chapters 3 and 4 of this thesis.

5. **Systemic multi-hazard perspective in drought monitoring:** A systemic approach combining centralised and decentralised monitoring is recommended. Current monitoring systems, which focus on extreme events, often miss the nuances of local resilience and vulnerability.

As mentioned earlier, the diversity of scales, levels, and actors spread across them implies that there is no single best combination of these elements. Reiterating our previous conclusion, creating a drought impact index that is both local and replicable presents a significant challenge, if not an unachievable goal. But if additional objectives of DEWSs are to focus on the specificity of impacts or the vulnerability and resilience drivers to drought impacts, to empower local populations, and improve the quality of decision-making at any spatial level, then drought monitoring does not necessarily need to be a centralised (for examples at the state level only), institutional process; this only makes it useful for state- and municipality- level practitioners. Instead, drought monitoring should be decentralised. Decentralisation refers to the process of distributing decision-making and management authority from a central location or authority to smaller, local units. In practical terms, when it comes to drought monitoring, decentralisation would mean that instead of having a national or state-level authority responsible for monitoring and responding to drought conditions (like the Brazilian Drought Monitor), the responsibility would be shared with local governments, community organisations, or regional agencies. These local entities would have the autonomy to conduct the monitoring, make decisions and take actions that are more tailored to the specific needs, conditions, and challenges of their area. Decentralisation is often advocated for because it can lead to more efficient, responsive, and context-sensitive management practices (Hegga et al., 2020; Meijerink and Huitema, 2015; Rondinelli et al., 1983), as local authorities are typically more attuned to the specific circumstances and needs of their communities. However, as mentioned earlier, local authorities with the capability to provide appropriate responses are not yet established. Therefore, this task could be shared with competent services equipped to handle such responsibilities. Total decentralisation processes can prove highly ineffective and/or inefficient, and their success is conditional upon navigating or overcoming political resistance, integrating effectively, and fostering cooperation with existing institutions, in addition to allowing new organisations sufficient time to establish their effectiveness (Adhikari and Tarkowski, 2013; Carr et al., 2012; Cosens and Chaffin, 2016; Hegga et al., 2020; Meijerink and Huitema, 2015). This underscores the importance of not entirely delegating the responsibility of drought monitoring to the local level but, instead, gradually integrating it with local authorities or technical organisations.

This need is highlighted in a recent study by Walker et al. (under consideration) also in the Brazilian semi-arid region. Their analysis of a drought impacts monitoring dataset from Ceará, showed that impacts still occur but are often normalised during mild or non-drought periods. The main drivers of these impacts were either non-extreme hydrometeorological conditions or socio-technical vulnerabilities. In Walker et al. (under consideration), monitoring non-extreme drought impacts is done by agricultural technicians within the municipality, possessing rich local knowledge from past drought experiences and from operating in the communities within the municipality on the daily basis of their work *outside of the monitoring. Though the reporting is at the municipality level, the nuances regarding how and why different communities are affected by drought in various ways can still be discerned, provided the technicians report it. This type of monitoring is a good compromise between what is logistically feasible in terms of monitoring and capturing the local nuances of (resilience to) drought impacts before they escalate to extreme levels, thereby helping bridge the monitoring gap. For drought monitoring, this does imply a systemic multi-hazard perspective and combination of centralised and decentralised approaches.*

Such initiatives of 'local observatories' already exist elsewhere. For example, the EU-funded CitiObs project (Cordis | European Commission, 2024) aims to enhance citizen observatories, which are community-based environmental monitoring initiatives. These observatories involve a diverse range of stakeholders like citizens, community groups, and civil society organisations in gathering and sharing environmental data. The project focuses on improving both existing and new observatories, with an emphasis on formalising, valuing, and legitimising citizen observations to better engage citizens and marginalized communities in monitoring urban environments. Such a project exemplifies decentralisation by enhancing citizen observatories, demonstrating how local community engagement in monitoring can lead to more context-sensitive management. This concept can be similarly applied to drought monitoring, where instead of relying solely on state-level processes, responsibilities could be shared with local entities. These local units, much like those in CitiObs, would have the autonomy to conduct monitoring and take actions tailored to their specific regional challenges and needs.

6. Incorporating qualitative data in drought monitoring: Many human drivers of resilience and vulnerability to drought impacts are qualitative and are not easily accommodated in current monitoring frameworks. Integrating these observations is crucial for capturing the full spectrum of drought impacts.

Finally, it is important to realise that even when human drivers of resilience to drought impacts are investigated, the challenge remains how to integrate them into drought monitoring or early warning systems which are currently predominantly based on physical drivers. Many human drivers of resilience and vulnerability to drought impacts are qualitative, as shown in this thesis (e.g. adherence to programs, diversification of the water, food, or livelihood system), or the Brazilian drought monitoring impact study (e.g. high costs of energy, planting in low-lying areas; Walker et al., under consideration). Current drought monitoring systems often have a strict framework that does not easily accommodate qualitative data. Yet, qualitative observations play a pivotal role in local *decision-making at household and community levels, which can have ripple effects at higher spatial levels or further in time (Chapter 4; G. Ribeiro Neto et al., 2023). Therefore, an important challenge for drought monitoring lies in developing frameworks that allow the integration of such crucial qualitative data.*

5.2 Scientific contributions to sustainable development

5.2.1 Reflection on and relevance for the fields of socio-hydrology, social-ecological systems, and drought management

The main findings of the thesis align with recent developments and perspectives in the fields of socio-hydrology (SH), social-ecological systems (SES) and drought management. The thesis critically evaluates the limitations of conventional drought indices, echoing the socio-hydrological discourse on the inadequacy of single-value drought characterisation (Aghakouchak et al., 2023; Bachmair et al., 2016; Svoboda and Fuchs, 2016) and the complex interplay between human activities and drought impacts (Van Loon et al., 2016a; Van Loon et al., 2022; Savelli et al., 2021; Gautier et al., 2016). This approach also aligns with the latest drought management recommendations that emphasise the integration of indigenous and traditional knowledge alongside various risk assessments (UNDRR, 2021; Hagenlocher et al., 2019) advocating for a shift from expert-driven models to more inclusive and comprehensive strategies.

The thesis's focus on local contexts, socio-economic impacts, and agricultural systems intersects with the need for multi-scale data on drought vulnerability and adaptive capacity (Hagenlocher et al., 2019; Kim et al., 2019; Gonzales and Ajami, 2017) and underscores the importance of participatory governance and multi-stakeholder collaboration (Campbell and Vainio-Mattila, 2003; Healy and Ascher, 1995; Camacho-Villa et al., 2016). Furthermore, the thesis aligns with the recognition of systemic challenges and barriers in drought management (Gillard et al., 2016; Gautier et al., 2016; Vogel and Van Zyl, 2016) and the importance of adapting to interconnected risks (Cramer et al., 2018; UNDRR and UNU-EHS, 2022). Additionally, the thesis's insights into community resilience and long-term adaptability align with the advocacy for integrated, inclusive, and adaptable strategies to enhance drought resilience (UNDRR, 2021; Aghakouchak et al., 2021; Di Baldassarre et al., 2019). However, while the combination of physical and human factors was termed as 'local context' in Chapter 2, it remained at a broad level of analysis, focusing on entire countries of geographic regions. The term 'local context' should ideally refer to a more local than regional scale. Moreover, the aspects labelled as 'local context' (physical conditions, socio-economic conditions, data availability, and scientific interests) are not dynamic but rather static categories that partially explain the disparity in drought focus. They categorised broadly some of the types of human drivers influencing drought risk, rather than being the drivers themselves. Therefore, we focused on the specific context of two rural communities in Chapters 3 and 4.

The focus on holistic resource management in the thesis also aligns with the necessity of integrated landscape management and ecosystem resilience against drought impacts (Yao et al., 2022; De Vries et al., 2012). While the study supports many conclusions through its multi-sectorial approach and highlights the escalation of drought risks through the loss of social-ecological resilience, it primarily emphasises social aspects. The ecological components could have been explored more deeply, indicating a potential area for future research (Sebesvari et al., 2016; Hagenlocher et al., 2019). This is even more important in situations where the livelihood and the ecosystem are tightly connected.

5.2.2 Relevance to other drought-affected areas

Building on insights 5.1.4 from Northeast Brazil (see Section 5.1.4), it is interesting to see if this approach and the concept of resilience would hold true in other drought-affected regions of the world. It is understood that the local context of impacts and drivers will vary. The critical consideration is whether this system perspective and the emphasis on resilience are effectively applicable across various geographical and socio-economic contexts. Walker et al. (2022) provided a comprehensive examination of drought events in different geographic areas. A summary can be outlined as follows (Table 5.1).

In each of these drought-affected regions, the occurrence and severity of droughts are shaped by a mix of climatic, environmental, and socio-political factors. The repercussions are extensive, impacting not only water availability but also agriculture, livelihoods, and public health, and even contributing to conflicts and migration. Moreover, these factors demonstrate states of tipping points and dynamics that are already familiar in each of these areas, and where drought acts both as a catalyst and is exacerbated by these factors. Despite the diverse local contextual human drivers and impacts of drought, which can indeed form the basis for tailored indices, the interplay between these drivers and impacts, and the blend of biophysical and human components, remain consistent. The dynamics driving the overall loss of resilience in the systems under consideration are also recurring patterns across these different regions. This seems to support that the conclusions of this thesis can be extended to other drought-affected areas.

