Potential shifts in the aboveground biomass and physiognomy of a seasonally dry tropical forest in a changing climate

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Abstract

Seasonally dry tropical forests (SDTFs) account for one-third of the interannual variability of global net primary productive (NPP). Large-scale shifts in dry tropical forest structure may thus significantly affect global CO2 fluxes in ways that are not fully accounted for in current projections. This study quantifies how changing climate might reshape one of the largest SDTFs in the world, the Caatinga region of northeast Brazil. We combine historical data and future climate projections under different representative concentration pathways (RCPs), together with spatially explicit aboveground biomass estimates to establish relationships between climate and vegetation distribution. We find that physiognomies, aboveground biomass, and climate are closely related in the Caatinga—and that the region’s bioclimatic envelope is shifting rapidly. From 2008–2017, more than 90% of the region has shifted to a dryer climate space compared to the reference period 1950–1979. An ensemble of global climate models (based on IPCC AR5) indicates that by the end of the 21st century the driest Caatinga physiognomies (thorn woodlands to non-vegetated areas) could expand from 55% to 78% (RCP 2.6) or as much as 87% (RCP8.5) of the region. Those changes would correspond to a decrease of 30%–50% of the equilibrium aboveground biomass by the end of the century (RCP 2.6 and RCP8.5, respectively). Our results are consistent with historic vegetation shifts reported for other SDTFs. Projected changes for the Caatinga would have large-scale impacts on the region’s biomass and biodiversity, underscoring the importance of SDTFs for the global carbon budget. Understanding such changes as presented in this study will be useful for regional planning and could help mitigate their negative social impacts.

1. Introduction

Climate change has the potential to fundamentally reshape tropical ecosystems, particularly those already at the edge of ecological or climatic niches (Malhi et al 2009, Huang et al 2015, Higgins et al 2016, Allen et al 2017, Aguirre-Gutiérrez et al 2019). Although seasonally dry tropical forests are by definition well-adapted to dry conditions and episodic droughts, they are often close to the biological limits required to sustain relatively high-biomass physiognomies. This makes them particularly vulnerable to abrupt climate-induced changes in biodiversity, ecosystem function and ecosystem services (Gonzalez et al 2010, Hirota et al 2011, Stavers et al 2011, Allen et al 2017, Li et al 2018). Global field research has detected biome shifts and attributed them to anthropogenic climate change at sites around the world (Gonzalez et al 2010, Gonzalez et al 2012, Allen et al 2017). Much work has been done to project the extent and severity of future climate change on tropical ecosystems.
climate changes in tropical forests (Oyama and Nobre 2003, Salazar et al 2007, Hirota et al 2010, Staver et al 2013, Boit et al 2016, Li et al 2018), but determining the resilience and tipping points of these ecosystems in the face of regional drying and warming remains a significant challenge.

The Caatinga Phytogeographical Domain (referred to as Caatinga region, from this point for simplification) of northeastern Brazil is the largest continuous Seasonally Dry Tropical Forest (SDTF) on earth (Miles et al 2006, Allen et al 2017). The region contains ~1700 species, at least 300 of which are endemic (Leal et al 2005, Pagano et al 2013, Moro et al 2014). Although Caatinga (sensu stricto) is dominated by xerophilous thorn woodlands—a combination of shrubs and small trees with a seasonal herbaceous layer—it also encompasses many other vegetation physiognomies whose distribution is closely related to its heterogeneous climate (Silva de Miranda et al 2018). These include mosaics of semi-deciduous and evergreen forests at higher elevation (residual Atlantic Rainforest), as well as cactus scrublands or rocky soil in the driest regions (Sampaio and Rodal 2000, Velloso et al 2002, Prado 2003, Rocha 2004, Moro et al 2014). Field and satellite based estimates of above ground biomass have been explored for the region (Sampaio and Costa 2011, Castanho et al in press). High spatial resolution satellite biomass product was retrieved for 30 and 500 m (Baccini et al 2012, Zarin et al 2016). The average AGB of the Caatinga is relatively low (~43 Mg ha\(^{-1}\)) (Sampaio and Costa 2011) but highly variable, ranging from nearly 0 to > 130 Mg ha\(^{-1}\). The AGB values are closely associated with different vegetation physiognomies: deciduous thorn woodlands have the lowest AGB, followed by dry tropical deciduous forests, semi-deciduous forests, and higher-elevation humid tropical forests (Castanho et al in press). About 50% of the region averages < 2 Mg ha\(^{-1}\) of AGB, including landscapes such as cactus scrublands, rocky soil, and deforested areas.

