Agronomy for Sustainable Development (2022) 42: 48
https://doi.org/10.1007/s13593-022-00780-w

RESEARCH ARTICLE

Cabruca agroforestry systems reduce vulnerability of cacao plantations to climate change in southern Bahia

Neander Marcel Heming[1] · Goetz Schroth[2] · Daniela C. Talora[1] · Deborah Faria[1]

Accepted: 27 April 2022 / Published online: 1 June 2022

Abstract
In southern Bahia, Brazil's traditional cacao region, cacao is mostly grown under the shade of thinned Atlantic Forest (known as *cabruca*). These agroforestry systems are gradually being replaced by unshaded cacao monocultures that might be more vulnerable to changes in climate; however, the impacts of climate change have not been evaluated yet. We assessed the impact of climate change on the climatic suitability of cacao plantations in southern Bahia and evaluated to what extent the *cabrucas* reduce the vulnerability of cacao as compared to unshaded plantations. We measured the maximum temperature in a gradient of canopy cover during the warmest month of the year and projected ecological niche models (MaxEnt) on climate projections for 2050 simulating the microclimate of three production systems: *cabrucas*, intermediate shading, and unshaded plantations. We found that canopy cover drastically reduces daily maximum temperature, so that understory temperature in *cabrucas* can be up to 6.0 °C lower than in unshaded plantations. We show for the first time that all projected environmental changes negatively affect cacao in southern Bahia, diminishing its climatic suitability and reducing overall suitable areas across the region. More importantly, this study is the first one to show that *cabrucas* can reduce the negative impacts of climate change for cacao, especially where temperature extremes approach or exceed crop tolerance limits. We conclude that maximizing short-term profits by implementing unshaded monocultures will likely lead to production losses in the long term. *Cabrucas* have a central role in reducing the vulnerability of cacao to climate change and since these traditional agroforestry systems cannot be quickly restored, their conservation should be an important goal of agricultural policies in the region.

Keywords Shaded plantations · Climate-smart agriculture · Climate change adaptation · Ecological niche model · Temperature stress · *Theobroma cacao*

1 Introduction

Global climate change will remain a major threat for agriculture for decades to come (Nelson et al. 2014). Spatial and temporal changes in temperature and precipitation regimes and the intensification of extreme events have increasingly impacted main global commodities, in many cases hampering production by loss of climatic suitability (Lobell et al. 2008; Läderach et al. 2013; Schroth et al. 2016; Caetano et al. 2018). To increase resilience to such a pressing issue, the agricultural sector should take action to mitigate and adapt to climate change. Resilience is particularly key for smallholder, low-income farmers that are most dependent on natural resources and vulnerable to environmental fluctuations (Mbuli et al. 2021).

Agroforestry—the integration of trees in agricultural production systems—is a management practice adopted by many small producers from tropical regions, and known to potentially reduce crop vulnerability to climate change (Lin 2007, 2014; Gomes et al. 2020). The protective cover provided by shade trees can lower local air and soil temperatures while increasing humidity levels, thus reducing environmental stress at specific shading levels (Lin et al. 2008; Blaser et al. 2018). Shading increases microclimatic stability, buffering

✉ Neander Marcel Heming
neanderh@yahoo.com.br

[1] Applied Conservation Ecology Lab, Programa de Pós-graduação Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Rodovia Ilhéus-Itabuna, km16, Salobrinho, Ilhéus, Bahia 45662-000, Brazil

[2] C.P. 513, 68109-000 Santarém, Brazil

temperature, and humidity variability and decreasing daily temperature extremes (Beer et al. 1997; Lin 2007). By maintaining better microclimatic conditions for crops, agroforestry systems not only reduce the loss of climatic suitability (Lin 2007) but also avoid or delay the local loss or relocation of production areas triggered by climate change (de Sousa et al. 2019; Gomes et al. 2020).

Cacao (*Theobroma cacao*), the third most important global agricultural export commodity after coffee and sugar (Donald 2004), is a cash crop overwhelmingly produced by smallholder families from developing countries in Africa, Indonesia, and Latin America (Donald 2004), and highly vulnerable to climate shifts (Hutchins et al. 2015; Schroth et al. 2016; Gateau-Rey et al. 2018). Cacao trees are native to the Amazon basin and are cultivated in warm tropical areas with high and evenly distributed annual precipitation (Wood and Lass 2001). Average annual precipitation > 1200 mm, dry season (< 100 mm precipitation/month) shorter than 3 months, minimum temperatures > 15 °C, and maximum temperatures during dry months below 36 °C are crucial for growing cacao (Wood and Lass 2001; Food and Agriculture Organization, FAO 2020a). Because cacao trees are particularly sensitive to water deficiency and extreme temperatures (Wood and Lass 2001; Schroth et al. 2016; Gateau-Rey et al. 2018), exceeding tolerance limits lead to mortality of young trees, yield loss, and, in the worst conditions, the damaging of plantations (Wood and Lass 2001; Gateau-Rey et al. 2018).

Cacao plantations are traditionally established under shade trees (Rice and Greenberg 2000). Shaded cacao plantations are also a traditional practice in Brazil, the sixth-largest global producer of cacao (FAO 2020b). Most of the national cacao production (53%) is concentrated in the southern region of Bahia state and is dominated by farmers with less than 10 ha which comprise 62.4% of the 69,000 cacao-producing properties according to Brazilian Institute of Geography and Statistics (IBGE 2017). In southern Bahia, cacao is mostly grown under the shade of thinned Atlantic Forest, an agroforestry system known as *cabruca* (Fig. 1, Araujo et al. 1998). Although structurally less complex than the original native forest, this agroforestry system plays an important role in conserving part of the rich biodiversity that characterizes the Atlantic forest hotspot (Faria et al. 2007; Schroth et al. 2011; Cassano et al. 2012). Despite their economic and ecological importance, the *cabrucas* have been progressively thinned to gain shade levels for short-term productivity increase (Sambuichi et al. 2012). The effects of thinning on the gain of cacao trees to climate change are, however, unknown for southern Bahia. Because most of the regional rainfall is carried inland by the sea breeze fronts as small and narrow rain bands lasting up to 6 h (de Angelis et al. 2004), local plantations are prone to drought events. A recent (2015–2016) El Niño drought had severe impacts on southern Bahia cacao plantations, leading to high yield losses (89%) and, most

Fig. 1 Cacao plantation shaded by *cabruca* agroforest in southern Bahia, Brazil. Photograph by Neander M. Heming.

importantly, a high cacao tree mortality (~ 15%) that was independent of shade tree cover (Gateau-Rey et al. 2018). This confirmed findings from other cacao producing regions that shade trees cannot protect understory crops under extreme drought events (Padovan et al. 2015; Abdulai et al. 2018b). In addition to drought, temperature changes can worsen the fragile balance of climatic conditions for local cacao production. Although tree cover might not reduce drought effects of climate change, it can prevent temperature-driven loss of resilience of cacao plantations in future climatic scenarios (Blaser et al. 2018).

Cabruca plantations of southern Bahia have gradually been converted into low shaded (rubber, *Hevea brasiliensis*) or unshaded (full sun) systems to maximize short-term profits (unshaded) or to complement farmer`s income (rubber) (Piasentin and Saito 2014). Distinct shading systems differ in several environmental properties that can either negatively and/or positively affect cacao trees. Potential negative impacts of increased shading include throughfall interception and belowground competition for water, which reduce water availability for cacao (Schroth 1998; Köhler et al. 2014; Abdulai et al. 2018b; Niether et al. 2018). Potential positive impacts of increased shading include more adequate microclimate for cacao such as lower temperature and higher humidity

(Pinheiro et al. 2013; Agele et al. 2016; Niether et al. 2018). The microclimatic and climatic conditions are of particular interest to develop adaptation strategies to the projected changes in climate due to global warming (Gomes et al. 2020).