Table 5.1: Drivers, Impacts, effects on resilience or vulnerability of the system and systemic thinking approach (Walker et al., 2022).

Drivers	**Impacts**	**Effect on System Resilience or Vulnerability**	**Systems Thinking Approach**
Cape Town, South Africa			
• **Socioeconomic disparities in water use:** Higher consumption in affluent areas Reliance on municipal water for non-essential uses (gardens, golf courses, and swimming pools) Private water sources (boreholes, rainwater tanks) used by wealthier households	• **Unequal experiences of drought across social groups** Lower-income groups were the most affected in terms of water usage reduction and economic Lifestyle maintenance for wealthier households that can afford the increased water prices	• **Reduced overall resilience** due to unequal distribution of resources Wealthier households could adapt better, widening the socio-economic divide. Furthermore, the water infrastructures installed during the drought allowed the wealthier household to increase their water availability after Day 0, therefore potentially increasing their future water uses. Therefore, **the wealthy elite increased its resilience to drought.**	Integration of socio-economic factors in water management: Policies aimed at equitable water distribution Stakeholder involvement in decision-making

Table 5.1 (continuation): Drivers, Impacts, effects on resilience or vulnerability of the system and systemic thinking approach (Walker et al., 2022).

California, USA			
• Assumption that increasing groundwater abstraction would buffer water shortage • High agricultural water use conflicting with drinking water use • Extensive infrastructure developments and urban expansion • Reliance on out-of-state waters, such as from the Colorado River • Complex water rights system favouring historical claims.	• Groundwater depletion and environmental degradation • Inefficient water distribution affecting underprivileged communities and ecosystems • Reduced hydroelectric power generation and effects on agriculture and downstream ecosystems • Socio-economic disparities in water access • Conflicts over water distribution between states	**Short-term solutions:** Reliance on groundwater abstraction as a quick fix has depleted resources and failed to address the balance between water demand and supply **Legacy Issues:** Extensive infrastructure developments have entrenched high water consumption patterns, and the water rights system, which favours older claims, has led to unequal water distribution. This imbalance disproportionately benefits those with senior water rights, often at the cost of ecological health and less privileged communities **Climate Change:** Anthropogenic climate change has worsened the situation by reducing snowpack and altering precipitation patterns, making the state more vulnerable to droughts and less able to manage these effectively	• Implementation of sustainable Groundwater Management • Integrated water resource management considering urban, agricultural, and environmental needs • Revision of water rights system for equitable distribution

Table 5.1 (continuation): Drivers, Impacts, effects on resilience or vulnerability of the system and systemic thinking approach (Walker et al., 2022).

Horn of Africa			
• Sparse rainfall and high evapotranspiration in an arid to semi-arid climate • Rapid population growth exacerbating resource demands • Land degradation and desertification, often worsened by overgrazing and poor land management • Political instability and lack of comprehensive drought management strategies	• Chronic water and food insecurity, with millions facing humanitarian emergencies • Pastoral communities severely affected, facing preventable deaths and malnutrition • Increased conflict over declining resources • Displacement of populations • Reliance on emergency aid, which often fails to reach the most vulnerable due to conflict and instability	• **Diminished Resilience Due to Fragmented Response:** The region's resilience is critically undermined by the lack of comprehensive, integrated drought management. The reliance on emergency aid and the absence of sustainable development measures have left the population vulnerable and dependent. • **Need for Holistic and Proactive Strategies:** The current approach, focusing on fragmented and reactive measures, fails to address the root causes of vulnerability. As a result, the region's ability to anticipate, cope with, and recover from droughts is severely compromised.	• Development of region-specific drought management strategies. • Investment in sustainable agricultural practices and water resource management.- Building political stability and improving cross-border collaboration • Implementation of drought early warning systems and capacity building for local communities

5.2.3 Relevance to the Sustainable Development Goals of the United Nations

Sustainable development is a holistic approach that seeks to balance economic growth, environmental protection, and social equity (United Nations, 2024a). These three dimensions of sustainable development are translated into 17 Sustainable Development Goals (SDGs), which serve as more specific targets to achieve sustainable development. The relationship between sustainable development, drought and poverty is intricate and interdependent. Drought directly impacts sustainable development by affecting environmental and economic stability. It can lead to water scarcity, reduced agricultural productivity, and loss of biodiversity, all of which are crucial elements of environmental sustainability. Economically, drought can cripple agricultural sectors, lead to food shortages, and increase prices, affecting local and national economies. Drought exacerbates poverty by reducing access to water and food resources, particularly affecting communities that rely on agriculture for their livelihoods. Poor communities often have fewer resources to cope with and recover from drought, leading to a cycle of increased vulnerability and poverty. Poverty is both a cause and a consequence of unsustainable practices. Poverty often limits individuals' choices, making them resort to unsustainable practices for survival, such as overusing natural resources (such as overgrazing and deforestation), creating a cycle of poverty and environmental damage. Conversely, sustainable development initiatives can alleviate poverty by creating employment, ensuring equitable resource distribution, and improving health and education. Therefore, better drought preparedness by definition contributes to sustainable development.

This thesis, while not directly addressing specific research questions related to the Sustainable Development Goals (SDGs) of the United Nations, frequently revisits them in the discussions and conclusions of the chapters (Figure 5.1). Food and water security represent some elements of SDGs 2 and 6 (Zero Hunger and Clean Water and Sanitation, respectively), while livelihood security is an aspect of SDG 1 (No Poverty). SDG13, which focuses on climate action, is particularly aligned with the thesis. Three of its five targets include strengthening resilience and adaptive capacity to climate-related disasters, integrating climate change measures into policies and planning, and building knowledge and capacity to meet climate change

The relevance of this thesis's results to the SDGs lies in: (i) each of the SDGs can be viewed as a system of systems, with multiple individual elements that collectively influence overall system behaviour, for example, human welfare; (ii) their role as universally agreed indicators of optimal human welfare, aiming for "peace and prosperity for people and the planet, now and into the future" (United Nations, 2024b).

Drought is cross-cutting and can hinder the achievement of virtually all SDGs (United Nations, 2015, 2023). This is demonstrated in this thesis and for other drought-affected areas, as shown in Section 5.2.2. Droughts have far-reaching and multifaceted impacts, affecting more than just the achievement of SDG6 through, for example, water insecurity, which typically cascades into food insecurity (SDG2). In Chapter 2, we explored the link between drought, food security (SDG2), and issues like corruption or weak political institutions (SDG16), and in Chapters 2 and 3, we examined how drought can lead to market shocks and erode financial resources (SDG1). Additionally, as discussed in section 5.2.2, drought contributes to worsening socio-economic disparities and widening inequalities (SDG10), impacting hydropower energy (SDG7) and ecosystems (SDGs 14 and 15).

Similarly, the relationship can be reciprocal. At times, it is a factor of vulnerability related to another SDG, or the incomplete realisation of an aspect of an SDG other than SDG 6 (which is most directly linked to water) that exacerbates drought conditions. For instance, in Chapter 1, I discussed the example of the Horn of Africa, where political instability (SDG 16) leads to migration (SDG 10) which leads to overgrazing or deforestation (SDG15), thereby intensifying drought conditions.

In Chapter 2, it is emphasised that water and food securities are reported in scientific studies for countries that are socio-economically different, such as those in the Sahel and the USA (Figure 2.5), suggesting different experiences of water and food securities. Areas may face food and/or water insecurities, but these can vary in declination and severity. Livelihoods and socio-economic development can be understood and applied in various ways, ranging from subsistence farming to agribusiness (e.g. within Brazil) and the irrigation of crops intended for export (e.g. California). The same applies to food security indicators can range from malnutrition to the genetic adaptation of fruit and vegetable strains to droughts. Livelihood, water- and food-securities are context-specific and do not entail the same underlying mechanisms across the world. I also highlighted how food security is a complex concept underpinned by multiple factors, with poverty being a key element in countries of the Global South, as populations in low-income countries are most exposed to drought-related food insecurity. This is also reflected in Figure 5.2. Figure 5.2a illustrates countries' scientific focus on drought and poverty, while Figure 5.2b puts into perspective the regions' relative focus on drought and poverty alongside drought physical drivers and food- and water-securities. In comparison to the cartograms linking drought and food security (Figure 2.5e), some countries almost disappear (e.g., the US) while others, like Brazil and those in Sub-Saharan Africa, become larger in Figure 5.2. When contrasted with the focus on food security (Figure 5.2b), the emphasis on poverty further increases in Sub-Saharan Africa and Latin America; and as previously mentioned, poverty is both an impact of and a driver for drought risk.