Despite relatively low values of aboveground biomass (AGB), semi-arid ecosystems like the Caatinga are an important component of the global atmospheric CO\(_2\) cycle. The interannual variability of global atmospheric CO\(_2\) is closely related to variability in terrestrial net primary productivity (NPP) (Zha and Running 2010). Droughts and major climate events such as El Niño can trigger large changes in CO\(_2\) uptake in SDTFs (Huang et al 2016, Luo et al 2018). As a result, although semi-arid regions contribute a small fraction of global NPP, they account for about one third of the interannual variability of global NPP (Poulter et al 2014). Large-scale shifts in dry tropical forest structure may thus significantly impact global terrestrial CO\(_2\) fluxes in ways that are not fully accounted for in current projections.

Given these dynamics, climate change stands out as a particularly acute threat to the future of Caatinga forest structure. An extended drought beginning in 2012 has already had substantial economic and social impacts (Marengo et al 2017, Erfanian et al 2017, Brito et al 2018), and future climate simulations suggest that such drought episodes will increase in frequency (Marengo et al 2017). Modeling of potential vegetation suggests that such climate changes could lead to desertification of the driest regions of northeast Brazil (including the Caatinga) by the end of the century (Oyama and Nobre 2003, Salazar et al 2007, Lapola et al 2009, Salazar and Nobre 2010). Despite clear evidence that these areas are vulnerable to near-term climate changes, we know little about how Caatinga physiognomies will respond to those changes or how that response could affect the carbon budget of the region.

This study quantifies the relationships between climate, Caatinga vegetation physiognomies and associated AGB, with the goal of improving our understanding of how this important region will respond to future climate changes. We combine historical (observed) and future (simulated) climate data (Maurer et al 2007, Taylor et al 2012, Harris et al 2014); spatially explicit AGB estimates (Zarin et al 2016, Bacchi et al 2017); and established relationships between climate and vegetation distributions (Malhi et al 2009) to address three key questions: (1) How do the distributions of vegetation physiognomies relate to AGB and climate in the Caatinga? (2) What are historical shifts in the bioclimate zones? And (3) How might future shifts in climate reshape this bioclimate space and associated AGB?

2. Methods

2.1. Defining climate thresholds

The analysis presented here integrates key results from several previous studies. Moro et al (2014) conducted an extensive bibliographic review compiling the species compositions of different Caatinga physiognomies. (Silva de Miranda et al 2018) documented how spatial variability in climate determines species distribution in the Caatinga and distinguishes it from other Brazilian regions. Previous studies have also used high-resolution satellite images to map Caatinga vegetation physiognomies (figure S1, available online at stacks.iop.org/ERL/15/034053/mmedia) (Eva et al 2002, Rocha 2004). Finally, Castanho et al (in press) showed how woody AGB is distributed across vegetation physiognomies by combining field and spatial data from the Caatinga with a published pantropical 30 m map of AGB for the year 2000 (Zarin et al 2016, Baccini et al 2017). Following from those studies, we use a suite of satellite and ground based datasets (described below) to relate climate, biomass and vegetation in the Caatinga region.
2.2. Study area—Caatinga vegetation and ABG

The Caatinga region is located predominantly in the northeast region of Brazil (figure 1, insert), is considered one of the largest semi-arid regions in the world and recognized as unique ecoregion (Moro et al. 2015), spanning an area of 844 000 km² (IBGE 2018). Caatinga climate is predominantly semi-arid, with high potential evapotranspiration throughout the year (1500–2000 mm yr⁻¹) and low rainfall (300–1000 (± 200) mm yr⁻¹), which is usually concentrated in short time period (3–5 (±2) months) and is very erratic (Sampaio 1995). Average daily temperature ranges around 23 °C–28 °C. Caatinga physiognomies vary from bare-rocky ground to thornwood/shrubs/arboreal and evergreen broadleaf tropical forests (figure S1). This work uses a 30 m high spatial resolution satellite biomass product (Baccini et al. 2012, Zarin et al. 2016). This product was cross validated with ground estimate of aboveground biomass across the region in previous study, for detailed description of AGB distribution across Caatinga physiognomies, refer to Castanho et al. (in press). In this work we use the satellite retrieval 30m above ground biomass to estimate the average biomass within the climatic zones. For each climate zone the biomass < 2 Mg/ha was masked out and the mean and standard deviation of biomass in each climate region were computed (shown in figure 5(b)). Total carbon was estimated based on the corresponding biomass concentration in each pixel and corresponding area. The conversion factor from biomass to carbon used was 0.45, that has been defined based on field measurement for the region (Pereira Jr et al. 2016). The total carbon content within each climate zone is given by the sum of carbon in the pixels within the respective ones.

