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REVIEW ARTICLE

Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security

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Abstract

The semiarid lands of Northeast Brazil represent one of the most densely populated regions of the country. Rainfall variability together with land degradation and large-scale poverty in rural areas makes this region vulnerable to droughts. Most of the agriculture in this region is rainfed and deficient rainfall leads to severe drought impacts. In this review, we examine different short- and long-term strategies directed to cope with possible impacts of droughts proposed by the government, farmers, civil society, and the private sector. These are approaches to adaptation to drought in the Northeast of Brazil, and among them, we have agricultural management and soil conservation and better management of water resources. Other actions include seasonal climate forecasts and funds transfer and credits to affected small-scale farmers. Although some of these actions are for the short term and may help to survive the drought situation, they may be only postdisaster mitigation options that do not improve adaptive capacity. They favor maladaptation and create dependency of farmers to government actions. Some experiences such as AdaptaSertão show potential benefits for small-scale farmers. We identify key challenges for moving toward a more holistic risk management approach and highlight the need to integrate actions and tools for adaptation, combining technology-based solutions with in-depth knowledge of local and regional social, economic, and cultural aspects, among them seasonal climate forecasts and drought impacts studies, among some other proactive predisaster ways, rather than reactive postdisaster actions. Adaptation strategies must increase long-term resilience of food production in the Brazilian Northeast, going beyond an individual drought event.

KEYWORDS
adaptation, climate change, drought, food security, Northeast Brazil

1 | INTRODUCTION

The Northeast of Brazil (NEB) is a region encompassing close to 1.6 million square kilometers with a population of over 50 million people (Marengo et al., 2020). The eastern seaboard of NEB was the first to be explored by Portuguese colonists, and the region has a rich history and culture. The Caatinga is the predominant biome, but it also includes portions of the Atlantic Forest (Atlantic seashore) and Cerrado (western borders) (IBGE, 2004). The climate is hot and semiarid, varying from xeric in Caatinga, to mesic in Cerrado and hydric in the Atlantic Forest. Droughts are widespread and recurrent in the semiarid interior region of NEB, known as "Sertão" (Figure 1).

Nearly 80% of the agricultural labor in NEB is composed of subsistence farmers concentrated within the continental semiarid lands (IBGE, 2019). NEB has the highest proportion of people living in poverty in Brazil, with rainfed agriculture accounting for 95% of farmed land (IBGE, 2019), often leading to severe drought impacts. The combination of high spatial and temporal rainfall variability, lack of irrigation, land degradation due to inadequate soil management and large-scale poverty in rural areas makes the NEB particularly vulnerable to extremes of climate variability and to the impacts of climate change (Alvala et al., 2017; Marengo et al., 2016, 2017, 2020; Vieira et al., 2020).

There is strong evidence that climate change will increase drought risk and severity, depending on the regions, seasons, and drought indicators being considered (IPCC, 2014, Cook et al., 2020). Climate change is expected to significantly impact Brazilian agriculture, increasing the recurrence of droughts affecting crop yields and food security (Assad et al., 2013; Marengo et al., 2017, 2020). In Brazil, higher average temperatures and reduced rainfall in many regions are expected to increase the number of areas under high risk for crop production. This will have significant social and economic impacts at the local (municipalities and communities), regional, and national scales in Brazil. In regions with higher concentrations of subsistence farming such as NEB, productivity losses can lead to increased poverty and conflicts over land and mass migration to overpopulated urban centers. A changing climate may aggravate food insecurity, representing real challenges to Brazilian agricultural production, due to the increase in temperature, changes in the rain regime, and water availability that could cause loss of water and alter the geography of production (Pinto e Assad, 2008; Rossato et al., 2017).

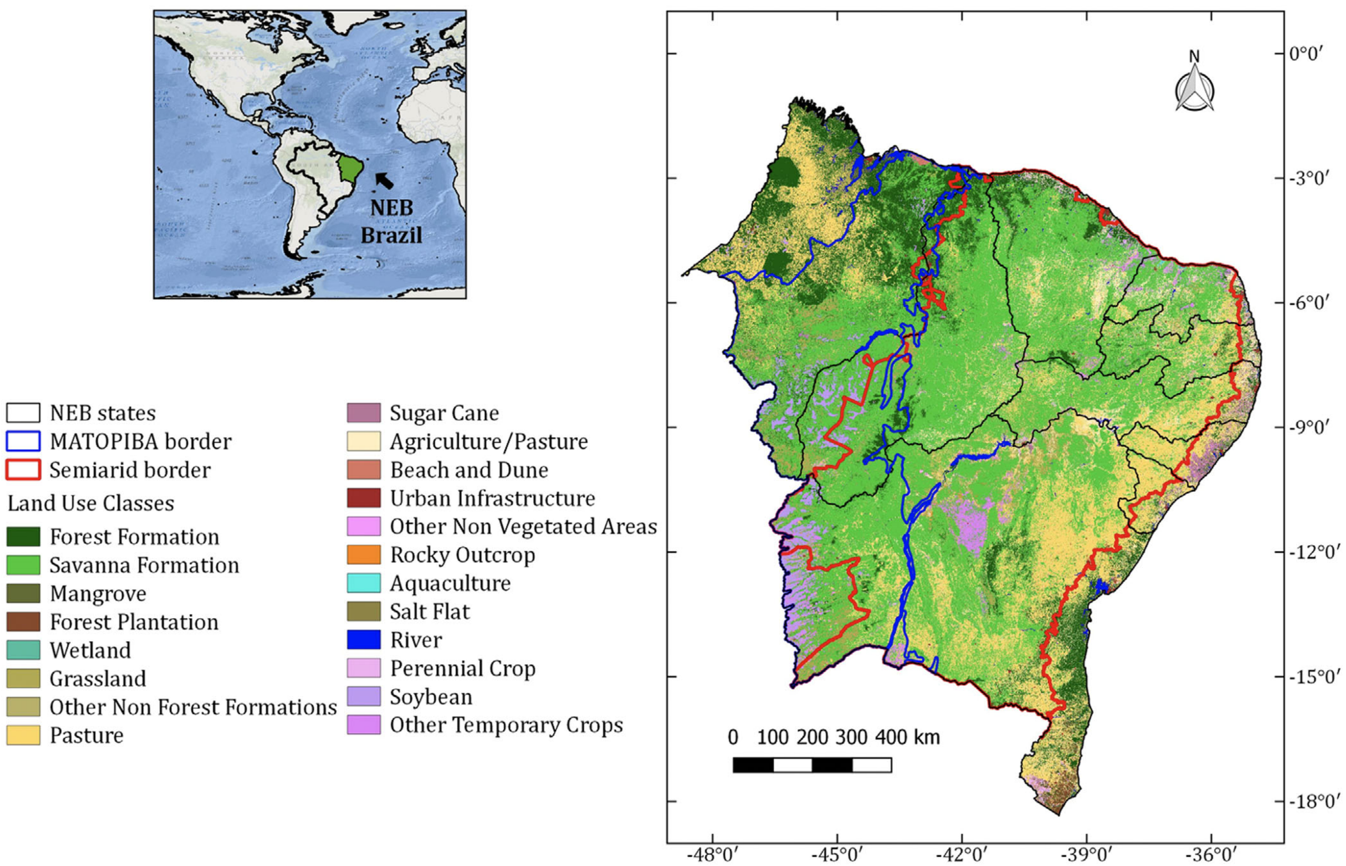

FIGURE 1 Map of NEB including the States' boundaries, the frontiers of MATOPIBA (region that includes the states of Maranhão, Tocantins, Piaui, and Bahia) and semiarid, and biomes

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In this review, we examine different approaches to adaption to drought in the NEB, discussing pros and cons of short- and long-term strategies by government, farmers, civil society, and the private sector. The discussion encompasses: (a) the promotion of agricultural management practices such as crop diversification and changing crop calendar, drought-tolerant cultivars, and soil conservation practices to preserve soil moisture; (b) better management of water resources with smart farming systems; water infrastructure projects such as interbasin water transfers, canals, waterworks, reservoirs, dams, and the pumping of water from aquifers; drought monitoring systems based on ground-based and satellite sensor networks, and crop and hydrological modeling applications; (c) the need to integrate actions and tools for adaptation, combining technology-based solutions with in-depth knowledge of local and regional social, economic, and cultural aspects; and (d) the importance of focusing on adaptation strategies that increase the long-term resilience of food production in NEB, going beyond short-sighted temporary actions.

