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ORIGINAL PAPER

Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C

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Abstract
Historically, during periods of extreme drought, food security in the drylands of the semiarid region of Northeast Brazil (NEB) is under severe risk due to agricultural collapse. The drought that started in 2012 continues to highlight the vulnerability of this region, and arid conditions have been detected during the last years mainly in the central semiarid region, covering almost 2% of the NEB. Climate projections show an increase in the area under water stress condition, covering 49% and 54% of the NEB region by 2700 and 2100, respectively, with a higher likelihood with warming above 4 °C. The projections of vegetative stress conditions derived from the empirical model for Vegetation Health Index (VHI) are consistent with projections from vegetation models, where semi-desert types typical of arid conditions would replace the current semiarid bushland vegetation ("caatinga") by 2100. Due to the impacts of the 2012–2017 drought, public policies have been implemented to reduce social and economic vulnerability for small farmers but are not enough as poor population continues to be affected. In the long term, to make the semiarid less vulnerable to drought, strengthened integrated water resources management and a proactive drought policy are needed to restructure the economy. Integrating drought monitoring and seasonal climate forecasting provides means of assessing impacts of climate variability and change, leading to disaster risk reduction through early warning. Lastly, there is an urgent need for integrated assessments because the possibility that under permanent drought conditions with warming above 4 °C, arid conditions would prevail in NEB since 2060.

Keywords Vegetation stress hazard · Climate change · Caatinga · Northeast Brazil · Climate change impacts · Risk of aridization

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1 Introduction

Climate- and weather-related extreme events, such as floods, droughts, heat waves and bushfires, are increasing in frequency and intensity in many parts of the world (IPCC 2014a, b). Agriculture and the economies of drylands are highly sensitive to climatic variability. Drought represents one of the most important natural phenomenon that threatens food and water security in many parts of the world. The overall impact of drought on these regions and its ability to recover from the resulting social, economic and environmental impacts depends on several factors that have been studied for several decades now, as in the semiarid region of Northeast Brazil, hereafter referred as NEB (Dantas et al. 2020). According to Huang et al. (2017) and Guan et al. (2019), drylands are home to more than 38% of the world's population and are among the most sensitive areas to climate change and human activities. Furthermore, poverty and underdevelopment are typical of populations living in semiarid regions in tropical and subtropical regions, making them more vulnerable to the risks of climate change (IPCC 2014a, b). In a future world in which warming exceeding 4 °C above preindustrial levels, it cannot be ruled out that droughts would be more common and intense in many regions, including drylands (World Bank 2013).

In South America, one of the regions affected by drought in the present and possibly in the future is the NEB (Fig. 1). This region is particularly vulnerable to drought and the experience from the recent event during 2012–2018 has shown that effective adaptation policies are urgently needed for poverty alleviation—(Martins et al. 2015, 2018; Alvalá et al. 2017; Marengo et al. 2017, 2019; Brito et al. 2018; Cunha et al. 2019; Dantas et al. 2020). The new delimitation of the NEB region from 2017 covers an area of 1,006,654 km^2 and encompasses 1171 municipalities, considering only those included in the Northeast Brazil states (SUDENE 2017a.) The Northeast Brazil region has a population of 26 million inhabitants, 28% of which are rural and owe their subsistence primarily to smallholding agriculture. Figure 1 shows a land cover map with farmland type dominates, with some patches of the original dry shrubland or caatinga.

The region has an economy based mostly on public services, and its human development indicators are among the lowest in Brazil (Cardoso et al. 2017). The blue line in Fig. 1 shows the official delimitation of the NEB. According to this definition from SUDENE (2017a), a municipality is part of the semiarid region if it satisfies at least one of the three climatic characteristics: it is within the 800 mm contour on the map of mean annual rainfall for 1981–2010; its aridity index is below 0.50 (precipitation/potential evapotranspiration); and it has an index of risk of drought above 60% (days of soil moisture deficit from water balance, also calculated from 1981 to 2010 data).

This region is subject to recurrent droughts, with strong impacts mainly upon the most vulnerable population. A chronology of droughts since the 16th century is shown in Table 1. From those, some intense droughts occurring during strong El Niño events (Brito et al. 2018). In addition, SST variability in the tropical North and South Atlantic (the tropical Atlantic SST 'dipole') also plays a leading role in rainfall variability in the region (Moura and Shukla 1981; Hastenrath 2012).

The recent drought started in 2012 started during a La Nina event (Rodrigues and McPhaden 2014) and partially ended in 2018 (Dantas et al. 2020). This drought has favor government and society discussions to improve drought response policies and management, both at the federal and state levels. Magalhaes et al. (1988) and Alvalá et al. (2017) show that several actions have been taken by governments, in particular the construction of *açudes* (reservoirs) and hydraulic infrastructures (dams and water