2.2.1. Historic climate data

To evaluate the role of (temporal) climate variability in Caatinga vegetation dynamics, we used observed climate data from several sources. We used three different historical climate datasets to ensure that our conclusions were not sensitive to uncertainties in observations. The main climatic data analyses were based on the Climatic Research Unit (CRU TS 3.24) of the University of East Anglia (Harris et al. 2014). The CRU dataset is 0.5° resolution with a monthly time step, and is based on a suite of climate variables observed at meteorological stations around the world, including mean temperature and precipitation for the period from 1950 to 2017. To check for reproducibility of the CRU precipitation trends (figure S2), we used data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al. 2015). CHIRPS incorporates 0.05° spatial resolution satellite imagery with in situ station data to create a gridded rainfall time series for trend analysis and seasonal drought monitoring, available monthly from 1981 to 2017. Finally, we used monthly precipitation and temperature data collected from 56 meteorological stations within the Caatinga region (INMET 2015) to characterize small patches of physiognomies not captured by the coarse resolution gridded datasets (figure S3).

2.2.2. Bioclimatic space

Here we adapted the climatic space concept (defined in Malhi et al. 2009, Silva de Miranda et al. 2018) which used current climatic conditions to delineate the boundaries separating rainforest, seasonal forest, and savanna regions. Their concept places each pixel of a region in a matrix defined by annual precipitation and the Maximum Cumulative Water Deficit (MCWD; figure 1)—an estimate of annual drought severity that is widely used to quantify meteorological drought (Malhi et al. 2009, Aragão et al. 2018). MCWD measures...
the cumulative deficit between monthly water supply (precipitation) and water demand (potential evapotranspiration, PET) within a year. Malhi et al use 100 mm as a fixed estimate of mean monthly evapotranspiration (ET)—a reasonable assumption for humid tropical forests—to calculate MCWD_{100} (Malhi et al 2009). In this study we calculated PET based on the Penman–Monteith equation to better estimate water demand for a semi-arid region (see below). We then assigned an AGB value to each pixel to create a new ‘bioclimatic space’ concept that refers both to the original climate and its associated biomass.

PET represents the maximum amount of water that would be transferred to the atmosphere by soils and vegetation if there were no water supply deficit. As such, it provides a better representation of drought-related vegetation water stress than ET (Beguería et al 2014). Here we calculated PET based on an FAO-56 Penman–Monteith equation (described in Allen et al 1998) using the Penman function, available in the SPEI package in R3.2 (Beguería et al 2014). The Penman–Monteith PET equation is physically based and depends on the monthly mean of the daily maximum and minimum temperature, relative humidity, cloud cover, wind speed, latitude and altitude (Beguería et al 2014). We used the monthly ET of a hypothetical reference short crop (0.12 m height) to estimate the potential evaporative demand of the atmosphere. This approach represents the atmospheric forcing relative to an initial condition (independent of the crop used) and is thus comparable across time and space (Sheffield et al 2012, Huang et al 2015, Huang et al 2017).

