



Influence of current and future climate on the seed germination of *Cenostigma microphyllum* (Mart. ex G. Don) E. Gagnon & G. P. Lewis

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Abstract Seasonally tropical dry forests are among the most threatened environments by climate change. However, these forests, which are at risk of desertification, are still poorly studied and conserved. Seeds of several species endemic to the Caatinga, a Brazilian dry forest, are also understudied, mainly regarding their ability to cope with a hotter and drier climate predicted for the future. For the first time in seeds of *Cenostigma microphyllum* (Leguminosae), we aimed to study the presence of physical dormancy, temperature and salt tolerance to ascertain the effects of current and future climate on seed germination. Intact and scarified seeds were investigated by incubating at constant temperatures (15 to 40°C) or in NaCl solutions (−0.2 to −1.0 MPa) at 25 and 30°C. Thermal and osmotic thresholds, as well as thermal time and hydrotime constants, were calculated using linear

regressions between the germination conditions and germination rate. To predict germination in the future, a heat sum model based on thermal time and hydrotime was applied to current and future climate scenarios. Seeds of *C. microphyllum* were permeable to water and did not have physical dormancy. The results indicated that increases in temperature are unlikely to affect germination, despite greater sensitivity to salinity presented at higher temperatures. In a future climate, the reduction in the number of weeks with at least 15 mm rainfall will affect the germination timing for the seeds. Thus, we can conclude that under the most pessimistic climate scenario predicted for the future, the seed germination of *C. microphyllum* may be restricted, likely leading to low seedling recruitment and establishment.

Keywords temperature · salt stress · climate change · thermal time model · hydrotime model

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Introduction

The early stages of the plant life cycle, such as seed germination, seedling establishment and recruitment, are the most susceptible to environmental change for many species (Vieira and Scariot 2006). The mechanistic knowledge of ecological processes of seeds and seedlings of tropical forest species and their adjustment to stressful environments facilitates the use of restoration techniques with greater success (Pereira et al. 2013). In this sense, seeds of species which are adapted to local environmental conditions are more likely to

tolerate temperature variation and extremes, lacking or excessive precipitation and changes in nutrient availability (Sovu et al. 2010).

Despite their distribution worldwide, most seasonally dry tropical forests occur as isolated patches and the only vast continuous area is the Caatinga Biogeographic Domain in north-eastern Brazil (Fernandes 2003). This ecosystem is characterized by vegetation adapted to a hot and semiarid climate with long periods of drought (Marengo 2014). Although the region shows good regeneration capacity of both its fauna and flora, increasing degradation of this ecosystem has resulted in intense desertification and, consequently, rapid loss of biodiversity (Marengo 2008; Siqueira Filho 2012). In addition, the Caatinga is predicted to be the most vulnerable Brazilian biome to a future climate scenario of global warming and decreased rainfall (Marengo 2014). According to the IPCC/AR5 projections for the semiarid northeastern region, the atmospheric temperature will increase by 1°C until the middle of the century and will increase by 3.5°C by the end of the century. This indicates significantly hotter conditions and a decrease of almost 50% in rainfall, thus worsening the water deficit in the region (IPCC 2014; Marengo 2014; PBMC 2014). This implies significant concerns for the Northeast region of Brazil regarding the socio-environmental effects of climate change and how these changes influence desertification process and the extinction of endemic species.

In arid and semiarid regions, the low rainfall, high temperature and evaporation contribute decisively to a greater water deficit and greater salinization of the soils (Pedrotti et al. 2015). In the Caatinga, saline soils are formed by the chemical weathering of rocks and by the rise of brackish groundwater due to high evaporation (Hirata et al. 2006). For Caatinga species, water is a particularly important factor because it is available in the soil in sufficient quantity for germination and seedling recruitment during only 3 to 4 months of the year, between December and March (Moura et al. 2007).