Ecological niche models (ENMs) have been commonly used to assess potential impacts of climate change on crops (Läderach et al. 2013; Caetano et al. 2018; Gomes et al. 2020). ENMs are statistical methods that associate the localities where an organism occurs to a set of environmental variables, allowing to identify where, in the environmental space (values of environmental variables), an organism has conditions that are suitable for its persistence (Elith et al. 2011; Peterson et al. 2011). The resulting inferred association with environmental variables (i.e., ecological niche) can then be projected into a map, allowing the prediction of the geographical distribution of the organism on reference (e.g., near current) and/or future (projected) climatic conditions (Elith et al. 2006, 2010; Peterson et al. 2011).

Potential impacts of climate change on southern Bahia's cacao plantations have not been assessed yet. Similar to what is expected to happen in West Africa over the next decades (Läderach et al. 2013; Schroth et al. 2016), climate change could geographically shift or shrink suitable areas for cacao in southern Bahia. The risks of losing suitable areas due to increasing temperature and decreasing precipitation are high and could be exacerbated by inadequate management practices. Understanding the potential effects of climate change on crop yield and distribution of cultivated areas under distinct management practices is crucial to develop effective adaptation strategies (Rosenzweig et al. 2014; Jacobi et al. 2015). Given the current tendency in the region to convert shaded plantations into low shade or unshaded plantations (see review in Piasentin and Saito 2014), this study is the first one to assess (1) the impact of climate change on suitability and vulnerability of cacao plantations, and, (2) if climatic suitability is decreasing, to what extent the *cabrucas* reduce the vulnerability of cacao in southern Bahia, as compared to unshaded plantations.

2 Methods

2.1 Study area

The cacao-growing region in Bahia is located in the southeastern part of the state between the coordinates 41°30′W and 18°15′S (Fig. 2), corresponding to an area of approximately 91,819 km^2 (Mori and Silva 1979). First introduced in the region by the end of the eighteenth century, cacao became the most important crop produced in Bahia for most of the twentieth century, placing Brazil among the world's largest producers. Today, the largest part of cacao is still grown in agroforests, concentrated on rich soils located 10–15 km from the coast, while the native forests remain on poor sandy soils along the coast. The native vegetation shows altitudinal and topographical variation and is classified as humid forests (Gouvêa et al. 1976). The mean annual temperature is 24 °C, and the mean rainfall is 1500 mm/year. Although there is no marked seasonality, there is a relatively drier period of one to three months from December to March (Mori et al. 1983).

2.2 Occurrence points

We obtained 131 coordinates from cacao farms that were previously used for classifying land use in the core cacao-producing area in southern Bahia (Landau et al. 2008). We obtained 4547 occurrence records of cacao from Global Biodiversity Information Facility (GBIF 2018) and selected 560 from Brazil. We also used 78 records of cacao farms studied by our team (unpublished data). In addition to the known occurrence records, we generated 2500 random sample points across cacao-producing municipalities from Brazil. We retrieved cacao planted area for each Brazilian municipality from the Brazilian Institute of Geography and Statistics (IBGE 2017) and generated random sample points proportional to the planted area of each municipality. In total, we obtained 769 occurrence records and generated an additional set of 2500 random sample points. Lastly, we removed 26 occurrence points falling outside cacao environmental tolerances (see section 2.5. Areas within Cacao Environmental Tolerances), totaling 3243 occurrence points to be used for ecological niche modeling (see Section 2.6. Ecological Niche Modeling).

2.3 Climate data

We used variables known from previous studies to affect physiological tolerances of cacao, i.e., max temperature of warmest month (Bio5), annual precipitation (Bio12), water balance during the dry season (WBdry), and number of consecutive months with precipitation below 100 mm (dry season length, Schroth et al. 2016). Two variables (Bio5 and Bio12) were obtained from WorldClim (Hijmans et al. 2005) and the other two (WBdry and dry season length) were calculated using customized functions in program R (R Core Team 2020). WBdry was computed as the difference between precipitation of driest quarter (Bio17, Hijmans et al. 2005) and potential evapotranspiration of driest quarter (PETdry). We computed PETdry using the Hargreaves and Samani (1982) equation based on a modified version of "ET.HargreavesSamani" function from "Evapotranspiration" package (Guo et al. 2020). Data used to compute PETdry consisted of minimum and maximum temperature data from WorldClim (Hijmans et al. 2005) and solar radiation, which was computed using a modified version of the "Insol"

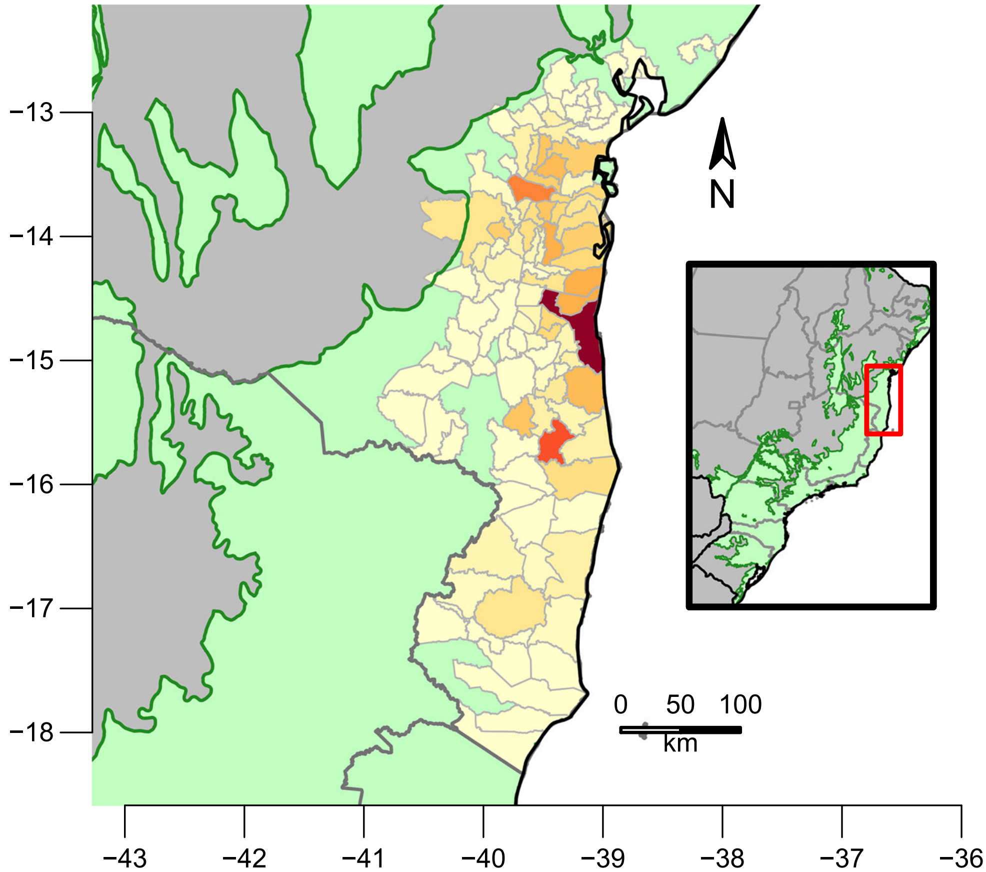


Fig. 2 Cacao-growing region in Bahia showing the cacao production (ton/yr, yellow to red colors indicate size production: darker shades for larger productions) by municipality according to Brazilian Institute of Geography and Statistics (IBGE 2017) and the region covered by the Atlantic Forest domain (green).

function from the "palinsol" package (Crucifix 2016). We computed dry season length with a customized function in R (R Core Team 2020) using precipitation data from WorldClim (Hijmans et al. 2005). All measured and calculated variables of climate projections were based on three general circulation models (GCMs: CCM4, MIROC-ESM, MPI-ESM-LR) (Flato et al. 2013), and two representative concentration pathways (RCPs: 2.6 and 4.5) (Meinshausen et al. 2011) from the Intergovernmental Panel on Climate Change (IPCC) for 2050 (Pachauri et al. 2014).