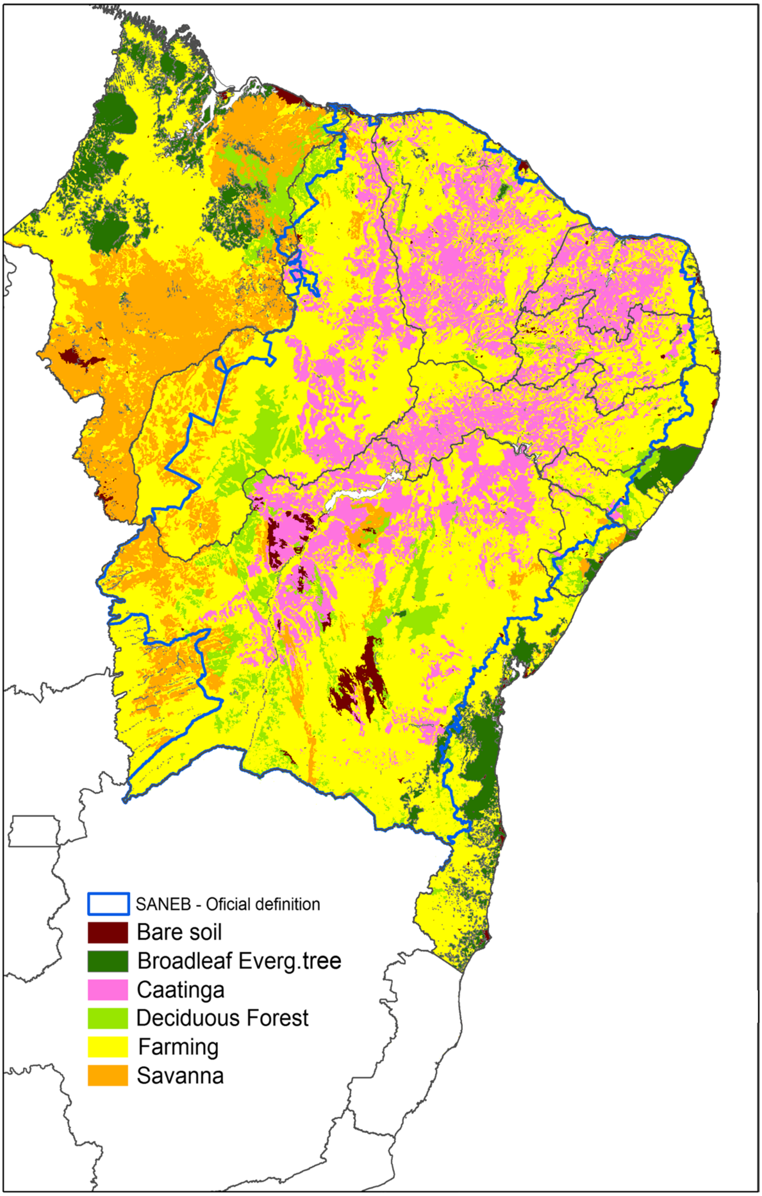

Fig. 1 Geographic limits of the semiarid region of Northeast Brazil according to (24) (blue line) and land use and land cover map of Northeast Brazil showing the distribution (blue line) of bare soil, vegetation types and farming. Adapted from Vieira et al. (2016)

channels) that transports the water from wetter areas to drier areas. Over the past decades, federal and state governments have attempted to mitigate the adverse impacts of drought by investing mainly in water infrastructure such as inter-basin water transfer, canals, waterworks, reservoirs, dams and the pumping of water from aquifers, as shown

Table 1 Historic drought episodes in Northeast Brazil (updated from Araujo 1982; Magalhaes et al. 1988; Marengo et al. 2017, 2018, 2019)

Century 16th	Century 17th	Century 18th	Century 19th	Century 20th	Century 21st
1583	1603	1707	1804	1900	2001–2002
1587	1608	1710–1711	1808–1809	1902–1903*	2005–07*
	1614	1721–1727	1810	1907	2010*
	1624	1730	1814	1915	2012–2018**
	1645	1736–1737	1816–1817	1919*	
	1652	1744–1747	1824–1825	1932–1933	
	1692	1751	1827–1829	1936	
		1754	1830–33	1941–1944	
		1760	1844–1845	1951–1953*	
		1766	1870	1958*	
		1771–1772	1877–1779*	1966*	
		1777–1778	1888–1889	1970	
		1783–1784	1891	1976	
		1791–1793	1897–1899*	1979–1981	
				1982–1983*	
				1986–1987*	
				1990–1993	
				1997–1998*	

*Shows that this was an El Nino year

**There was an El Nino in 2015–2016

in Marengo et al. (2019). These drought mitigation options for coping with this situation include action aimed at reducing future vulnerability and preparation for relief response.

Current-drought emergency relief measures include water distribution by trucks (*carros pipa*), plus cash transfer and state-sponsored micro-insurance programs for smallholders (Magalhaes and Martins 2011; Magalhães 2016). Actions are heavily concentrated on water distribution, initially to rural but also to urban and coastal communities that depend upon water supply originating in the semiarid regions. Besides that, recent anti-poverty programs such as education, health and extreme poverty alleviation significantly improved life conditions in the region (Alvalá et al. 2017).

Rain-fed agriculture in NEB—mostly of the smallholding subsistence type—has large economic expression and high social importance because that type of agriculture contributes to the maintenance of rural communities in the countryside. It incorporates very low levels of technology and is based on low-productivity labor, employing most of the rural labor force, and producing mainly corn, beans, and manioc, for self-consumption and for sale in the local markets (Lindoso et al. 2014). It is unsurprising that agriculture is the most impacted sector and when a drought hits, there is failure in agricultural production and unemployment follows (Magalhaes et al. 1988; Sun et al. 2007; Bretan and Engle 2017). Despite significant improvement in quality of life indicators in the past 15 years, levels of vulnerability (as measured by food security see Fig. 2) remain high, especially in rural households that are more dependent on agriculture (Bedran-Martins and Lemos 2017).

Drought is often confused with other climate conditions to which it is related, such as aridity or even desertification, since both are characterized by the lack of water. Aridity is

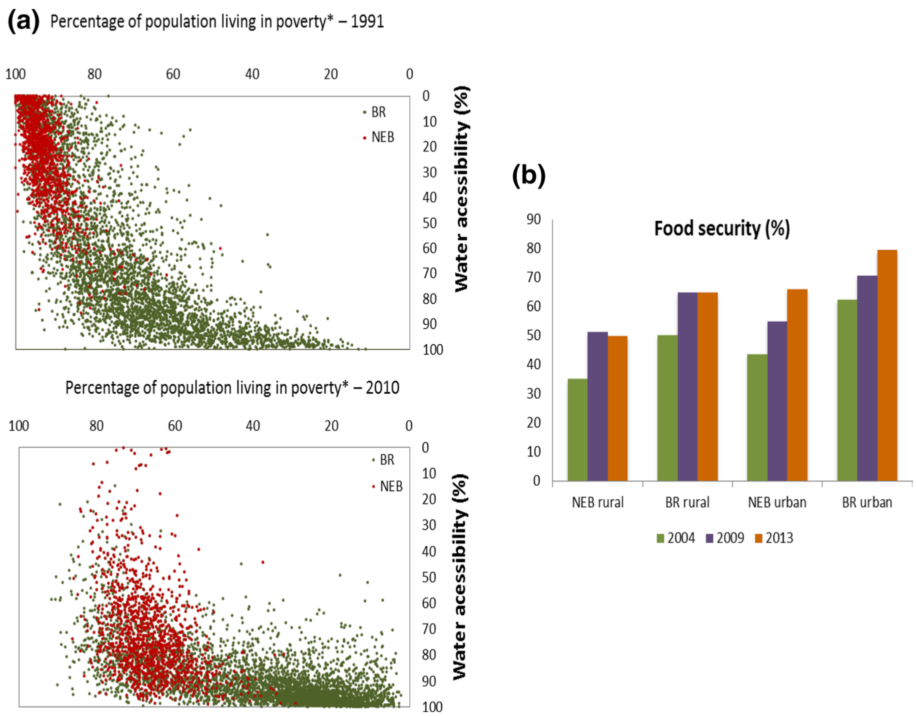

Fig. 2 **a** Percentage of population living below the poverty line versus percentage of the population with access to water, for municipalities in the semiarid region of Northeast Brazil (NEB) (red dots, 1136 municipalities), and municipalities of the rest of Brazil (green dots, 4430 municipalities), in the years 1991 and 2010; **b** percentage of households with food security, in the years 2004, 2009 and 2013. Source: based on Census data from IBGE (2010) and National Household Sample Survey—PNAD (IBGE 2013). Panel (a): *Poverty is measured as the proportion of persons living with less than BRL 255 per month (approximately US$ 70 at recent exchange rate). Panel (b): Food security is said to exist when the household has regular and permanent access to quality food in sufficient quantity, without compromising access to other essential needs

a permanent feature of climate and drought is an extreme feature of a temporally process. Drought is a period with abnormally dry weather long enough to cause a serious hydrological imbalance (IPCC 2012). It only becomes hazardous when translated into agricultural/vegetative or hydrological drought, and these depend on other factors, not just a lack of rainfall. On the other hand, dryness is defined as the absence or lack of moisture, while desertification is the process by which fertile land becomes desert, typically as a result of drought, deforestation or inappropriate agriculture.