With more than 1,500 plant species occupying the Caatinga (Queiroz 2009), the diaspores of only 352 have been studied, with the Leguminosae family being the most widely reported (88 species from 49 genera; Meiado et al. 2012). There is no information on the seed germination traits of *Cenostigma microphyllum* (Mart. ex G. Don) E. Gagnon & G. P. Lewis, despite its restricted distribution in Northeastern Brazil and its ecological and economic value. Furthermore, few

studies have related germination to current climatic data and future climate scenarios to predict if the germination of native Caatinga species will be limited in the future (Oliveira et al. 2019). Thus, in this study, we aimed to address the following questions for *C. microphyllum*: (1) Do seeds exhibit seed coat physical dormancy? (2) What are the temperature limits to seed germination? (3) What are the effects of salinity on germination? (4) Considering future climate predictions of temperature increase and decrease in precipitation, how will germination be affected by such changes?

Material and methods

Study species

Cenostigma microphyllum is a Leguminosae shrub endemic to the Caatinga. It is distributed in a relatively small area including the areas south of Piauí, south of Pernambuco and north of Bahia. This species has both economic and ecological importance. The wood is widely used in construction and as fuel, whereas the bark and flowers are used in traditional medicine for stomach ailments (Queiroz 2009). It is a nurse species, which favors the germination and the establishment of seedlings that grow under its canopy, thus creating positive interplant interactions (Paterno et al. 2016).

Collection, processing and storage of seeds

Mature fruits of *C. microphyllum* were collected from 50 shrubs in Petrolina, Pernambuco State, northeastern Brazil (09°19'50.8" S, 040°32'55.4" W, 374 a.s.l.). The fruits were manually collected before dehiscence, when their colour was changing from green to brown. After harvest, the fruits were dried on a canvas and protected from rain and sun until the fruit dehisced and the seeds were manually separated from the fruit remains (Matias et al. 2014). Although there is no information about the effect of seed storage on this species, seeds of *C. pyramidale* stored at similar conditions for more than six months showed no change in germination percentage and speed (Antunes et al. 2010). Thus, after processing seeds were placed in labelled plastic bags and stored in a temperature- and humidity-controlled room (10±2°C and 40±5% RH) for no more than 2 months until the beginning of the experiments.

Scarification and germination at constant temperatures

Intact and scarified seeds were used to evaluate the presence of physical dormancy. Seeds were scarified by cutting the seed coat with steel scissors ($9 \times 5 \times 2$ cm) in the region opposite the hilum.

The treatments were randomized in a 6×2 factorial arrangement (six temperatures: 15, 20, 25, 30, 35 and 40°C ; using intact and scarified seeds). For each treatment, 100 seeds were used; these seeds were divided into four replicates of 25 each. The seeds were divided into acrylic boxes ($11 \times 11 \times 3.5$ cm), which had been previously sterilized with concentrated sodium hypochlorite for 15 min. Each box contained two sheets of filter paper (10.5×10.5 cm) moistened with distilled water, equivalent in volume to 2.5 times the weight of the dry substrate (Brazil 2009). Seeds were incubated in Biochemical Oxygen Demand (BOD)-type germinators over a period of 22 days, adjusted to maintain constant temperatures of 15 to 40°C , at increments of 5°C with a 12-h photoperiod.

Germination at different temperatures and osmotic potentials

Based on the results for scarification, intact seeds were used to evaluate the influence of temperature on the germination of *C. microphyllum* seeds at different osmotic potentials. The treatments were randomized in a 6×2 factorial arrangement, represented by six osmotic potentials (0.0, -0.2, -0.4, -0.6, -0.8 and -1.0 MPa) at two temperatures (25 and 30°C). The osmotic solutions were prepared according to the van't Hoff equation (Lang 1967), with solutions of sodium chloride (NaCl) in distilled water. For each treatment, 100 seeds divided into four replicates of 25 seeds were used, which were, as previously described, sown in acrylic boxes, on filter paper moistened with 10 mL of NaCl solutions in distilled water. Boxes were sealed with Parafilm® and incubated in BOD-type germinators adjusted for constant temperatures at 25 or 30°C and a 12-h photoperiod. Every three days, 10 mL of solution was added to the substrate to maintain a constant osmotic potential.

