Implications of climate change on water availability in a seasonally dry tropical forest in the Northeast of Brazil

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10.1590/0034-737X202370030001

ABSTRACT

Climate change is already affecting life on Earth and mitigation measures must be taken, which require proper identification of the regions most vulnerable to these changes. This study assesses the impact of climate change on water availability (water surplus, water deficit and precipitation minus evapotranspiration) and climate classification across the Caatinga biome, located within the Brazilian semiarid region. To obtain the water surplus and water deficit, the water balance of Thornthwaite & Matther (1955) was applied considering the current scenario (historical series from 1961 to 2015); the optimistic scenario, considering the Representative Concentration Pathway (RCP) for a radiative forcing of 4.5 $W.m^{-2}$ (RCP4.5), i.e., considering a temperature increase of 1.5 ºC and a reduction in rainfall from 15%; and pessimistic, considering a radiative forcing of 8.5 $W.m^{-2}$ (RCP8.5), i.e. taking an increase in temperature of 4.0 ºC and a reduction in rainfall from 20%. The results showed that the Caatinga was strongly impacted, especially in the pessimistic scenario, with no water surplus and a negative water balance. For the optimistic scenario, only a small portion presented a water-surplus and a positive water balance. Projections also showed that a large part of the Caatinga changed from semiarid to arid climate.

Keywords: caatinga; semiarid; climatic classification; water balance.

INTRODUCTION

Many changes observed on planet Earth, such as increasing air and ocean temperatures, melting ice caps, rising sea levels, creating threats to the infrastructure of cities and reducing crop productivity are related to global warming and climate change (IPCC, 2013; Cheng *et al.,* 2020; Javadinejad *et al.*, 2020; Bolsen *et al.*, 2018; Kogo *et al.*, 2021).

Climate change has altered the seasonal and spatial variability of rainfall, causing more events of heavy rains and longer periods of drought (Zhang *et al.*, 2018), changing the characteristics of ecosystems and intensifying water scarcity, mainly in semiarid regions (Ouhamdouch & Bahir, 2017). Changes in precipitation lead to a variation in the temporal distribution of water resources which, in turn, may compromise our ability to meet water demands in some regions while having water surplus in others (Santos *et al.*, 2010).

Studies evaluating water availability in semiarid regions of Central Mexico pointed out that, in climate change scenarios generated by different climate models, average annual precipitation can reduce from 14 to 22% in the 2080s (Herrera-Pantoja & Hiscock, 2015), resulting in constant water deficits in these locations.

The International Panel on Climate Change (IPCC) in 2013 defined a new methodology to characterize climate change scenarios, by introducing the term *Representative*

Submitted on May 10th, 2022 and accepted on October 27th, 2022.

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Concentration Pathways (RCP). RCP scenarios refer to the portion of the concentration thresholds that extend until 2100, for which the integrated assessment models produce corresponding emission scenarios (IPCC, 2013). Thus, the RCP4.5 scenario is an intermediate stabilization level where the radiative forcing is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100 (the corresponding RCP assumes constant emissions after 2150). RCP8.5 scenario is a high threshold for each radiative forcing and greater than 8.5 W m^{-2} in 2100 and continues to increase for some time (the corresponding RCP assumes constant emissions after 2250).

Touhami *et al.* (2015) evaluated the frequency of annual precipitation in scenarios RCP8.5 (high projections, high population growth and slow economic and technological development) and RCP4.5 (low projections, slower population growth, rapid economic development and greater emphasis on environmental protection) of climate change in the recharge of an aquifer in a semiarid region of Spain during the periods 1961-1990 and 2011-2099. They found that, by the end of the 21st century, rainfall depths below 200 mm per year were predominant, characterizing an arid climate, and the average water recharge could decrease by up to 17% in the last 30 years of the century.

In Brazil, the semiarid region encompasses a major part of the Northeast of Brazil (NEB) and part of the state of Minas Gerais, Southeast of Brazil. That region is mainly occupied by the Caatinga biome, which covers about 11% of the Brazilian territory (Silva *et al.*, 2020a). Such biome has been greatly affected by anthropic action due to the removal of natural vegetation for energy production and subsistence agriculture (Holanda *et al.*, 2017).

Growing water scarcity threatens the economic development, human livelihoods and environmental quality. The increasing population in the Brazilian semiarid region, associated with low rainfall, threatens the sustainability of water and other natural resources, causing groundwater depletion, and drying up reservoirs and rivers. Previous studies have reported reductions of 50% of the areas covered by water bodies across the Brazilian semiarid region (Montenegro & Ragab, 2012; Silva *et al.*, 2020b), affecting the daily life of local inhabitants, as well as reducing agricultural production (Rocha & Soares, 2015).

Drought impacts the vegetation dynamics of the Caatinga, presenting a strong decrease in vegetation activity by reduction of the gas exchange between vegetation and atmosphere, contrasting with irrigated croplands that exhibit little sensitivity to drought (Barbosa *et al.*, 2019). Due to the vulnerability of the Caatinga to water availability, the present work aims to determine water availability through the water balance of Thornthwaite & Mather (1955) for the current scenario (1961-2015) and for future projections (2071-2100) of climate change, considering the optimistic (RCP4.5) and pessimistic (RCP8.5) scenarios and evaluating possible changes in the climate patterns of this region.