In this work, we study changes in vegetation stress hazard observed in the present and projected for future climate change scenarios in the semiarid Northeast Brazil. Drought impacts on vegetation are assessed in recent decades and also projected for future using CMIP5-Coupled Model Intercomparison Programme Version 5 model projections. It is important to assess in detail the risk of water stress and drought impacts in the region, both for the present and for the future, given the expected anthropogenic climate change. The analyses presented in this paper focus on changes in vegetation stress hazard (vegetative drought) associated with changes in exposure under projected changes in local or regional climate extremes. We refer to other publications to describe future climate change scenarios in NEB and to detail and update the methods and data used for the assessments of vegetation stress in the present and future (Marengo et al. 2019; Cunha et al. 2019). A permanent drier climate state in a regional warming above 4 °C scenario can exacerbate the aridization, that together with land degradation may lead to desertification in the near future in developing countries (Vieira et al. 2016; Huang et al. 2017). In this article, we consider regional and not global warming of 4 °C because the impacts would be higher on water stress and vegetation in the region.

2 Methods

- Climate-based drought indicators

Meteorological drought indices, such as Standard Precipitation Index SPI (McKee 1993), are recommended and widely used for drought monitoring. This is due to its simplicity and multiscale characteristic in quantifying the abnormal wetness and dryness. The SPI was first introduced by McKee (1993) and refers to a statistical monthly indicator that compares cumulated precipitation during a period of months with long-term cumulated rainfall distribution.

The SPEI (Standardized Precipitation-Evapotranspiration Index, Vicente-Serrano et al. 2009, 2013) can measure drought severity according to its intensity and duration and can identify the onset and end of drought episodes. The SPEI is a simple multi-scalar drought index based on a monthly climate water balance, defined as the difference between precipitation and potential evapotranspiration (E). SPEI produces a more comprehensive measure of water availability that takes into account atmospheric conditions that also affect drought severity such as temperature, wind speed and humidity (Stagge 2015). SPEI is obtained as standard values of probability distribution function of the deficit or surplus accumulation of a climate water balance at different time scales (Stagge 2015; McKee 1995).

In this study, for past and present conditions, SPI and SPEI were derived from monthly data from the Climate Research Unit (CRU TS4) time-series data version 4.0, available online at crudata.uea.ac.uk/cru/data/hrg/(Harris et al. 2014; New et al. 1999). PET (mm) used in the SPEI calculation is estimated according to the Penman–Monteith method (Allen et al. 1998; Stagge 2015).

The UNEP aridity index AI (Marengo and Bernasconi 2015) is also used to assess the geographic distribution and variability of dry conditions since the 1960s in the NEB region. This index is defined as the ratio of annual precipitation to annual potential evapotranspiration (P/PET) and thus conceptually represents the complex interplay of water supply and demand (Greve and Seneviratne 2015). The UNEP AI is calculated using rainfall P and potential evapotranspiration PET derived from CRU TS version 4.01 dataset (Harris et al. 2014), as well as from ground-based data from the PROCLIMA program from CPTEC/INPE that started 2001 (proclima.cptec.inpe.br) and updated by CEMADEN until 2016. The PROCLIMA dataset incorporates in situ meteorological data from CPTEC itself and from the National Meteorology Institute (INMET) and the State Meteorology Centers. The interpolation of the data from weather stations into a regular grid with 5-km resolution was performed using a technique called "kriging" that has been primarily applied in hydrology and other earth science disciplines for the spatial interpolation of various physical quantities given a number of spatially distributed measurements. Additional monthly precipitation dataset for the 1961–2016 period comes from Global Precipitation Climatology Center

(GPCC, Beck and Grieser 2005). All these data sources were used in order to compare the behavior of different precipitation datasets over NEB. Projected AI was obtained using P and PET from CMIP5 model simulations for the period from 2006 up to 2100. For maintaining methodological coherence with CRU and PROCLIMA, PET from CMIP5 was calculated using the Penman–Monteith method.

- Vegetation-based drought and water stress indicators

The Vegetation Health Index (VHI) (Kogan 2002; Bokusheva et al. 2016; Kogan and Guo 2017) is one of the several agricultural/vegetative drought indicators aimed to assess the vegetation response to droughts (Sivakumar 2011; Zargar et al. 2011). The VHI is a remote-sensing-based integrated metric of drought that offers the most direct possibility of assessing impacts on crops/vegetation at high spatial and temporal resolution. The VHI is more advantageous than rainfall-based drought indices because the assessment is done not only of rainfall anomalies but also on the vegetation response to water stress. VHI is calculated using the vegetation condition index (VCI) and thermal condition index (TCI) for each pixel and month of a given year, according to the following equations:

$$\mathrm{VCI} = 100 * \frac{\mathrm{NDVI} - \mathrm{NDVI_{min}}}{\mathrm{NDVI_{max}} - \mathrm{NDVI_{min}}} \tag{1}$$

$$\mathrm{TCI} = 100 * \frac{\mathrm{BT_{max}} - \mathrm{BT}}{\mathrm{BT_{max}} - \mathrm{BT_{min}}} \tag{2}$$

$$\mathrm{VHI}_i = \alpha \mathrm{VCI}_i + (1 - \alpha)\mathrm{TCI}_i \tag{3}$$

where NDVI ($NDVI_{max}$, and $NDVI_{min}$)) and BT (BT_{max} and BT_{min}) are statistically smoothed monthly NDVI and BT and their 1982–2016 absolute maximum and minimum representing climatology of theses indices, respectively; α and (1 − α) are coefficients to determine the contribution of each index, usually set as 0.5. The lower VHI indicated that the high incidence of drought whereas a higher VHI value show good conditions for vegetation, as shown in Table 2. VHI dataset is available at National Oceanic and Atmospheric Administration (NOAA; www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vhftp.php).

In comparison with drought indicators SPI and SPEI, the VHI can capture spatial details and is suitable for regionally oriented phenomena, like drought, monitoring and detection (Wang et al. 2001, 2004; Mukherjee 2014). In summary, SPI indicates deficiency in precipitation, and VHI represents vegetation health as response to soil moisture content and

Table 2 Drought severity classes for VHI (Kogan 2001)

Severity class	VHI
Normal	100 > VHI > 40
Mild drought	30 < VHI ≤ 40
Moderate drought	20 < VHI ≤ 30
Severe drought	10 < VHI ≤ 20
Extreme drought	0 < VHI ≤ 10

represents a better picture of drought impacts on vegetation (Mukherjee 2014). The VHI was adopted by CEMADEN as an index to monitor drought and drought impacts in Brazil.