Germination evaluation

Over a period of 22 days, daily counts were performed and seeds with protrusion of the primary root longer than 2.0 mm were considered to have germinated. Based

on the daily germination data, the germination percentage, germination speed index (GSI; Maguire 1962) and germination uniformity coefficient (GUC, Ranal and Santana 2006) were estimated. The data were checked for normality and homoscedasticity by Shapiro-Wilk and Levene tests, respectively. If data were normal and homoscedastic, these were interpreted using an analysis of variance (ANOVA) and the means were compared using the Tukey test at a significance level of 5% by the program Assisat (Silva and Azevedo 2016). Data that did not follow a normal distribution were arcsine-transformed and re-tested. If the data were still considered non-normal, analysis was conducted by the non-parametric Kruskal-Wallis test at a significance level of 5%.

Modelling of germination data

Thermal time

Germination percentage at each temperature was plotted against time, creating cumulative germination curves, which were then fitted using a Boltzman function (Oliveira et al. 2019). From these curves, the germination rate (GR, reciprocal of the time required for 50% germination, $\text{GR} = 1/t_{50}$) was calculated separately for sub- and supra-optimal temperatures (Covell et al. 1986). A linear regression analysis was performed to calculate the x-axis intercept of both the sub- and supra-optimal temperatures, which provided estimates of the base (T_b) and ceiling temperatures (T_c) for germination. Below and above T_b and T_c , respectively, the GR equals zero (Covell et al. 1986; Ellis et al. 1986). The intersection of the linear sub- and supra-optimal temperature regression lines was used to estimate the optimal temperature (T_o ; Hardegree 2006).

The thermal time of the population that germinated at sub-optimal temperatures ($\theta_{T_{\text{sub}}}$) and supra-optimal temperatures ($\theta_{T_{\text{supra}}}$) was the reciprocal of the slope of each linear regression, respectively (Covell et al. 1986).

Hydrotime

Germination percentage at each osmotic potential (Ψ) were plotted against time and fitted using a Boltzman function (Oliveira et al. 2019), from which $1/t_{50}$ was calculated. At each temperature, a linear regression analysis was performed between $1/t_{50}$ and Ψ , and the

intercept on the x-axis was calculated to provide an estimate of the base osmotic potential (Ψ_b) below which GR is equal to zero (Gummerson 1986). Seed germination responses to the osmotic potential were also described using a hydrotime scale (θ_H) calculated for each treatment level of salinity by the reciprocal of the slope (Gummerson 1986; Bradford 1995).

Prediction of germination under current and future climatic scenarios

To predict seed germination under different climate scenarios, historical climatic data were obtained from the Agrometeorology Laboratory of Embrapa Semiárido, specifically the meteorological station of the Caatinga Experimental Field (09°13' S, 40°29' W) to represent the current climate. Future climate scenarios were taken from the Fifth Report of the Intergovernmental Panel on Climate Change (IPCC/AR5), namely RCP 2.6 (+1°C) and RCP 8.5 (+3.5°C; IPCC 2014), with reductions of precipitation of 25% and 40%, respectively predicted by the Brazilian Panel on Climate Change (PBMC 2014). Because each 1°C increase in air temperature is associated with a 1.5°C increase in soil temperature (Ooi et al. 2012), we estimated soil temperature under current and future climate scenarios.

An environmental heat sum (the thermal requirement for germination to occur) was calculated using soil temperature. The heat sum was calculated weekly according to the following equation:

$$\text{Heat sum} = (T_m - T_b) / t [^{\circ}\text{C} \cdot \text{d}^{-1}], \quad (1)$$

where T_m is the weekly mean soil temperature, T_b is the base temperature below which there is no germination and t is the number of days needed to reach the thermal time for germination (θ_T). Small rainfall events (5 to 10 mm) in semi-arid environments are effective to increase soil microbial activity (Schimel et al. 1999) and trigger rapid physiological responses in well adapted dryland plants (Sala and Lauenroth 1982). Thus, we only considered the heat sum effective when the weekly precipitation was at least 15 mm (equivalent to three 5 mm rainfall events).