2.3. Future climate

Future climate data were based on the Coupled Model Intercomparison Project Phase 5—CMIP5 multimodel ensemble downscaled globally to 0.5° spatial resolution (Maurer et al 2007, Reclamation 2013) (https://gdo-dcp.ucarlnl.org/downscaled_cmip_projections/dcpInterface.html). Monthly data from 2018–2099 were bias-corrected against the observed historical data (CRU) (table S1). We considered three representative concentration pathways (RCP 2.6, 4.5 and 8.5 W m⁻²), which correspond to atmospheric concentrations of about 480, 650 and >1000 ppm CO₂-eq, respectively, by the end of the century (IPCC 2014). Of the downscaled climate models available, we used all models that included the variables needed for each emissions scenario in this study (table S1; 19 in total). For each scenario, we calculated the mean, upper and lower quartiles of the models simulations to have a better statistical representation of future trends than would be possible from a single model simulation (Duffy et al 2015). For the climatic analyses presented here, we summarized these data into ~30 year time steps (1950–1979; 1980–2009; 2010–2039; 2040–2069; 2070–2099), as well as decadal summary for 2008–2017 (corresponding to the latest observed data). Summaries for 1950–2017 came from observed data (CRU), while from 2018 to 2099 came from global climate model simulations (CMIP5).

3. Results

3.1. Caatinga bioclimatic space, AGB and physiognomies

Rainfall seasonality, rainfall intensity, and seasonal water deficit are critical variables controlling the different Caatinga physiognomies, and their associated biomass. The greater Caatinga region occupies a dry bioclimatic space distinct from that of other major South American regions (Silva de Miranda et al 2018) (figure 1). It is located at the dry end of the tropical forest climate space, with annual precipitation ranging from 500 to 1000 mm yr⁻¹, but as high as 1500 mm yr⁻¹ in a few isolated, high-elevation sites. The MCWD of the Caatinga ranges from −500 to −1300 mm yr⁻¹, exceeding mean annual rainfall by 500 mm or more throughout the region (figure 1). In contrast, the Amazon rainforest is defined by wet conditions with precipitation greater than 1500 mm yr⁻¹ and a short to moderate dry season, while the Cerrado is characterized by moderate precipitation (1000–2000 mm yr⁻¹) and a moderate to strong dry season (Malhi et al 2009). Unlike the Caatinga, in both the Cerrado and Amazon mean annual rainfall always exceeds MCWD.

Our results indicate that the lowest AGB values (≤40 Mg ha⁻¹, reds in figure 2) are also associated with the driest regions of the Caatinga—those characterized by low precipitation (<800) and high water deficit (MCWD < −800 mm yr⁻¹) (figure 2(b)). These low-biomass areas are distributed predominantly in the central to central-north region (semi-arid depression [1]), which is dominated by thorn woodlands. Higher AGB values (>60 Mg ha⁻¹, darker greens in figure 2(a)) occupy the Caatinga’s wetter bioclimatic zones (highest precipitation and lowest water deficit, figure 2(b)), which occur primarily at higher elevations (e.g. Borborema Plateau [2], Diamantina Plateau [3], Ibiapaba Plateau [4], and Baturite Mountains [5], figure 2(a)). These areas are occupied predominantly by humid forest physiognomies (e.g. Deciduous, Semi-Deciduous, and Evergreen Tropical Forests).

Where meteorological station data was available, we developed higher resolution analyses of the climate space associated with each physiognomy (S3). While such higher-resolution analyses can provide important insights into vegetation dynamics in highly heterogeneous and fragmented landscapes like the Caatinga, data limitations made it impossible to do this analysis for the entire Caatinga domain.

3.2. Historical shifts

Our results show an ongoing shift in climate towards increased water stress throughout the Caatinga. From
the baseline period (1950–1979) to the following historical period (1980–2009), 62% of the 0.5° pixels in the Caatinga shifted towards increased water deficit (lower MCWD) and 61% experienced decreased annual precipitation (figures 3(a), 4(a), (b)). In the last 10 years (2008–2017), more than 90% of the pixels shifted towards lower precipitation and increased water deficit (figure 3(b)), compared to the baseline period. During the baseline period, the drying trend was more evident around the central Caatinga (very low AGB <10 Mg ha⁻¹) and in the transitional forests of the southeast (AGB ~40–80 Mg ha⁻¹) (figures 4(a)–(c)).