- VHI and water stress impacts on vegetation in future climate

Precipitation is the principal supplier of moisture to plants (mainly in semiarid regions). It is also a key driver of VHI (Liu et al. 2013; Ibrahim et al. 2015). In addition, extremely high temperatures generate thermal stress in vegetation, lower moisture content and thereby adversely affect vegetation health (Bhuiyan 2017).

To assess the impacts of a future drier climate on vegetation, a predictive empirical model for VHI was used. This predictive model is an improved version of the one previously shown by Marengo et al. (2019). In this new version, besides the precipitation and temperature, PET is included also as independent variable in the multiple regression analyses (VHI modeled as the dependent variable). The inclusion of PET improved the model´s accuracy, as evaluated by the determination coefficient between predicted and observed VHI, which ranged from 0.5 to 0.8 in the SANEB region (previous values ranged between 0.3 and 0.6, Marengo et al. 2019).

For the predictive model, we used the VHI at 4 km spatial and 7-day composite temporal resolution, from 1982 to 2000. Drought categories were defined according to VHI intervals (Table 2). In addition to the monthly VHI data, the CRUTS4 dataset of gridded monthly *P*, *T* and PET at the global scale, with a spatial resolution of 0.5, was used. The VHI dataset was rescaled to 0.5° using a re-scale technique (geoprocessing tool that alters the raster dataset by changing the cell size and resampling method) to match to CRU dataset spatial resolution. Then, to build a predictive model for VHI in the future, multiple linear regression analyses for VHI as a function of *P*, *T* and PET were performed considering the following regression equation:

$$\mathrm{VHI} = a.P + b.T + c.\mathrm{PET} + k \tag{4}$$

A least-squares fit to the multiple linear regression model was obtained; more details can be consulted in (Chatterjee and Hadi 1986). The validation was applied on VHI from 2000 to 2017. *P*, *T* and PET from CRU are used because of their relatively high spatial resolution (50 km), while the *P* and *T* come from the CMIP5 models, available only at coarser than 200 km resolution. PET calculated from CMIP5, as well as PET from CRU, was calculated using the Penman–Monteith method. With the regression coefficients (*a*, *b*, *c* and *k*) already calculated, we used this relation to calculate VHI for the future:

$$\begin{aligned}\mathrm{VHI\ (future)} = \mathrm{aVHI\ (future)} &= a\ (\text{precipitation anomalies from CMIP5}) \\ &+ b\ (\text{temperature anomalies from CMIP5}) + c\ (\text{PET anomalies from CMIP5}) \\ &+ d\ (\text{precipitation anomalies from CMIP5}) + b\ (\text{temperature anomalies from CMIP5}) \\ &+ c\ (\text{PET anomalies from CMIP5}) + d\end{aligned}$$

This regression is based on the assumption that vegetation types will respond the same way in the future to climate forcing as they responded to last 35 years (VHI time-series). It is known that in the future some adaptation can occur in vegetation in response to a warmer and drier climate. However, to simplify, in the predictive model for VHI this was not taken into account, similar to the static vegetation models. Nevertheless, the projections of VHI are useful to show general a picture about the impact of a drier (and hotter) climate on the occurrence and the spatial pattern of vegetative drought, even considering the present (last 35 years) relationship between precipitation, evapotranspiration, temperature and VHI.

To evaluate the impact of climate change on dryness we used monthly *T*, *P* and PET data from the suite of CMIP5 model projections for the past and projected climate for the period from 1862 up to 2100. The difference P-PET is an indicator of dryness. The RCP (Representative Concentration Pathways) scenarios used in this study are RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (Moss et al. 2010; Meinshausen et al. 2011; Van Vuuren et al. 2007, 2011; IPCC 2013).

- Potential vegetation model (PVM)

In order to assess if complex biophysical models reproduce those projected changes in vegetation, we used the PVM. This was developed by Oyama and Nobre (2003) and shows a good skill in reproducing the current natural vegetation distribution patterns both globally and for South America. While they applied it to Northeast Brazil, later work by Sampaio et al. (2007) and Salazar et al. (2007) applied it for Amazonia. In this study, we used the version 2 of the PVM (PVM2.0) by Lapola (2009) that considers the CO_2 "fertilization effect" in its formulation.

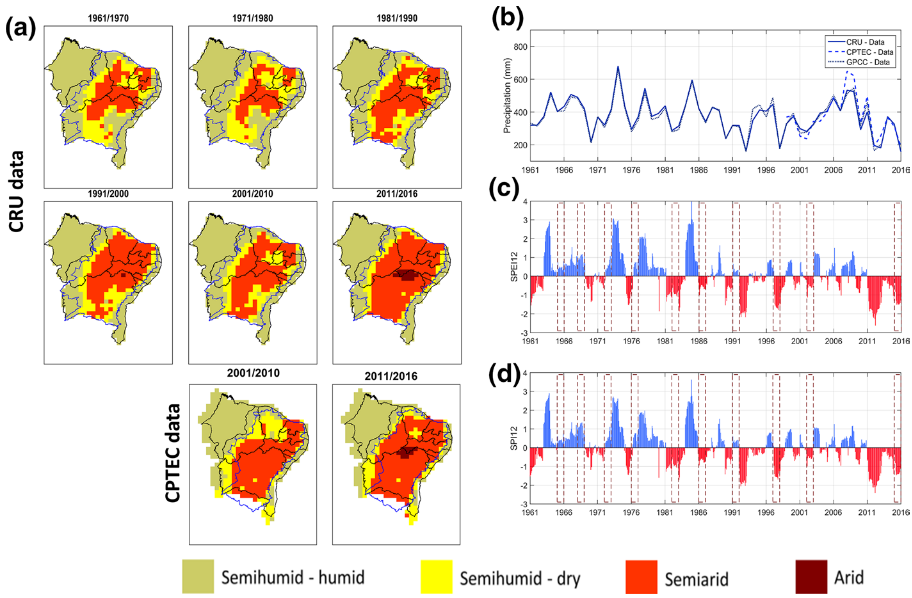

Fig. 3 **a** Pentad maps of the UNEP Aridity Index (Marengo and Bernasconi 2015) for Northeast Brazil. The blue line shows the official extent of the Semiarid region of Northeast Brazil (NEB) according to SUDENE (2017a); **b** Time-series of February–May rainfall from CPTEC and CRU in NEB (19); **c** evolution of 12-month SPEI (Vicente-Serrano et al. 2013) in NEB, dry (negative SPEI values) and humid (positive SPEI values) periods are represented by red and blue bars, respectively; **d** Evolution of SPI in NEB. Rainfall and PET data come from CRU (Vicente-Serrano et al. 2013). Light red bars show the occurrence of El Niño events (NOAA)