2.4 Microclimate land cover scenarios across landscape

To quantify to what extent the young cacao plants would benefit if they were growing up under the shade of a mature *cabruca* plantation, as compared to reduced shading scenarios (i.e., intermediate shade and unshaded cacao), we estimated the impact of shading on microclimate by measuring canopy cover index (CCI) using GLAMA app (Tichý 2016) and recording air temperature using 10 HOBO data loggers (model UA-002-64). The field measured microclimate temperatures (maximum daily temperatures) were then used to change the raster of temperature (Bio 5, maximum temperature of the warmest month) across the study area. This allowed us to estimate more closely the cacao environmental niche and to estimate cacao response to climate change under three microclimate scenarios based on shade management used across southern Bahia. Details are explained below.

The 10 data loggers were distributed across a canopy cover gradient comprising four different land-use categories as follows: five sites of *cabruca*, one rubber (*Hevea brasiliensis*) shaded cacao plantation, one unshaded cacao plantation, and three pasturelands. At each site, on the first day of temperature recording, we measured CCI using GLAMA installed on a smartphone and an external fish-eye lens for smartphone. Lens calibration was performed once and image calibration (i.e., cut level between "black" and "white" pixels) was performed for every picture, following the GLAMA's user manual (https://www.sci.muni.cz/botany/glama/GLAMA%20manual.pdf). The picture was taken at the same height of HOBOs placement (see below).

Mean air temperature (°C) was recorded once every 15 min over 6 days (from 11 to 16 March 2020) during the warmest month of the year in the study region. Young cacao is the most vulnerable development stage in cacao and will be most affected by climate change (Lahive et al. 2019). Therefore, to simulate the conditions of early cacao regeneration, sensors were placed at ~ 80 cm above the ground. During early cacao regeneration, some shade is always provided, at least temporary, which was simulated by placing the sensors in the shadow of trees or shrubs. Placing sensors under the shade also avoided any direct effect of sunlight warming the sensors, minimizing the effect of ground reflection at open areas. Some pastures were abandoned, but all had scattered shrubs. The unshaded cacao plantation had a relatively open canopy with some scattered bananas (*Musa* sp.) and common guava (*Psidium guajava*) trees planted.

Measurements were quality controlled by removing outliers. We fitted a local polynomial regression to the values of each site, extracted the residuals, and identified outliers using the same procedure used for boxplots—i.e., assumed that residual values beyond 1.5 interquartile range of the upper and lower quartiles were outliers (Hawkins 1980). We also removed the second day of measurement, which was rainy and colder than the other days (Fig. S1, Heming 2021a). We calculated daily maximum temperatures at each site, and then averaged daily maximum temperatures of all six days for each site.

We ran a linear regression using daily maximum temperature as response variable and CCI as predictor variable. Then we estimated the expected temperatures for three shading scenarios: high shade (average CCI of *cabruca* sites, *cabruca* hereafter), unshaded cacao (CCI measured at the unshaded site), and intermediate shade (midpoint CCI between *cabruca* and unshaded cacao).

To account for the microclimatic differences among shading types in the modeling process, we classified the tree canopy height raster (Simard et al. 2011) as potential open areas/unshaded cacao (from 0 to 6 m high), intermediate shaded cacao (higher than 6 m to 15 m), and *cabruca* (higher than 15 m). Then, in the raster of the maximum temperature of the warmest month (Bio 5, Hijmans et al. 2005, see Section 2.3. Climate Data), we subtracted the differences in daily maximum temperatures from unshaded cacao to *cabruca* and intermediate shaded cacao based on the classification of the tree canopy height raster. This subtraction was performed only for southern Bahia and allowed us to recreate a microclimate temperature on a regional scale and to create three land cover-based microclimate scenarios for future projections across all southern Bahia: unshaded (no change in Bio 5), intermediate shade, and *cabruca* plantations.

2.5 Areas within cacao environmental tolerances

We retrieved the environmental tolerance of cacao from the FAO crop database (FAO 2020a). Then we checked where, within our study area, environmental variables lie within the tolerance of cacao (i.e., be suitable for cacao) under shaded (*cabruca*) and unshaded conditions in the present and future scenarios (Figs. S2-S5, Heming 2021a).

2.6 Ecological niche modeling

ENMs estimate the relationship between environmental variables and the sites where species are known to occur, allowing to make geographical predictions of species distributions across time and space (Elith et al. 2011; Peterson et al. 2011). There are several algorithms for estimating species' niche and they differ in input requirements, parameterization, and performance (Elith et al. 2006; Sillero et al. 2021). A common feature is that they generate a geographical surface containing values of environmental similarity (interpreted as environmental suitability) between each surface cell (pixel) and the known occurrence records (Elith et al. 2011). We modeled the ecological niche of cacao using MaxEnt (version 3.4.1, Phillips et al. 2006; Phillips and Dudík 2008) a machine learning algorithm that requires only presence and environmental data and has superior performance compared to other algorithms (Elith et al. 2006).

2.6.1 Model tuning

We delimited the calibration area for the present climate creating a buffer of 1.5° around the minimum convex polygon of all occurrences (Anderson and Raza 2010; Barve et al. 2011; Anderson 2012) using "ENMwizard" package (Heming et al. 2019). We fine-tuned MaxEnt parameters by generating a set of candidate niche models with all combinations of four feature classes (FC): linear (L), quadratic (Q), product (P), and hinge (H). The FCs are transformations applied to the predictor variables, allowing flexibility of species suitability response to each predictor variable (Elith et al. 2011). Each combination of FC interacted with ten regularization multiplier (RM) values (from 0.5 to 5.0 in increments of 0.5) to determine the best selection of predictor variables (Muscarella et al. 2014). RMs penalize models, shrinking variable coefficients (Elith et al. 2011), so that, within models specified with the same set of variables and FCs, those with higher RM values will end up with less variables. The specification of a range of FCs generates models that vary the balance between model fit and complexity and the predictive performance of these models is then evaluated (see below).

Each model was evaluated using cross validation performed with "block" partition of occurrences and background locations, which divides occurrence and background locations in 'baskets' of data of (as much as possible) the same size (Muscarella et al. 2014). The "block" partition mode is the most appropriate for studies that require spatial and/or temporal transferability, i.e., scenarios different from those in which the models were initially built (Veloz 2009; Hijmans 2012), as in the present study. In this data partition mode, a preliminary model is calibrated with n−1 "baskets," and the records in "baskets" excluded in the calibration process are used for evaluation. The number of iterations applied is equal to the number of "baskets"; therefore, each "basket" is used once for an evaluation. We carried out model tuning and evaluation with "ENMeval" package (Muscarella et al. 2014) in the R program (R Core Team 2020).

2.6.2 Model selection, calibration, and projection

For each model, we calculated the second-order Akaike information criterion (AICc) for MaxEnt niche models (Warren and Seifert 2011) using "ENMeval" package (Muscarella et al. 2014). Then we selected the lowest AICc model using the "ENMwizard" package (Heming et al. 2019). These procedures ensure that the selected MaxEnt model is configured to balance the model performance and complexity, thus maximizing its predictive power while avoiding overfitting (Warren and Seifert 2011; Anderson and Gonzalez 2011; Warren et al. 2014; Radosavljevic and Anderson 2014). The selected model was then calibrated using all occurrence locations to ensure that the model coefficients are properly adjusted for all the environmental variations present in the calibration area. The calibrated model was then projected onto the present climate and on the six abovementioned climate scenarios for 2050 from IPCC (Pachauri et al. 2014); three GCMs: CCM4, MIROC-ESM, and MPI-ESM-LR (Flato et al. 2013); and two RCPs (2.6 and 4.5) (Meinshausen et al. 2011), interacting with three microclimate land cover scenarios (*cabruca*, intermediate shade, and unshaded plantations).