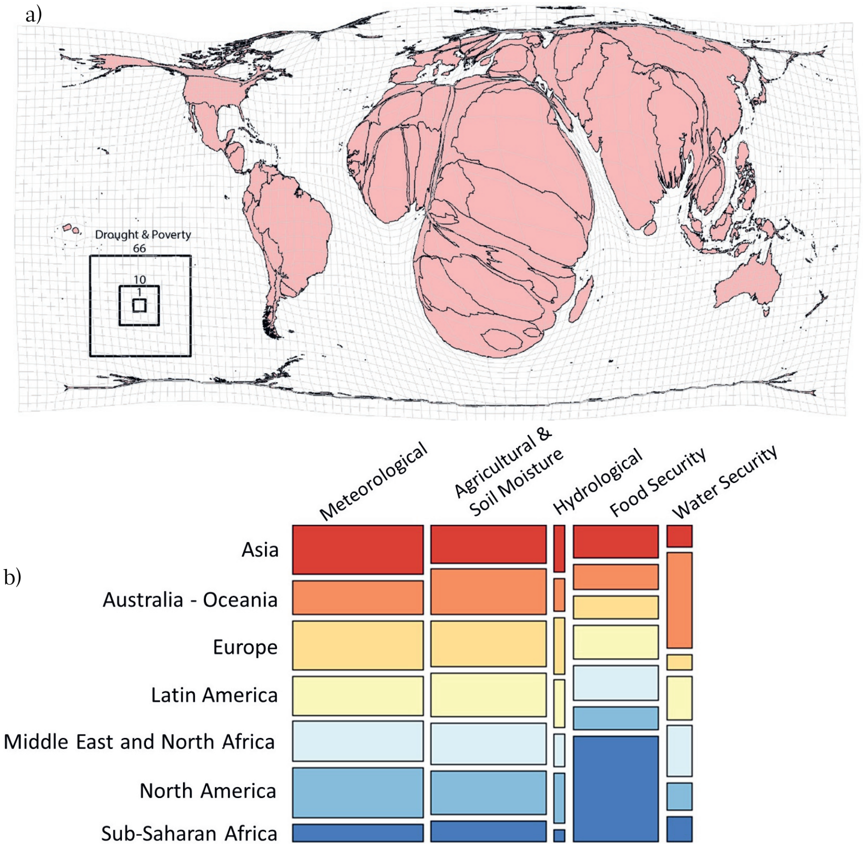

Figure 5.2: a) Cartogram of the world with each country rescaled in proportion to the number of studies on Scopus related to drought and poverty. The size of the square relates to the size of the countries and indicates the number of studies; b) Extended analysis based on the methods of Chapter 2 with a mosaic plot showing how frequently keywords, related to types of drought and impacts, were mentioned in the titles, abstracts and keywords in drought-related studies on the Scopus literature database. The height (vertical) of each box indicates how frequently the keyword is used for each region (the frequency was scaled by the number of papers for each region; that is, the plots show the keyword frequency if all the regions had an equal number of papers). The width (horizontal) of each box indicates the relative frequency of each keyword category.

This variability in drought impacts, as seen through the lens of water and food security in different socio-economic contexts, underscores the interconnection between the SDGs and the complexity, or little relevance it makes, of addressing the SDGs separately.

Furthermore, the multifaceted nature of drought and its impacts on livelihoods, socio-economic development, and sustainability show that there is no one-size-fits-all solution. To effectively tackle these issues, a research perspective focused on systemic risk is necessary. This approach would account for the interconnectedness of different SDGs and the diverse ways in which drought affects various regions and communities.

A research perspective focused on systemic risk is not new in the field of natural hazards and climate change. The interconnectedness of systems and agents (i.e., actors within the system), resulting from the interactions of individual risks leading to cascading failures, can be applied broadly in disaster risk reduction. This perspective recently applied to the COVID-19 pandemic (UNDRR and UNU-EHS, 2022) highlights that the exacerbating factors of COVID-19 were not solely health-related, nor were their indirect impacts confined to the health sector alone. The same report highlighted that the countries analysed were not only prone to climate-related extremes and natural hazards but also faced multiple hazards during the pandemic (such as floods, droughts, earthquakes, and wildfires, among others). This combined with COVID-19 burdened societies, challenging physical distancing measures and straining healthcare systems due to damage to infrastructure like homes and hospitals, and overall reduced the much-needed capacity in hazard-affected areas to cope with the pandemic. Furthermore, the COVID-19 crisis triggered ripple effects beyond health risks, affecting economic, social, and political domains. These complex impacts and new risks included increased social distrust leading to protests and civil disobedience, a rise in child marriage and human trafficking, and disruptions in education (UNDRR and UNU-EHS, 2022). While the pandemic's direct impacts were predominantly health-related, the cascading effects largely stemmed from containment measures and pre-existing vulnerabilities, like poverty or heavy reliance on a single economic sector (UNDRR and UNU-EHS, 2022). This demonstrates how the interdependencies within and between systems amplify the hazards' overall impact on societies. Both COVID-19 and droughts can be heightened by compound risks and conversely, efforts to address one risk can lead to unforeseen impacts in other sectors, thereby creating feedback loops that generate new risks and reinforce existing vulnerabilities. Addressing drought risk in a systemic manner is valuable not only for reducing natural hazards and climate change risks but also for broader risk reduction. This highlights the need to focus not only on specific risks like drought, flood, or COVID-19, but also underscores the necessity of prospectively building societies that are less vulnerable and more resilient to systemic shocks. This can be achieved by addressing the issues highlighted in the SDGs.

In this endeavour, the SDGs offer an effective framework which remains a central tool for addressing risks systemically, given the interconnections and co-benefits among the goals. Countries are encouraged to understand and leverage the benefits arising from SDGs interactions during and post-disaster, using this insight to reinforce their commitment to achieving these global goals (UNDRR and UNU-EHS, 2022).

Although SDGs are typically framed at the national level, their application extend to individual levels. However, there is a lack of clear guidance on how to adapt these investigations to more localised contexts. Similar to drought indices, the global nature of SDGs may lead to an oversight of local specifics. Recognising and integrating these local particularities is essential for achieving SDGs at the community level, whether it be through mitigation efforts for droughts, floods, or health crises like COVID-19.

5.3 Advances, limitations, lessons and recommendations for future research

5.3.1 Who can 'afford' to monitor and address drought?

As explained in Chapter 2 and summarised in Section 5.1.1, physical conditions, socio-economic conditions, data availability, and scientific interests, shape how drought is experienced, understood, and managed in different geographic areas. For instance, in sub-Saharan Africa, the local context includes factors such as climate conditions, agricultural dependence, and socio-economic status, all contributing to the region's vulnerability to drought impacts, especially concerning food security. Similarly, in Australia-Oceania, the arid climate and water management policies form a part of the local context that influences how drought affects water security. In Sub-Saharan Africa, which faces immediate and severe consequences of drought, like food and water insecurity, research on understanding and mitigating these direct impacts on human welfare draws more attention. In contrast, northern countries, with better resources and infrastructure – or more resilience, focus on understanding the physical drivers of drought, such as meteorological and hydrological aspects, aided by their greater data availability and research capabilities, shaping a different research emphasis compared to Sub-Saharan Africa. In other words, focusing on physical drivers of drought is an advantage more apt to be of interest in areas where more basic and essential needs, such as food security, have been met.

During the United Nations Convention to Combat Desertification (UNCCD) COP14 that was held between 2-13 2019 September in New Delhi, India, scientists from African countries urged the UN to improve drought research, through support for data collection so that they can better identify and prepare for drought (Padma, 2019). Two lacunes were raised:

drought data and early warning of drought risk, echoing the content of this thesis, or rather, this thesis echoing the African researchers' call. The scientists pinpointed the persistent lack of consensus on what drought is beyond "*an abnormal deficiency of water*" while methods to spot early signs of drought disaster that could lead to water scarcity, migration and famine, are needed. Furthermore, while encouraging initiatives such as the "Drought Risk Assessment Visualization Tool" (https://maps.unccd.int/drought/) combining hazard, exposure and vulnerability, were praised as a first step towards a more holistic assessment of drought, other concerns were raised.

Such indices (Carrão et al., 2016) rely on data regarding the social, economic, environmental, and physical causes of drought. However, the scientists from the African countries also questioned their feasibility and accuracy, noting that many low- and middle-income countries systematically lack such data. This lack includes information on rainfall, aridity, and water stress, thereby necessitating additional assistance from the UN (Padma, 2019). Upon accessing the website, the limitations of the map toolbox are clearly disclosed. The website explicitly states that it serves as a tool for offering a global, data-driven analysis for initial drought risk screening, with an emphasis on agricultural production and water demands. Additionally, it recommends conducting local assessments for more targeted drought preparedness and mitigation.

Therefore, who can afford to monitor drought risk (through drought hazard, exposure, and vulnerability data) also influences the global visibility of drought-affected areas. As highlighted by African researchers at the UNCCD COP14, the lack of local data in many African countries hampers their ability to accurately estimate or monitor drought, potentially making their drought struggles less visible or prioritised on the global stage. This disparity suggests that regions with the resources to conduct thorough drought monitoring can more effectively bring attention to their drought challenges, while those without such capabilities, like many regions in Sub-Saharan Africa, might remain underrepresented and inadequately addressed in global drought risk management efforts. Let's assume one is not aware of the disparity in financial means and capabilities between the Global North and South countries. In this scenario, by looking at the cartograms showing drought indices studies (Figure 2.5 and 2.6), one might assume that Sub-Saharan Africa is entirely exempt from droughts and their impacts, due to the very few studies conducted there. This is an absurd example used to illustrate the framing power of drought indices and data in general. As we addressed in Chapter 4, indices and DEWSs have the power to frame the drought, highlighting what to focus on or exclude, so that they only confirm predetermined responses.