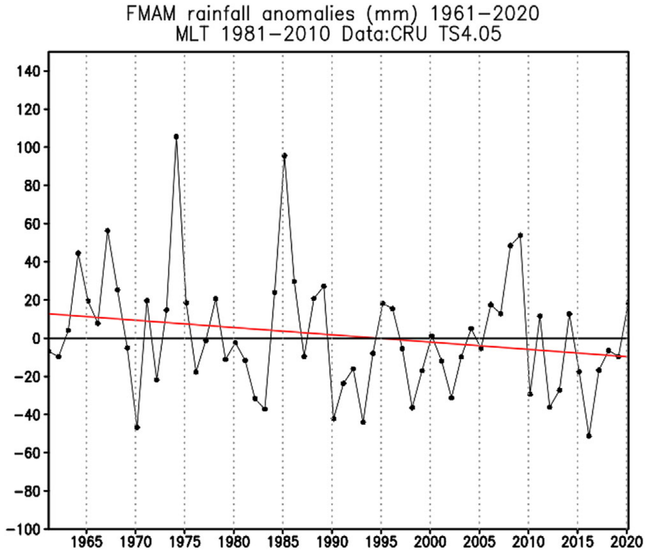

FIGURE 2 Tendencies of rainfall anomalies (in mm) for NEB from 1961 to 2020 for the February–May peak of the rainy season, relative to the long term mean 1981–2010 (Source: CRU.TS4.04)

2 | DROUGHT IN NORTHEAST BRAZIL: HISTORICAL ASPECTS AND IMPACTS

Drought critically influences agricultural productivity and, in turn, livelihoods of small and marginal farmers in the drylands of NEB. Substantial increases in frequency and intensity of drought have been noticed in this region (Brito et al., 2018; De Nys et al., 2016 and Magalhães 2016) are likely to intensify by the end of century (Cook et al., 2020; Marengo et al., 2016, 2020). A meteorological drought (a serious water deficit caused by meteorological factors, particularly negative rainfall anomalies) only becomes hazardous when translated into agricultural/vegetative or hydrological drought, and these depend on other factors, not just lack of rainfall. The drought risk is a product of the interactions between exposure to the natural hazard (water deficit) and socioeconomic and environmental vulnerabilities associated with the event. In this context, reduction in drought risk may also benefit from diversifying regional economies on different sectors of activity and reducing the dependence of their gross domestic product (GDP) on agriculture.

Mean annual rainfall in the semiarid region of NEB is below 650 mm and with the peak of the rainy season between February and May. NEB is under the influence of the Atlantic trade winds that converge along the Intertropical Convergence Zone ITCZ, and this zone located in the northern and the semiarid region during the peak season. Figure 2 shows interannual variations of rainfall anomalies from 1960 to 2020 during the peak of the rainy season. Years with drought were observed during El Nino in 1983, 1998, and 2016 as well as in other years characterized by warm surface waters in the Tropical North Atlantic. This was the case of the 2012–2018 drought with warmer tropical North Atlantic and aggravated by an El Nino event in 2016 (Marengo et al., 2020). Influences from the tropical Pacific Ocean by means of El Nino and from a warmer tropical North Atlantic that moves the ITCZ anomalously to the north are the main causes of rainfall deficiency and drought in the region (Brito et al., 2018; Brasil Neto et al., 2020, 2021; Dantas et al., 2020; Hastenrath, 2012; Moura & Shukla, 1981).

A chronology of droughts in NEB since the 16th century has been summarized by Araujo (1982), Magalhaes et al. (1988), and Marengo et al. (2017, 2019, 2020). Although recent droughts have not directly led to fatalities (even though social and economic impacts were significant), the drought in 1877–79 left an estimated death toll ranging from 200,000 to 500,000 (Villa, 2000; Davis, 2001; Greenfield, 2001) and constitutes the largest environmental disaster in South America in recorded history (Aceituno et al., 2009). The history of droughts and impacts in this region shows that its ability to recover from the resulting social, economic, and environmental consequences depends heavily on federal government support (Alvala et al., 2017; Dantas et al., 2020; Magalhaes et al., 1988; Magalhães & Glantz, 1992).

From 1997 to 1999, NEB experienced one of the worst droughts of the century, affecting 181,000 km^2, an area twice the size of Portugal. More than 1200 municipalities were declared disaster areas, leaving 10 million people at risk of hunger, morbidity, and mortality. Dry reservoirs contributed to the loss of crops and livestock, forcing small

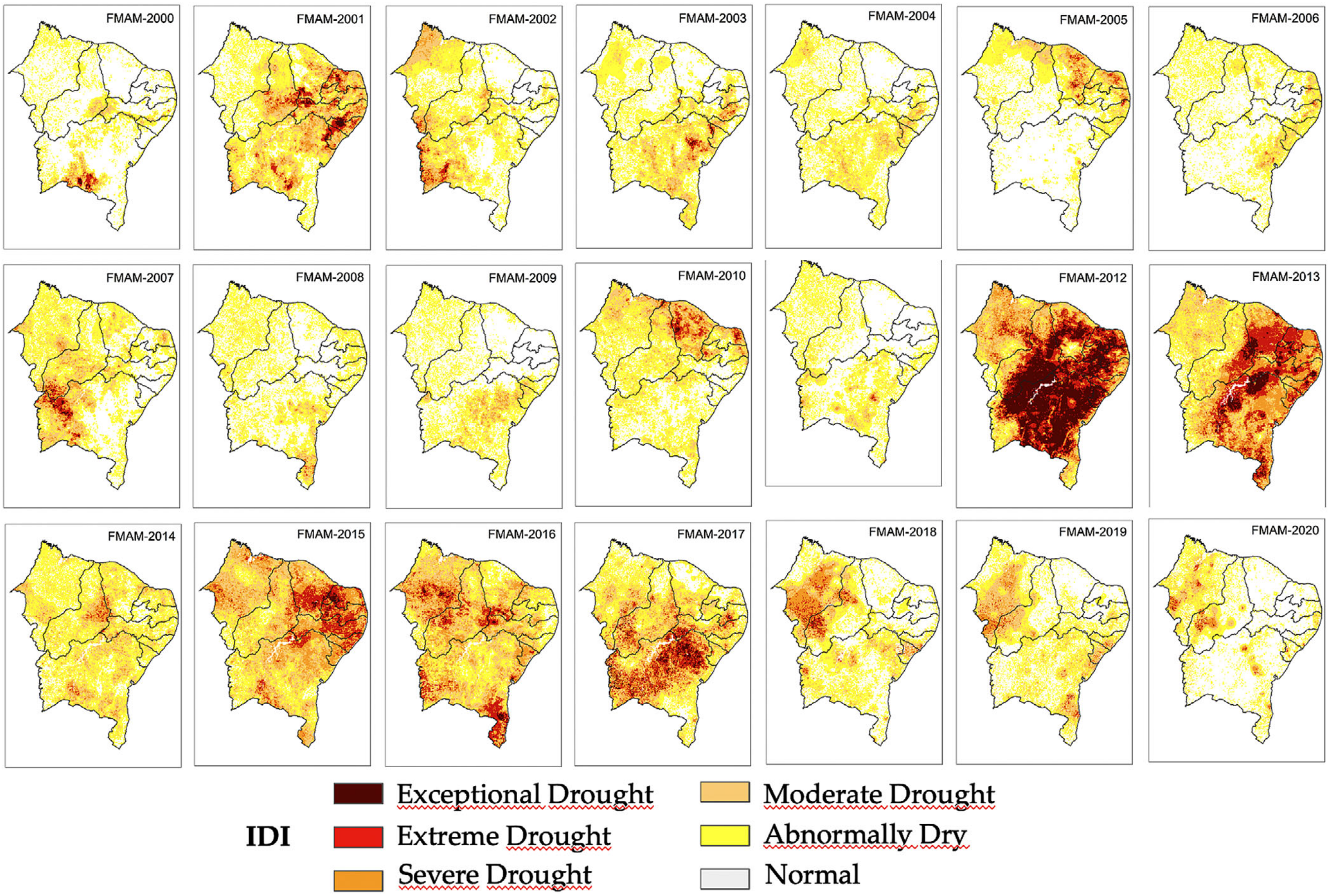

FIGURE 3 Maps showing the spatial distribution of the Integrated Drought Index (IDI) for the peak of the rainy season February–May in Northeast Brazil, from 2000 to 2020. Categories of drought are shown in the color scale at the lower side of the panel

farmers to migrate in search of work. Water rationing was implemented even in the highly urbanized capital cities of Fortaleza and Recife (Kenny, 2002). The 2012 drought put 1717 municipalities of NEB (96% of total) in a state of emergency, which included rural food insecurity (S2iD, 2020). Food and water insecurity was particularly observed during the recent drought from 2012 to 2018, and it shows that this region is vulnerable to drought, with potential aridification and desertification in the next decades (Alvalá at al., 2017; Brito et al., 2018; Cunha, Zeri, et al., 2019; Dantas et al., 2020; Marengo et al., 2017, 2019, 2020; Martins et al., 2015, 2018; Pontes Filho et al., 2020; Vieira et al., 2015, 2016, 2020). Due to the 2012–2018 drought, the volume of water in the reservoirs on the São Francisco River, an important Brazilian river that crosses the region was reduced to minimum levels. This was coupled with an increase in demand for irrigation water and evaporation from the reservoirs. As a result of the sharp reduction in the flow of the São Francisco River since 2012, it became necessary to modify the operation of the reservoirs—which were designed in the 1970s—to preserve the water stocks available and supply the various water uses, mainly the water supply of several cities along the river and large irrigation projects (Camilloni et al., 2020).