After calibrated and evaluated, we projected the contemporary (between the 1950s and 2000) and future (2050) climate scenarios. Finally, we converted the final models into binary maps of "suitable" vs. "unsuitable" habitat using the 'maximum training sensitivity plus specificity' threshold calculated by MaxEnt. This threshold finds the suitability value that correctly classifies the largest number of presences and background points in the prediction surface.

2.7 Variables causing loss of suitability

We ran a multivariate environmental similarity surface (MESS) analysis then computed the most dissimilar variable (MoD) across the projection area to check which variables are responsible for suitability loss in future climate scenarios. MESS measures the similarity of environmental variables between a projection and a reference dataset while MoD finds the variable that is most dissimilar to the reference dataset (Elith et al. 2010). These analyses are typically used during model transference (past/future climate or new geographic areas) to find variables responsible for novel climatic conditions in comparison with the calibration area (Elith et al. 2010). Here, we used the present day climate of the suitable (not the calibration) area as a reference to map areas on future projections that hold climatic conditions that are distinct from suitable areas. We restricted the calculation of MoD to the areas where cacao was projected to lose suitability on future projections. This allowed us to access which variables are the strongest responsible for the loss of suitable area in future climate scenarios. In areas where cacao was projected to maintain or increase suitability, MoD was not calculated because climatic conditions were not novel and, therefore, none of variables was dissimilar from reference conditions (i.e., all variable values were within the suitable range for cacao).

3 Results

3.1 Effect of shading on microclimate

Canopy cover index (CCI) ranged between 0.87 and 71.7 across all sites and negatively affected understory daily maximum temperatures (Fig. 3) during the warmest period of the year in southern Bahia ($R^2 = 0.96$, $F(1, 8) = 193.8$, $p \leq 0.001$). The fitted regression model was daily maximum temperature = 34.942 – 0.112*CCI (Std. Err.: 0.008). Fitted daily maximum temperatures were 34.9 °C for sites without any canopy cover, 33.4 °C (confidence interval, CI: 32.7–34.2 °C) for unshaded cacao (CCI = 13.6), 30.4 °C (CI: 29.9–30.9 °C)

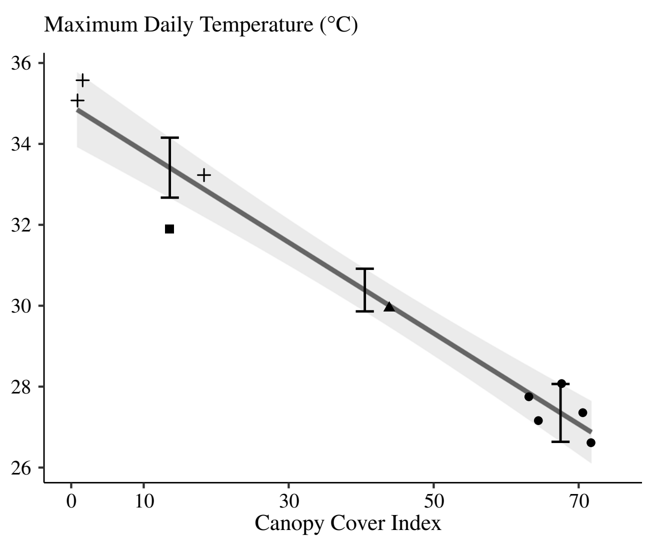


Fig. 3 Relationship between canopy cover index and understory maximum daily temperature (°C) across ten sites comprising four different land-use categories in southern Bahia, Brazil: *cabruca* agroforests (circles), rubber (*Hevea brasiliensis*) shaded cacao (triangle), unshaded cacao (square), and pastureland (plus signs). Shaded area corresponds to the confidence interval of the regression estimate and whiskers show the confidence interval for the understory maximum daily temperature at the climate scenarios onto which ecological niche models for cacao were projected.

for intermediate shading (CCI = 40.5), and 27.4 °C (CI: 26.6–28.1 °C) for *cabruca* (high shade, CCI = 67.5). Therefore, daily maximum temperatures in *cabrucas* were 3.0 °C (1.8–4.3 °C) lower than in intermediate shade, and 6.0 °C (4.6–7.6 °C) lower than in unshaded cacao.

3.2 Projected changes of climate

General circulation models at RCP 4.5 for 2050 project increasing temperatures and number of dry months and decreasing annual precipitation and water balance in cacao production areas of Southern Bahia, Brazil. The maximum temperature of the warmest month is projected to increase between 1.5 and 4.3 °C in *cabrucas* in the GCMs considered optimistic and pessimistic, respectively, while it is projected to increase between 5.7 and 8.5 °C if *cabrucas* are converted to unshaded systems, under the optimistic or pessimistic scenarios, respectively (Table 1, Fig. S6, Heming 2021a). The number of dry months in a year is projected to increase up to 3.6 months for the GCM considered pessimistic (MIROC-ESM, Table 1, Figs. S3, S6, Heming 2021a). Annual precipitation is projected to decrease up to 338 mm, while water balance during the dry season is projected to decrease up to 151 mm*month^{-1} for the GCMs considered pessimistic (MIROC-ESM, Table 1, Fig. S2, S6, Heming 2021a).

3.3 Environmental variables explaining cacao suitability

Maximum temperature of the warmest month explained 43.7% of the variation in cacao suitability, while annual precipitation, number of dry months, and water balance during the dry season explained 26.2%, 22.5%, and 7.6%, respectively, of the variation in cacao suitability.

3.4 Main environmental changes threatening cacao

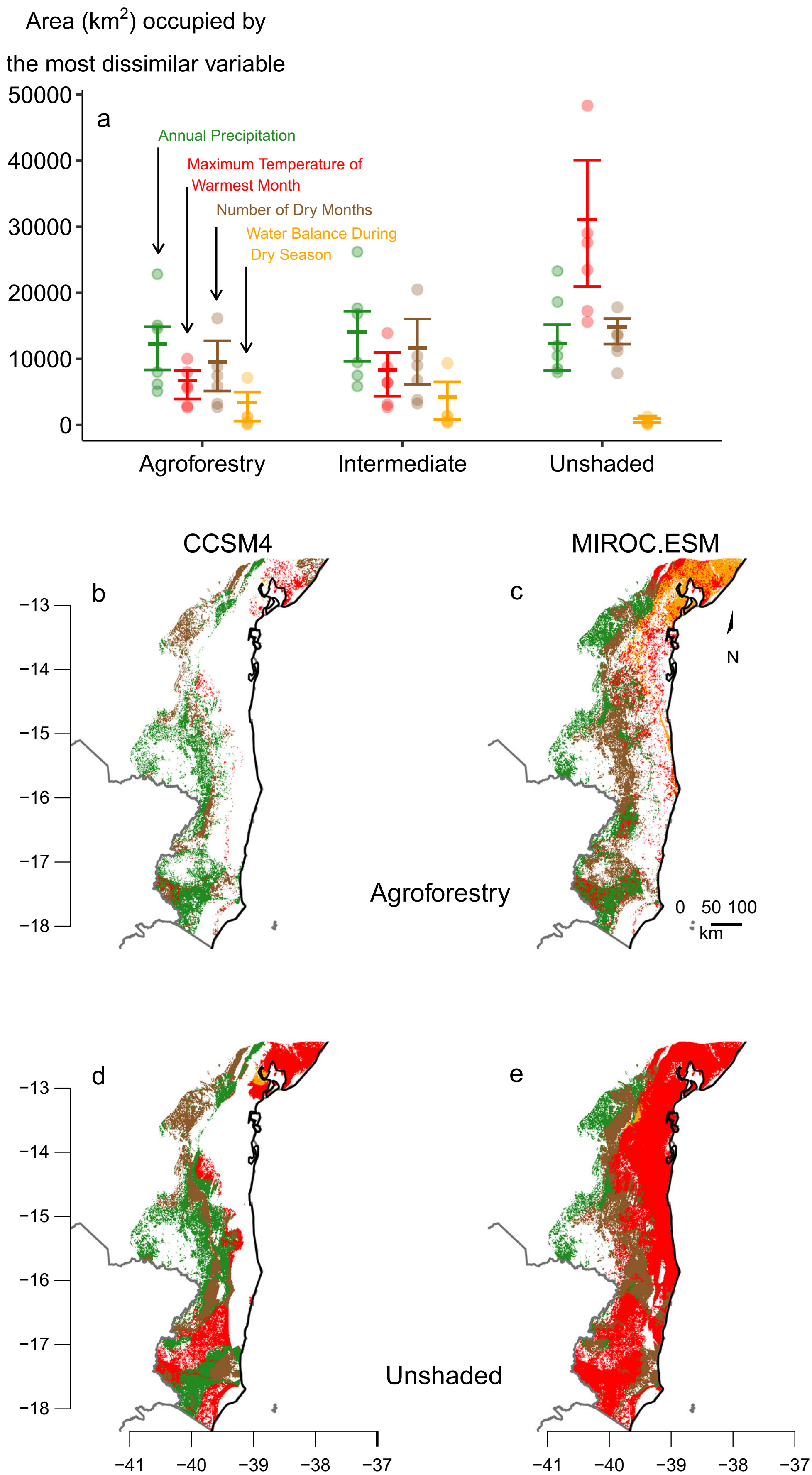
Loss of suitable areas for *cabrucas* is projected to be mainly caused by changes in annual precipitation and the number of dry months. On the other hand, unshaded cacao is projected to lose most of its area due to the increase of the maximum temperature of the warmest month (Fig. 4). In all GCMs and plantation systems, the projected decrease in annual precipitation and the increase in the number of dry months are projected to cause most of the losses in suitable area across the west and south of the cacao belt (Fig. 4). For unshaded cacao, however, warmer temperatures cause losses of suitable area in the north and south of the cacao belt in the GCM considered optimistic (CCSM4) scenarios and across almost all the cacao belt, including the core of production area, in the GCM considered pessimistic (MIROC-ESM). For *cabrucas*, the core of the cacao belt is unaffected in the GCM considered optimistic and has scattered losses in the GCM considered pessimistic due to changes in all variables, including stronger negative water balance.