Another observation regarding the "Drought Risk Assessment Visualization Tool" is that hazard, vulnerability, and exposure are assigned equal weights (summed and then raised to the power of 1/3, representing the Euclidean distance) and merged into a composite indicator. This approach does not account for the possibility that in some regions, either the hazard or the vulnerability may play a more significant role in drought risk. Moreover, composite indicators often amalgamate incommensurable information. For instance, vulnerability and hazard, key components of drought risk assessment, have each distinct characteristics and measurement units. Besides being highly dynamic, it is not straightforward that vulnerability can be quantified or broken down into variables with quantitative units (see Vogt et al., 2018 for detailed methods). Equally comparing these diverse elements might oversimplify the complex and nuanced nature of drought risk, accentuating certain aspects while overlooking others. This could disproportionately spotlight attention on specific areas while obscuring others. Therefore, indices and DEWSs hold the potential to shape narratives around drought risk, a topic further explored in the next sub-section.

5.3.2 The redistributive power of drought indices

As extensively discussed in this synthesis and the chapters, drought monitoring is primarily conducted remotely. Consequently, in assessing drought severity, most studies and decision-makers remain detached from the actual experiences of the people impacted. The creators of drought indices and models often do not consider those who will be impacted when they develop an indicator or a model that informs policy recommendations. While this is not the focus message of the article "*Don't Blame the Rain*" (Savelli et al., 2021), I think the Cape Town Day-Zero countdown provides a good example of this disconnect. Meteorological and hydrological drought indices clearly signalled a severe drought-induced water crisis, with the resulting restrictions affecting all social strata. In other words, drought indices convey the message that "the drought is for everyone". This included informal dwellers, who had a minor role in causing the disaster but suffered significantly more from these restrictions and the drought's impacts than the primary contributors to the human-induced aspect of the water shortage: the wealthy elite. The article does not explicitly address it, but for me, this triggered the question of whether the situation would have differed if the drought indices had included risk components. Savelli et al. (2021) take a political ecology perspective to show how these restrictions, loose for the elite and tight for the informal dwellers, stem from the legacy of the Apartheid era. Next to it, I wonder whether the development and reliance on purely physical and quantitative drought indices reflect the positionality of their 'creators and implementers' - usually well-educated researchers and policy-makers with above-average socio-economic status. Could it be that overlooking the local context in drought monitoring is because it is not *'in the eye of the beholder'*?

As a matter of fact, natural sciences researchers are seldom prompted to consider their positionality. The practice of reflecting on one's positionality is commonly emphasised for Masters and PhD students in the social sciences, acknowledging that their ontological and epistemological beliefs shape their research (Reich, 2021; Holmes, 2020). This raises a question: Why isn't this self-reflection a standard expectation for natural scientists, including environmental scientists studying drought? While some may argue that quantitative research is inherently objective, it is extensively proven that quantitative researchers also carry their own positionality - driven by biases when conducting their research, which ultimately influences the outcome. Taking some examples directly related to drought research: hydrological modelling. The positionality-driven biases of hydrological modellers significantly impact both the methodology and outcomes of hydrological research (Addor and Melsen, 2019; Melsen, 2022; Melsen, 2023). These biases often manifest in the form of legacy-driven model selection, where researchers prefer models they are familiar with or that are institutionally established, potentially overlooking more suitable alternatives. Such biases can result in an incomplete or inaccurate representation of hydrological processes, and hinder the adoption of innovative approaches and hypotheses (Melsen, 2023), which ultimately influence the validity and applicability of research findings. Given the role of hydrological models in informing policy and decision-making, especially in areas like water management and climate adaptation, these biases can have significant real-world implications, potentially affecting the effectiveness of policies and decisions based on these models (Addor and Melsen, 2019; Melsen, 2022; Melsen, 2023).

The same is true for the selection of drought indices, often selected without comprehensive consideration of their relevance or effectiveness in describing the full scope of drought impacts (Bachmair et al., 2016). Drought managers also exhibit biases, tending to show regional preferences in the use of certain drought indices, to choose drought indices they are familiar with or that are institutionally established (Bachmair et al., 2016). Furthermore, drought indices are seldom 'ground-truthed', i.e., validated against local conditions or impacts (Bachmair et al., 2016). This is alarming when considering that there is a trend toward the design and use of composite indicators for drought, as noted by Bachmair et al. (2016), but with limited evaluation of how these indicators link to drought impacts. Numbers are often seen as objective facts detached from values, but with immersion in these facts, (drought and/or composite) indices supporters might become less aware or attentive to underlying value disagreements or ethical considerations (Saltelli and Di Fiore, 2023). Quantification practices share common problematic features, such as their subjective nature and the social conditions of their creation, which can affect their reliability and lead to the perpetuation of bad practices (Saltelli, 2020)

There are broader issues associated with the aggregation capabilities of indices and excessive dependence on numerical data. Saltelli (2020) notes that numbers can create a false sense of certainty and precision, leading to "quantification hubris", which refers to the overconfidence in the ability of numerical data or statistical methods to accurately represent and address complex issues. This can lead to policy decisions that may not account for uncertainty or the multifaceted nature of social problems. It can overshadow important political debates, reduce complex decisions to simple numerical comparisons, and ultimately misguide actions. In Chapter 4, examples of the 'monitoring gap' are illustrative of this issue. Municipality-level agricultural monitoring has omitted activities crucial for the community of Olho d'Água.

For example, it focuses on cotton, which was prominent elsewhere and in the past, before completely collapsing in Ceará around the mid-1980s, and on dairy, which is not the local central source of income. Instead, activities like fruit production and processing, and honey – whether omitted or only represented at the municipality level – are key. Honey production is the main activity in the community, and during droughts, the production significantly dipped, but this is not reflected in the aggregated data. This raises the critical question of how practitioners looking at the agricultural data can recognise that the central source of a community's income is threatened, and subsequently intervene appropriately. Moreover, contrasting this with the municipality of Quixeramobim, where the goal is to become a major milk producer, demonstrates that indices geared towards a specific activity, like livestock, are more apt for some municipalities than others. Reducing complex issues to numbers or rankings makes them easily communicated; but this reductionism can sway public opinion by presenting a seemingly objective and authoritative perspective, which is in fact the product of subjective choices about what data to collect and how to interpret it (Saltelli, 2020).

Another example is the Irrigation Efficiency (IE) which is often viewed as a simple performance measure implying positive benefits. However, its application in water management is complex and misunderstood, which can hinder policy goals (Lankford et al., 2020). IE varies across scales and stakeholders, making generalisations difficult and this can even lead to paradoxical outcomes. For example, efforts to increase IE might paradoxically lead to higher overall water consumption in irrigated farming systems (Grafton et al., 2018). Water savings often benefit the original water users and their immediate neighbours more than nature and society. This challenges the assumption that water conservation in agriculture directly benefits broader ecological and societal needs *(see literature on the Paracommons; Lankford, 2013; Lankford and Scott, 2023)*. However, this generalisation is not always true, as the fate of these losses, before and after changes to irrigation technology and efficiency, can be unpredictable and variable (Lankford et al., 2020; Lankford, 2023). But this shows that IE, as a contested and subjective term, requires a broader understanding beyond conventional metrics, and inclusive approaches in water management, recognising the diverse perspectives and definitions of IE across different disciplines.

Quantification–through metrics, algorithms, and models–plays a crucial role in shaping societal structures and maintaining certain power dynamics. The techniques employed in quantification are not neutral or unbiased. Instead, they can be manipulated or selected to support specific agendas, reinforcing certain interests (Saltelli, 2020; Saltelli et al., 2020). This manipulation can occur in several ways. For instance, the selection of what to measure (and how) can be a powerful tool to direct policy and opinion. Metrics can be designed to highlight certain aspects while downplaying or ignoring others, effectively shaping the narrative around a topic. For example, authorities can employ the opacity of algorithmic decision-making as a shield against scrutiny, thus avoiding the political or administrative debate that would otherwise accompany policy decisions (Saltelli, 2020). I also observed this in some drought management practices during my fieldwork.

In Chapter 5, we already discussed how governments can frame and manage problems like droughts within their jurisdiction using specific indicators, such as the 'Water Requirement Satisfaction Index', to standardise responses and resource allocation within predefined administrative boundaries, exemplified by the Garantia Sáfra index-based insurance. This carries the risk of farmers not receiving compensation if agriculture extension officers, during their random field visits, assess fields where crop losses are below the stipulated 50 percent threshold for payout (also bearing in mind that farmers even with losses under this threshold may still experience significant damages). One other example related to Northeast Brazil is the Jaguaribe-Metropolitano system, encompassing the Metropolitan Region of Fortaleza and the Jaguaribe River Basin, which is subject to critical water allocation deliberations involving six basin committees. Fortaleza, as a major metropolitan hub in Northeast Brazil, has substantial water needs for its industries, agriculture, tourism, and state institutions. The system, consisting of two canals and eight reservoirs, primarily aims to transfer water to Fortaleza. Funceme, Ceará's Meteorology and Water Management Institute predicts rainfall patterns and potential influences on it like El Niño. Based on these predictions, Cogerh, the National Company of Water Resources, prepares various water allocation scenarios using models and simulations. However, the process and decision-making lack transparency, as crucial data about water usage, dam operations, and user information is exclusively held by Cogerh (Seigerman, 2018). During the critical annual June and July meetings, basin committees, including representatives of rural populations, must choose from the scenarios presented by Cogerh. These scenarios, however, are often influenced by a predetermined political agenda that prioritises water supply to Fortaleza, relegating the needs of upstream rural communities to a minor position. This approach is driven by the assumption that Fortaleza's water supply is the priority, as "*Fortaleza must have water after all*" (Seigerman, 2018). Nonetheless, over the past five years, the involvement of a River Basin Committee working group in determining scenarios before the large allocation meeting has increased transparency in decision-making regarding water allocation (Lemos et al., 2020).