MATERIAL AND METHODS

Study area

The Caatinga is a unique ecosystem characterized by a seasonally dry tropical forest occupying about 70% of the Northeast region and hosting a population of 27 million people (Figure 1).

Rainfall spatial distribution is widely variable across the Caatinga, ranging from 200 mm yr^{-1} to 1000 mm yr^{-1}. Mean annual temperatures vary from 23 to 27 °C across the biome and, in some areas the temperature exceeds 32 °C and relative humidity are below 50%, resulting in high potential evapotranspiration (above 1500 mm yr^{-1}) and negative water balance (Menezes *et al.*, 2012).

The Caatinga has shallow and stony soils, although relatively fertile, the biome is rich in genetic resources given its high biodiversity. It has three strata: arboreal (8 to 12 meters), shrub (2 to 5 meters) and herbaceous (below 2 meters) (Alves *et al.*, 2009; WWF, 2022).

Data

Precipitation (PREC) and temperature (TEMP) data from 42 meteorological stations distributed throughout the Caatinga (Figure 1) were obtained from the National Institute of Meteorology (INMET), a Brazilian government agency. The used data were from the Climatological Normal for the period from 1961 to 2015, available in https://portal.inmet.gov.br/.

Calculation of water balance

It is important to quantify the water availability of the Caatinga for present and future planning purposes. One of the methods widely used for this is the climatological water balance (WB). The present method was developed by Thornthwaite (1948) and later improved by Thornthwaite & Mather (1955), who, at the time, counted the precipitation in the balance calculation.

Thornthwaite & Mather (1955) method was used to determine the Climatological Water Balance (CWB), which requires precipitation and temperature as inputs. The first step, based on these data, is the computation of the potential evapotranspiration (PET). In this study, PET is calculated using the Thornthwaite (1948) method. For the present study, we assumed Available Water Capacity (AWC) being 50 mm, because the Caatinga soil is stony and shallow, and it has low water retention capacity (Moro *et al.*, 2015).