Figure 3 shows the area affected by drought in NEB from 2000 to 2020, during the rainy season February–May, assessed by the Integrated Drought Index (IDI, Cunha, Zeri, et al., 2019). This index combines the lack of precipitation and the surface response to water stress. Droughts affected the region in 2001 and 2010, and more intense from 2012 to 2018, being the worse in 2012, where about 60% of the semiarid region of NEB was affected by severe and exceptional drought.

3 | THE BRAZILIAN NORTHEAST FARMING SYSTEM

Nearly 80% of the agricultural labor in NEB is composed of subsistence farmers concentrated within the continental semiarid lands (IBGE, 2019). NEB has the highest proportion of people living in poverty in Brazil, with rainfed agriculture accounting for 95% of farmed land (IBGE, 2019), often leading to severe drought impacts. The combination

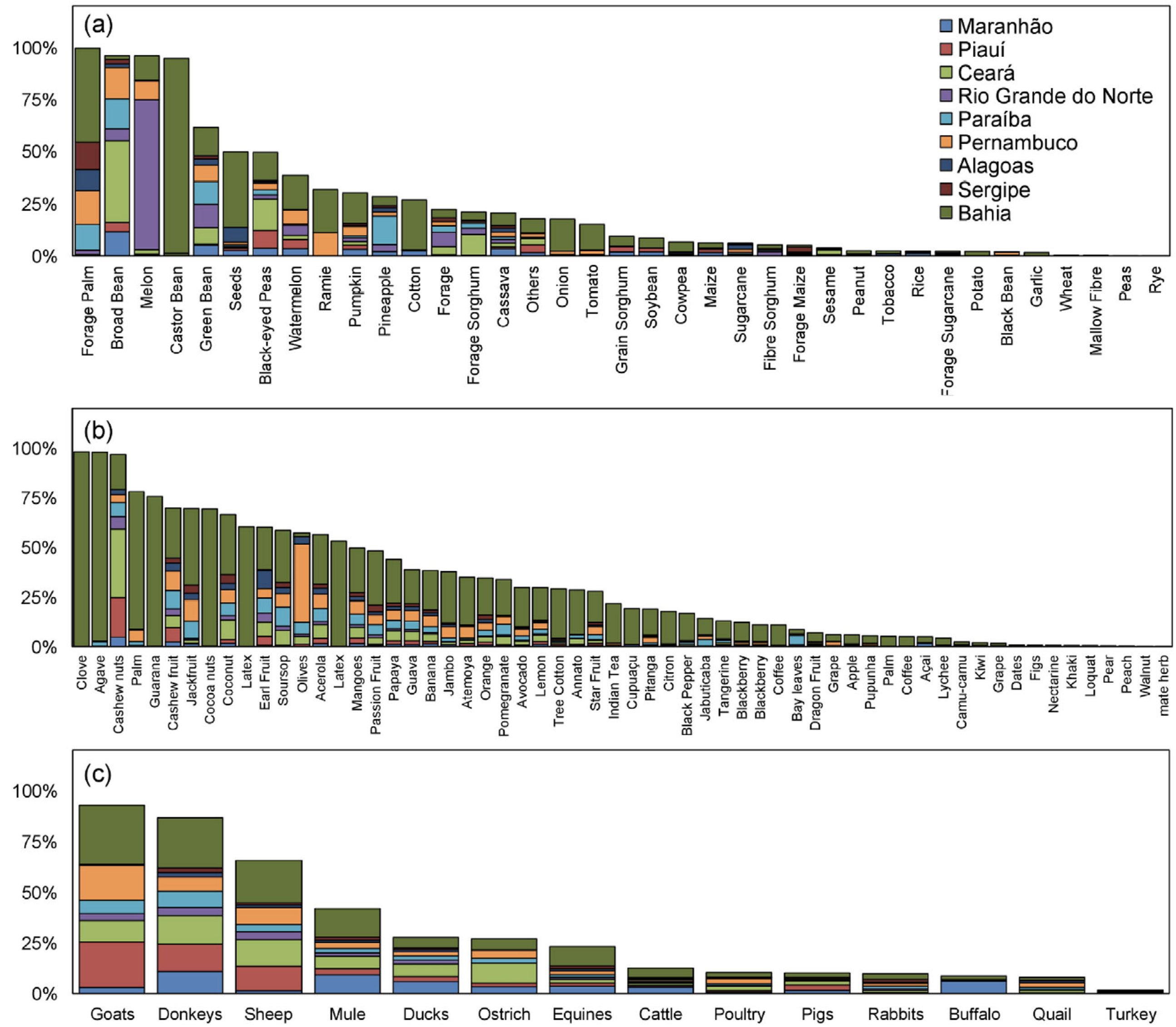

FIGURE 4 Share of the national agriculture production in NEB by annual crops (a), perennial (b), and livestock (c) (Source: IBGE, 2019)

of high spatial and temporal rainfall variability, lack of irrigation, land degradation due to inadequate soil management and large-scale poverty in rural areas makes the NEB particularly vulnerable to extremes of climate variability and to the impacts of climate change (Alvala et al., 2017; Magalhães & Martins, 2011; Marengo et al., 2017, 2020; Vieira et al., 2020).

Agriculture has a long history in NEB, having been established in the early decades of the colonization of Brazil (Naritomi et al., 2012). Despite of the semiarid climate in most of its extension, NEB contains 7.8 M ha of agricultural lands, with a share of 6–13% of the Brazilian production of soybean, maize, coffee, sugarcane, milk, and beef (CONAB, 2020). Most of grain production (90%) in NEB is farmed on the MATOPIBA region, an important new agricultural frontier including the States of Maranhão, Tocantins, Piauí, and Bahia where in spite of lack of infrastructure, the cheap land prices, climate, and topography are favorable for extensive rainfed agriculture (Araújo et al., 2019). Coffee production in NEB is concentrated in the Southern part of Bahia state, whereas over 70% of sugarcane in NEB is produced in the coastal regions of Alagoas, Pernambuco, and Paraiba states (CONAB, 2020; Souza et al., 2020). The state of Bahia holds most of the national production of perennial crops and a significant share of annual crops farmed in NEB, including important commodities for Brazil, such as citrus and cotton (Figure 4).

NEB agriculture is also responsible for over 90% of national production of forage palm, broad bean, melon, and castor bean, including the perennial clove, agave, and cashew nuts (IBGE, 2019). In contrast with other regions, the farming of goats, donkeys, and sheep (Figure 4) accounts for a significant share of livestock production

TABLE 1 Share of family agriculture ordered by area for all NEB states and Brazil

Federative unit	Share of family agriculture	
	Area	Holders
PE	51.9%	82.6%
CE	48.4%	75.5%
SE	46.6%	77.3%
PB	42.1%	76.9%
PI	38.5%	80.3%
RN	34.8%	79.9%
AL	33.7%	83.6%
BA	32.2%	77.8%
MA	30.9%	85.1%
NEB	36.6%	79.2%
Brazil	23.0%	76.8%

Source: IBGE (2019).

in NEB, which are important components of the regional diet, draught power, and transportation in subsistence agriculture (Anjos & de Melo, 2019).

Although extensive agriculture is established within the MATOPIBA frontiers, the central region of NEB ("Sertão") marked by semiarid climate is considered as one of the most vulnerable regions of Brazil. Smallholder farmers strive to maintain its production in this region, which is often drought-stricken. According to the last IBGE census of 2019, the NEB accounts for the higher share of family agriculture (FA) in Brazil (36.6%). An even larger share of FA is found in the state of Pernambuco (PE), where over half of its agricultural lands are of smallholder farmers (Table 1). The census also shows a majority share of FA in NEB agriculture holders (>80%), evidencing the importance of government programs to foster resilient agriculture and aid livelihood of smallholder farmers.

In this context, agricultural production in semiarid areas of NEB is of high relevance from a social point of view, especially for family farming, which is an important segment within the agriculture sector in Brazil (Martins et al., 2017). A larger fraction of farms in NEB are family farms (Banco do Nordeste, 2010) and this segment is the one that is most affected by drought events, partly because of their few resources for adaptation. Special focus on these areas is therefore given by the Brazilian Government as well as civil society (Fonseca et al., 2014).