Results

Influence of scarification on germination

Scarification resulted in a significantly lower final germination percentage (73%) than observed for intact seeds (77%; $P < 0.05$, $F = 4.245$). There was no interaction between scarification and temperature ($P = 0.782$, $F = 0.489$).

On the other hand, the interaction of scarification and temperature had a significant effect on germination speed and uniformity ($P < 0.05$). However, scarification had a significant effect on GSI only at 15 and 40°C C. At 20°C, GSI of scarified seeds was higher than that of the intact seeds, indicating that germination was faster. As there were few benefits to germination using the scarification treatment, it was decided to use intact seeds for the remaining experiments.

Influence of temperature on germination

Over 85% germination was achieved at temperatures between 15 and 35°C (Table 1). At 40°C, only 15% germinated. At temperatures of 20 to 40°C the germination was more uniform (higher GUC; Table 1). The GSI, which considers the percentage and speed of germination, was higher in seeds that germinated at 20 and 35°C than at 15 or 40°C (Table 1).

The thermal limits for the germination of *C. microphyllum* seeds were obtained using linear regressions relating temperature and $1/t_{50}$ (R^2 : sub-optimal temperature = 0.7852 and supra-optimal temperature = 0.6265; Fig. 1a). The optimum temperature (T_o) was estimated to be 25.9°C, the base temperature (T_b) was 11.6°C and the ceiling temperature (T_c) was 55.4°C (Fig. 1a). θ_{Tsub} and θ_{Tsupra} were estimated as 729 and 1.448°C·d⁻¹, respectively.

Influence of temperature on germination in salt solutions

At 25 and 30°C, germination decreased with the gradual increase in the concentration of NaCl (Table 2). Germination was highest at 25°C from -0.2 to -0.6 MPa and was significantly reduced at lower osmotic potentials. At 30°C, no germination occurred below -0.6 MPa. This result contrasted with that at 25°C, where germination was lower but continued until -1.0 MPa.

Table 1 Germination percentage (%), germination uniformity coefficient (GUC) and germination speed index (GSI) of *Cenostigma microphyllum*. Seeds were either scarified or intact and germinated at constant temperatures from 15 to 40°C.

Scarification	Germination [%]	GUC [day ⁻²]
Intact seeds	77.33 a	0.4613 a
Scarified seeds	73.66 b	0.8751 a
Temperature [°C]		
15	85.0 a	0.067 b
20	85.5 a	1.044 a
25	86.0 a	0.599 a
30	85.0 a	0.498 ab
35	93.5 a	0.547 ab
40	15.0 b	1.255 a
	CV [%] = 8.16; W = 0.250 ^{ns} ; F = 2.016 ^{ns}	CV [%] = 79.27; W = 0.000*; F = 5.416**
	GSI [germinated seeds·day ⁻¹]	
	Scarification	
Temperature [°C]	Intact seeds	Scarified
15	2.1196 cA	2.2508 bA
20	5.3369 bB	6.3292 aA
25	6.0518 aA	5.9786 aA
30	6.2723 aA	5.7738 aA
35	6.4250 aA	6.3661 aA
40	1.1250 dA	0.9083 cA
	CV [%] = 8.85; W = 0.230 ^{ns} ; F = 1.428 ^{ns}	

Germination and GSI mean values followed by the same letter, lowercase in the columns and uppercase in the rows, do not differ from each other based on ANOVA with a post-hoc Tukey test at 5% significance level. GUC mean values followed by the same letter, lowercase in the columns, do not differ from each other based on the Kruskal-Wallis ranking values at 5% probability.