3 Results

- Current trends of dryness in SANEB

The drought that started in 2012 is an example of a multi-year water deficit that has strong impacts on regional population. Figure 3a shows the pentad scale distribution of the UNEP AI since the early 1960's, and the sequence of maps shows the increase in the area covered by semiarid conditions. Both CRU and PROCLIMA datasets for 2011–2016 show AI with arid conditions expanded in the central semiarid region (Fig. 3a). The monthly time-series of precipitation from CRU (Fig. 3b) for the February-May NEB peak rainy season shows a downward trend during the last 3 decades, with the lowest values in 2012–2013. This is in agreement with PROCLIMA and GPCC rainfall data. The figure shows that rainfall in the peak season has been decreasing in the region since 2000, and areas with increasing water stress are now manifesting as agricultural or hydrological droughts. The 12-month SPEI (Vicente-Serrano et al. 2009) time-series (Fig. 3c) shows the predominance of negative values since the late 1980's, with low values in 1993, 1997–1998 and particularly in 2012 and after.

The drought that started in 2012 is extremely critical in terms of precipitation deficit and land vegetation stresses in comparison with other droughts from recent decades (Brito et al. 2018). The drought affected not only the semiarid region but also the wet eastern coast of Northeast Brazil where sugarcane production fell 19% in 2015 relative to the previous year (CONAB 2017).

- Dryness scenarios under climate change for NEB

Tropical and subtropical semiarid regions are prone to be more seriously affected by intensity and frequency of droughts in climate change scenarios (IPCC 2014a). This is also the case for Northeast Brazil (Marengo and Bernasconi 2015; Alvalá et al. 2017) where irreversible drier conditions and tendencies toward water stress and aridization are projected for the second half of the 21st century (Marengo et al. 2018). Indices of annual maximum number of consecutive dry days (CDD), and very wet days index (R95P), indicate a significant increase in the number of dry days per year as compared to the present—and in the frequency of heavy precipitation episodes for the entire region for RCP8.5, particularly in NEB where projected regional warming is above 4 °C (Marengo et al. 2019).

Changes in the amount and timing of precipitation (e.g., intense daily rainfall amount and the number of consecutive dry days) strongly influence the extent of the area with severe or extreme drought. In fact, an occasional increase in intense rainfall episodes and longer dry spells in between may cause erosion of fertile soils in those areas, and irreversible extreme drought and aridity, and together with inadequate land use and soil erosion may lead to desertification (Magrin 2014). The P-PET Hovmöller diagram from Fig. 4 shows negative P-PET rates that are increasing through the end of 21st century, suggesting that the period with water deficit would increase in duration and intensity, projecting a situation of longer dry seasons in the future. The UNEP AI Hovmoller diagram of Fig. 5 shows arid conditions increasing until 2100, and with the dry season starting 1 month earlier and ending 1 month later in comparison with the present.

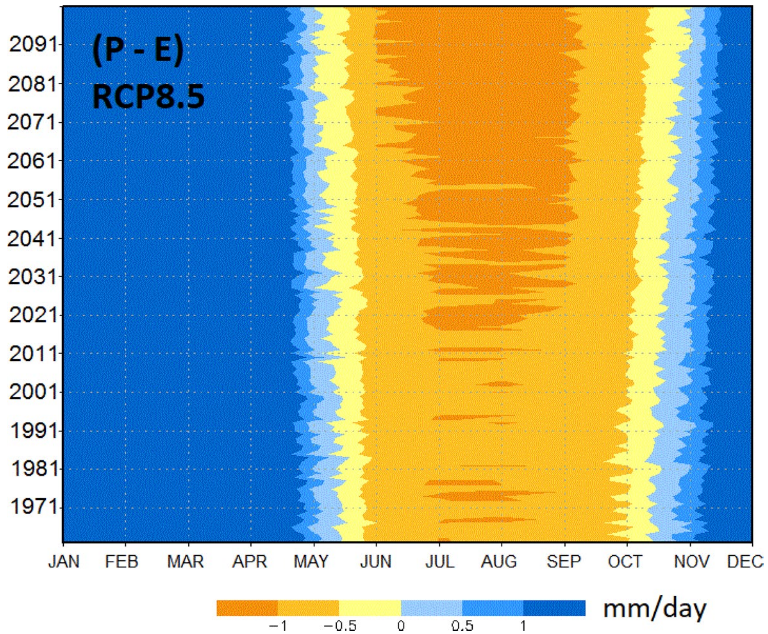

Fig. 4 P-PET Hovmöller diagram (mm/day)

- Changes in vegetation stress hazard in NEB

Figure 6 shows a decline in VHI values from 2012 to 2016 (observed VHI) for NEB, which was the result of the prolonged rainfall deficit in the region, as shown by the SPI and SPEI time-series (Fig. 3c, d). Although in the area-average VHI, the minimum value found was close to 30, indicating moderate drought (Table 2), when VHI is spatially evaluated (pixel by pixel), it is possible to identify regions with minimum VHI values equivalent to the severe and extreme drought categories. It is emphasized that especially in the year 2016, the simulated VHI was 29, indicating moderate drought, whereas the simulations showed higher VHI values (38), indicating mild drought condition. Among other reasons, such discrepancy that occurs to the CMIP5 simulations is not meant to capture on a predictive mode, for instance, the actual rainfall anomalies for the first decade in a simulation. Therefore, it was not supposed to have captured the anomalous drought events of the period 2012–2016 (Ukkola et al. 2018).

From the simulated VHI for the future, it is observed that NEB could experience more intense vegetation stress condition (VHI < 30) from the middle of this century. For VHI-RCP8.5, it is highlighted to the end of the century, a persistent condition of extreme drought (VHI < 10) as a consequence of the warmer and drier conditions in the region. An explanation for this scenario is that grassland that covers the region in the present may exhibit low photosynthetic activity, similar to becoming bare soil. Intense warming and dryness suggest semi-desert-type conditions in the second half of 21st century, with environmental degradation and with vegetative stress condition (vegetative drought) that would be irreversible if warming surpasses 4 °C.