Over the last century, most of smallholder farmers within the semiarid NEB relied on annual crops not well adapted to drought, such as maize, beans, and cassava. This has led to strong cultural and traditional beliefs that still shape the regional economy and farmers' decision-making around rainfall events. For example, despite of awareness of the high risks of yield loss due to the recurrent dry spells, maize is still largely sown when the rainy season onsets in NEB (Silva & Neto, 2019). Under these conditions, maize yields are generally lower than 1 ton ha^{-1} (a fifth of the average national yield), with high rates of crop failure, which is alleviated by the use of crop residues as animal fodder (Silva & Neto, 2019). Nevertheless, alternative drought-resilient crops such as forage palm, broad bean, and sorghum have gained credibility and currently comprise a large share of the agricultural outputs in the region (IBGE, 2019). Furthermore, the increasing development of irrigation technologies and adoption of high-value fruit production has turned arid regions in the valleys of the Sao Francisco and Açu rivers into large exporters of melons, grapes, mangoes, and bananas (Castro, 2012).

4 | REVIEW OF CURRENT ADAPTATION AND ADAPTATION-LIKE STRATEGIES TO MINIMIZE DROUGHT IMPACTS ON FOOD SECURITY

Drought history is well documented in NEB, and despite considerable uncertainties about future changes with respect to the incidence of droughts, adaptation processes must be developed based on the best available scientific knowledge (Camilloni et al., 2020 and references quoted in). Northeast Brazil has been targeted for remedial projects to combat drought for more than 100 years, although drought mitigation policies have been mostly ineffective in reducing vulnerability for the majority of the population (Kenny et al., 2002). It is interesting to note the study by Nelson and Finan (2009) who present a critical perspective of drought policies in this region, arguing that they constitute an example of maladaptation via undermining resilience. First, we review measures that are intended to reduce the potential drought, followed by measures that are intended to reduce the potential exposure and/or vulnerability.

Structural measures, such as dams or reservoirs and subsurface storage has been harnessed historically as a buffer against drought hazards (Ward et al., 2020). In this section, we investigate how such hazard reducing measures can impact, and are impacted by, the opposite hazard in NEB. Adaptation policies have ranged from the building of small dams ("açudes") by the imperial government in Brazil after the drought of 1877–79 to the current actions for water infrastructure and socioeconomic programs from the federal and NEB state governments to cope with drought impacts. In fact, some of these measures, especially emergency actions such as water tankers and cash transfer, cannot be considered strictly as adaptation options, because they may not be sustainable and end when the hazard ends.

In the following section, we present a list of initiatives that can be considered as adaptation options to cope with drought in NEB in the long term. Some are technical options, whereas others can be considered more political. Yet, others are related to monitoring and early warning of drought and seasonal climate forecasts from national and regional agencies. Although monitoring and prediction of drought serve to reduce disaster risk, other actions such as government credits and water delivery are considered as mitigation for disaster risk management. The target of all these actions is the protection of the vulnerable populations and small-scale farming in the semiarid region of NEB. Similarly, Gutierrez et al. (2014) summarized strategies for drought preparedness in NEB as water delivery, support for farmers, and support for municipalities.

4.1 | Water infrastructure and irrigation

Irrigation is the most effective practice to combat water shortage in agriculture. Over 40% of global food production is sustained by less than 20% of cropland areas that maintain high levels of yields through irrigation systems (Borsato et al., 2020; FAO, 2019). On the other hand, irrigation accounts for about 70% of global freshwater use (Rockström et al., 2017), requiring large amounts of freshwater transposed, stored, or extracted from ground reservoirs, potentially resulting in severe landscape and environmental impacts (Khan et al., 2006).

The largest water infrastructure project in the Brazil is under construction in NEB (Transposition of the Sao Francisco River), designed to transfer water at 26.4 m^3/s through two main axes, Northern and Eastern (Roman, 2017). The volume transported by the channels is mainly intended for human and animal consumption and may not meet the full demand of irrigated agriculture (Castro, 2012). Although this project was designed as a potential adaptation to climate change, Pontes (2018) concludes that the distribution of water in the Eastern Axis of the transposition does not contribute to the adaptation of the most vulnerable populations in the semiarid region. Furthermore, an equivalent investment is needed to the improve water quality and poor sanitation infrastructure to secure public health, reinforced by a growing number of detected cases of water-related diseases (e.g., schistosomiasis) along sites where the new channels are been deployed (Silva Filho et al., 2017). Castro (2012) also alerts the risk of mass migration to areas around the new water channels, and the need of government regulation to promote land security to vulnerable local populations.

Although predicting all possible impacts of such large and controversial project remains a challenge, integrated data and modeling analysis studies can aid decision-making, helping prioritize actions to mitigate potential impacts (Borsato et al., 2020; Krol & Bronstert, 2007; Roman, 2017). Although the transposition of Sao Francisco River is not completed, most of the irrigated agriculture in NEB is concentrated in developed regions along the Sao Francisco River. The regions of Petrolina and Juazeiro, and west of Bahia State are marked by its land use change over the last decades due to widespread irrigation practices (Bassoi et al., 2017). Smallholder farmers, generally located far from large water bodies, must resort to other practices including: (i) groundwater extraction, (ii) rainfall reservoirs (*Cisterna*), (iii) small dams (*Barraginhas*) to promote targeted soil infiltration and reduce erosion, (iv) weirs (*acudes*), and (v) underground dams to rise water table levels (Melo & Voltolini, 2019). An *acude* is a type of dam, an artificial barrier, used to retain large amounts of water for any of the following purposes: supplying agricultural, residential, industrial areas, producing electricity, defending against river floods, and regularizing a flow. *Barraginhas* are small basins excavated in the ground with a diameter of up to 20 m, with a radius of 8–10 m and smooth ramps. They are built dispersed in the properties with the function of capturing runoffs, controlling erosions and providing the infiltration of rainwater in the land.

In all the cases, the quality of water must be controlled to avoid soil salinization and erosion, and prolonged exposition of crops to high levels of boron, chloride, sodium, or heavy metals (Foster et al., 2018). More efficient irrigation technologies, including drip irrigation (Herwehe & Scott, 2018), associated with better practices to determine crop water requirements (Marin et al., 2019) and weather forecast (Martins et al., 2018), are key to improve the rational use of the scarce resource. Yet, stallholder farmers still face economical and technical challenges on deploying, running, and maintaining such practices, requiring governmental and third-sector support. Common adaptive strategies for the mitigation of droughts in the region are the use of wells, weirs, and cisterns. Wells and weirs present the best impacts on agricultural production.

In turn, the use of cisterns, which is commonly used to supply water for human consumption, presents no positive impact on agricultural production. On the other hand, its negative impacts may indicate a specialization in subsistence activities, as cisterns have been implemented by public and private agencies in the poorer farms (Maia et al., 2018). The ASA (Brazilian semiarid articulation) nongovernment organization has implemented the "Programme for One Million Cisterns" (P1MC) since 1999. The goal is to build one million cement cisterns for storage of rainwater collected through gutters attached to house roofs (Fonseca et al., 2014).

Another program of relevance for the semiarid region is the "One Land and Two Waters Programme (P1 + 2)" initiated in 2007, also coordinated by ASA. The program aims at the construction of rainwater harvesting technologies focusing on small agricultural productions (Boardwalk Cister, cement-plate tanks, underground dam, stormwater tank, etc). The P1 + 2 program was designed to strengthen the effects of P1MC and is aimed at streamlining rural development processes in the region through building participatory processes. The P1 + 2 program has benefited 104,000 families to date and helped the small farmers achieving higher agricultural yields than nonbeneficiaries. In addition, the program promotes the use of agricultural practices with lower environmental impacts, by encouraging agroecological practices (Alencar et al., 2018; ASA, 2020; Fagundes et al., 2020; Shubo et al., 2020).

4.2 | Current agricultural practices and future scenarios

The adoption of agricultural best practices and diversification can improve climate resilience in NEB. Although maize, beans, and cassava are still part of traditional practices of smallholder farmers, Melo and Voltolini (2019) present many options to diversify production and income, including: (i) adoption of drought-tolerant species and cultivars; (ii) intercropping and agroforestry; (iii) farming native species as forage and wood; (iv) selection of adapted animal species and breed; (v) adoption of beekeeping; and (vi) use of water reservoirs for aquaculture.