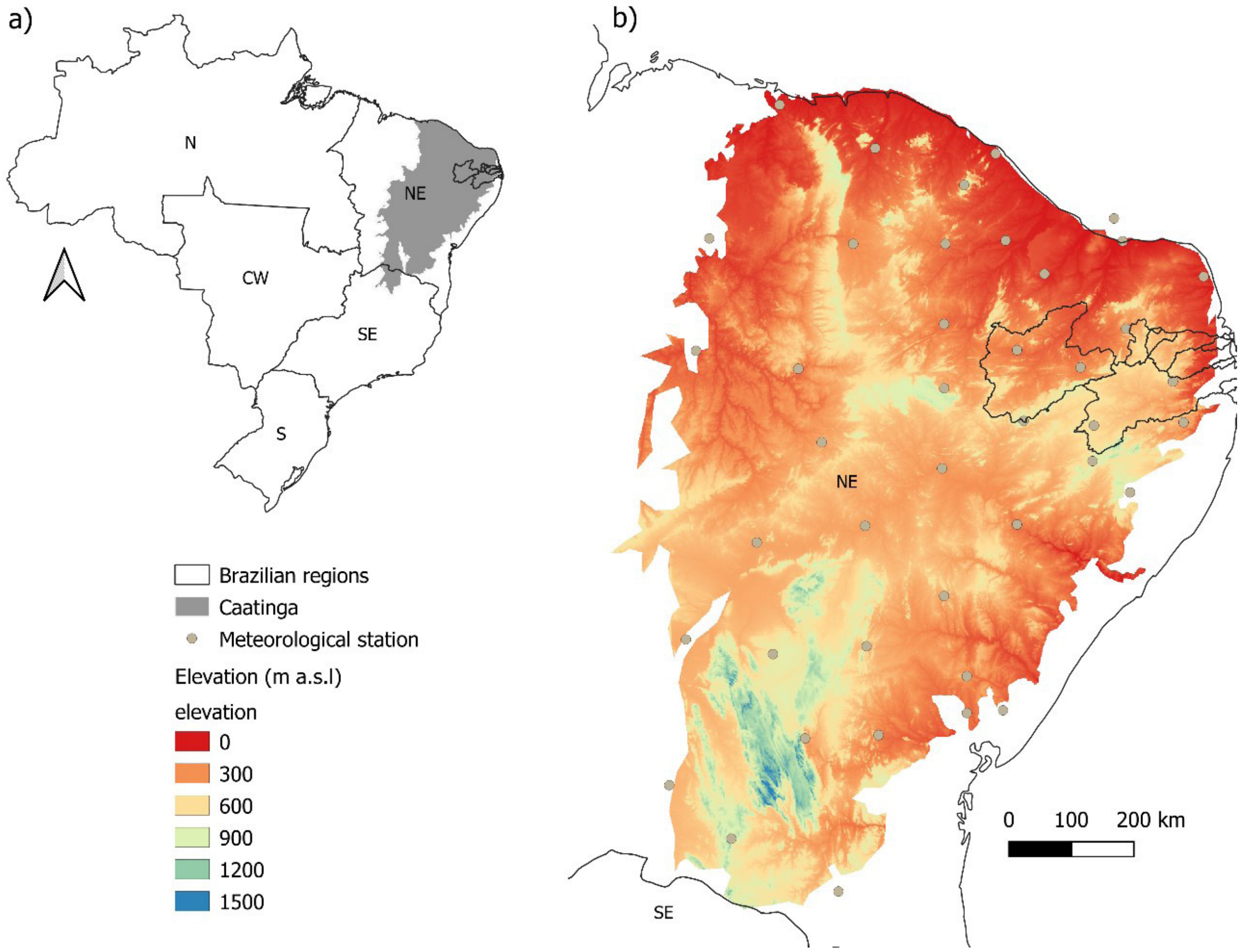

Figure 1: Study area and location of the meteorological stations: a) Brazilian regions: North (N), Northeast (NE), Center-West (CW), Southeast (SE), South (S); b) Topography. Source: Adapted from Beck *et al.*, 2018.

Climate change scenarios

The future climate change scenarios considered in this study were based on the RCP4.5 and RCP8.5 scenarios, defined in the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2013). The RCP4.5 scenario, resulting from the implementation of severe mitigation policies to the emission of greenhouse gases by humans, predicts a temperature increase of up to 1.5 °C by the end of the century. The RCP8.5 scenario, resulting from the absence of any mitigation measures, projects a 4.5 °C temperature increase by the end of the century.

We used the projections of temperature and precipitation change for the NEB obtained by Ambrizzi *et al.* (2007) and Chou *et al.* (2014) for the period from 2071 to 2100. We considered the period between 1961 and 2015 as the control period, i.e., the current scenario. Thus, that authors found projections of an increase in temperature of 1.5 ºC and a 15% reduction in precipitation for the RCP4.5 scenario (optimistic), and an increase in temperature of 4.0 ºC and a reduction in precipitation of 20% for the RCP8.5 (pessimistic) scenario.

The current scenario was taken with the average values of precipitation and temperature to calculate the WB of the historical series. For the optimistic scenario (RCP4.5), the value of 1.5 ºC was added in the average temperature for each month and a 15% reduction in the average rainfall for each month, and thus the WB for this scenario. Finally, 4.0 ºC was added to the monthly average temperature and a 20% reduction to the monthly average rainfall to formulate the pessimistic scenario (RCP8.5) for water balance.

Climate classification

To identify possible changes in the climate classification for the Caatinga, the aridity index (AI) was calculated by equation 1 (UNEP, 1992).

$$AI = \frac{PREC}{PET} \quad (1)$$

Where, PREC is the mean annual precipitation (mm year^{-1}) and PET is the mean annual potential evapotranspiration (mm year^{-1}). The AI values used to obtain the climate classification of a given location are presented in Table 1.

Table 1: Climatic classification according to Aridity Index values (UNEP, 1992)

Type of Climate	Aridity Index
Hyperarid	AI < 0.03
Arid	0.03 < AI < 0.2
Semiarid	0.2 < AI < 0.5
Dry sub-humid	0.5 < AI < 0.65
Sub-humid	0.65 < AI < 1.0
Humid	AI > 1.0

Maps were plotted using SURFER Software® demo version 13.6 and QGIS version 3.16. The interpolation was done using Kriging method present in the own software.

RESULTS AND DISCUSSION

Water availability

Spatial distribution of the water surplus for the Caatinga is shown in Figure 2. The comparison among the scenarios is made using the current scenario as a reference, considering that it represents the real situation of the current water conditions.

In Figure 2a is shown water surplus during the current scenario, so that a large area with low values is observed, in which more than 50% of the Caatinga has a surplus of up to 50 mm. It is presented a surplus between 100 and 500 in Central region (dotted rectangle), and two small nuclei in the south of the Caatinga that reached 300 mm (solid circle); the highest values (~900 mm) were found in a small portion in the north of the Caatinga (solid rectangle).

In the optimistic scenario the water surplus area of up to 50 mm is expanded, highlighting that, in center-east of the Caatinga, the water surplus was reduced considerably (Figure 2b). This region had an annual surplus of up to 500 mm and now reached a maximum of 300 mm (dotted rectangle). There also occurred a reduction in the coverage area and in the values of water surplus in the north region of the Caatinga. The maximum water surplus in this region was 700 mm (solid rectangle), however, restricted to a small area near the north coast.

In the pessimistic scenario for water surplus, the situation is critical, as practically the entire Caatinga in which had a water surplus of up to 50 mm (Figure 2c). Only a small region in the north of the Caatinga (solid rectangle) reached a value of 300 mm, reducing the area covered by the water surplus when we compared to previous scenarios.

The water deficit for the scenarios under study is shown in Figure 3. In the current condition, In the east and the southeastern parts of the Caatinga occurred a water deficit up to 600 mm, as well as the north portion, highlighted by the solid rectangle (Figure 3a). However, the greatest water deficits were found in the northeast (solid circle) and central part, extending to the western part of the Caatinga (dotted circle), reaching values of up to 1400 mm.