Often and particularly in evidence-based policymaking, a political issue is converted into a technical issue through the process of quantification (Ravetz, 1971; Saltelli and Di Fiore, 2023). The focus shifts from basing policies on evidence to using evidence to justify policies. This marks the point where technocratic governance methods merge reductionism, the simplification of complex phenomena into a single, linear measure, with the dismissal of ignorance. (Saltelli and Di Fiore, 2023). Indices and DEWSs ability to concretise complex issues is a double-edged sword. The conversion of multifaceted concepts (like food and water securities, and poverty - (see Hadley and Wutich, 2009; Padilla and FAO, 2000; Young et al., 2021; Jones and Tvedten, 2019; Salite and Poskitt, 2019) into quantitative measures carries inherent risks such as reductionism, justifications, and an illusion of neutrality. In other words, “to a man with a hammer, everything looks like a nail” (Maslow, 1966) and equipped with a drought index, every drought looks the same.

Saltelli (2020) underscores the necessity of “ethics of quantification”, with ethical guidelines aiming to implement responsible quantification practices akin to those in innovation and technology use. While the field of statistics routinely addresses ethical considerations, disciplines like mathematical modelling, big data, and AI lag in developing similar frameworks. This need is particularly pressing today, in 2024, as the utilisation of AI, text-mining, and big data in forecasting and managing drought impacts is gaining significant momentum.

5.3.3 Notes on positionality and its importance when accounting for the local context

During my field-based research, I unavoidably brought along my own background, already detailed in the introduction (1.5.3). It influenced my methodological choices, like conducting field-based research which retroactively fed my critical thinking beyond only the political power of indicators but also of ethical considerations surrounding fieldwork. While some challenges required me to rethink my initial approach, they also broadened my learning on topics beyond the immediate scope of my study, like the also complex interplay between research methods, cultural contexts, and the nuances of local realities.

Unanticipated conditions leading to research design changes in the field, such as amending research questions and/or using different methods

The initial research proposal included an additional chapter focused on the participatory process of co-creating and validating local drought impact indices with rural populations. However, this aspect of the study was not realised, primarily due to the COVID-19 travel restrictions which delayed the start of my fieldwork by one and a half years. This delay necessitated a realignment of the PhD research within the constraints of the thesis and funding schedule, leading to a stronger than originally planned emphasis on the multi-scale and level dynamics of drought.

Field-based research, especially in Northeast Brazil and specifically in the state of Ceará, can be marked by territoriality and disputes due to its extensive use as a site for drought research by various research units. On numerous occasions, I received requests to avoid certain communities. One primary reason, which I fully agree with, is to prevent stakeholder fatigue, as their well-being is the priority. However, I noted instances where communities, initially designated for visits by specific groups, ultimately remained unvisited by those who had ‘reserved’ (*Dibs/shotgunned*) them. This is not to imply any negative intentions but to highlight the unanticipated conditions that may necessitate a recalibration of research plans. It does also underscore a certain territoriality prevalent in field-based research, where collaboration between researchers can be overshadowed by exclusive claims to certain areas. In an ideal collaborative environment, proposals for joint research efforts, such as visiting these communities together, could have been more beneficial to shared learning and outcomes.

On one occasion, I was invited to participate in an ambitious focus group, which was to include state and municipal practitioners, academics, and members of the rural population. This opportunity was presented as a compensatory gesture for previous requests to avoid certain communities. However, less than an hour before the scheduled start of the session, my colleague and I were unexpectedly barred from attending. The explanation provided was the disproportionate number of academics and practitioners compared to the few representatives from the rural community. Proposals to allow either of us to attend merely as observers, without active participation, were not accepted, nor was access granted to the primary data collected in the session. Therefore, concomitant work from other research units, rather than being collaborative, manifested as exclusive and in a certain way, redirected my choice towards specific communities for my research. As a consequence of being the only researcher investigating these communities–an unspoken rule, it seemed–I felt very insecure in my research due to the absence of comparative analysis with previous studies or work by other researchers.

The value of atypical and extreme observed cases as a research catalyst and generalising findings from field observations.

While several communities I visited fit the Social-Ecological Systems (SES) theory to varying extents, I showcased it in detail for only one community (Chapter 3) and suggested the theory's applicability is generalisable to other rural drought-affected communities. I insist that the communities visited and interviews conducted within them relate facts that can be analysed through a SES lens (considering my own bias, of course, see 1.5.3), among others. However, the case of the Riacho da Cruz community was exceptional. It was the only community that underwent multiple shifts in stability states, experienced multiple collapses and reorganisations, and displayed clear revolt-remember connections and more or less graspable metrics of these evolutions, such as livestock heads, within a time frame still remembered by residents. This was an 'exceptional case' with a convincing and clear storyline, of course within the context of my research and the communities I explored. A general rule is to avoid generalisations based on a single observation - although the threshold for generalisation is undefined. Hesitation and uncertainty may occur when generalising and elaborating theories based on field research. This reluctance can be rooted in the comparison with other disciplines and methods that typically utilise larger quantitative datasets (when not aware of their limitations – see section 5.3.2), and may lead to the depreciation of qualitative methods. Discussions with colleagues brought me to Flyvbjerg's work (2001,

2006) which posits that 'atypical' cases tend to involve more mechanisms and actors in a shorter period than more frequently observed cases. Studying extreme cases can be akin to observing an accelerated version of what other cases might look like in months or years, like a living lab. Contrary to popular belief, generalisation is entirely possible from extreme cases, as long as it is thoroughly investigated in the field, which was the case for the Riacho da Cruz community.

Extractive fieldwork: when the nature of the field research means that it is unlikely to have shared benefits; dealing with the feeling of taking advantage of vulnerable and marginalised populations' distressful situation for the benefit of one's own research

This situation partly results from the circumstances described in the first sub-section. As previously mentioned, COVID-19 related travel restrictions limited our available time in the field. With the reduced time I had, I made a deliberate choice to focus primarily on the 'investigation part'. If I were to estimate, about 90% of my time was dedicated to investigation, including extensive rounds of triangulation and confirmation, while only 10% was allocated to the strict presentation of research findings to the visited stakeholders. In addition, this thesis was accompanied by a persistent feeling of conducting extractive fieldwork. I did not create any tangible product that would improve in the short or medium term, the quality of life for the rural communities I visited. It is important to clarify that this is a personal reflection and not a sentiment expressed by local stakeholders or my supervising team. Essentially, my perspective is that, in the short term, the primary benefit of this research appears to be for my own academic benefit, as I am developing a PhD thesis and research that will, presumably, lead to the obtention of my doctoral degree.

It was not the case with all the farmers I visited, but the stories of some deeply moved me. For these individuals, drought added another layer of humiliation to their existing geographical, social, political, and economic invisibility and isolation. The main focus of my research was on collective resilience to drought impacts, yet I was profoundly struck by the individual resilience of these people. They shared stories of their local context, marked by chronic diseases and poverty, and how these factors impeded their tenacity and insistence to engage in agricultural activities to earn a living. In some interviews, it seemed absolutely senseless, from a standpoint of basic human empathy, to initiate or continue the interview when participants began sharing such poignant narratives.

I frequently cogitated the justification for my presence in the investigated area, wondering if the allocated funds might have been more effectively used for social work or immediate relief solutions. Even now, I am unsure about what to say with genuine conviction if someone would experience similar struggles, beyond offering comforting words I may not fully believe in. However, in the context of this section, I believe many practitioners and designers of drought indices might have a perception of drought impacts in semi-arid areas that are socially and economically vulnerable, that is skewed towards focusing solely on water infrastructure or water availability for soil and plants. I see no other reason for drought to still be predominantly regarded as a water-related natural hazard rather than a combined natural and human disaster. As previously discussed regarding the unseen positionality of drought modellers and managers, I think this bias is an important reason why studies on drought impacts often focus narrowly on water and food security, the latter mostly in terms of irrigation, while neglecting a crucial aspect that stood out to me: livelihoods.

Romanticisation of fieldwork and deliberate pursuit of discomfort

To set the tone of this final section, I will share a somewhat humorous yet genuine conversation I had with a highly experienced professor who had spent over three decades conducting field research. During a discussion, I mentioned the severe illnesses I caught during my fieldwork. Unfazed, the professor topped my experience, sharing that he too had contracted all the similar diseases but also malaria and chikungunya, from which he still experiences occasional flare-ups. He casually remarked, “*It’s just part of the job*”. This anecdote serves to underline some reflections that accompanied me during my research: the inherent risks and sometimes self-inflicted or actively sought discomfort when conducting fieldwork research.