Soil conservation practices can also improve crop resilience to drought, while reducing soil degradation in NEB. Intense use of heavy machinery promotes soil compaction, which, in turn, causes soil degradation and substantial decrease in soil water infiltration. No-tillage and soil mulching practices bring numerous benefits to soil structure, biodiversity, and fertility, and also conserve surface soil moisture by reducing soil evaporation. Although cover crops are an effective strategy of soil conservation, its adoption may be limited where water availability is scarce. Yet, the implementation of some adapted species of legumes, grasses, oilseeds and crucifers (e.g., *Mucuna aterrima, Raphanus sativus, Sorghum bicolor, Ricinus communis, Jatropha curcas*) is considered as an option in NEB (Melo & Voltolini, 2019).

As the aboveground biomass is also an important source for animal feeding in NEB, crop residues are not always present in sufficient quantities to sustain an adequate soil mulch. Thus, intercropping and combination of adapted species for cover cropping are viable strategies for increased biomass production and soil coverage (Giongo et al., 2014). Plastic mulching is also adopted in fruit production (e.g., melon) for weed control and to preserve soil moisture. However, not all growers have access to biodegradable material and in contrast to biomass mulching, the excessive soil heat and moisture resulting from this practice may be detrimental to some vegetables. New technologies such as low-cost superabsorbent hydrogels with slow-N release function and precision irrigation may help increase soil moisture availability and improve rational use of water in arid environments (Cheng et al., 2018; Kamienski et al., 2019). However, its long-term effect on soil chemical and biological characteristics is still unknown, while water availability and the costs of acquiring and maintaining irrigation equipment are barriers for irrigation in many parts of NEB.

Traditional crops such as maize, beans, and cassava have cultivars bred specifically to the semiarid conditions. Silva and Neto (2019) describe three well-tested maize cultivars for the NEB conditions, with potential yields ranging from 3 to 4.4 ton ha^{-1}, namely, “BRS Gorutuba,” “BRS Sertanejo,” and “BRS Caatingueiro.” Moreover, numerous maize cultivars are currently developed and tested for the NEB region by EMBRAPA, the Brazilian Agricultural Research Corporation (Carvalho et al., 2017). Another important aspect is that smallholder farmers usually produce their own seeds by storing a fraction of their grain production for the next season, resulting in an empirical isolation of the most adapted genetic material for maize and beans (Silva & Neto, 2019)">(Silva & Neto, 2019). Novel techniques of exposing young plants to moderate water stress in nursery conditions may also help amplifying drought tolerance of crops such as sugarcane (Marcos et al., 2018). Cassava and beans also have many adapted cultivars for NEB, evaluated according with the soil characteristics and type of management employed (Silva & Neto, 2019). In addition, most of major annual and perennial crops have cultivars presumably bred specifically to the NEB conditions or to dry and hot environments that could be adopted by NEB's farmers. Among the successful breeding programs are cashew and cotton. The first led to a substantial increase in nut production in Ceará, Rio Grande do Norte, and Piauí, and the second bred a naturally colored cotton fiber, now processed in small clothing industries in Paraiba, supplying clothing feedstock for local and international markets (Queiroz et al., 2012).

Despite the existence of cultivars adapted to the NEB environment, it is now widely accepted that climate change will impact agriculture in this century. Challinor et al. (2016) alert for the need of faster breeding programs, while emerging technologies associated with artificial intelligence can potentially accelerate breeding programs (Harfouche et al., 2019; Zuffo et al., 2020). Integrated modeling assessments, using rigorous physiological-based models, may play an important role on aiding breeding programs to explore the Genotype x Environment x Management (GxExM) interactions at the context of future climate scenarios (Ramirez-Villegas et al., 2020). This type of framework has been applied in other Brazilian regions to examine and aid breeding implications of drought stress under future climate for beans and upland rice (Heinemann et al., 2017; Ramirez-Villegas et al., 2018).

In NEB, Martins et al. (2017, 2019) and Souza et al. (2019) concluded from simulation studies that maize cultivars with longer growth periods and higher thermal requirements could partially mitigate the negative effects of a warming climate on crop production and food security in the study area. Further, process-based crop models can also be employed to optimize inputs and crop managements (e.g., planting dates and irrigation) or identify suitable genotypes to maintain or increase the levels of crop production. Modeling studies in Brazil generally suggest that improved crop resilience to droughts can be achieved on genotypes with traits of deeper root systems and better water use efficiency (Battisti et al., 2017). Shifting sowing dates to avoid dry spells during critical stages of crop development is also an alternative adaptation that can be assessed using process-based models in Brazil (Bender, 2017; Rio et al., 2016).

This is evident in Brazilian maize production, due to shortening of the crop growing cycle and greater water deficit in future climate scenarios (Bender, 2017). Souza et al. (2019) and Martins et al. (2018, 2019) estimated that yield losses of maize in NEB can vary from 30% to 60% for global warming scenarios of 2.0 and 4.0°C, respectively. Marengo et al. (2020) show that under a regional warming of 4°C, the area under water stress condition in NEB would cover 49% and 54% of the region by 2070 and 2100, respectively. The projections of vegetative stress conditions show that semidesert vegetation types typical of arid conditions would replace the current semiarid bushland vegetation ("caatinga") by 2100.

Alternative species such as forage palm, castor bean and broad bean, sorghum, agave, and pineapple are drought-tolerant crops widely cultivated in NEB (Figure 5). Originated in sub-Saharan Africa, sorghum is a versatile crop, producing grains for human consumption and animal feed, and biomass for forage. Additionally, it is a crop with high tolerance to drought and can regrow after harvest (similar as perennial grasses), minimizing replanting costs and operations. Different varieties adapted to NEB climate are also available to farmers, according to output interest (biomass, sugar, and/or grains) (Silva & Neto, 2019)">(Silva & Neto, 2019). Crassulacean acid metabolism (CAM) species are potential solutions for arid regions. Forage palm, agave, and pineapple are examples already well adapted to the NEB environment (Figure 4). Although agave has been generally used as a feedstock for fiber and forage in NEB, other species such as *A. tequilana* or *A. americana* are currently considered as alternative feedstocks for bioethanol production in dry regions of Australia (Yan et al., 2020).

If the lack of infrastructure for the establishment of new biorefineries could be addressed by governmental or market incentives, farmers could also explore this option by taking the advantage of the well-developed bioethanol economy in Brazil. In the context of risk management, the Climatic Risk Agricultural Zoning (ZARC) developed by EMBRAPA is an important tool for agroclimatic risk zoning for risk management. The ZARC is obtained using meteorological information associated with the bioclimatic characteristics of the cultivated crop species. The tool generates information such as the crop calendar, municipalities suitable for cultivation, ideal date for sowing with low climatic risk, cultivars adapted to the region, and type of soil for cultivation.

4.3 | Seasonal climate forecast

Seasonal climate forecasts in NEB and Brazil in general started at the National Institute for Space Research (INPE) in the late 1990s using empirical and dynamical models. INPE conducts seasonal climate research and operational forecast efforts, while also coordinating its work with collaborating institutions. INPE's seasonal forecasts are created using the outputs from several global climate models, which are both generated in-house and from other climate centers in the world. The raw output models are combined and discussed among scientists and users during monthly climate outlook forums. The main products generated are probability maps for seasonal rainfall distributions, with terciles of above-normal/normal/below-normal categories (Nobre et al., 2006). At the regional level, FUNCEME, the Ceará Foundation for Meteorology and Water Resources, develops a suite of dynamical forecast methods for climate forecast in the state of Ceará, and in collaboration with other states in NEB. The use of seasonal climate forecasting constitutes an effort to mitigate the impacts of drought nationwide. Forecasts have been directed at state and local-level policymakers in the areas of agriculture, water management, and emergency drought relief (Lemos et al., 2003).