In the optimistic and pessimistic scenarios, an increase in water deficit is expected (Figs. 3b and 3c). The formation of some nuclei in which water deficit is more intense can be seen, both in the optimistic and pessimistic scenarios. In the optimistic scenario, the nucleus located in the north part of the Caatinga (solid rectangle, Figure 3b) reached a deficit of up to 1000 mm, but reached up to 2300 mm (solid rectangle, Figure 3c) of water deficit in the pessimistic scenario for this same area, demonstrating a considerably greater increase when we compared to the current scenario.

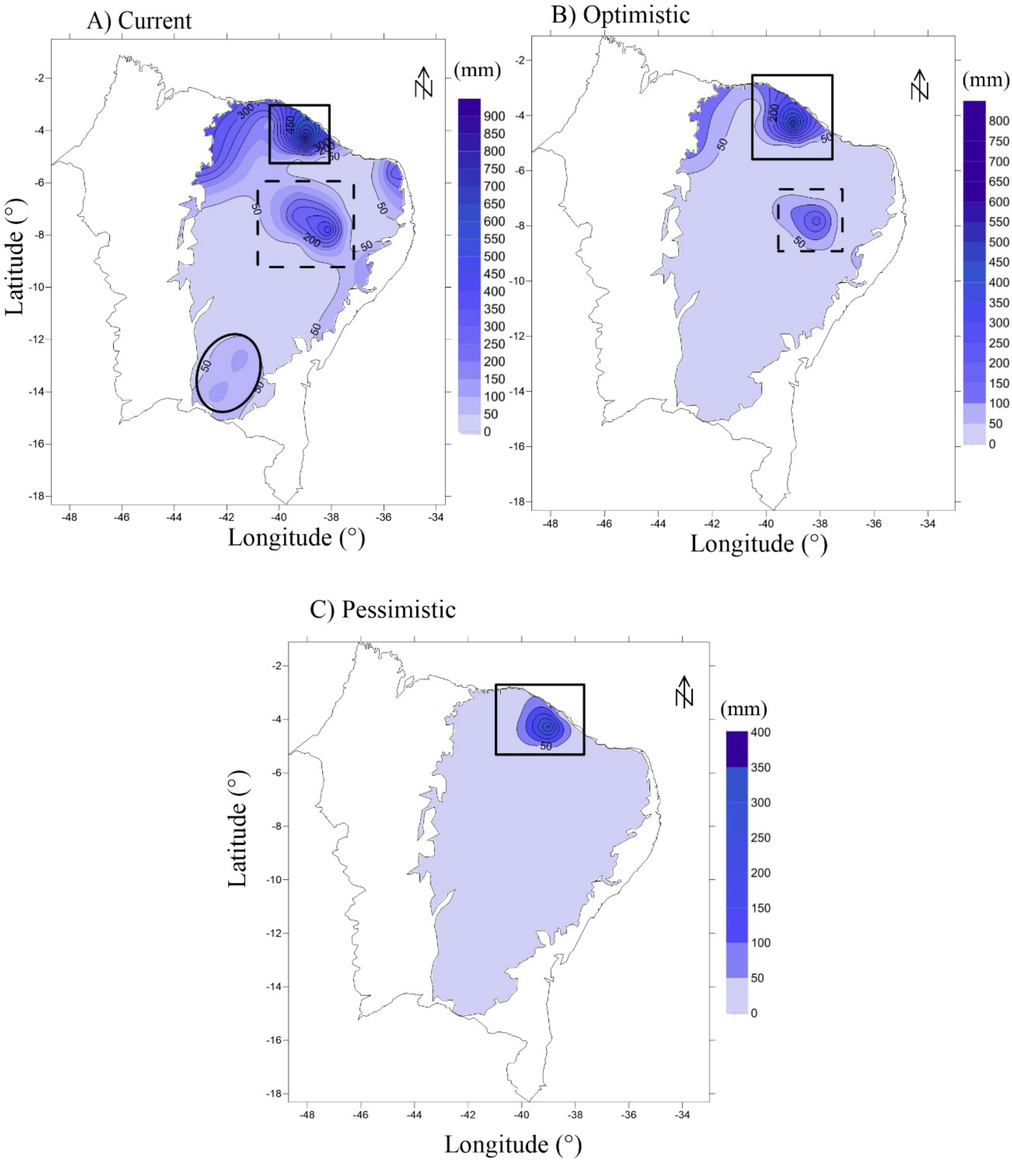

Figure 2: Water surplus in millimeters (mm) for the Caatinga during scenarios A) Current, B) Optimistic and C) Pessimistic. The solid rectangle, dash rectangle and solid circle represent a highlighted area in the scenarios studied.