3.5 Effects of cabrucas on reducing the vulnerability to climate change

Loss of suitable area for cacao is projected to be more pronounced for unshaded cacao than for *cabrucas* (Figs. 5 and 6). Across the whole cacao belt, unshaded plantations are projected to retain 26 ± 20% (20.540 km^2), while *cabrucas* are estimated to retain 63 ± 23% (48.928 km^2) of current suitable area (77.226 km^2) on RCP 4.5 for 2050. Across municipalities, in unshaded plantations, between 2 ± 4 and 81 ± 32% of the current suitable areas are projected to remain suitable for cacao under the GCM considered pessimistic (MIROC-ESM) and the GCM considered optimistic (CCSM4) for 2050, respectively. On the other hand, in *cabrucas*, between 59 ± 23 and 96 ± 9% (45.563 km^2 and 74.137 km^2) of the current suitable areas are projected to remain suitable under the GCM considered pessimistic (MIROC-ESM) and the GCM considered optimistic (CCSM4) for 2050, respectively. For both plantation

Table 1 Mean and standard deviation (between parentheses) values of macroclimate variables for the near current conditions and three general circulation models (GCMs) at representative concentration pathway (RCP) 4.5 for 2050 across southern Bahia's cacao belt. Variables shown are maximum temperature of the warmest month for *cabrucas* (Bio5 *cabruca*, °C) and for unshaded cacao (Bio5 unshaded, °C), number of dry months (consecutive months with precipitation below 100 mm), annual precipitation (mm), and water balance during the dry quarter of the year (WBdry, mm*month^{-1}). Bio5 *cabruca* was calculated based on microclimatic differences between unshaded cacao and *cabruca* sites, measured using HOBO data loggers (see methods for specific details).

GCM	Bio5 *cabruca* (°C)	Bio5 unshaded (°C)	Dry months	Annual precipitation (mm)	WBdry (mm*month^{-1})
Present	24.3 (0.8)	28.5 (0.7)	2.7 (2.3)	1466.1 (304.1)	− 73.37 (52.5)
CCSM4	25.8 (0.8)	30 (0.7)	3.7 (2.2)	1287.6 (265.1)	− 144.9 (43,1)
MIROC ESM	28.6 (0.8)	32.8 (0.4)	6.3 (2.7)	1127.1 (247.8)	− 225.0 (27.9)
MPI ESM LR	26.1 (0.9)	30.2 (0.7)	3.7 (1.9)	1457.6 (287.8)	− 154.5 (36.8)



Area (km2) occupied by
the most dissimilar variable
50000
40000
30000
20000
10000
0
a
Annual Precipitation
Maximum Temperature of Warmest Month
Number of Dry Months
Water Balance During Dry Season
Agroforestry
Intermediate
Unshaded
CCSM4
MIROC.ESM
b
c
d
e
N
0 50 100
km
Agroforestry
Unshaded
−13
−14
−15
−16
−17
−18
−41
−40
−39
−38
−37

◀ **Fig. 4** Area occupied by variables that are most dissimilar from variables in current suitable area for cacao in southern Bahia, Brazil. Each variable is represented by a color: annual precipitation in green, maximum temperature of the warmest month in red, number of dry months (consecutive months with precipitation below 100 mm) in brown, and water balance during the dry quarter of the year in yellow. Colors represent the same variables throughout all five subplots. Panel '**a**' shows total area occupied across general circulation models (GCMs) and representative concentration pathways (RCP) for 2050, for *cabruca* agroforests, intermediate shading, and unshaded cacao. Semi-transparent circles denote total area at combinations of GCMs and RCP for 2050, full colored bars show mean and standard errors for each group. Maps in panels '**b**' to '**e**' show the regions in which each variable is projected to be most dissimilar from current suitable area for cacao. Top map panels ('**b**' and '**c**') are for *cabruca* agroforests and bottom map panels ('**d**' and '**e**') are for unshaded cacao, both for the GCM considered optimistic (CCSM4, panels '**b**' and '**d**') and the pessimistic (MIROC.ESM, panels '**c**' and '**e**') at RCP 4.5 for 2050.

systems (unshaded and *cabrucas*), loss of suitable area is projected to occur mainly at the margins of the cacao belt of southern Bahia for the CCSM4 GCM (Fig. 6). However, for MIROC-ESM with *cabrucas*, there are drastic reductions projected in the suitable areas at the core of cacao belt, where are situated the main cacao producers of the region (Fig. 6). With unshaded plantations, there are no suitable conditions projected at the core at all and few suitable areas at the margins of the cacao belt.

Climatic suitability for cacao in unshaded plantations is projected to decrease to 9 ± 3% and 65 ± 21% of present suitability under the GCM considered pessimistic (MIROC-ESM) and the GCM considered optimistic (CCSM4) for 2050, respectively. By contrast, climatic suitability for *cabrucas* is projected to decrease to 42 ± 13% and 92 ± 15% of present suitability under the GCM considered pessimistic (MIROC-ESM) and the GCM considered optimistic (CCSM4) for 2050, respectively.