Climate forecasting offers an opportunity for state and local-level bureaucracies to engage in proactive drought planning to ensure water security. Several factors have limited the effectiveness of seasonal climate forecast use in Brazil and in NEB in particular. Lemos et al. (2003) explains that: (a) the current level of skill of the forecasts is inadequate for the needs of policy development and farmer decision-making; (b) forecast information application has been subject to distortion, misinterpretation, and political manipulation; and (c) focus on the forecast as a product

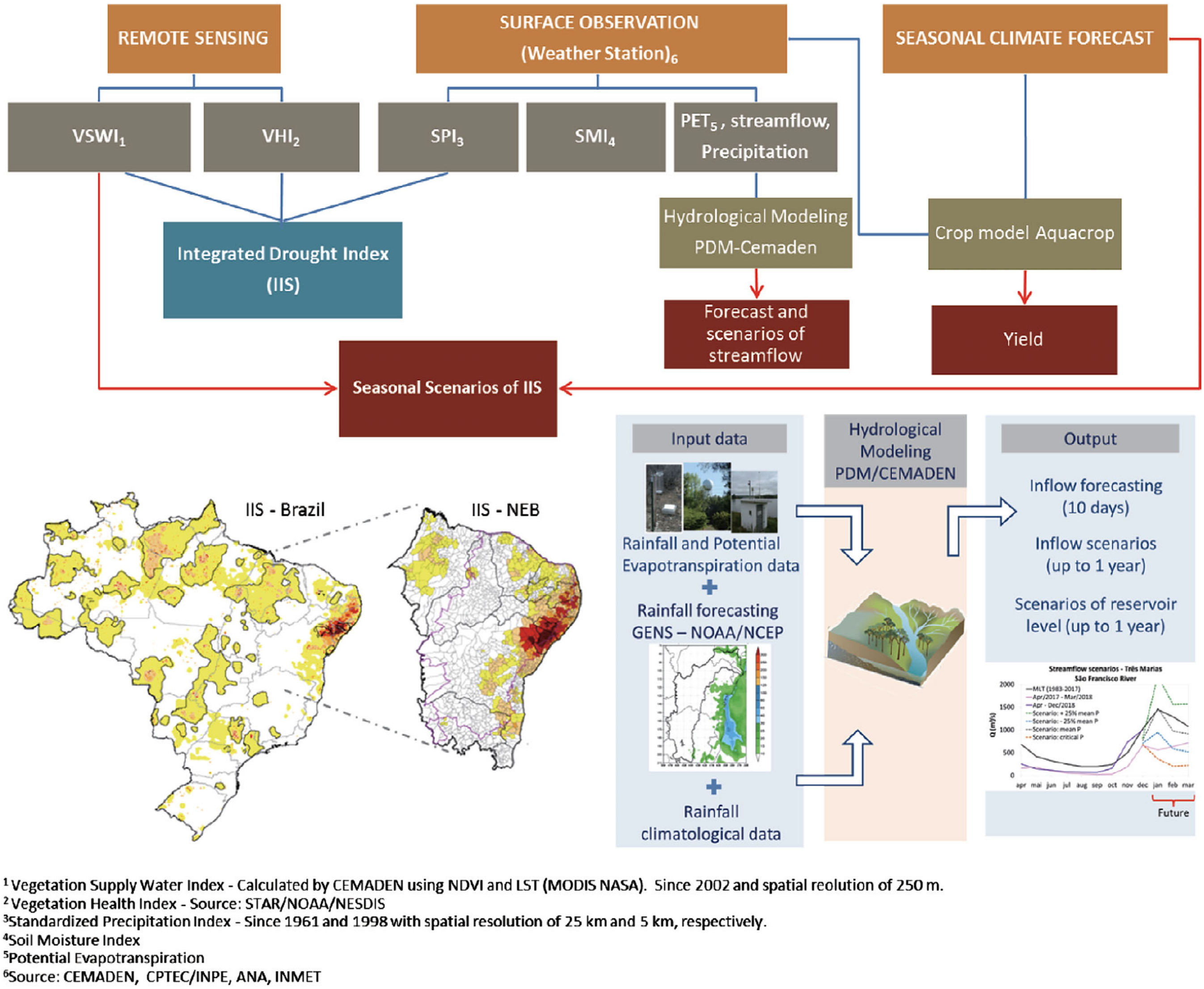

FIGURE 5 Flowchart of CEMADEN monitoring and forecasting drought impact (Source: Cunha et al., 2019b-ICHARM)

until recently neglected to take into account end user needs and decision-making behavior. Currently, while models and model skill have improved, concerns (b) and (c) are still valid. Although some studies have documented success stories of climate prediction in NEB (Nelson & Finan, 2000; Nobre et al., 2006), it is widely recognized that the best option in the long term is an integration of drought risk monitoring and seasonal forecasts.

Currently, seasonal climate forecast with details for Brazil or South America is done using dynamical models produced by INPE/CPTEC (clima.cptec.inpe.br) and IRI (iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts/) at the beginning of each month. The climate forum for NEB (http://www.funceme.br) issues the seasonal forecast for the peak of the rainy season, using forecasts from INPE/CPTEC, IRI, and the UK Met Office. This latter has been issued for the NEB wet season (March–May) since 1987. It is based on an established physical link between rainfall and SST and using statistical techniques (Folland et al., 2001).

5 | REGIONAL ADAPTATION PROGRAMS FOCUSED ON DROUGHT IN NEB

Adaptation of the agriculture and livestock sectors to climate change can be seen as the promotion of and use of nature-based practices that can provide excellent results. In agricultural systems, to adapt implies the use of technologies and practices that can take advantage of biodiversity, ecosystems services, and ecological processes on natural or modified biomes to increase the adaptive capacity of crops and livestock to changes in climate conditions (Assad et al., 2019)

Any official program directed toward adaptation must encourage vulnerable economic sectors and population groups to adopt self-reliant measures that promote risk management. They also should promote sustainable use of the agricultural and natural resources and facilitate early recovery from drought through actions consistent with national drought policy objectives (Wilhite et al., 2014). Coordination of drought programs may help in planning and response efforts in an effective, efficient, and customer-oriented manner. As drought affects a wide range of sectors, the involvement of appropriate stakeholders in the consultation process to create a national drought policy is a key to ensure successful drought adaptation policy implementation.

This section presents policies from the Brazilian Federal Government and some projects directed to mitigate the impacts of droughts in NEB, particularly in activities related to the agriculture sector. A review is made on some of these actions, considering published literature. Emergency relief policies did somewhat diminish the adverse impacts of droughts as in 1997–98 and 2012–18, but they were insufficient to withstand that exceptional multiyear drought. However, these policies are implemented during or postdisaster and are more reactive than preventive.

This provides evidence that isolated government support to local populations and small farmers may not help them develop resilience to drought on the long term. Besides that, the main actions and public policies for drought risk mitigation are exclusive for municipalities included on Brazilian semiarid. On the other hand, the recent major drought (2012–2018) demonstrated that disasters associated with droughts are not limited only to the Brazilian semiarid, as other regions were also severely affected (Cunha, Marchezini, et al., 2019).

5.1 | Garantia-safra

In some countries, loans and crop insurance are a general practice prevalent among the farming community to survive drought consequences. When a municipality in NEB is affected by extreme drought, the Brazilian federal government releases emergency funds, similar to farmer's insurance, so small-scale producers can cope with drought impacts. This program is called Garantia Safra (Alvalá et al., 2017). In 2012 alone, the Garantia-Safra insurance payment was approximately U$ 660 mi. In the 2012–2016 period, this amount exceeded U$2.1 bi in agricultural insurance payments (Alvalá et al., 2017; SAF/MDA, 2017). The intensity and impact in the regional economy and society of the 2012–2018 drought in NEB had not been seen in several decades (Martins, Quintana, et al., 2016; Martins, Vieira, et al., 2016).

This government program was effective in reducing acute social unrest or large-scale migration out of NEB in the 2012–18 drought, as compared to intense droughts in 1983 and 1998 (Finan & Nelson, 2001). They helped in reducing social and economic vulnerability and supporting the poor small farmers and rural workers in NEB. As proposed by Alvalá et al. (2017), there is a need to strengthen integrated water resource management, implement a drought policy that would be proactive instead of reactive, restructure the economy of the semiarid areas to make it less dependent on the climate, and improve human capacities, especially through education.

5.2 | Adapta sertão

Family farmers in Brazil's semiarid region (the Sertão) are highly vulnerable to climate change. In this context, the Adapta Sertão Coalition (Cesano et al., 2012; Obermaier et al., 2014), which is based on community-based adaptation (CbA), was created in 2006 with the purpose of identifying technologies and strategies that could make family farming more resilient to drought through CbA. This involves directly engaging the local communities in dissemination and replication of technologies and strategies. The CbA consists of self-organized community groups setup to face emergencies or environmental changes, such as drought. CbA relies on the concept that it is necessary to prepare communities for such eventualities, working with the community. This approach is useful in poor and more remote areas and becomes a fundamental adaptation mechanism. The program has contributed to improving rural livelihoods, especially through local capacity building. However, the impacts of the 2012–2018 drought, the most severe recorded in the last 50 years, continue to affect local populations. CbA in semiarid Brazil may thus need to interact more broadly with those public policies, plans, and programs to help reduce vulnerability to climatic, social, environmental, and economic stressors in general, in order to help family farmers better adapt to future climate change.

Adapta Sertão coalition was a pioneer project in Brazil and was probably one of the first in the world to create mechanisms to scale up resilient practices. Over the last decade, the practices and knowledge learned from smallholder families in the State of Bahia were condensed into a corporate and institutional module called MAIS (2018). Currently, the MAIS module is dedicated in helping and training smallholder farmers of semiarid NEB to become more resilient to current and future climate change impacts by utilizing climate smart practices.