CV – coefficient of variation; W – Shapiro-Wilk's test statistics for data normality; F – Levene's test statistics for homoscedasticity; ^{ns} – not significant; ** – $P < 0.01$

At 30°C, the GSI was affected by the increase of NaCl concentration, with a significant reduction beyond -0.8 MPa (Table 2). However, at 25°C, the GSI did not significantly differ from -0.4 to -1.0 MPa. No differences were observed in the GUC values at 25°C at any osmotic potential. At 30°C, germination was more uniform from -0.2 to -0.6 MPa.

Using values of $1/t_{50}$, an evaluation of the effect of temperature on germination under different osmotic potentials from saline solutions indicated the Ψ_b was -1.8 MPa (~ 50 dS·m⁻¹) at 25°C and around -1.1 MPa (~ 30 dS·m⁻¹) at 30°C (Fig. 1b).

Germination of the *C. microphyllum* seeds under current and future climate change scenarios

Based on the results obtained from the thermal and hydro time models, the environmental heat sum for germination to occur was calculated only when there

was a rainfall volume over 15 mm (Fig. 2). The modeling of germination of the current climate and the future scenarios (RCP 2.6 and 8.5) shows that the predicted temperature increase will not limit the germination of *C. microphyllum*, as the soil temperature will always be lower than the T_c of the seeds. With a reduction in the precipitation index of 25% in the RCP 2.6 scenario (Fig. 2b) and of more than 40% in the RCP 8.5 scenario (Fig. 2c), the number of weeks that germination may occur is reduced from 14 to 6 weeks.

Discussion

Several Caatinga seeds, mainly of the Leguminosae family, commonly have integuments that are impermeable to water (Freire et al. 2017) and are thus can be classified with physical dormancy (Baskin and Baskin 2004). Physical dormancy is often identified in seeds

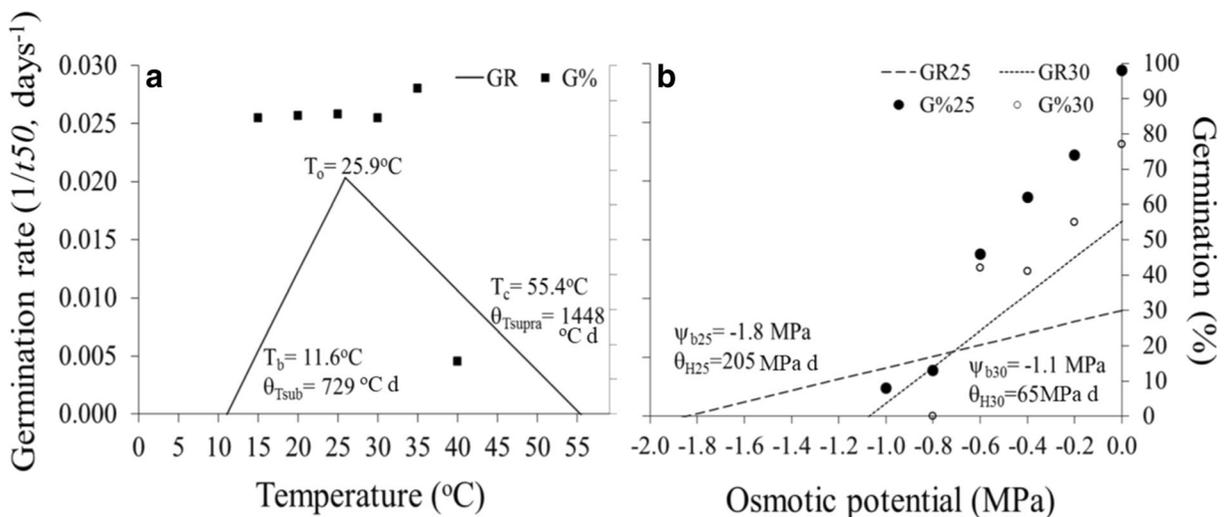


Fig. 1 Germination rate (GR) and percentage (G%) of intact seeds of *C. microphyllum* incubated at different temperatures A – in distilled water (R^2 : GR at sub-optimal temperatures = 0.785** and GR at supra-optimal temperatures = 0.627*) and B – in different osmotic potentials at 25 (GR25 and G%25) and 30°C (GR30 and G%30; R^2 : GR25 = 0.667* and GR30 = 0.627*).