The climate zone defined as the ‘Dry Zone’ [Precipitation < 800 mm yr⁻¹, MCWD <−800 mm yr⁻¹ (figure 5(b)—box 1)] ranges from thorn woodlands to no vegetation (figure S1). The Dry Zone represents 55% of the total area of the Caatinga in the baseline time period (1950–1979), and shifts to 58% in 1980–2009 and 67% in the last 10 years 2008–2017 (figures 4, 5(c), (d)). The ‘Extreme Dry Zone’ [precipitation <800 mm yr⁻¹ and MCWD <−1200 mm yr⁻¹ (figure 5(b)—box 2)] has essentially no vegetation (AGB < 2 Mg ha⁻¹), representing ~8% of the Caatinga’s total area in the baseline time period (1950–1979), 7% in the 1980–2009 period, and expanded to 14% during the last 10 years 2008–2017 (figures 4, 5(c) and (d)). The shifts in climate towards increased water deficit observed from the baseline period to the present are likely exerting a strong influence on regional carbon stocks. Based on the spatially explicit AGB data and its relationship to bioclimatic zones, we estimate that the observed bioclimatic shifts from (1950–1979) to (1980–2009) would be consistent with a ~5% reduction in the AGB in equilibrium with climate (from initial 0.79Pg C).

Assuming that AGB changes occur relatively slowly (i.e. decadal timescales), our results are an estimate of the potential change that could occur if such climate changes persist.

3.3. Future shifts

Simulations suggest that the observed historical shift towards warmer-drier climatic conditions is likely to continue into the future (figure 3(c)). By the late 21st century (2070–2099) under the high emission scenario (RCP8.5 W m⁻²), the Dry Zone is predicted to expand to 87% (64%–92% upper and lower quartile) of the total Caatinga. Most of that area will be in the Extreme Dry Zone, which is estimated to expand to 74% (42%–91% upper and lower quartile) of the total Caatinga area (figures 4(d)–(f), 5). Much of the semi-deciduous and deciduous physiognomies found in the (historically wetter) southeastern part of the region would shift into the Dry Zone, which supports little biomass (where thorn-woodlands are found today). The wettest regions (the remaining 13%), which today have the highest AGB, would be limited to the transition with Atlantic Forest in the east and the transitional ecotone in the northwest. These zones would have similar annual precipitation (>800 mm yr⁻¹) but increased dry season water deficits (MCWD <−1200 mm yr⁻¹), that are unprecedented for the region (figures 4(f), S8). In the low emission scenario (RCP 2.6 W m⁻²) the Dry Zone expands to 78% and the Extreme Dry Zone to 39% of the Caatinga by the late 21st century (figure 5), climate space shifts for RCP 2.6 and 4.5 are presented in figure S5–S7.

Overall, our results indicate that large areas of the Caatinga’s existing vegetation physiognomies will be incompatible with future climatic regimes. Based on the spatially explicit AGB data and its relationship to bioclimatic zones (figures 2, 5(b)), we estimate that the resulting bioclimatic shift would take the observed AGB (0.79 PgC, (Castanho et al in press) to a new and lower equilibrium state, where the biomass is about half of the initial value (42%–58% ±32%) at the end of the century under the high emission scenario (RCP 8.5 W m⁻²). The RCP 2.6 scenario indicates similar changes in AGB in the early 21st century, but would stabilize at 73%(±32%) of the initial AGB (figure 5(a)).
at the end of the century. The decrease in biomass suggest the replacement of the current vegetation by a vegetation with lower stature and lower biomass in the equilibrium state of a dryer ecosystem. This implies within the transition an increase in mortality of less tolerant species and the increase in recruitment of more tolerant species to the dryer conditions at the end of a period. This type of biome transition has been observed from field experiments in other locations across the globe as well as in other biomes (Gonzalez et al 2010, Esquivel-Muelbert et al 2017).

4. Discussion and conclusion

This study integrates biomass estimates, and climate projections to examine the historic and potential future distribution of vegetation in Brazil’s Caatinga region—the largest remaining seasonally dry tropical forest (SDTF) in the world and a globally important biodiversity hotspot. In doing so, it addresses key questions about how climate-induced shifts in vegetation may contribute to total carbon emissions; substantially reduce the capacity of the global land surface to sequester carbon in the future; and push today’s ecosystems into unprecedented climatic zones that have no analogue under historic climate conditions.