Examples of some of the practices include the adoption of Opuntia-ficus (forage palm), a CAM species that acts as a substitute for maize and as a natural water and food storage system; restoration of pastureland through the planting of drought-resistant trees and indigenous fruits; and the adoption of livestock management systems suitable for semiarid climates. The program also provides capacity building to smallholder farmers on running and deploying water storage tanks and diversion ditches to limit the impact of rainfall peaks; producing animal feed that consumes less water (e.g., forage palm or sorghum); building larger containers and silos to store more animal feed when prices are low, as climate shocks can quickly raise prices; and becoming independent of external inputs, as extreme weather conditions can disrupt the supply chain, affecting the viability of agricultural activities. Through the MAIS module, the Adapta Sertão program has helped over 650 farmers in the Jacuípe Basin in Bahia over the last 12 years, improving their socioeconomic conditions while enhancing environmental aspects by improving pastureland conditions and decreasing the water footprint of farms.

5.3 | Pronaf semiarido

The National Programme to Strengthen Family Farming (PRONAF-2020) is a Brazilian governmental program created in 1995 to provide financial support to FA. Currently, it is one of the largest rural credit programs in the country, amounting to more than US$ 4 billion in the 2019/2020 season (MAPA, 2020). Twelve types of financial credit are provided by PRONAF, including a specific line for the semiarid region of NEB, the "PRONAF Semiarido." This program is aimed at providing credit for setting up, expanding, recovering, and modernizing infrastructure, including those related to agricultural and nonagricultural projects to cope with the semiarid conditions, where 50% of credit must be allocated to water infrastructure (BCB, 2020).

Farmers in the semiarid region could get up to US$ 4000 that could be used for building or improving small reservoirs or underground dams. However, there is still a lack of information and capacity building of smallholder famers to build and manage such infrastructures (Cirilo et al., 2019). Therefore, providing financial resources may not be the main solution and programs dedicated to capacity building in climate-smart and resilient agriculture are key to engage farmers and optimize such resources.

5.4 | Agro nordeste

The AgroNordeste (2019) is a recent governmental program dedicated to boost the socioeconomic and sustainable development of the NEB. It is being implemented in 230 municipalities in the nine states of the NEB in addition to Minas Gerais and is expected to reach 1.7 million people by 2021. The program is aimed at small and medium producers who already sell part of the production and want to expand the business generating more income and jobs. AgroNordeste's goal is to increase producer income between 20% and 50% in the medium term, by increasing the coverage of technical assistance, expanding access and diversifying markets, promoting and strengthening the organization of producers, guaranteeing water security, and developing products with high quality and added value.

5.5 | ABC plan (low carbon emissions in agriculture)

Created in 2010, the ABC Plan ("*Agricultura de Baixo* Carbono," low carbon emissions in agriculture) was designed to support GHG reductions and increased C sinks in Brazilian agriculture. Low-interest loans are made available to farmers who adopt low carbon emission practices, including no-till agriculture, the restoration of degraded pasture, afforestation, biological nitrogen fixation, treatment of animal wastes, and the integration of crops, livestock, and forest. The program's goals include rehabilitating 15 million hectares of degraded pastures and increasing the area under zero tillage from 25 million hectares to 33 million hectares by 2020, and significantly reducing GHG emissions from agriculture (Amaral et al., 2011; Assad et al., 2019)

A series of climate change adaptation strategies are proposed in the ABC plan as well, aiming at more resilient and diversified agricultural practices through science-based solutions. The program has drawn from Stakeholders from government, academia, and industry to develop strategies on crop breeding, more efficient ways of utilizing water resources and catchment, adaptation of production systems, generating climate indexes, mapping, and modeling of crop vulnerabilities and risks. These efforts are expected to be translated into five major actions comprising: (i) developing the Climate Intelligence in Agriculture Programme and integrating it with the National Plan of Reduction of Risks and Disasters; (ii) updating rural insurance to new climate conditions; (iii) amplifying investment in research and technology transfer toward more climate-smart strategies and accelerated crop breeding; (iv) incorporating the risk of emerging pests and diseases in agriculture due to climate change in the Risk Assessment of Pest And Disease System (ARP); and (v) identifying priority areas based on the climate vulnerability maps.

5.6 | Drought stipend (*Bolsa Estiagem*)

The *Bolsa Estiagem* or Drought Stipend is a federal benefit instituted by law in 2004 with the objective of assisting families of family farmers with an average monthly income of two minimum wages, and that live in municipalities under a state of public calamity or in an emergency. These situations must be recognized by the Federal Government, through the Department of Regional Development (Martins, Quintana, et al., 2016; Martins, Vieira, et al., 2016). The beneficiaries of this program are families registered in this program and cannot receive other benefits from the government, and they must live in the municipality affected by intense drought from January to October 2014 (the period where de drought started) and cannot receive *Garantia Safra*. This benefit consists of a transfer of R$ 400.00 (about US$ 80) per month.

6 | EXPERIENCES IN DETECTION AND MONITORING OF DROUGHTS IN NEB

Capacity building and information-based adaptation strategies include drought monitoring, forecast, early warning, better management, training, and education. Integrated drought monitoring and seasonal climate forecasting provide means of assessing impacts of climate variability and change, leading to disaster risk reduction through early warning (Cunha, Zeri, et al., 2019). These drought mitigation options include actions aimed at reducing future vulnerability and preparation for relief response, as strategies for disaster risk management. In the following section, we describe two important efforts for drought monitoring: the IDI (Cunha, Zeri, et al., 2019) developed at the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) and the Drought Monitor developed by the Meteorology and Water Resources Foundation of Ceará State (FUNCEME, Martins et al., 2015).

To perform the drought monitoring and impact assessment, CEMADEN has developed and applied drought indicators that combine surface observation-based drought indices (precipitation anomalies, Standardized precipitation index [SPI], potential evapotranspiration, and soil moisture) and remote sensing-based indices (vegetation health index [VHI], 4 km, and vegetation supply water index [VSWI], 250 m). Recently, CEMADEN also developed the IDI, which combines the SPI, VHI, and VSWI anomalies. The SPI is calculated considering the time scales of 3, 6, and 12 months, whereas VSWI anomalies and VHI are calculated at the monthly scale. The IDI is calculated on the monthly scale and computed at the municipal level in the entire country (Figure 5) (Cunha, Zeri, et al., 2019; Cunha, Marchezini, et al., 2019).

An extensive network of soil moisture sensors was established in 2014/2015 by CEMADEN to monitor soil water dynamics in NEB. Soil moisture is currently being monitored at close to 600 locations, in depths ranging from 10 to 40 cm. This information is used to support the development of tools and numerical models, such as land surface models, to characterize and quantify the risks associated with drought conditions (Zeri et al., 2021). Regarding crop yield scenarios, the AquaCrop model has been used for crop yield forecasting in the Brazilian semiarid using a combination of meteorological observations and seasonal climate forecasts as input data (Martins et al., 2018, 2019). Future developments aim at coupling subseasonal forecasts of weather variables to the model and generate scenarios of yields for monitoring drought for NEB and some adjacent states.

The Drought Monitor (Martins et al., 2015) involves federal and state entities and aims to achieve a coordinated monitoring action between the different administrative spheres and providing a cooperative arrangement of institutions federations and states, as well as increasing awareness about drought conditions in NEB. This concept was based on similar monitoring programs in the United States and Mexico and was adapted to Brazil. It represents a robust system for monitoring drought for NEB and some adjacent states, and it is based on meteorological (SPI and SPEI) and hydrological (Standardized Runoff Index [SRI]) indicators. This monitor is hosted at the National Water Authority of Brazil, ANA (monitordesecas.ana.gov.br, De Nys et al., 2016).

7 | DISCUSSIONS ON ADAPTATION STRATEGIES: WHAT DO WE HAVE AND WHAT DO WE NEED?

Several studies summarized by De Nys et al. (2013), Marengo et al. (2020), and show that although there is a rich history of drought management throughout Brazil, there are short- and long-term gaps and opportunities on which decision makers might consider focusing to improve monitoring, forecasting, and early warning systems, vulnerability/resilience and impact assessments, and mitigation and response planning measures (Gutierrez et al., 2014). As proposed by Alvalá et al. (2017), there is a need to strengthen integrated water resource management, implement a drought policy that would be proactive instead of reactive, restructure the economy of the semiarid areas to make it less dependent on the climate, and improve human capacities, especially through education.