I believe this stems from the romanticisation of the fieldwork researcher as extremely tough, resilient, and deeply invested in their research to the point of enduring dangerous situations. This comes from my personal experience: more than ten years ago, my first research internship with a French research institute set a precedent for the rest of my many experiences in that research unit, marked by a voluntary pursuit of discomfort. The rationale was that the populations I studied lived in precarious conditions, and to show empathy, encourage their openness and honest responses, and overcome stakeholder fatigue and mistrust of strangers leading to withholding the truth, I needed to mirror their hardships.

The process of deconstruction of this belief is still ongoing. I am not advocating for field researchers to flaunt signs of wealth during fieldwork, like using extravagant field cars, wearing expensive clothes, or consuming sophisticated food. But, I also argue that deliberately seeking discomfort does not address these challenges effectively. There is little one can do about stakeholder fatigue except to respect it and leave the affected population alone. Insisting on participation by any means only highlights the extractive nature of fieldwork, and the idea of imposing interviews for their supposed long-term benefit is, to my opinion, unreasonable. Regarding stakeholders ‘omitting the truth,’ to my knowledge, I have never experienced this. However, if it were to happen, I believe it could also reflect stakeholder fatigue or a lack of agreement to engage with researchers, among many other possibilities. However, persisting in such situations amounts to forcing their consent. When data and explicit consent are obtained, proven methods such as triangulating information and, when possible, repeatedly asking the same questions, are effective in ensuring reliability. I see no benefit in drinking unsafe water or sleeping on a cardboard-thin mattress on the ground as a means of social immersion with vulnerable populations, neither for the research nor the communities involved. Sometimes, in what seems like a trial by fire, field researchers and supervisors might compel students to endure hardships, like walking long distances under the same semi-arid-area-afternoon sun from which local populations would shield themselves at home, without proper funding for transport, often compromising personal safety, especially for women. This practice, I believe, is mistakenly accepted as normal by young researchers who experience it, potentially perpetuating this norm when they become supervisors themselves.

One explanation for self-inflicted hardship during fieldwork might relate to the contrast outlined previously: we have everything, they have nothing, and therefore we should endure suffering as they do. This might be a way to rationalise feelings of taking advantage of marginalised communities.

In 2022, I read with horror in the positionality section of a former PhD colleague's thesis (Dessalegn, 2023) that her fieldwork was abruptly shortened due to social unrest in the area which also led to the murder of her field translator. This extreme example also highlights how the local context of research influences the distinction between controlled and uncontrolled research conditions, further emphasising the point made in the first paragraph of this section about the unforeseen need to redesign research due to external factors, that are mostly predominant when investigating the local context through field-based research.

On a final note, investigating the local context can be a lengthy and demanding process, both in terms of time and human resources. It can also be loaded with uncertainties and safety issues. However, it does not necessarily have to be this way. Field-based research inherently carries certain risks, but those that are self-inflicted are entirely avoidable. These risks should not deter researchers from conducting fieldwork or lead to a preference for creating drought indices in an office setting to ensure controlled conditions. Field research, despite its challenges, remains a vital aspect of understanding local contexts.

While this thesis highlights the importance of the local context in drought monitoring, I also brought in this section my context, which I integrated into a predefined academic and research framework. These various contexts have led me to form my own conclusions and recommendations regarding the objectives toward which appropriate drought monitoring should aim.

In the end, positionality influences my methods, and the outcomes of these methods, in turn, shape my positionality; this is also a dynamic, rather than static, relationship. It is as Hommes (2022) beautifully and with surgical precision described to be a process of *co-evolving research and researcher.*

5.4 Final remarks and future outlook

This thesis provided a comprehensive analysis of drought monitoring, impacts, their human dimensions, and the ways in which these are currently captured and understood. The aim was to provide recommendations towards drought monitoring methods that would accurately capture how drought impacts are experienced in the local and relevant context.

Drought monitoring primarily uses indices based on meteorological, agricultural, and hydrological data. Current monitoring systems tend to focus on precipitation and remotely sensed data, including very little contextual information further than the physical drivers' statistical average in the area. This leads to a misalignment between studies on drought's physical drivers and its impacts on food and water securities that are very context-specific. Countries of the Global North are the focus of more studies on physical drivers and regions like sub-Saharan Africa and Australia-Oceania on impacts. The emphasis of research on physical drivers or food- and water- securities varies based on the local physical conditions, socio-economic factors, data availability, and scientific interests, also affecting how drought is experienced and managed across different regions.

The case studies of Riacho da Cruz and Olho d'Água illustrate the dynamics of resilience and vulnerability in the face of drought. Local impacts of drought are intricately connected to the social-ecological resilience within community food, water and livelihood systems. The dynamic resilience of these systems is influenced by a myriad of factors, including environmental conditions and community- to state-level decisions, made in the past and still reverberating today. The historical trajectory of Riacho da Cruz's livelihood, evolving from manual labour to intensive and then subsistence farming, demonstrates adaptations to changing conditions and levels of resilience. Reliance on the Pirabibu dam and the effects of consecutive droughts led to a critical point where their livelihood system had to adapt or face collapse. Conversely, the historical trajectory of another community in the area, Olho d'Água, exemplifies how also adaptable decisions and resources management maintained their water, food and livelihood systems resilient, still impacted by droughts but not to the point of collapsing. It also revealed that surprisingly, resilient communities – although desirable in drought management – pose challenges for conventional drought monitoring and indices, thereby widening a 'monitoring gap'.

A "drought-monitoring gap" exists when current monitoring methods fail to accurately capture the full range of impacts on local communities. This gap is characterised by mismatches in spatial and temporal levels, and the overlooking of crucial elements of community resilience or vulnerability to drought. This thesis suggests that a systemic approach combining centralised and decentralised monitoring, delegated to local technical extensions, which includes non-extreme events and stakeholder consultations, could help bridge this gap. Another gap that such decentralisation could bridge is the gap between different levels of policy implementation. Policies created at national or state levels often lack effective safety or control mechanisms at the local level, leaving individuals to face drought challenges by themselves. This leads to a solitary struggle for local communities, particularly farmers, who must cope and act independently, disconnected from broader initiatives. As a result, decision-making becomes a largely individual effort, leading to unintended consequences such as unregulated resource use and unsustainable practices, where cumulative individual practice reverberates and worsens drought conditions. It is important to clarify that I am not advocating for coercive measures or restrictions on farmers' freedoms, nor am I disregarding their free will and contributions. My emphasis, as outlined in Section 5.2.3, is on how poverty can limit the range of sustainable practices available to individuals; it is a classic example of the tragedy of the commons.

Rural households' decisions are primarily driven by the need to secure livelihoods, which is vital at the community level. This is especially evident in Riacho da Cruz, where choices regarding water use and farming practices were heavily influenced by immediate economic needs. This underscores the role of governmental programs aimed at diversifying productive activities (like in Olho d'Água), and thus the sources of livelihoods, thereby enhancing resilience and focusing more on "coping with drought" rather than "fighting against it" (Cavalcante et al., 2022). "Fighting with drought" can be exemplified by the introduction of a reservoir, which may temporarily increase water availability but, in the long term, could prove maladaptive by increasing reliance on such a resource.

Next to the decentralisation of monitoring methods to the local level, an additional recommendation involves the inclusion of qualitative data in drought monitoring. This is supported by a study in the area (Walker et al., under consideration) which found that the main drivers of vulnerability or resilience to drought impacts are not only non-extreme but also predominantly qualitative in nature. This also illustrates that local populations often do not rely heavily on the quantification aspect provided by drought indices and the drought monitor. This advocates for more qualitative, context-relevant data in drought monitoring. Current drought monitoring systems are not designed to accommodate qualitative data, and choices must also be made regarding the spatial and temporal levels to be monitored. There is not one optimal combination of scale, level, or perspective for drought monitoring due to the complexity and varied impacts of droughts across different scales and stakeholders. Thus, creating a drought impact index that is both localised and replicable presents a significant challenge, probably even being unachievable. This is particularly crucial at present, as there is significant momentum in drought management to develop drought impact indices. Such indices may just perpetuate the existing problem of drought indices inaccuracy by missing critical elements for certain localities, sectors, populations, or other exposed systems. Drought indices, as quantification practices, have a very subjective nature, despite numbers being perceived as factual and neutral. They influence social structures and power dynamics through decisions about which aspects to accentuate while downplaying or ignoring others, thus shaping the narrative around a topic and reducing complex decisions to simple numerical comparisons. In essence, indices or drought monitoring systems that accurately depict locally experienced drought impacts should also be local. Whether this is feasible in terms of human or financial resources is another matter; here, I highlight the ideal drought monitoring approach to comprehensively account for drought impacts in the local context, and the danger of standardising and simplifying complex phenomena into linear values.