The western part of the Caatinga reached values ranging from 1800 to 2600 mm (dotted rectangle, Figure 3b) in the optimistic scenario, but this area also was affected during the pessimistic scenario, reaching values ranging from 2700 to 3300 mm (dotted rectangle, Figure 3c). In the optimistic scenario, a nucleus that was not present in the current scenario located in the east part of the Caatinga emerged (dotted circle, Figure 3b). This area presented values the range from 1800 to 2600 mm during optimistic scenario. However, in this same area, an increase in water deficit was expected in the pessimistic scenario (dotted circle, Figure 3c). On the other hand, the region with the greatest deficit shifted to the west, as highlighted by the dotted rectangle. The reduction of surpluses and expressive increases in the water deficits throughout the Caatinga will provide direct implications in several sectors of the economy, but mainly in agriculture and livestock production. Crops such as corn and beans, traditionally performed in familiar arrangements and with dependency on rainfall, will be highly impacted in the evaluated scenarios, as their water requirements are around 300 mm and 500 mm, respectively (Futemma *et al.*, 2020).

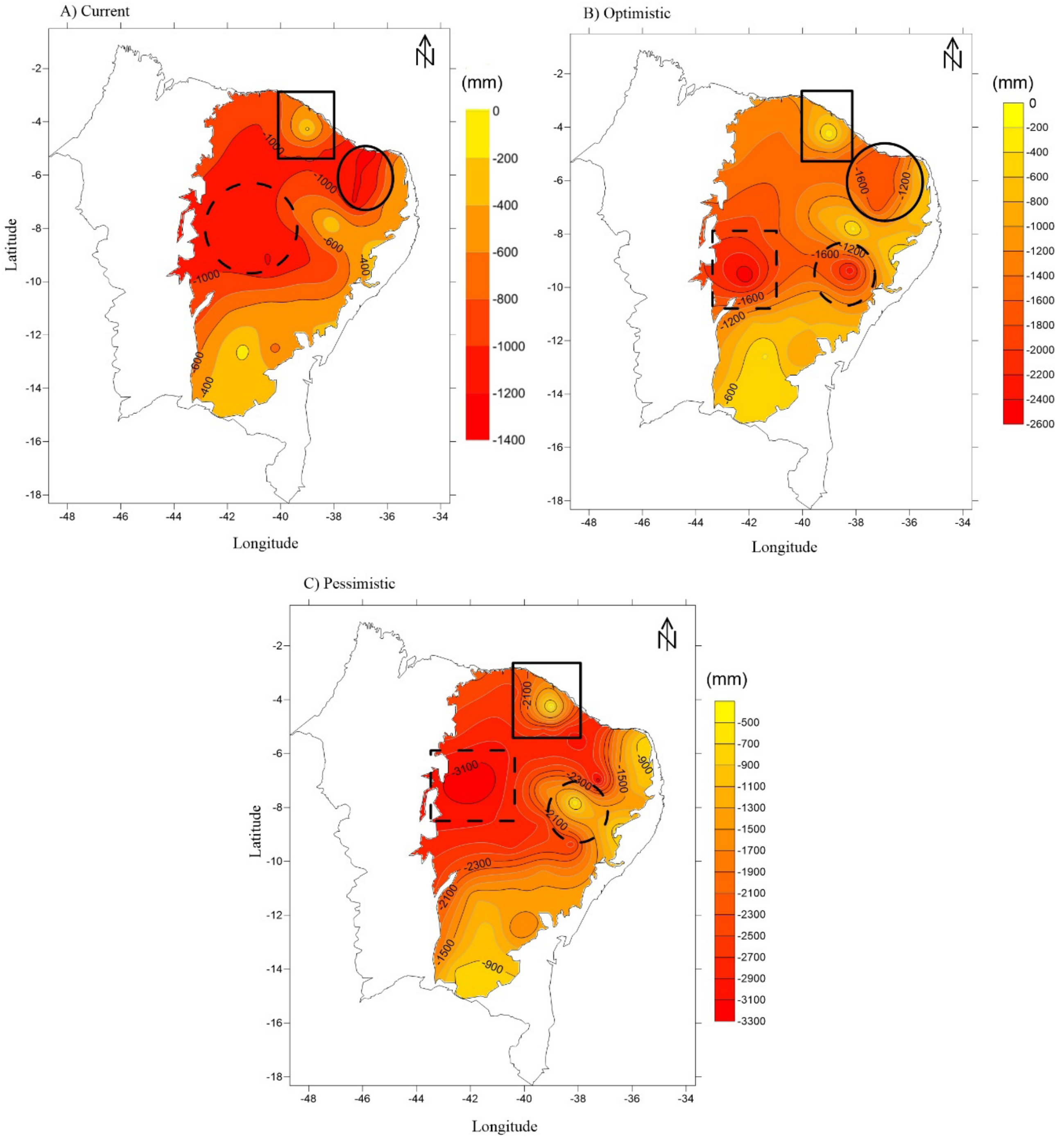

Figure 3: Water deficit in millimeters (mm) for the Caatinga during scenarios A) Current, B) Optimistic and C) Pessimistic. Solid rectangles, dashed rectangles, dashed circles and circles represent highlighted areas in the scenarios studied.