T_o – optimal temperature for germination; T_b – base temperature; T_c – ceiling temperature; Φ_{Tsub} – thermal time at suboptimal temperatures; Φ_{Tsupra} – thermal time at supraoptimal temperatures; Ψ_{b25} and Ψ_{b30} – base osmotic potential at 25 and 30°C, respectively; and Φ_{H25} and Φ_{H30} – hydrotime at 25 and 30°C, respectively. * – $P < 0.05$; ** – $P < 0.01$.

produced in dry environments (Cardoso 2004). However, when the seed collection sites are compared for some Leguminosae such as *Cenostigma pyramidale* (Tul.) Gagnon & G.P. Lewis, which are found throughout the Caatinga, there is evidence that species behave differently according to their maternal location (Alves et al. 2007; Dantas et al. 2008; Antunes et al. 2010). Seeds of *C. pyramidale*, harvested at sites close to those used in this study, do not exhibit physical dormancy either (Antunes et al. 2010; Dantas et al. 2008; Dantas et al. 2014). However, at less favorable germination temperatures (15 and 40°C), scarification allowed greater speed and more uniformity of germination. Thus, even though no deep physical dormancy exists, scarification is linked to a wider thermal envelope for germination. This is advantageous for seeds in semiarid environments such as the Caatinga, where germinate is required to complete as quickly as possible during the short time when water is available. *C. microphyllum* is an important forage species in the Caatinga (Wiersema and León 2016), and the scarification of the seed coat can occur by acid and mechanical digestion during rumination of sheep and goats. Also, the seed coat can weaken by the action of the microorganisms present in the soil (Vásquez-Yanes and Orozco-Segovia 1993) or due to specific changes in the environment, such as thermal fluctuations (Fenner and Thompson 2005).

Seeds of Caatinga species usually germinate over a wide temperature range to cope with temperature fluctuations of the region (Oliveira et al. 2019). The GR threshold model estimated a T_c of 55.4°C although the germination experiment did not test these conditions (Fig. 1). Native seeds of the Caatinga are known to be tolerant to high temperatures and a small percentage can germinate at temperatures as high as 40°C, such as seen for *Myracrodruon urundeuva* (Oliveira et al. 2019), at 45°C, such as *Discocactus zehntneri* subsp. *petr-halfarii* (Nascimento et al. 2018), and at 47°C, such as *Anadenanthera colubrina* var. *cebil* (unpublished data).

This ability to germinate over a wide range of temperatures, from a T_b of 11.6°C to a T_c of 55.4°C (Fig. 1), demonstrates that if water is available, *C. microphyllum* seeds can potentially germinate at any time of the year in the Caatinga region. In this region, historical data has shown that minimum air temperature is never below 12°C (Moura et al. 2007) and warming due to climate change could result in soil temperatures of up to 47°C (IPCC 2014; Marengo 2014). Similar results were found for different species adapted to this environment, such as *Myracrodruon urundeuva* (Oliveira et al. 2019), *Amburana cearensis* (Guedes et al. 2010) and *Anadenanthera colubrina* (Paim et al. 2016), which showed high germination within an average air temperature range of 15 to 35°C. The data obtained for

Table 2 Temperature and germination (%), index of germination velocity (GSI), and germination uniformity coefficient (GUC) of *C. microphyllum* seeds imbibed in NaCl at different osmotic potentials (0.0, -0.2, -0.4, -0.6, -0.8 and -1.0 MPa) at 25 and 30°C