Our results reveal a close relationship among the vegetation physiognomies, aboveground biomass, and climate of the Caatinga. In general, lower biomass physiognomies (e.g. thorn woodlands) occurred in dryer climate zones, while higher biomass physiognomies (e.g. semi-deciduous, deciduous, and mountain evergreen forests) occurred in wetter climate zones. The highest-biomass regions fall into two distinct groups. The first occurs in the northwest, a region at the transition with the Cerrado that has relatively high precipitation and highly negative MCWD. The second occurs in the east and southeast, regions at

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**Figure 3**: Historical observed and future simulated shifts in Caatinga climate space in the high emission scenario RCP 8.5 W m⁻². Arrows represent the change in bioclimatic space for each 0.5° pixel across three different time steps: (a) from the observed historical baseline (1950–1979) to (1980–2009); (b) from the observed historical baseline (1950–1979) to the latest decade (2008–2017); (c) from the observed historical baseline (1950–1979) to the end of the 21st century (2070–2099). The circle at the base of the arrow represents the mean climate of each pixel in the baseline period; the tip of the arrow represents the climate in the corresponding end period. Note the difference in the x-axis scale for figures (a)–(c). The climate space is subdivided into zones to facilitate description and interpretation. Zones have a size of 800 by 800 mm yr⁻¹ of precipitation and MCWD and vary from dryer (red) to wetter (green).
Figure 4. Change in Caatinga bioclimatic zones from the observed historical to the simulated future derived from RCP 8.5 W m$^{-2}$. Maps of the spatial distribution of the climate zones for each 0.5° pixel at each time interval are presented for 6 time periods (a) observed 1950–1979, (b) observed 1980–2009; (c) observed 10yr interval 2008–2017, (d) simulated 2010–2039, (e) simulated 2040–2069, (f) simulated 2070–2099. The climate legend (at right of each map) corresponds to dryer (red) and wetter (green) climate zones (where each zone has a size of 800 by 800 mm yr$^{-1}$ of precipitation and MCWD). Black dots represent the locations of individual pixels in climate space over each time interval.
the transition to dry and semi-deciduous forests that have lower precipitation but less negative MCWD. The lowest-biomass physiognomies occur in regions where precipitation is low and MCWD is highly negative.

Climate exerts a particularly strong control on AGB and vegetation physiognomies across the Caatinga, delineating their current distributions and potential shifts as climate changes. Indeed, we found that the Caatinga’s bioclimatic envelope has already shifted, with over 60% of the region moving into a dryer state (less precipitation and increased MCDW) during the period 1980–2009, compared with the baseline period (1950–1979). This change accelerated in the last ten years (2008–2017), with over 90% of the region shifting into a dryer bioclimatic zone. By contributing to our understanding of how the Caatinga climate, physiognomies and biomass are related, these results represent an important first step in predicting how climate change may affect the region in the near and distant future.

Our analyses of future climate projections indicate that the climate may continue to dry in the coming decades. An ensemble of global climate model outputs based on the IPCC AR5 shows (figures 5, S7) that by the end of the 21st century the Dry Zone of the Caatinga (thorn woodlands to non-vegetated areas) could expand from 55% of the region to 87% in the high-emission scenario (RCP 8.5). Even in the low-emission scenario (RCP2.6 W m⁻²), the shift in climate space and expansion of dry areas across the region tightly follows the RCP8.5 scenario until the 2040s. After that point, RCP 2.6 W m⁻² begins to change more slowly, but the driest climate continues to expand until the 2070s (figure 5), reaching a maximum of 78% of the total region.

Our findings suggest that these large projected changes in the bioclimatic envelope would trigger large corresponding shifts in the equilibrium vegetation and AGB across much of the Caatinga. In fact, at least 25% of the region would shift to an unprecedented climate zone—comparable to arid regions found today only in the African Sahel and northwest Australia (figure S9). The climate zones associated with thorn woodlands would shift to an arid climate zone. Likewise, transitional, semi-deciduous, deciduous, and mountain evergreen forests would shift to a climate zone that today is associated with thorn-woodlands or dryer-adapted physiognomies (under RCP8.5, figures 4, S1). The northern thorn-woodlands would be even dryer than today and expand to the south; the Extreme Dry Zone in the central Caatinga
would also expand substantially. Such climate-induced shifts in Caatinga physiognomies would cause substantial reductions in aboveground biomass. We estimate that the equilibrium AGB would decrease between 30% (RCP2.6) and 50% (RCP8.5) by the end of the century.