In addition to assessing vegetation stress hazard for NEB as a whole, it is relevant to study its sub-regional distribution. As an indicator of impacts, we consider the area under

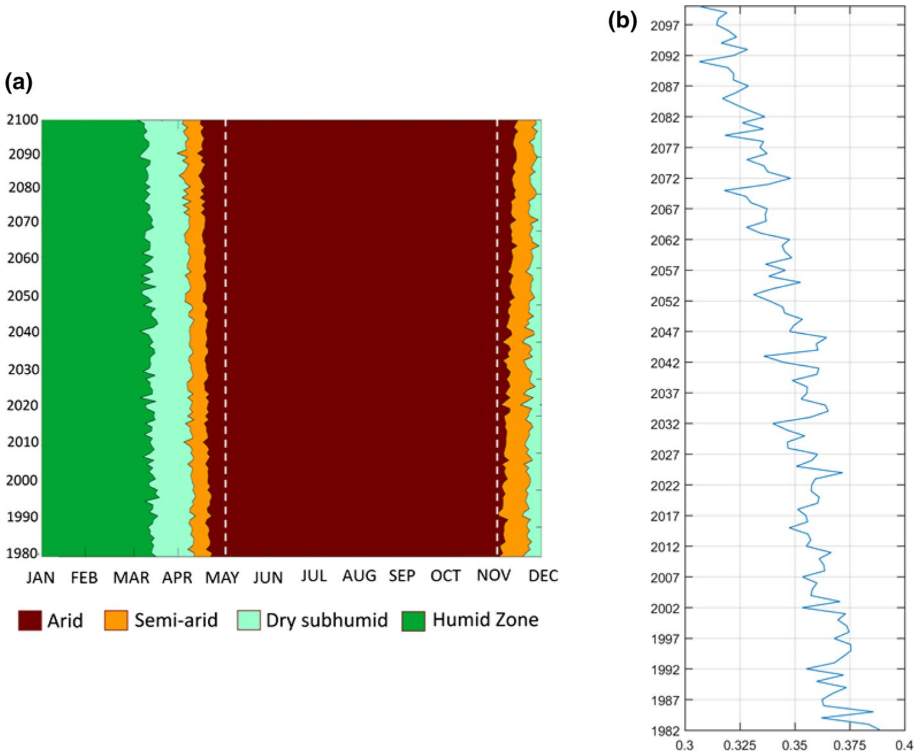

Fig. 5 UNEP Aridity Index derived from the ensemble of CMIP5 models for RCP8.5 for 1961–2100. **a** Hovmöller diagram of Aridity Index (Color scale on the lower side of panel); **b** annual time-series of area-average Aridity Index

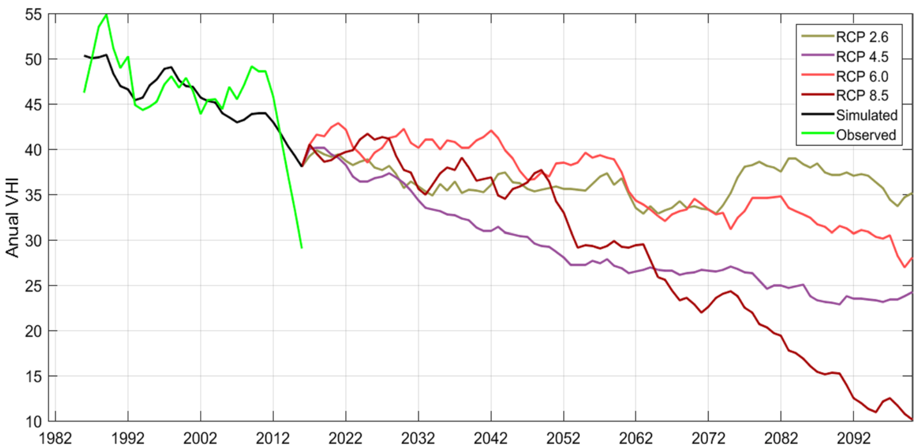

Fig. 6 Time-series of observed and simulated mean VHI for the period of 1982–2016 (black line) and future projection of VHI (2017–2100) obtained from CMIP5 models in the semiarid region of Northeast Brazil. Colored lines represented projected VHI for different RCPs: RCP2.6 (gray); RCP4.5 (yellow); RCP6.0 (orange); RCP8.5 (red)

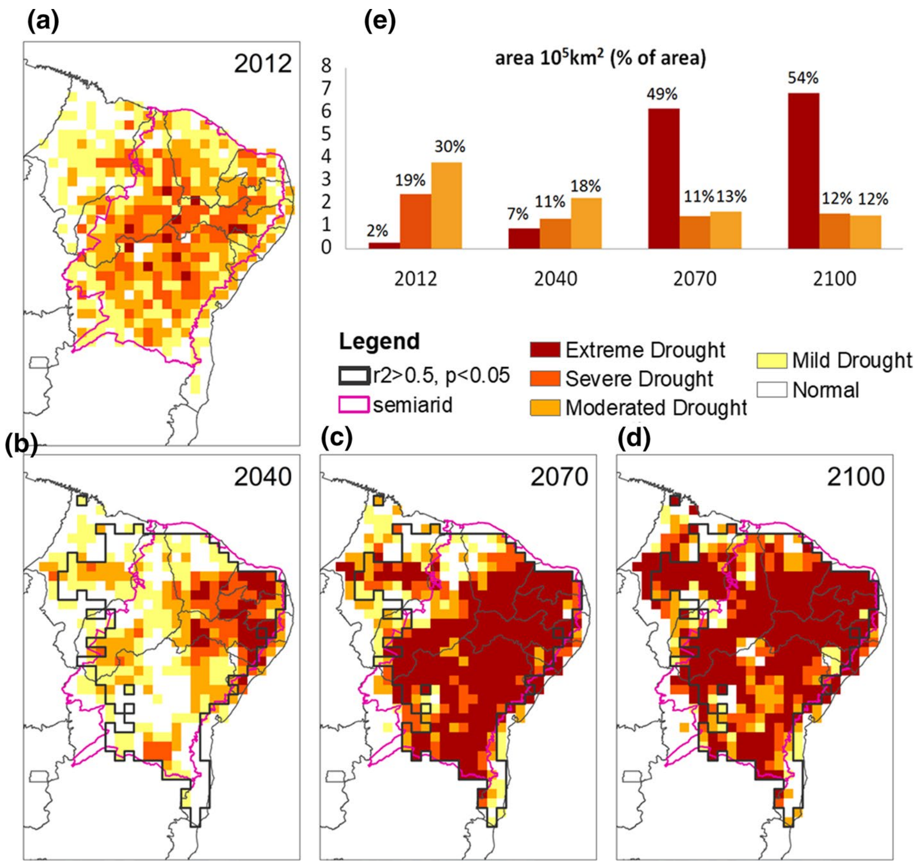

Fig. 7 Spatial distributions of area with mild, moderate, severe and extreme drought according to vegetation health index (VHI) for **a** 2012; **b** projected for 2040 **c** projected for 2070, **d** projected for 2100 from an ensemble of CMIP5 models for the RCP8.5 projections. The black contour denotes regions with the coefficient of determination greater than 0.5 and 95% significance level. The area (km^2) is shown in bar diagrams at bottom (**e**), with the colors identifying the levels of drought: yellow-mild, light orange-moderate, dark orange-severe and brown-extreme

risk of moderated, severe and extreme vegetative drought. For present conditions, we consider the year 2012 (Fig. 7a), that was the driest year in the last decade (as shown in Fig. 3b, c). The predictive VHI model includes *P*, *T* and PET, and the analysis considers the geographical distribution of areas with various levels of drought risk, for the present and the short, middle and long term until 2100. Warming levels were defined by Marengo et al. (2019) as +1 °C in 2012, +2 °C in 2040, +4 °C in 2070 and +5.5 °C in 2100 based on the CMIP5 models ensemble.