	Germination [G%]	GSI [seeds·day ⁻¹]	GUC [day ⁻²]
Temperature	25°C		
Osmotic potentials			
0	98.0 a	4.252 a	0.144 a
-0.2	74.0 ab	3.251 ab	0.130 a
-0.4	62.0 abc	2.873 abc	0.068 a
-0.6	46.0 abc	1.222 abc	0.150 a
-0.8	13.0 bc	0.289 bc	0.616 a
-1.0	8.0 bc	0.207 bc	2.125 a
<i>P</i> value ($\alpha = 0.05$)	0.000	0.001	0.387
Temperature	30°C		
Osmotic potentials			
0	77.0 a	4.200 a	0.558 ab
-0.2	55.0 ab	2.149 ab	1.048 ab
-0.4	41.0 ab	1.729 ab	0.636 ab
-0.6	42.0 ab	1.992 ab	2.063 a
-0.8	0 b	0 b	0 b
-1.0	0 b	0b	0 b
<i>P</i> value ($\alpha = 0.05$)	0.001	0.001	0.002
	CV% = 13.45; <i>W</i> = 0.007*; <i>F</i> = 3.465*	CV% = 15.32; <i>W</i> = 0.042*; <i>F</i> = 2.318*	CV% = 143.99; <i>W</i> = 0.000*; <i>F</i> = 17.701*

Mean values followed by the same letter, lowercase in the columns, do not differ from each other based on the Kruskal-Wallis ranking values at 5% probability

CV – coefficient of variation; *W* – Shapiro-Wilk's test statistics for data normality; *F* – Levene's test statistics for homoscedasticity; ^{ns} – not significant; * – *P* < 0.05

C. microphyllum showed that a high percentage of germination occurred at 15°C, but the time taken for germination was three times slower at 15°C than at 25°C (Table 1; Fig. 1). This may be undesirable, since agility during germination is very important to reduce seed and seedling exposure to unfavorable environmental conditions (Alves et al. 2014). However, an air temperature of 15°C is seldom encountered at Caatinga regions where *C. microphyllum* occurs.

Saline solutions retain water that would otherwise be available for germination, thus reducing the water potential of the substrate, resulting in lower water availability for the seed (Nasr et al. 2012). This lack of accessibility to water also prolongs the time required for the absorption of water by the seeds (Moreno et al. 2018). Consistent with this, at 30°C, the germination of *C. microphyllum* at osmotic potentials lower than -0.6 MPa was reduced and where germination did

occur, it was slower. This suggests that the combination of faster influx of saline solution associated with the higher temperature and toxicity caused by excess Na⁺ (Alsaedi et al. 2018) has a detrimental effect on germination, in comparison to 25°C.

As well as experiencing limited water, Caatinga soils are also affected by salinity. Furthermore, in this region of Northeast Brazilian, 30% of its area is geologically formed by peculiar crystalline rocks, which upon weathering produce brackish groundwater with an electrical conductivity of around 4 dS·m⁻¹ (SUDENE 1980). Unfortunately, as the forecast for the IPCC/AR5 report is a reduction of up to 50% in the amount of rainfall in the Northeast over the next 80 years, it can be anticipated that salinity will increase in these soils (IPCC 2014). Thus, although seeds are tolerant to osmotic potentials of NaCl lower than -1MPa (> 15 dS·m⁻¹), the lack of rainfall may still restrict seed germination.