The Caatinga (Santos et al 2014) and semi-arid vegetation in general (Donohue et al 2013) have been considered resilient to drought because they have evolved physiological mechanisms to respond to occasional droughts. Although it is unclear how long vegetation can persist under drought conditions, our findings are consistent with recent observations published from a variety of disciplinary perspectives. For example, in a review of ecosystem processes across SDTFs globally, Allen et al (2017) found that climate is driving fundamental changes to species distributions and ecosystem processes. Using satellite data, Higgins et al (2016) also observed globally shifts in regions associated with climate change. In a modeling study, Yang et al (2016) found that semi-arid ecosystems exhibited high sensitivity to future climate changes, while (Huang et al 2015, Huang et al 2017) estimated that drylands would expand significantly under RCP8.5. Field research has detected biome shifts and attributed them to anthropogenic climate change at sites around the world, as for example a long term (40 years) monitoring shifts in a dry vegetation area in African Sahel (Gonzalez et al 2010, Gonzalez et al 2012). Acosta Salvatierra et al (2017) observed a strong relationship between droughts and decreased Caatinga productivity, and higher resilience of intact vegetation to drought stress compared to degraded vegetation. Campos (2019) observed an increase in tree mortality in the last 7 years (2012–2018) during an extended drought period, in comparison to a previous wet period from 2009 to 2011, in a fragment of Caatinga dry seasonal forest region, indicating not only exposure but significant sensitivity to the extended drought. If this climatological condition persists, and becomes a new normal (or continues to get drier), the region would most likely shift to a new biome with species more adapted to the new condition and with lower biomass. Model studies have indicated a high vulnerability to biome shifts in the central Caatinga arid region (Oyama and Nobre 2004, Gonzalez et al 2012). Given these findings and the predicted changes reported here, we expect that vegetation in the Caatinga will reach a new, lower-biomass equilibrium despite individual species’ resistance to episodic droughts.

Particular species within the SDTFs may gain some resilience to future climate change due to the increase in photosynthetic water use efficiency associated with increased atmospheric CO₂ concentrations (Donohue et al 2013, Lu et al 2016). However, the scale of potential efficiency gains is unknown for most species, and so is the threshold of CO₂ saturation beyond which efficiency gains level off. While we do not attempt to account for the potential CO₂ fertilization effect, we acknowledge that increased water use efficiency in plants could partially offset future shifts in vegetation physiognomy.

A key insight from this analysis is the fact that, despite the uncertainties and diverging precipitation projections among global climate models (figure S4), future temperature change alone has the potential to increase drought severity and cause significant bioclimate shifts by increasing the potential evaporative demand of the atmosphere (Salazar et al 2007, Lapola et al 2009). If precipitation also decreases, as more than 50% of numerical models suggest, then the shifts in bioclimatic space, physiognomies, and AGB will be even more severe than what we report here.

These shifts in AGB and physiognomies could have significant social and economic impacts. The Caatinga provides important ecosystem services that are central to the regional economy and the livelihoods of its 27 million inhabitants (ICMBIO 2018) – particularly in light of the region’s extreme water scarcity (Sampaio 1995, Sampaio et al 2006). The shifts predicted here would severely handicap the extraction of food, fiber, and fuel from the native Caatinga species (Marengo et al 2017). Agricultural activities would need to adapt to much greater water demand and fewer water resources. Fire, whose occurrence has been sensitive to drought events (figure S9), may become a major threat if effective suppression of ignition sources does not occur. Therefore, to potentially extend the resilience of this ecosystem to climate change deforestation, and degradation, including by fire must be avoided, reforestation fostered, and more protected areas are needed (Leal et al 2005).

Understanding such changes as presented in this study could be useful for regional planning and could help mitigate their negative social impacts. The data produced is available for download, as well as via an interactive tool developed with Earth Engine App (Gorelick et al 2017) to facilitate visualization of the dynamic changes in climate space over time (https://acastanho.users.earthengine.app/view/caatingas). The results could thus be used immediately to evaluate implications for biodiversity, socioeconomic impacts, or climate feedbacks in the Caatinga. While the approach presented here is applicable at any spatial or temporal scale, future work could include higher-resolution climate data for application to local management.

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The data that support the findings of this study are openly available (Castanho et al. 2019).

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