This thesis began with a riddle on drought, caricaturing its elusive nature. Although I tried to uncover many aspects of drought and strategies to address it, there remain challenging unknowns. To conclude, the intent is not to solve the riddle but to advance our understanding. Therefore, I revisit my riddle of drought as follows:

"I am drought, and this thesis confronts what is portrayed of me.
I am said to be an event but I never truly end.
Instead, I leave traces that evolve into new iterations of myself.
My history is often described as one of destruction, yet it is also filled with lessons
-from which many remain reluctant to learn.
In my course, some stubbornly fought against me achieving temporary victories,
only to see their fight eventually exacerbate their plight.
Some others learned to cope with my presence, showing the true meaning of resilience.
But both remain unnoticed in the images lenses cast of me.
This is why my tragedy is not Greek, but of the commons
as choices made to confront me, beyond thirst and hunger, are sustained by income.
Tracked through numbers, I transcend what can be revealed by data alone.
Therefore to recognise my arrival, some portrayed me wearing lenses not available to all.
Little did they know that because I manifest in so many forms,
they marginalised other accounts.
This is why, addressing me requires acknowledging those left out
and crafting responses as multifaceted as the lives I touch."

Annexes
Code and data

Annexes

TABLE A1: Table of queries used in the advanced search of Scopus to retrieve the scientific studies of the drought indices and impacts. The search was realised in August 2019.

"M/A/H[1] drought" indices mentioned in the study	Acronym	Query
Standardized Precipitation Index	SPI	TITLE-ABS-KEY (("Drought") AND ("SPI" OR "Standardized Precipitation Index"))
Standardized Precipitation Evapotranspiration Index	SPEI	TITLE-ABS-KEY (("Drought") AND ("SPEI" OR "Standardized Evapotranspiration Precipitation Index"))
Aridity Index	AI	TITLE-ABS-KEY (("Drought") AND ("Aridity Index"))
Precipitation Deciles	Deciles	TITLE-ABS-KEY (("Drought") AND ("Precipitation Decile*" OR "Rain decile*" OR "rainfall decile*"))
Keetch-Byram Drought Index	KBDI	TITLE-ABS-KEY (("Drought") AND ("Keetch-Byram Drought Index" OR "KBDI"))
Palmer Drought Severity Index	PDSI	TITLE-ABS-KEY (("Drought") AND ("Palmer Drought Severity Index" OR "PDSI"))
Percent of Normal Precipitation (Index)	PNPI	TITLE-ABS-KEY (("Drought") AND ("Percent of Normal Precipitation" OR "Percent of Normal Precipitation Index" OR "PNPI"))
Rainfall Anomaly Index	RAI	TITLE-ABS-KEY (("Drought") AND ("Rainfall Anomaly Index" OR "Rainfall Anomaly" OR "RAI"))
Self-Calibrated Palmer Drought Severity Index	scPDSI	TITLE-ABS-KEY (("Drought") AND ("Self-Calibrated Palmer Drought Severity Index" OR "sc-PDSI"))
Crop Moisture Index	CMI	TITLE-ABS-KEY (("Drought")AND ("Crop Moisture index" OR "CMI"))
Evaporative Stress Index	ESI	TITLE-ABS-KEY (("Drought") AND ("Evaporative Stress Index" OR "ESI"))
Evapotranspiration Deficit Index	ETDI	TITLE-ABS-KEY (("Drought") AND ("Evapotranspiration Deficit Index" OR "ETDI"))

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[1] M: Meteorological; A: Agricultural and Soil Moisture; H: Hydrological.

Enhanced Vegetation Index	EVI	TITLE-ABS-KEY ((“Drought”) AND (“Enhanced Vegetation Index” OR “EVI”))
Normalized Difference Vegetation Index	NDVI	TITLE-ABS-KEY ((“Drought”) AND (“Normalized Difference Vegetation Index” OR “NDVI”))
Leaf Area Index	LAI	TITLE-ABS-KEY ((“Drought”) AND (“Leaf Area Index” OR “LAI”))
Palmer Moisture Anomaly Index – known as the Palmer Z index	PZI	TITLE-ABS-KEY ((“Drought”) AND (“Palmer Z Index” OR “Palmer Moisture Anomaly Index” OR “PZI”))
Soil Adjusted Vegetation Index	SAVI	TITLE-ABS-KEY ((“Drought”) AND (“Soil Adjusted Vegetation Index” OR “SAVI”))
Soil Moisture Anomaly	SMA	TITLE-ABS-KEY ((“Drought”) AND (“Soil Moisture Anomaly” OR “SMA”))
Soil Moisture Deficit Index	SMDI	TITLE-ABS-KEY ((“Drought”) AND (“Soil Moisture Deficit Index” OR “SMDI”))
Soil Water Deficit Index	SWDI	TITLE-ABS-KEY ((“Drought”) AND (“Soil Water Deficit Index” OR “SWDI”))
Soil Water Storage	SWS	TITLE-ABS-KEY ((“Drought”) AND (“Soil Water Storage” OR “SWS”))
Vegetation Condition Index	VCI	TITLE-ABS-KEY ((“Drought”) AND (“Vegetation Condition Index” OR “VCI”))
Vegetation Drought Response Index	VegDRI	TITLE-ABS-KEY ((“Drought”) AND (“Vegetation Drought Response Index” OR “VegDRI” OR “Veg DRI”))
Vegetation Health Index	VHI	TITLE-ABS-KEY ((“Drought”) AND (“Vegetation Health Index” OR “VHI”))
Reservoir Level		TITLE-ABS-KEY ((“Drought”) AND (“Reservoir level*” OR “water level in reservoir” OR “water levels in reservoirs”))
Palmer Hydrological Drought Index (PHDI)	PHDI	TITLE-ABS-KEY ((“Drought”) AND (“Palmer Hydrological Drought Index” OR “PHDI”))
Streamflow Drought Index	SDI	TITLE-ABS-KEY ((“Drought”) AND (“Streamflow Drought Index” OR “SDI”))
Standardized Runoff Index	SRI	TITLE-ABS-KEY ((“Drought”) AND (“Standardized Runoff Index”))
Standardized Streamflow Index	SSFI	TITLE-ABS-KEY ((“Drought”) AND (“Standardized Streamflow Index” OR “SSFI”))
Streamflow anomaly		TITLE-ABS-KEY ((“Drought”) AND (“streamflow anomaly”))

Standardized Water-level Index	SWI	TITLE-ABS-KEY (("Drought") AND ("Standardized Water Level Index" OR "SWLI"))
Surface Water Supply Index	SWSI	TITLE-ABS-KEY (("Drought") AND ("Surface Water Supply Index" OR "SWSI"))
Drought impacts studies		
Food security	TITLE-ABS-KEY("drought" AND ("food secur*" OR "food insecur*" OR "famine" OR "hunger" OR "hidden hunger" OR "malnourish*" OR "undernourish*" OR "malnutrition" OR "undernutrition" OR "crop loss*" OR "yield loss*" OR "agricultural loss*" OR "agricultural product* loss*" OR "loss of agricultural land*"))	
Water security	TITLE-ABS-KEY (("drought") AND ((("safe") AND ("water access" OR "drinking water")) OR (("clean") AND ("drinking water" OR "drinking source")) OR "freshwater availability" OR "water secur*" OR "water insecur*" OR "water crisis"))	
Poverty	TITLE-ABS-KEY (("drought") AND ("poverty"))	

Code and data availability

For Chapter 2, both code and data link of access is https://doi.org/10.4121/14452845.v2

For Chapter 4, I do not have permission to share the content of the interviews. However, a detailed narrative is provided. Available data link of access is https://doi.org/10.4121/6edb96df-569e-41e8-9e6c-ba0a324c4729.v1

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English summary
Resumo em português

English summary

Drought Monitoring and Early Warning Systems (DEWSs) aim to tackle drought at an early stage to limit the possibility of harm or loss. This is currently done based on indices primarily focusing on the natural aspect of drought while neglecting the human dimensions such as anthropogenic drivers and impacts on human populations, including livelihood, water, and food securities. Despite DEWSs utility, this narrow focus simplifies the complex interaction between human activities and drought propagation and reduces DEWS' effectiveness in capturing the full scope of drought impacts and informing proactive, informed decision-making. These oversights are due to two main reasons. Firstly, anthropogenic drivers and impacts on human populations introduce complexity and variability as they are highly dynamic and non-static. It is complex and challenging to consider all the sectors and stakeholders exacerbating and impacted by droughts, nested at different levels of spatial, temporal, and decisional scales. Secondly, the drivers and impacts on human populations are highly context-specific, meaning that how drought impacts are experienced and managed depends on the unique characteristics and circumstances of a particular locality. Therefore, there is a need to rethink drought indices so that drought monitoring can comprehensively account for the human dimensions of drought in the relevant local context. By conducting a comprehensive review and analysis, this thesis highlights the reasons underlying the misalignment between the monitoring of physical drought drivers within DEWSs, with a predominant focus on meteorological and remotely sensed data, and the impacts on water and food securities. The Social-Ecological Systems theory is applied to a drought-affected rural community in Northeast Brazil to unravel the dynamics that drive the transformation of drought disturbances into impacts across various spatial levels and over time. It highlights the critical role of the resilience of specific systems (food, water, and livelihood systems) within these communities in the transition from drought disturbances to tangible impacts, and how such resilience is influenced by multi-level decisions, the communities' ability to adapt and manage resources, and environmental conditions. This thesis introduces the Monitoring Efficacy Matrix (MEM) to assess the alignment between conventional drought data and the impacts experienced by rural communities, revealing mismatches and blindspots. This analysis suggests a reimagined approach to drought monitoring that prioritises qualitative, local data alongside conventional indices, aiming to bridge the identified "drought-monitoring gap", a concept that reflects the disjunction between large-scale physical indices and the actual experience of drought impacts at the community level. This thesis also contributes to the fields of socio-hydrology, social-ecological systems, and drought management, highlighting its relevance to the Sustainable Development Goals

(SDGs) and other drought-affected areas beyond Brazil. It critically addresses the economic and political dimensions of drought monitoring, questioning who can afford to monitor drought and how drought indices have the power to shape the narratives that surround drought. This discussion sheds light on the inherent biases and power dynamics that influence the visibility and management of drought impacts, suggesting a more equitable and systemic approach to drought monitoring.