It is also important to quantify the annual water balance (surplus minus deficiency), as shown in Figure 4 for the scenarios under study. In the current scenario, Figure 4a, the Caatinga was characterized by negative water balances, with only two regions showing a positive balance: the north part of the Caatinga (solid rectangle) that reached 800 mm; and in the central part of the Caatinga (dotted circle), 200 mm of balance. Two regions with the most negative balances stood out, one located in the northeast part (solid circle) with -1400 mm and another in the central part extending to the West part of the Caatinga (dotted rectangle) which presents -1200 mm of water balance. The other regions ranged from 0 to 1000 mm of negative balance.

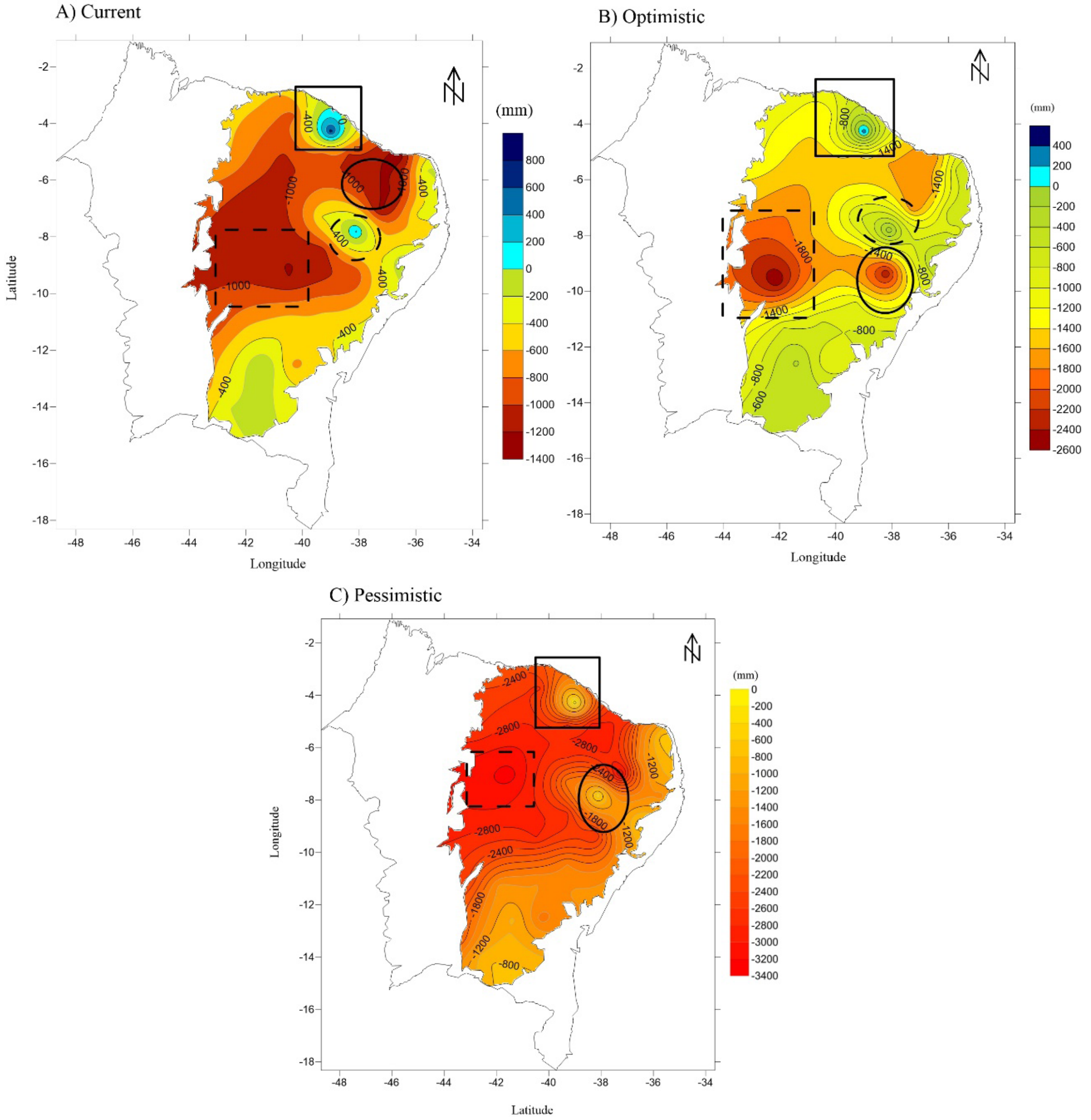
A) Current
B) Optimistic
C) Pessimistic

Figure 4: Water balance (Surplus minus Deficit) in millimeters in the scenarios: A) Current, B) Optimistic and C) Pessimistic. Solid rectangles, dashed rectangles, dashed circles and solid circles represent highlighted areas in the scenarios studied.