TABLE 2 Current measures to cope with drought, from long-term adaptation (disaster risk reduction) to mitigation (disaster risk management) and maladaptation (short-term or instantaneous solutions that do not favor adaptation nor mitigation) (disaster risk mismanagement that ends when the hazard ends)

Measure	Adaptation	Mitigation	Maladaptation
Acudes	Yes	Yes	No
Water trucks (*carro pipa*)	No	Yes	Yes
Transposition Sao Francisco River	No	Yes	Yes
Water tanks (*cisternas*)	Yes	Yes	No
Seasonal climate forecast	Yes	No	No
Drought monitoring	Yes	Yes	No
Federal crop insurance Program focused on family farmers (*Garantia-Safra*)	No	Yes	No
Adapta Sertão Project	Yes	Yes	No
Food Acquisition Program (PAA)	No	Yes	Yes
Technical Assistance and Rural Extension services (ATER)	Yes	Yes	No
Sustainable Agriculture and Livestock Program (2077 Program)	Yes	Yes	No
National Program for the Strengthening of Family Agriculture (Pronaf)	Yes	Yes	No
Research and Innovation Program for Agriculture (2203 Program)	Yes	Yes	No
AgroNordeste	Yes	Yes	No
Agricultural practices	Yes	Yes	No
Food baskets (*Cestas básicas*)	No	Yes	Yes

Adaptation of agriculture and livestock systems to climate change brings financial benefits for rural producers, and economic, social, and environmental benefits for society, as well as reduces the risk of investments and insurance companies. Various adaptation strategies used in crop cultivation, soil and water conservation, livestock, and financial management in NEB have shown that the knowledge of these strategies was not of any specific advantage among the farming community. In addition to knowledge, there seems to be other constraints that are equally critical. The small-scale farming and cattle ranching in this region and their dependence on rainfall make it one of the most vulnerable to droughts. As discussed in Martins, , Quintana, et al. (2016), and Martins, Vieira, et al. (2016), identifying some key dimension of vulnerability of crop production as well as risk of experiencing low crop yields on a more detailed spatial scale for NEB may be a crucial step toward the goal of a more targeted planning of current and future investments in adaptation options.

Lemos et al. (2016) indicate that to decrease climate vulnerability of poor agricultural households, development interventions, such as anti-poverty programs, have to go beyond cash transfer and should incorporate risk management policies that enhance synergies between generic and specific capacities. After the experience of the 2012–2018 drought in NEB, it has become evident that the current expansion of the social protection provided by mitigation policies of Federal and State governments may not be sustainable in the long term. The crop failure insurance programs and the provision of basic means of subsistence for rural populations may run out of money if they are implemented for longer droughts. The current model of subsistence agriculture may be unsuitable in a warmer and drier future climate and calls for an innovative sustainable development strategy to increase societal resilience.

Some programs or strategies that include credits for small farmers, improvements in water distribution for irrigation and storage, and better crop management may be considered as adaptation options when, in fact, they are more short time solutions that may be considered as maladaptation. These include crop failure insurance programs and the provision of basic means of subsistence for rural populations, in addition to permanent infrastructure for guaranteeing water supply to both urban and rural populations in NEB. More importantly, they reveal the unsuitability of the current model of subsistence agriculture and highlight the need for innovative sustainable development pathways to increase societal resilience.

Table 2 summarizes some actions that constituted adaptation strategies or that were planned for adaptation but ultimately did not work. Emergency relief funds (*bolsa estiagem* and *garantia safra*) cannot be considered as effective adaptation options. In Brazil, most of the actions are of reactive nature and not preventive, and a larger share is for mitigation (postdisaster) than predisaster. Some of them constitute maladaptation, meaning actions that can be effective in the short term, but that end when the hazard ends, such as credit, food baskets, and water tankers. These are not sustainable and do not promote long-term adaptation—on the contrary, they create social and economic dependency from the government. Perhaps, monitoring and early warning and seasonal forecasts of drought risk, as well as changes in crop and livestock practices are the best option for long-term adaptation. It is also important to take into account changes in suitability of land to current and new crops with climate change (Assad et al., 2013). The results presented in this table may help policy makers to formulate more specific adaptation policies to decrease the vulnerability of small households whose livelihoods depend mostly on rainfed agriculture.

The 2012–2018 drought reinforced perception of the need for planning, so that adaptation alternatives prior to the impacts can be carried out. However, several challenges limit the development of a culture of adaptation, including those related to the use and limitations of public policies (Mesquita et al., 2020). In summary, the information presented in Table 2 shows measures that are necessary as a way to minimize the impacts of climate extremes on food security in NEB and in Brazil as a whole. Some of them are not sustainable nor induce real adaptation, creating dependency and ultimately perpetuating the current situation. In agriculture, impacts on crop yields can be mitigated by adopting management practices that are more sustainable to the environment, with productivity and conservation benefits. While funds transfer in the form of *bolsa estiagem* ou *garantia safra* have been positive in increasing income, it has not been sufficient to manage the risk of food insecurity during drought events, suggesting what Lemos et al. (2016) calls "poverty trap" in which families are constantly coping with drought but failing to overcome the conditions that make them vulnerable (reactive measures). Table 2 shows some strategies promoted to incorporate the perspective of climate change and enable the increase in the adaptive capacities of family farmers so that they can anticipate events (proactive) and not just respond to its impacts (reactive).

There is a need for more investment in specialized technical assistance to train family farmers in appropriate agricultural practices. The use of new varieties will become a viable alternative in obtaining increased productivity, with crops that are more resistant to high temperatures and scarce water. Climate change will necessarily lead to adjustments in the suitability of land for crop production. Temperature and precipitation limitations will probably cause the phase out of more vulnerable crops.

The links between the community-based approach for adaptation to extremes of climate variability and climate change, and the national and NEB state programs are still relatively weak. There is a need for coordinated national and regional drought adaptation policy frameworks. As in other regions of the world, there is a lack of social indicators comprising a comprehensive monitoring and drought early warning system, as basis for sustainable adaptation policies. There is a need for improving policy coherence and adaptive management from local to national, and from seasonal to long-term time scales.

Initiatives such as *Adapta Sertão* have transformed the lives of thousands of family farmers through the Intelligent and Sustainable Agroclimatic Module. This experience shows that it is urgent and necessary to develop public policies to better integrate access to water, dissemination of climate resilient technologies, and implementation of production systems more adequate to semiarid conditions. There is also a need to improve preparation and response measures for drought episodes. Integrating drought monitoring and seasonal forecasting provides a better way to forecast possible impacts of drought, identifying risks and vulnerabilities and allowing for better decision-making in terms of coping measures that can guarantee water, energy, and food security for the NEB population. All adaptation options listed in Table 2 show synergies and trade-offs as well as barriers to be implemented, either technical or political, but are a good starting point on actions to protect vulnerable people in the semiarid region of NEB from the extremes of a changing climate, particularly small-scale farmers.

Previous studies (Gutierrez et al., 2014) have shown that the adaptive capacity that had been built in Ceará State, for example, hydraulic infrastructure and management actions, coupled with emergency measures taken to cope with the 2012–2018 drought, reduced its vulnerability. On the other hand, at the regional scale, the Transposition of the Sao Francisco River—even though it was designed as a potential drought adaptation action—has not clearly contributed to the adaptation of the most vulnerable populations in the semiarid region, based on the results from the distribution of water by the Eastern Axis of this river.

Governance and institutions are critical determinants of adaptive capacity and resilience in NEB, from the municipal to federal levels. Yet, the makeup and relationships between governance components and water governance mechanisms that may shape the adaptive capacity of water systems to extremes of climate variability and climatic change is still an issue to be explored (Engle & Lemos, 2010). Measures and strategies for drought preparedness could be strengthened by regional, national, and international financing mechanisms on the longer term for disaster risk reduction and disaster risk management. Most of the current so-called adaptation strategies from the government are merely reactive mitigation options for post disaster recovery or maladaptation. With the likelihood of more frequent droughts in NEB, there is a need for a better perception that adaptive capacity in NEB is still low, as shown by the consequences of recent droughts in the region. In order to prepare for this, it is necessary to consolidate drought risk management in Brazil, which requires exploring synergies between all of the institutions involved. It is necessary to create mechanisms for the integration and articulation of technical and scientific knowledge of the various dimensions of risk, by ensuring a linkage between policy related to disaster risk reduction, climate change adaptation, and the UN Sustainable Development Goals.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could constitute a potential conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors conceived this paper and wrote it.

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AUTHOR CONTRIBUTIONS

Andrew J. Challinor: conceptualization; formal analysis; investigation; methodology; project administration; resources; supervision; writing-original draft; writing review and editing. Ana Paula Martins do Amaral Cunha: conceptualization; data curation; formal analysis; investigation; methodology; supervision; writing-original draft. Murilo Dos Santos Vianna: conceptualization; formal analysis; investigation; methodology; supervision; writing-original draft; writing-review and editing. Fabiani Bender: data curation; investigation; methodology; software; visualization; writing-original draft.

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