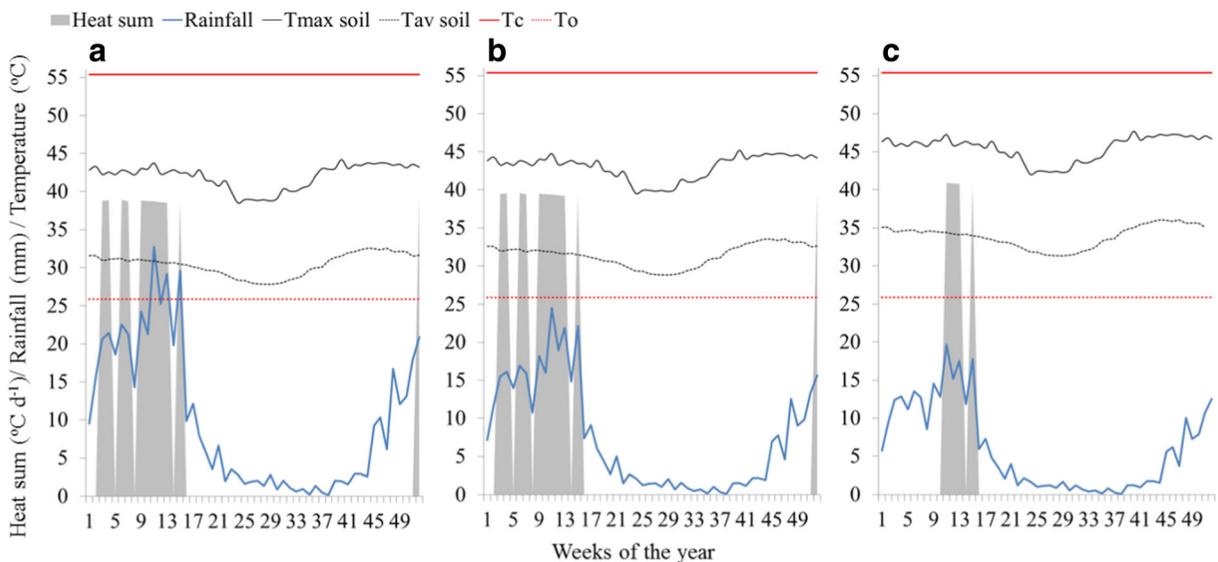


Fig. 2 Environmental heat sum needed for germination events of *C. microphyllum* under current climatic scenarios (A) and projected climate change scenarios RCP 2.6 (B) and RCP 8.5 (C) from the Fifth Report of the Intergovernmental Panel on Climate Change – IPCC/AR5 (IPCC 2014). Heat sum – calculated

heat sum (°C·d⁻¹) for germination events when rainfall was > 15 mm; Rainfall – accumulated weekly rainfall; T_{max} soil – maximum soil temperature; T_{av} soil – average soil temperature; T_c – ceiling temperature for seed germination. T_o – optimum temperature for seed germination.

Species occurring in dry tropical forests, such as the Caatinga, must have strategies to overcome factors such as low water availability, salinity and high temperatures in order to allow fast seedling emergence and for plants to establish (Merino-Martín et al. 2017). In this sense, the results of this work indicate that in order to cope with the most pessimistic climate change scenario, studies are needed on how to promote reforestation by increasing the number of seeds that germinate and seedlings that establish quickly taking advantage of the short time of available water. In this way, species with highly tolerant seeds may be more efficient for use in environmental restoration.

The most pessimistic scenario of an increase of 3.5°C in air temperature (+5.25°C soil temperature) and a 40% reduction in precipitation index, predicts a decrease in the number of weeks of rainfall suitable for germination to occur (Fig. 2c). The rainfall of at least 15 to 20 mm per week is considered the volume of rain needed to maintain soil moisture that provides seed germination for a week (Santos et al. 2011). Thus, by the end of the century, the time period of water availability useful for germination, as well as seedling development and establishment, is estimated to be reduced for *C. microphyllum* (Fig. 2c) and for *Myracrodruon urundeuva* Allemão (Oliveira et al. 2019). As such, seeds that are able to germinate might not produce

seedlings tolerant to dry conditions during the dry season and thus seedling establishment may fail.

For the first time, we report that seeds of *C. microphyllum* do not have physical dormancy. Climatic temperature increases will not influence the germination of the species because this will not exceed T_c for germination to occur. However, the anticipated decrease in precipitation will lead to a shorter time period for the recruitment of seedlings that are able to tolerate the dry season until the next rainy season. Although seeds are tolerant to electric conductivities higher than found in Caatinga soils currently, the increase of soil temperature and water deficit will lead to increased salinity through capillarity of brackish groundwater, which might restrict seed germination in some sites of the Caatinga biome.

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