Resumo em português

Os Sistemas de Monitoramento e de Alerta Antecipado de Secas (DEWSs, na sigla em inglês) têm como objetivo lidar com a seca em estágios iniciais para limitar a possibilidade de danos ou perdas. Atualmente, isso é feito com base em índices que se concentram principalmente no aspecto natural da seca, enquanto negligenciam as dimensões humanas, como as causas antropogênicas e os impactos nas populações humanas, incluindo meios de subsistência, segurança hídrica e alimentar. Apesar da utilidade dos DEWSs, esse foco estreito simplifica a interação complexa entre as atividades humanas e a propagação da seca, reduzindo a eficácia dos DEWSs em capturar todo o espectro dos impactos da seca e informar a tomada de decisões proativa e informada. Essas omissões ocorrem por dois motivos principais. Em primeiro lugar, as causas antropogênicas e os impactos nas populações humanas introduzem complexidade e variabilidade, pois são altamente dinâmicos e não estáticos. É complexo e desafiador considerar todos os setores e partes interessadas que são exacerbados e impactados pelas secas, inseridos em diferentes níveis de escalas espaciais, temporais e decisórias. Em segundo lugar, as causas e os impactos nas populações humanas são altamente específicos do contexto, o que significa que como os impactos da seca são vivenciados e gerenciados depende das características e circunstâncias únicas de uma localidade específica. Portanto, há uma necessidade de repensar os índices de seca para que o monitoramento da seca possa abranger integralmente as dimensões humanas da seca no contexto local relevante. Por meio de uma revisão e análise abrangentes, esta tese destaca os motivos subjacentes ao desalinhamento entre o monitoramento dos fatores físicos da seca dentro dos DEWSs, com um foco predominante em dados meteorológicos e de sensoriamento remoto, e os impactos nas seguranças hídrica e alimentar. A teoria de Sistemas Socioecológicos é aplicada a uma comunidade rural afetada pela seca no Nordeste do Brasil para desvendar as dinâmicas que impulsionam a transformação das forçantes de seca em impactos em diversos níveis espaciais e ao longo do tempo. Isso destaca o papel crítico da resiliência de sistemas específicos (sistemas alimentares, hídricos e de subsistência) dentro dessas comunidades na transição de seca para impactos tangíveis, e como essa resiliência é influenciada por decisões em vários níveis, a capacidade das comunidades de se adaptar e gerenciar recursos e condições ambientais. Esta tese introduz a Matriz de Eficácia de Monitoramento (MEM) para avaliar o alinhamento entre dados de seca convencionais e os impactos vivenciados por comunidades rurais, revelando desajustes e pontos cegos. Essa análise sugere uma abordagem reimaginada para o monitoramento de seca que prioriza dados qualitativos e locais juntamente com índices convencionais, visando preencher a "lacuna de monitoramento de seca" identificada, um conceito que reflete a desconexão entre índices físicos em grande escala e a experiência

real dos impactos da seca no nível comunitário. Esta tese também contribui para os campos da socio-hidrologia, sistemas socioecológicos e gestão de secas, destacando sua relevância para os Objetivos de Desenvolvimento Sustentável (ODSs) e outras áreas afetadas pela seca além do Brasil. Aborda criticamente as dimensões econômicas e políticas do monitoramento de seca, questionando quem pode arcar com o custo de monitorar a seca e como os índices de seca têm o poder de moldar as narrativas que cercam a seca. Esta discussão lança luz sobre os preconceitos inerentes e as dinâmicas de poder que influenciam a visibilidade e o gerenciamento dos impactos da seca, sugerindo uma abordagem mais equitativa e sistêmica para o monitoramento de seca.

Acknowledgements

Education certificate

List of publications

About the author

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List of publications

First-authored publications

Kchouk, S., Melsen, L. A., Walker, D. W., and van Oel, P. R.: A geography of drought indices: mismatch between indicators of drought and its impacts on water and food securities, Nat. Hazards Earth Syst. Sci., 22, 323-344, 10.5194/nhess-22-323-2022, 2022.

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Dataset

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Netherlands Research School for the
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The Netherlands research school for the
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(SENSE) declares that

Sarra Kchouk

born on the 9th of August 1990 in Tunis, Tunisia

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Wageningen, 14th of May 2024

SENSE coordinator PhD education	The SENSE Director
Dr Ir Peter Vermeulen	Dr Jampel Dell'Angelo

The SENSE Research School declares that **Sarra Kchouk** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 53.3 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2019)
- Research in context activity: 'Use of participatory 3-dimensional model in the state of Ceará, in Northeast Brazil' (2022)

Selection of Other PhD and Advanced MSc Courses

- Project and Time Management, Wageningen Graduate Schools (2019)
- Effective and efficient communication in academia and beyond, Wageningen Graduate Schools (2020)
- Economics of farm households, Wageningen University (2020)
- Companion Modelling, Wageningen University (2020)
- Working on your PhD research in times of crisis, Wageningen Graduate Schools (2020)
- Career Orientation, Wageningen Graduate Schools (2021)
- Adobe Illustrator – Scientific artwork & Infographics (online training) Wageningen Graduate Schools (2021)
- Media Outreach for Young Climate Researchers, University of Delft (2022)
- Scientific writing, Wageningen Graduate Schools (2023)
- Remote Sensing, Wageningen University (2019)
- Natural Hazards in the Anthropocene, Centre of Natural Hazards and Disaster Science Uppsala University, Sweden (2022)
- Land Dynamics in an Era of Change Learning from the past to face the future, Wageningen University, University of Free State, South-Africa (2023)

Management and Didactic Skills Training

- Organiser of bi-weekly seminar series (2021-2022)
- Chair group representative for WIMEK graduate school (2021-2022)
- Organiser and convener of the workshop "Drought in the Anthropocene" in Potsdam on July 2023 (2023)
- Co-Organiser of the closing workshop of the 3DDD project in Ceará, Brazil (2023)

Oral Presentations

- *Selecting indicators of drought impacts: the importance of context.* European Geoscience Union 2021, 09 April 2021, Online
- *Accounting for spatiotemporal complexities of drought in water accounting to inform integrated drought management.* Sociohydrology Conference Delft 2021, 6-9 August 2021, Delft, the Netherlands;
- *Accounting for spatiotemporal complexities of drought in water accounting to inform integrated drought management.* European Geoscience Union 2022, 28 March, online
- *Marginalised communities at the centre of drought (resilience). Ceará, Brazil.* Water Grabbing Observatory and University of Bologna, 10 September 2022, Bologna, Italy

About the author

Sarra Kchouk was born in Tunis, Tunisia, to a Lebanese mother and a Tunisian father. Her childhood was shaped by a multicultural upbringing as her parents worked and lived abroad in Senegal, Canada, Greece, and Syria. She initially pursued a technical background, graduating in Rural Engineering (2013) with a major in Hydraulics and a minor in Rural Development from the National Institute of Agronomy of Tunisia. In 2014, she obtained her Master's degree in Environmental Engineering from Agrocampus Ouest Rennes, France, focusing on Water Systems and Soils.

Her first professional experiences were in hydraulics and well-drilling consultancies, where she gained a strong understanding of the technical aspects of water management. However, she also observed conflicts arising around water sharing and scarcity. This sparked an interest in the human aspect of water management, particularly in areas with limited resources. Driven by this interest, Sarra sought research experiences that combined social theories with technical knowledge. These experiences took place across several countries, including Lebanon, Tunisia, Morocco, France, and Brazil.

In 2016, Sarra moved to Fortaleza, Brazil, to join the Meteorology and Water Management Institute of the State of Ceará (Funceme). Here, she supported research projects linked to drought in Northeast Brazil, such as desertification, the monitoring of experimental basins, and the development of indicators that combine physical and social drivers of water scarcity. The nearly four years she spent at Funceme laid the groundwork for her PhD research, which she began in 2019.

Her PhD was part of the "Diagnosing Drought with 3D: Dimensions, Dynamics, and Dialogues" (3DDD) project within the Water Resources Management Group. Her research focused on the human dimension of droughts (the first "D" in the project title). The project was conducted between Wageningen University in the Netherlands and Northeast Brazil, involving Funceme, Embrapa (the Brazilian Agricultural Research Corporation), and rural communities.

Sarra has a strong interest in interdisciplinary topics, particularly those that bridge geosciences and social theories. She is especially curious about unravelling the impacts of climate change on vulnerable populations. In her free time, she enjoys travelling the world and exploring local cuisines.

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