For the optimistic scenario, Figure 4b, only the small area in the north of the Caatinga presented a positive balance (solid rectangle), however reduced to 400 mm. The area with a positive balance located in central part presented in the current scenario disappeared during the optimistic scenario, giving way to an area with water deficit that reached -800 mm (dotted circle). The most expressive negative balance values are in the west (dotted rectangle) and east parts (solid circle) of the Caatinga. The nucleus located in the west part (dotted rectangle) reached -2600 mm of balance. Furthermore, the negative balance nucleus located in the east part (solid circle) that was not present in the current scenario and appeared during the optimistic scenario, showed values of up to -2400 mm. In the pessimistic scenario the water balance did not present any region with positive values (Figure 4c). However, the nuclei presented in the optimistic scenario were accentuated in the pessimistic scenario by more higher values of negative balance. The nucleus located in the north part of the Caatinga (solid rectangle) had a negative balance that reached 2600 mm. The nucleus located in the western part of the Caatinga (solid rectangle) reached a negative balance of 3400 mm, while the region in the east of the Caatinga (solid circle) obtained a negative balance of up to 1600 mm. It is important to note that, because its relatively low water storages, the Caatinga is highly vulnerable to changes in the climate variables under both optimistic and pessimistic scenarios (Figure 4). This will produce measures to mitigate the damage caused by the absence of water resources in the soil, something of extreme importance for agricultural production and livestock development.

Salati *et al.* (2007) performed studies on water availability in optimistic and pessimistic scenarios based on the fourth IPCC report for the northeast region of Brazil, carrying out the projections using the average of HadCM3, GFDL, CCCma, SCIRO and NIES models, and concluded that the water balances performed for the two analyzed scenarios (optimistic and pessimistic) indicated a decrease in water surplus of up to 100% in 2100 in the Northeast of Brazil. These results differ from those presented here for the optimistic scenario, which presented a water surplus of up to 400 mm. On the other hand, there is agreement during the pessimistic scenario, as in both studies it was found that there was no water surplus for such prediction.

Thus, it is observed that climate change negatively impact the Caatinga, conducting the region to suffer accentuated water stress (~3000 mm in some areas). It has an impact on the lives of people and animals that belong to this biome. Agriculture will suffer from water scarcity, impacting agricultural production in the region.

A similar observation was made by Guo & Shen (2016) for an arid region of China, in that observed that climate change will impact this region by decreasing water supply for agriculture and human use. Climate change will impact groundwater, reducing water availability for irrigation (Kirby *et al.*, 2016; Wang *et al.*, 2016) due to the increase in temperature, and consequently, in evapotranspiration (Reshmidevi *et al.*, 2018; Desai, 2021; Muluneh, 2020). With this, the loss of water by evapotranspiration, which is already high in semiarid regions, will reduce the soil water amount in the pessimistic scenario. Consequently, the Caatinga will not present water surplus, as can be seen in Figure 4c.

Climate classification

Climate classification for the Caatinga in the scenarios under study has been showed by the Figure 5. Despite the Caatinga being presented as a semiarid biome, in the current scenario, it has different climatic classifications, ranging from semiarid to humid climate (Figure 5a). The semiarid region occupies 36% of the Caatinga, while the dry sub-humid, sub-humid and humid occupy 64% of the Caatinga, indicating that the Caatinga is not totally semiarid. The humid climate is found only in the north part of the Caatinga, region in that occurred positive water balance.

During the optimistic scenario, Figure 5b, the semiarid climate region occupied an area of approximately 84% of the Caatinga territory, corresponding to an increase of 48% compared to the current scenario. Also in this scenario, a small arid area (0.34%) appeared that was not present in the current scenario. With the increase in the semiarid surface area, there occurred a reduction in areas with dry and sub-humid climates from 42% to 13.50% and from 21% to 2.19%, respectively. The humid climate region, located in the north and central-eastern part of the Caatinga, reduced surface area in some regions and disappeared in others during this scenario.

The Caatinga presented during a pessimistic scenario only the arid and semiarid climates, with 12% and 88% occupancy, respectively. The increase in arid and semiarid areas at the expense of the decrease in places under humid subtropical climate (Figure 5c) agrees with the classification projection presented by Beck *et al.* (2018) to Caatinga area, based on data from the Coupled Model Intercomparison Project (CMIP5), scenario RCP8.5, period 2071-2100.