4 Discussion

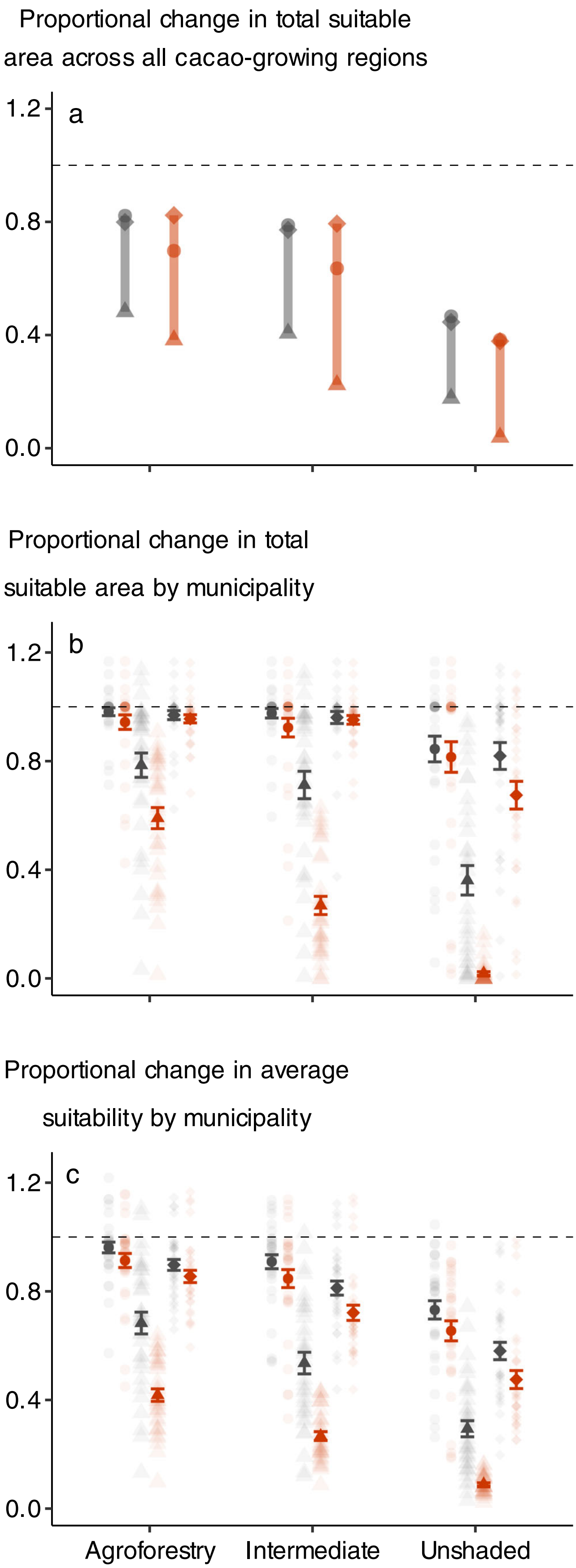
We used ecological niche models to assess the impacts of climate change on cacao suitability under three shading scenarios for southern Bahia's cacao belt. The most relevant findings are that (i) the shading provided by *cabrucas* attenuates maximum temperature for cacao; (ii) all projected environmental changes will cause a negative net effect for cacao in southern Bahia, pushing it toward its physiological tolerance limits, diminishing its suitability and reducing overall suitable areas across the region; (iii) annual precipitation and dry season length are the most prevalent variables reducing crop suitability across GCMs, whereas maximum temperature during the dry season emerges as the main responsible for suitability reduction in unshaded plantations; and (iv) *cabrucas* can reduce the negative impacts of climate change for cacao, especially where those are related to temperature extremes approaching or exceeding crop tolerance limits.

4.1 Effect of shading on microclimate

Shading reduced temperature extremes compared with their unshaded cacao counterparts. Maximum daily temperatures during the warmest period of the year were markedly reduced by canopy cover, being distinct among shading scenarios for cacao plantations. Shaded plantations usually have reduced maximum temperature compared with unshaded cacao counterparts. In Bahia, for instance, mean annual temperature was 0.7 °C lower in *cabrucas* than in open areas and, more important, maximum temperature was almost 3 °C lower in *cabrucas* (Pinheiro et al. 2013). In Nigeria, dense shading provided by a plantain crop reduced dry season temperature by 4 °C and 1 °C in comparison with unshaded and moderate shaded cacao, respectively (Agele et al. 2016). Even when average annual temperatures of cacao agroforestry and unshaded systems are similar, like in Bolivia, shading lowered temperature amplitude by 2.4 °C before pruning compared with the unshaded system (Niether et al. 2018). In Ghana, where temperatures often exceed 40 °C and cacao was planted on cleared forestland, shade did not affect maximum air temperatures (Asare et al. 2017). Shading effects on maximum temperature have also been verified for coffee plantations in Brazil (Partelli et al. 2014) and Uganda (Liebig et al. 2019). Although shading does not always affect annual average temperatures (Asare et al. 2017; Niether et al. 2018), increasing shade-tree cover tends to reduce extreme temperatures (Blaser et al. 2018). Moreover, differences between shaded and unshaded systems tend to be greater during warmer and dryer periods of the year (Lin 2007; Partelli et al. 2014; Agele et al. 2016; Asare et al. 2017), which reinforces the role of shading in reducing temperature extremes in warming climate projections and reducing physiological stress of crops (Lin 2007; Niether et al. 2018).

4.2 Projected changes and impacts of climate

All GCMs projected increases in the maximum temperature of the warmest month and in the number of dry months, decreased in annual precipitation, and stronger water deficit during dry season. The forecast changes in all variables are predicted to have negative effects for growing cacao due to its sensitivity to temperature and drought (Wood and Lass 2001; Schroth et al. 2016; Gateau-Rey et al. 2018; Igawa et al. 2022). A key indicator of these negative changes is that there is no major geographical shift projected for suitable areas in southern Bahia at all. While some locally positive changes are expected to occur in some West African countries (i.e., Liberia, Côte d'Ivoire, Cameroon, and Ghana, Schroth et al.



◀ **Fig. 5** Proportional changes in total suitable area and suitability for growing cacao considering projections of three general circulation models (GCMs: CCSM4 [circles], MIROC.ESM [triangles], and MPI.ESM.LR [diamonds]), and two representative concentration pathways (RCPs, 2.6 in black and 4.5 in red) for 2050, for *cabruca* agroforests, intermediate shading, and unshaded cacao in southern Bahia, Brazil. Panel '**a**' shows the proportional change in total suitable area averaged across all cacao-growing region in the cacao-growing region in Bahia and grouped by RCP and shading system. Panel '**b**' shows the proportional change in total suitable area by municipality and panel '**c**' shows the proportional change in average suitability by municipality. Panels '**b**' and '**c**' are grouped by RCP and GCM. Semi-transparent symbols in bottom row denote each municipality, full colored symbols show mean and error bars (standard errors) for each group.

2016), the suitability for cacao production is projected to decrease in Brazilian Amazon due to reduced precipitation and higher temperatures, with reductions between 37 and 73% in suitable area (Igawa et al. 2022). Similarly, southern Bahia's suitable areas will mostly experience climatic deterioration and shrinking of suitable areas.

Present day suitable areas for cacao in southern Bahia are located along the coast in a belt of about 500 km long and 150 km wide within the Atlantic Forest biome. Suitability declines westwards of the cacao belt, toward the inner continent, where the mild and wet climate historically occupied by the Atlantic Forest gives place to the hot and dry climate occupied by the semi-arid adapted Caatinga vegetation (Simões et al. 2018; IBGE 2019). Suitable area for cacao is projected to become narrower in all climate scenarios due to losses of suitable areas closer to the Caatinga biome. A decay of the suitability in the western portion of the cacao-belt will be mainly due to changes in precipitation related variables (i.e., annual precipitation and dry season length). South America's climate is projected to become warmer and dryer (Torres and Marengo 2014), a pattern that has been corroborated by paleoclimate reconstructions (Pontes et al. 2020), with semi-arid climate expanding over their boundaries, including southern Bahia (Rajaud and de Noblet-Ducoudré 2017). Loss of suitable areas due to lower precipitation in southern Bahia contrasts with projections for West Africa, where higher water demand from increased temperatures will be partly compensated by increased rainfall and a shorter dry season (Schroth et al. 2016).