Figure 7b–d shows the potential conditions of drought severity levels for 2040, 2070 and 2100 considering the RCP8.5. In short term, projections show that from 2040 most of the NEB can experience drought conditions (18% moderate drought, 11% severe drought and 7% extreme drought), conditions that may become irreversible by the end of the century (12% moderate drought, 12% severe drought and 54% extreme drought). In addition, it is highlighted the increase in the area with extreme vegetative drought and a decrease in the area with moderate vegetative drought until 2100, particularly in the NEB region.

Although the focus of the study is on NEB, it is observed that regions outside this limit, where the accumulated rainfall is higher than in NEB, may also experience extreme drought from 2070.

- Increased risk of desertification due to climate change in NEB

Presently, desertification in drylands is a growing risk mostly due to the combination of land use change by human removal of natural vegetation for agriculture and grasslands for livestock, coupled with the likely increase in the frequency of high precipitation episodes and drought situation. This process is also taking place in EB where 94% of the region presents moderate-to-high susceptibility to desertification and the areas that were susceptible to soil desertification increased by approximately 4.6% (83.400 km^2) from 2000 to 2010 (Vieira et al. 2015). More recently, Vieira et al. (2020) recognized that land use/land cover changes is one of the main drivers of desertification since environmental degradation is always triggered by the removal of natural vegetation cover.

Studies by Tomasella et al. (2018) estimated the degree of degradation using an index calculated from the persistence and frequency of bare soil from NDVI. Their results indicated that the degraded areas increased in the period of the study, mainly in areas of pasture and caatinga. This expansion has been accelerated due to the current severe drought. Thus, if the VHI scenarios show persistently lower values (intense droughts), it also indicates persistently lower NDVI and with surface temperature persistently higher, it can be inferred that areas degraded or prone to aridization and desertification will increase until the end of the century.

Consistent with CMIP5 models for the RCP8.5 scenario for 2040, 2070 and 2100 for NEB, regional climate change projections suggest an increase in dryness in the region due to overall reductions in mean annual rainfall (Magrin 2014; Marengo et al. 2018). In fact, if temperature and water deficit increase, and dry spells become longer, this leads to a situation with possibility of irreversible drought, and toward increasingly arid conditions expected to prevail by the second half of the 21st century. If these conditions are maintained over time, it can lead to intensification of land degradation in NEB. To avoid this scenario, there is a need to radically change land use practices toward ecosystem restoration.

- Projection of vegetation changes in SANEB

The response of vegetation to water stress was assessed using an empirical equation of VHI based on multiple linear regression analyses considering P, T and PET. In order to assess if complex biophysical models reproduce those projected changes in vegetation, we used the Potential Vegetation Model Version 2- PVM2.0 (Lapola 2009) run with projections with the ensemble mean of 35 CMIP5 models for RCP 2.6, 4.5 and 8.5. In RCP 8.5, the corresponding value in 2100 is 950 ppm (Moss et al. 2010). Reference precipitation and surface temperature climatology (1961–1990) are provided at monthly/0.5° resolution from (Willmott and Robeson 1995).

These data and the climate scenarios were then aggregated to T62 spectral resolution (~2°) to drive the PVM2.0 (Lapola 2009) including the land vegetation carbon cycle used to quantify how these scenarios may affect the distribution of major biomes in Northeast of Brazil. The PVM2.0 preserves the particularly good performance of its predecessor the PVM (Oyama and Nobre 2003) for biomes in South America. The model considers seasonality in precipitation as a determinant for the delimitation of forests and savannas and is

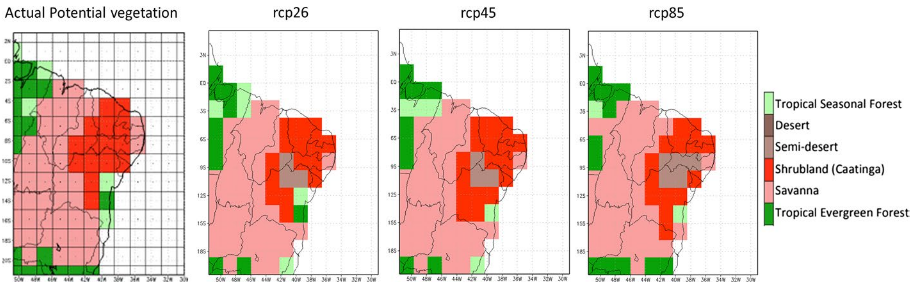

Fig. 8 Projected distribution of natural biomes in Northeast of Brazil for 2071–2100 from ensemble mean of 35 CMIP5 under three RCPs-2.6, 4.5 and 8.5 for time slice 2071–2100

able to account for varying atmospheric CO_2 concentration on plants' primary productivity. The PVM2.0 assigns a biome—atmosphere equilibrium solution to each grid cell using monthly climate information (surface temperature and precipitation), incident photosynthetically active radiation and atmospheric CO_2 concentration as inputs.

The PVM2.0 considers the so-called CO_2-fertilization effect, which influences stomatal conductance with important implications in future projections of vegetation under water scarcity conditions. The results of this simulation are presented in Fig. 8 and are consistent with vegetation projection changes calculated with the VHI index, that is, aridization trends in the interior of Northeast Brazil.

For the dry shrubland (caatinga) biome in the NEB, there is a replacement by semi-desert biome in the center area. The results are similar to those presented in (Salazar et al. 2007)—that used an earlier version the PVM without carbon cycle projecting the presence of semi-desert biome by 2100 in areas where caatinga is the current vegetation type. We conclude that precipitation and temperature changes are the main drivers of vegetation changes, not fully compensated by the "CO_2-fertilization" effect.

In overall, projected low values of VHI (Figs. 6 and 8), which represents water stress for vegetation in the future, are very consistent with PVM2.0 projections of semi-desert vegetation type, a prolonged water stress could lead to aridity and it happened in some regions of Northeast Brazil during the recent drought. This is consistent with negative P-E projections. All of these projections agree with the condition of a drier climate, which can create a new normal drought condition.