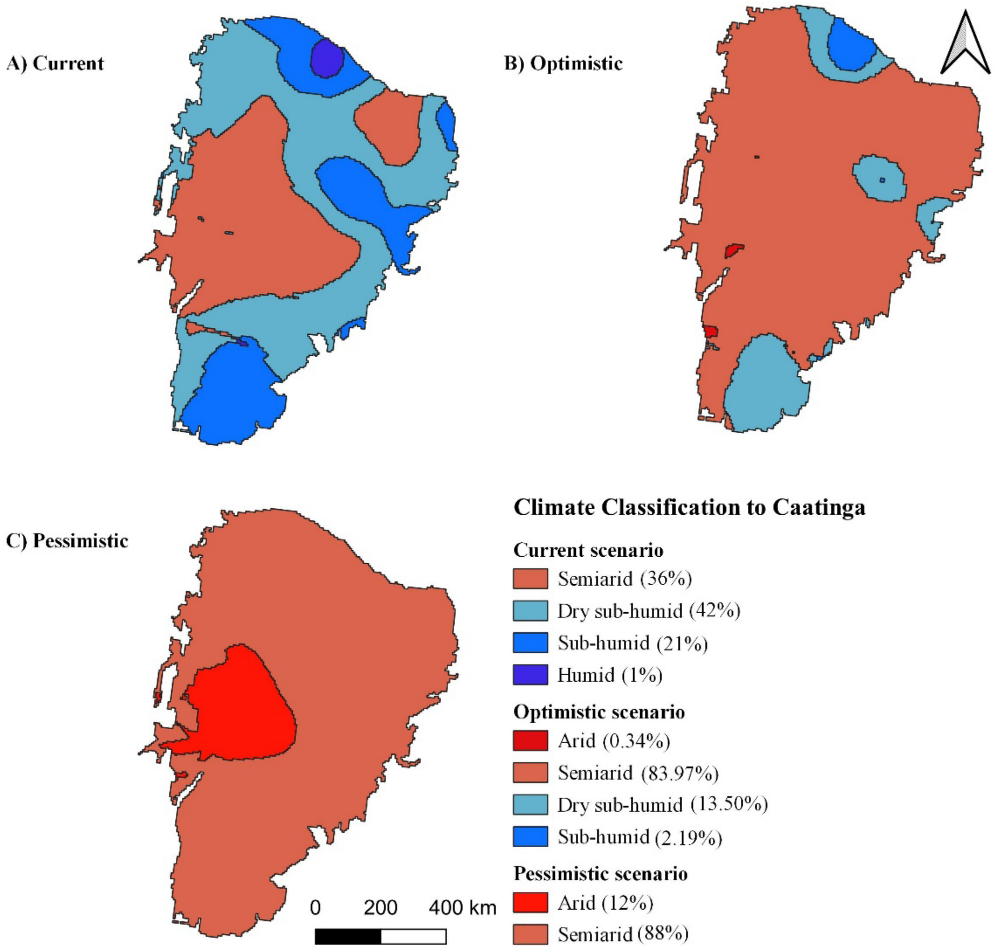

Figure 5: Climate classification based on the aridity index for the scenarios: A) Current, B) Optimistic and C) Pessimistic.

The Figure 5c has shown how much climate change has influenced the climate of the region, in which a large area changed from semiarid to arid. Also, areas that previously had a dry sub-humid climate became semiarid. Salati *et al.* (2007) also found for the Caatinga climate change for dry and sub-humid climate with little or no water surplus, for a normal classification from 1961 to 1990, and for humid arid climate with little or no surplus water for the optimistic scenario. During the pessimistic scenario, Salati *et al.* (2007) found a more drastic change in the climate classification, with the climate changing from sub-wet semiarid climate with little or no surplus water to dry semiarid.

The results found in this study show more accentuated changes in the climate classification than those projected by Salati *et al.* (2007). In a way, our results showed how much the Caatinga is affected by climate change, which will affect the population of this region economically and socially. The projections indicated that the climate of this region will become warmer and drier, possibly causing water shortages throughout of them, and the water balance might, in the future, be strongly influenced by climate change, affecting the water availability and streamflow patterns. As a result, water resources may not be sufficient to support population, economic, and environmental demands by the end of the 21st century (Andrade *et al.*, 2020). Lima *et al.* (2021) also verified a drastic impact mainly over the agricultural in a pessimistic scenario because occurred an increase in the arid area due to change from semiarid region to arid region.

Pinheiro *et al.* (2017) observed that in a climate change scenario the greatest change in soil-water components was observed for deep drainage, accounting only for 2% of the annual rainfall, and soil-plant-atmosphere fluxes seem to be controlled by the top layer (0.0-0.2 m), which provides 80% of the total transpiration, suggesting that the Caatinga forest may become completely soil-water pulse dominated under scenarios of reduced water availability.

In a pessimistic scenario in which occurred a considerable reduction in the amount of water stored, many families will be affected due to the difficulty in accessing these reservoirs, so that the vast majority of families have access to alternative reservoirs, and these reservoirs cannot supply a prolonged demand (Lira Azevêdo *et al.*, 2017).

Another important factor that will impact the Caatinga is the land use/land cover change, as areas of vegetation are being changed into agricultural areas will affect the climate, as shown by Jardim *et al.* (2022).

Therefore, it is important that the authorities, from now on, start planning for measures that mitigate these impacts, especially regarding water storage.

CONCLUSIONS

The Caatinga is highly impacted during climate change scenarios, especially during the pessimistic scenario, as it does not present a positive water balance in this condition.

Similarly, changes also occur in the climate classification of the Caatinga. Still within the optimistic projection, with an increase of 1.5 °C in the average temperature, the semiarid climate is predominant in the Caatinga, occupying 84% of the Caatinga, corresponding to more than five times the covered area by dry sub-humid and sub-humid together that is of 16.97%. Thus, dry sub-humid and sub-humid present a reduction of about 47% in the optimistic scenario, disappearing humid region.

In a pessimistic scenario, whole Caatinga become a semiarid (88%) and arid (12%) climate. Such changes lead to losses mainly in agriculture and livestock, as the water sources are affected, intensifying the desertification process in certain areas that are already susceptible.

It is clear that planning is needed to mitigate the future impacts that climate change will cause on the Caatinga.

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