Precipitation declines are not projected to drop below cacao tolerances across most of southern Bahia cacao-belt but may not be as evenly distributed along the year as this crop requires (Wood and Lass 2001). This increased seasonality, with a longer and more marked dry season, can reduce cacao productivity (Wood and Lass 2001; Schwendenmann et al. 2010). Although southern Bahia dry season is considered relatively short (i.e., 1 month) (Wood and Lass 2001), this pattern is based on areas close to the coast. Across the southern Bahia cacao-belt we found that the dry season length averages

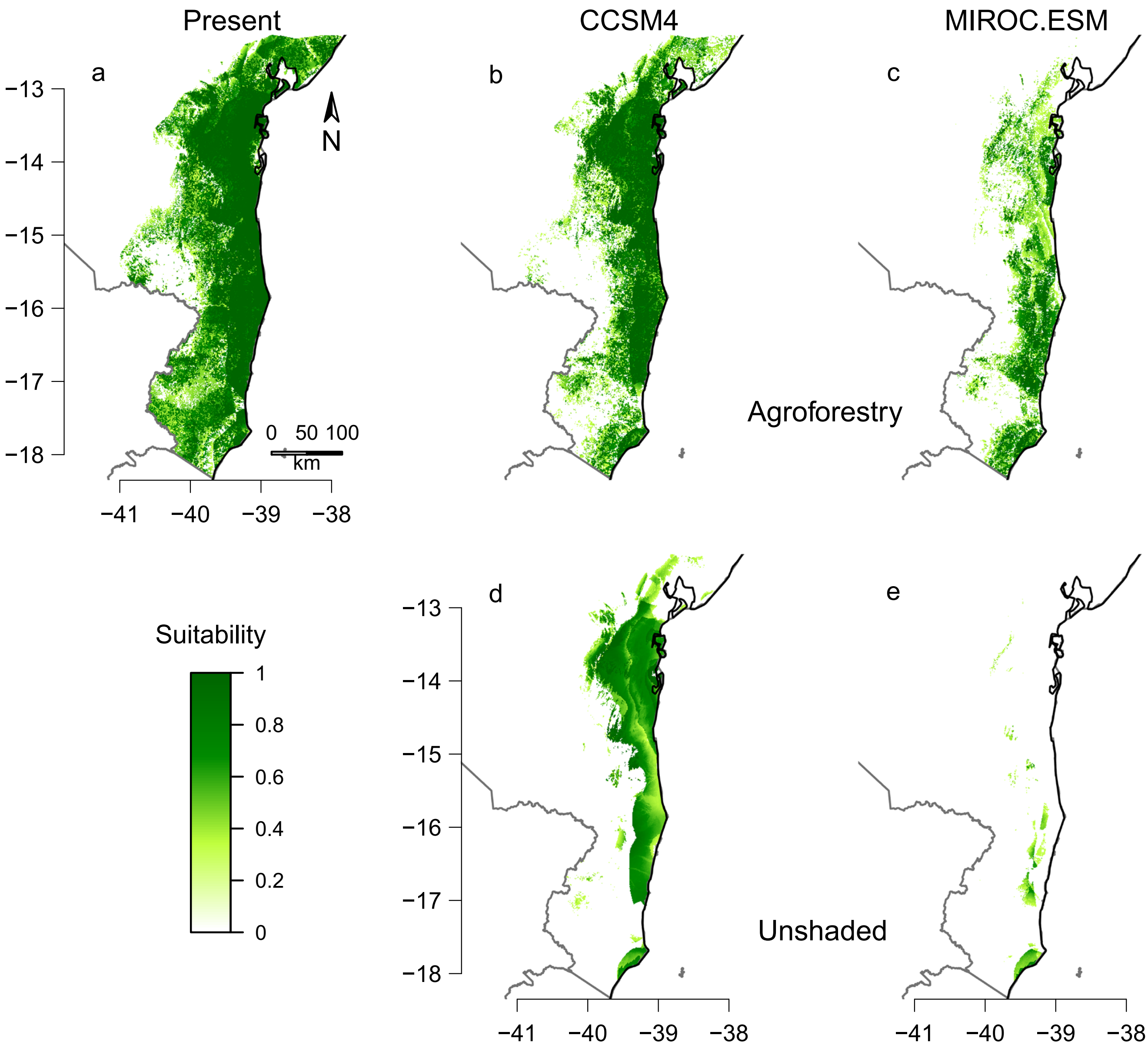


Fig. 6 Suitable area and suitability values for growing cacao in southern Bahia, Brazil projected for current conditions (panel '**a**'), and for the General Circulation Model (GCM) considered optimistic (CCSM4, panels '**b**' and '**d**') and pessimistic (MIROC.ESM, panels '**c**' and '**e**') for considering *cabruca* agroforests (panels '**b**' and '**c**') and unshaded cacao (panels '**d**' and '**e**') scenarios at Representative Concentration Pathway (RCP) 4.5 for 2050.

2.7 months, thus being near the limit of cacao tolerance in most of the region, being longer westwards. The average length of the dry season is actually closer to that of West Africa (2–4 months) and longer than that of southeast Asia (0 months, Wood and Lass 2001; Schroth et al. 2016). In southern Bahia, the dry season in 2050 is projected to become longer, with some areas projected to be beyond the cacao tolerance limit, similar or worse than the current 4-month-long dry season of West Africa (Schroth et al. 2016). This longer dry season is expected to become worse due to an increase in water demand, from 74 mm to between 145 and 225 mm in the scenarios considered optimistic and pessimistic, respectively. As a result, the region that already is prone to droughts during El-Niño years (Gateau-Rey et al. 2018) is predicted to become even more susceptible to droughts. Again, this situation is opposed to West Africa, where temperature increase is projected to be partly compensated by precipitation, creating climatic pattern comprising a shorter and wetter dry season (Schroth et al. 2016).

In the core of the cacao belt, most of the projected losses in suitable areas are due to increasing maximum temperature. However, this result should be taken with caution, since southern Bahia has relatively mild temperatures (up to 30.5 °C) compared to other cacao-producing regions (Wood and Lass

2001), and these temperatures are not projected to reach the limit of cacao tolerance under future climatic scenarios. Temperatures of today's warmer cacao-producing regions (e.g., West Africa and southeast Asia) average 32–33 °C (Wood and Lass 2001), reaching up to 35–36 °C in some localities (Schroth et al. 2016). Temperature in West Africa, for example, is projected to increase by 2050, rising above 36 °C but not reaching 38 °C within cacao-producing areas.

4.3 Effects of cabrucas on reducing the vulnerability to climate change

High shade levels of *cabrucas* can reduce the 2050s projected impact of climate change on cacao suitability for southern Bahia (Figs. 5 and 6), the main producing Brazilian region (IBGE 2017). Loss of suitable area will be greater in unshaded cacao (will retain 26 ± 20% of total current cacao suitable area) than *cabrucas* (will retain 63 ± 23% of total current suitable area), highlighting the role of agroforestry systems in maintaining a more stable microclimate that protects the crop from risks associated with climate change (Lin 2007). A clear positive effect of increasing shade-tree cover during the dry season is the reduced maximum temperatures (Blaser et al. 2018), thus maintaining the understory microclimate within the range of cacao tolerance. An indirect effect of lower temperature is the reduction in cacao transpiration. The increasing shade-tree cover might result in a slight increase of relative humidity during the dry season (Blaser et al. 2018). Even if relative humidity itself is not changed under shade, this system lowers air temperature which decreases vapor pressure deficit (VPD) and thus, plant transpiration (Lin 2010; Lambers and Oliveira 2019). Agroforestry systems have lower VPD than monocultures and open areas (Pinheiro et al. 2013; Niether et al. 2018) and the difference is higher during the warm and the dry months (Pinheiro et al. 2013). Reduced VPD is especially important for cacao trees, as this species has inefficient mechanisms to prevent water loss from transpiration (Sena Gomes et al. 1987; Valle et al. 1987). Cacao transpiration is more affected by VPD changes on leaf boundary layer conductance than stomatal closure/conductance (Sena Gomes et al. 1987; Köhler et al. 2014), being lower on densely shaded cacao than on unshaded cacao (Köhler et al. 2014). As a result, on sunny days, unshaded cacao loses more than twice the water lost by shaded cacao (Valle et al. 1987). By lowering temperature, shading not only reduces plant transpiration but also soil evaporation, thus maintaining soil water content (Lin 2010). Therefore, the role of shading goes beyond keeping temperatures within the physiological tolerances of cacao, but also reduces water loss from cacao transpiration and soil evaporation, resulting in lower vulnerability to drought stress under future climatic scenarios (Lahive et al. 2019).