4 Discussion and conclusions

Warming has been increasing at 0.10–0.25 °C per decade above preindustrial levels (IPCC 2014a, b). As a consequence, several regions in the planet have or are already experiencing significant changes in weather and climate extremes (e.g., droughts and floods). Therefore, dangerous levels of warming may induce social conflicts and environmental problems with strong impacts for local and regional economic development (Bäckstrand et al.2017; Dryzek 2016). In NEB, warming between 1981 and 2019 was estimated to be 0.45 °C as derived from the HadCRUT4 dataset. Population from the most vulnerable communities in NEB is at risk due to extreme drought situation. This reduces subsistence production, reduces income and increases prices of agricultural products. This was observed in 1983, 1998 and from 2012 to 2018. Adding the harshness of drought upon pre-existing socioeconomic and political failures, this places intense pressure on water resources availability in the NEB region, and threatening food production and security (De Nys et al. 2013; Taddei 2011; Gutiérrez et al. 2014). In the past, people would migrate and many would die (Magalhães 2016; Dantas et al. 2020). Now they depend on social government programs, such as money transfers and relief measures to survive (Magalhães and Glantz 1992; Magalhães 2016). In the past, there was a dependency of the rural workers on the landowners. Historically, and even in present-day drought situations, politicians take advantage of water crises trying to maintain their power by not increasing resilience of the population with political decision making. This is an indicator that the NEB region is still vulnerable and not adapted to the impacts of drought (Magalhães and Glantz 1992).

The recent drought event highlights the vulnerability of the NEB region and confirm the risk of major impacts due to continuing climate change. For instance, recent work by (GVces 2018) for the Pianco-Piranhas-Acu river basin in the region covering parts of the states of Rio Grande do Norte and Paraíba showed projections of an increase in water deficit by 133% in 2010–2065 as compared to the present. The authors estimated that the direct cost of the drought in that basin from July 2012 to July 2017 was estimated at US$ 1 billion, or 3.2% of the regional Gross Domestic Product (GDP).

Vegetation stress in NEB is projected to increase if warming surpasses 4 °C, due to water deficit leading to dryness and irreversible drought, and an aridization process would affect natural vegetation and smallholder agriculture (IPCC 2014a). In locations where small-scale agriculture is mostly to satisfy family needs, drought can cause poor harvests and crisis in local economies (Alvalá et al. 2017; Rossato et al. 2017). Therefore, in a future scenario with high risk of drought and possible desertification in regions with warming above 4 °C, agricultural activities can be affected by severe water stress and they may devastate for population.

Currently, when a municipality in NEB is affected by extreme drought, the Brazilian federal government release emergency funds, similar to farmer's insurance so small-scale producers can deal with drought impacts (*Garantia Safra*, Alvalá et al. 2017). Only in 2012 the *Garantia-Safra* insurance payment was approximately R$ 1.3 bi (around U$ 660 mi in Table 3). For 2012–2016, this amount exceeded R$ 5 bi (around U$2.1 bi in Table 3) in agricultural insurance payments (Alvalá et al. 2017; SAF/MDA 2017).

Although semiarid vegetation is highly resistant to water deficits, vegetation health or robustness in semiarid regions is controlled by interannual variations in water availability, and a decrease in water availability may trigger land degradation (Vicente-Serrano et al. 2009). Furthermore, adaptation of semiarid vegetation to increased drought and warming under climate change still remain difficult to achieve. Recurrent drought in semiarid regions may induce low resilience of vegetation affecting its ability to recover, rendering plants more vulnerable to recurrent dry conditions (Cunha et al. 2015a, b).

The drought that affected NEB in 2012–2018 shows an intensity and impact not seen in several decades in the regional economy and society (Martins et al. 2016a, b). Emergency relief policies (Table 3) did somewhat diminish the adverse impacts of droughts, but they may have been insufficient to withstand this exceptional multi-year drought. These government programs were effective in reducing acute social unrest or large-scale migration out of NEB in the current drought, as compared to intense droughts in 1983 and 1998 (Finan and Nelson 2001). These policies have played an important role in reducing social and economic vulnerability and supporting the poor small farmers and rural workers in NEB. To make things worse, environmental vulnerability may have increased, owing to land degradation and desertification (Magalhães 2016; Tomasella et al. 2018).

Table 3 Main Northeast Brazil drought emergency relief actions during the period 2012–2016 (SAF/MDA 2017; MI 2014; MDS 2017; FNE/BNB 2018)

Action	Description	Number of municipalities	Number of inhabitants or families served (million)	Expenditures (2012–2016) US$[b]
Operation of water trucks (*carro pipa*)	Distribution of safe water with trucks to population under situation of emergency	1133	3.9	1.6 billion
Crop failure insurance (*Garantia Safra*)/year	Insurance to low-income small landholding farmers affected by the drought in semiarid area	~ 1015	900*	2.1 billion
Drought stipend (*Bolsa Estiagem)/year*	Support to low-income farming households living in municipalities under a state of emergency or calamity	1112	676*	1.5 billion
Water tanks (*cisternas*) construction	Installing reservoirs that collect rain water through a system of pipes	1426	~ 1*	1 billion
Well drilling and recovery[a]	Granted to producers acknowledged by the National Program of Family Agriculture and located in municipalities declared to be in a state of public calamity			96 million
Growth acceleration program (*PAC-Programa de Aceleração do Crescimento*) equipment	The provision of construction equipment such as backhoes, bulldozers, loaders, bucket trucks, and water trucks to affected municipalities.	1415		1.1 billion
Emergency loan program/year	Available in the municipalities in situations of emergency as recognized by the Federal Government	1989	~ 1.5	1.6[a] billion
Total				9 billion

*Families

[a]Considering only the years 2012 and 2013

[b]Estimates of expenditures were performed through the total amount in Brazilian Real (BRL) converted to dollar considering yearly average exchange rate

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.

These projected climate scenarios clearly call for expansion of the social protection net provided by mitigation policies of Federal and State governments. This includes 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 stress the unsuitability of current model of subsistence agriculture and would call for innovative sustainable development pathways to increase societal resilience, for instance, by a socially inclusive form of exploitation of the vast potential of renewable energy sources (e.g., wind and solar photovoltaic) (Sudene 2017c; Hccengenharia 2018).

In summary, we have shown that in a drier and hot climate, a higher vegetation stress hazard is expected, especially in the drylands of northeast Brazil. This condition can make drought irreversible and a prolonged water stress could lead to aridity and land degradation. Droughts and arid conditions may increase through 2100, and with the likelihood of dangerous levels of warming above 4 °C in the next 30–40 years, there may be clearly limits of adaptation for maintaining a large population in NEB. That points out to the critical importance of mitigation. There is scientific evidence that feasible emissions pathways that there are technically and economically can help to limit the warming to 1.5–2 °C (Hope 2017). Coincidentally, poverty and underdevelopment are typical of populations living in semiarid regions in tropical and subtropical regions, making them more vulnerable to the risks of irreversible drying conditions leading to aridization. The semiarid region of Northeast Brazil is particularly vulnerable to present and future climate change and effective adaptation policies—including poverty alleviation—are in need of urgent implementation.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest or competing interests.

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