Nevertheless, a downside is that, in certain circumstances, shade trees may compete with cacao for water (Schroth 1995, 1998) or reduce water availability through rainfall interception (Niether et al. 2018), hence reducing soil moisture along the increasing shade-tree cover gradient (Blaser et al. 2018). The role of shade trees in reducing the vulnerability of crops to climate change has been mostly challenged due to the competition of trees for water during drought events (e.g., Abdulai et al. 2018b). In shaded plantations with lower tree diversity (e.g., Abdulai et al. 2018b) than agroforestry systems shaded with thinned native forests (Schroth et al. 2011), tree root competition for water with crops may become more likely if root systems are not complimentary (Schroth 1995, 1998). In some regions of West Africa where climate is relatively dry and the dry season is long (e.g., Nigeria), cacao plantations have low shade-tree cover (Wood and Lass 2001) because farmers notice competition for water between cacao and shade trees during the dry season (Willey 1975). On the other hand, higher densities and diversity of shade trees are found in cacao plantations of drier regions of Ghana compared to the wetter regions (Abdulai et al. 2018a). Indeed, the 2015–2016 El Niño-related drought event caused high mortality of cacao trees in *cabruca* agroforestry systems of Barro Preto, Bahia, although cacao mortality was independent of shade tree cover (Gateau-Rey et al. 2018). In summary, evidence about the belowground water competition is conflicting and the response seems to depend on local characteristics, such as temporal variation in temperature and precipitation, spatial variation in soil hydrological properties, and rooting complementarity (Schroth 1998; Lin 2010; Niether et al. 2017) that determine the balance between above and belowground interactions.

There are still uncertainties related to understory daily maximum temperature differences between *cabruca* agroforestry systems, intermediate shading, and unshaded cacao plantations. The differences in the confidence interval ranged from 1.8 to 4.3 °C between *cabruca* and intermediate shading and from 4.6 to 7.6 °C between c*abruca* and unshaded cacao plantations. If the differences between microclimate scenarios are minimal (i.e., 1.8 and 4.6 °C for intermediate shading and unshaded plantations, respectively) the benefits of *cabruca* high shading levels might not be so evident. In this minimal benefits scenario, the temperature as cause of suitability loss (Fig. 4) should become less important and the other climatic variables might become the main drivers of loss of suitability, especially in unshaded cacao plantations. In this scenario, the loss of suitability and suitable area (Figs. 5 and 6) should be more similar among microclimate scenarios, with loss of both (suitability and suitable area) being greater for the shaded scenarios (*cabruca* and intermediate shading). In contrast, if the differences between microclimate scenarios are maximal (i.e., 4.3 and 7.6 °C for intermediate shading and unshaded plantations, respectively), the benefits of *cabruca* high shading levels might be even larger than anticipated by our results. In this maximal benefits scenario, the temperature is expected to drive most of suitability loss (Fig. 4), especially in unshaded cacao plantations across the region, and its indirect effects on VPD should be even more beneficial for shaded plantations. In this scenario, the loss of suitability and suitable area (Figs. 5 and 6) should be larger among microclimate scenarios, with shaded scenarios (*cabruca* and intermediate shading) preventing loss of suitability and suitable area especially under the GCM considered pessimistic (MIROC-ESM). Despite the uncertainties in the extent of reduction in the understory maximum temperature, it is safe to conclude that shading will be beneficial for cacao plantations under climate change.

Our results support the importance of shading for reducing the vulnerability of cacao plantations to climate change. Although aboveground beneficial effects of *cabrucas* on understory microclimate (i.e., temperature and relative humidity, Pinheiro et al. 2013) are recognized, too little is known about how above and belowground characteristics interact in *cabrucas* and how do they compare to unshaded cacao. It is not clear to what extent *cabrucas* will respond to the forecast shortages of rainfall and raising temperatures, especially because too little is known about the magnitude of microclimatic changes (irradiance, temperature, and vapor pressure deficit that mediate soil evaporation and cacao transpiration) that native tree cover provides for cacao. Much less is known about root characteristics of most of Atlantic Forest trees in one of the world's tree richest forest sites (Martini et al. 2007; Thomas et al. 2008), although there is some information about characteristics of trees from agroforestry systems in other regions of Atlantic Forest (Souza et al. 2010). General strategies to reduce vulnerability of cacao plantations to climate change scenarios include the maintenance of shade trees and shade management to an intermediate shade cover (Binternagel et al. 2010; Tscharntke et al. 2011; Blaser et al. 2018). Ideally, *cabruca* tree species should provide proper microclimate for cacao at low rates of water competition. Cacao has low water use efficiency under dry conditions (Sena Gomes et al. 1987; Valle et al. 1987). *Cabrucas* potentially provide a water use efficient ecosystem, more resilient to dry and warm conditions than unshaded plantations can do.

5 Conclusion

Globally, cacao agroforestry systems are gradually being replaced by unshaded cacao monocultures (Ruf and Schroth 2004). Similarly, *cabruca* agroforestry systems from southern Bahia are being gradually replaced (see review in Piasentin and Saito 2014) with no concerns to climate change scenarios. Climatic conditions in the southern Bahia cacao belt are currently favorable for growing cacao and have wide margins for change before reaching cacao tolerance limits. In spite of this, as shown for the first time by this study for Bahia, projected changes in all climatic variables will be negative for growing cacao. The wide margins for climatic change to reach cacao tolerance limits give some time for farmers to adapt but may also leave them too comfortable or skeptic about the consequences of climate change. This situation results in a search for maximizing short-term profits that can lead to production and economic losses in the long term. We show for the first time that *cabrucas* can reduce the negative impacts of climate change for cacao in southern Bahia, Brazil. As a result, the maintenance of such climate-smart agriculture gains relevance particularly when prospects of climate change scenarios are worrying, as is the case for cacao in Bahia. Thus, farmers and stakeholders should be aware that *cabrucas* have a central role in reducing the vulnerability of cacao to climate change and since *cabrucas* cannot be quickly restored, the conservation of these traditional agroforestry systems should be an important goal of agricultural policies in the region.

Supplementary information Figures S1-S6 are deposited in the Dataverse repository https://doi.org/10.7910/DVN/RBAXFW (Heming 2021a).

Acknowledgements We thank for Mirco Solé and Caio V. Mira-Mendes for lending and instructing us how to use the temperature sensors used in this research. We thank to João Emanoel de Matos Santos for field work assistance. We also thank two anonymous reviewers and an associate editor for their valuable comments and suggestions that improved the quality of this manuscript.

Authors' contributions N.M.H., G.S., and D.F. contributed to the study conception and design. N.M.H. collected field data, performed all necessary analyses, generated figures and tables, and was responsible for data curation. D.C.T. and N.M.H. structured the manuscript. N.M.H. wrote the first draft of the manuscript and G.S., D.C.T., and D.F. reviewed the manuscript. All authors read and approved the final manuscript.

Funding Neander M. Heming received a post-doc fellowship (#88882.314922/2019-01) from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Data availability Field temperature measurements, and occurrence and calculated environmental data used in this research are deposited in the Dataverse repository https://doi.org/10.7910/DVN/EB1Q2P (Heming 2021b). Environmental variables used in the study were downloaded, and are available, from free public sources (see methods and R code). Resulting suitability rasters are deposited in the Dataverse repository https://doi.org/10.7910/DVN/EB1Q2P (Heming 2021b).

Code availability The code used for generating environmental variables, running ecological niche modeling, and creating figures and tables is deposited in the Dataverse repository https://doi.org/10.7910/DVN/EB1Q2P (Heming 2021b). All used software is freely available.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflicts of interest The authors declare no conflict of interest.

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