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Impact of climate changes in the suitable areas for *Coffea arabica* L. production in Mozambique: Agroforestry as an alternative management system to strengthen crop sustainability

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ABSTRACT

Climate changes (CC) are a main global phenomenon, with a worldwide impact on natural and agricultural ecosystems. The objective of this study was to analyse the potential impact of future CC on the suitability of areas for rainfed coffee growth, both at the Mozambique national scale and in the Gorongosa Mountain, under Agroforestry (AFS) and Full Sun (FS) management systems. The latter study site is part of the Gorongosa National Park (PNG), one of the most biodiverse places and an outstanding case of successful ecosystem restoration, including the rainforest from Gorongosa Mountain. Additionally, coffee cultivation in PNG under AFS is part of a strategy to strengthen the socio-economic sustainability of the local population, and the recovery of biodiversity in a degraded tropical rainforest ecosystem. Future climate assessments were elaborated through bioclimatic and biophysical variables (Elevation), with *Coffea arabica* L. being modeled under the current conditions and four global climate models (GCMs) using four Shared Socio-economic Pathways (SSPs). Isothermality, annual precipitation, and altitude were the most important variables influencing suitable areas in Mozambique. The analysis revealed that currently suitable areas where *C. arabica* is grown in Mozambique will be negatively affected under future scenarios (SSP126 to SSP585) in both systems (AFS and FS), although with clear worst impacts for FS. Under AFS, suitable areas will be reduced between about half and two-thirds by 2041–2060, and up to 91% by 2081–2100 (depending on scenarios) at the whole country level. Additionally, in Gorongosa Mountain, almost all scenarios point to a 30% reduction of the suitable area by 2041–2060, reaching 50% by 2081–2100, both in SSP126 and SSP245 scenarios. In sharp contrast, at the whole country level, the FS system is

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projected to be unsuitable for most of Mozambique, with area losses close to or above two-thirds already in 2021–2040, and greater than 80% by 2061–2080. Under this system, the projections were even more dramatic, pointing to a total absence of adequate areas at Gorongosa Mountain already by 2021–2040. Overall, our study provides clear evidence that the implementation of AFS greatly reduces CC deleterious impacts, being crucial to guarantee the sustainability of the coffee crop in the near future.

1. Introduction

Coffee is grown in more than 80 tropical countries and provides an income to more than 25 million families, making it one of the most traded commodities on the global market (DaMatta et al., 2019; Hunt et al., 2020; FAO, 2022). The genus *Coffea* has 124 species, widespread and adapted to tropical and subtropical areas, particularly in Africa, the center of endemism (Anthony et al., 2010; Davis et al., 2019), although *Coffea arabica* L. (Arabica coffee) *and Coffea canephora* Pierre ex A. Froehner (Robusta coffee) species dominate the coffee trade, representing about 99% of the coffee global economy (DaMatta et al., 2007; Anhar et al., 2021).

Agriculture production depends directly on natural resources, as well as climate and weather conditions, and thus, keeping agriculture production under a scenario of Climate Changes (CC) configures an urgent challenge (FAO, 2016). Global warming will increase continuously as projected by the Intergovernmental Panel on Climate Change (IPCC, 2018). Mozambique is one of the African countries where Arabica coffee has been recently introduced, due to adequate agroecological conditions in some areas and the existence of native coffee species (Almeida, 2013; OOSullivan, 2017). Arabica coffee grows at optimal yearly mean temperatures of about 20–23 ºC and needs over 1200 mm of rainfall annually (or irrigation), while extended periods of temperatures above 30 ºC can already promote negative implications to yields (DaMatta, 2004; DaMatta and Ramalho, 2006; Ovalle-Rivera et al., 2015). In Mozambique, worst-case model scenarios predicted an increase in temperature from 0.9 to 4.47 ºC while precipitation may decrease, particularly in the inner countryside (Mavume et al., 2021). Within the coffee genus, *C. canephora* and, particularly, *C. arabica* have been pointed as vulnerable to climate changes (CC), namely to excessive heat and water shortage, which could lead to important losses of cropping areas, reduced bean yield, and quality, and greater pest incidence (van der Vossen et al., 2015; Magrach and Ghazoul, 2015; Davis et al., 2019). These projections show how deeply the climatic changes and global warming might affect crop distribution and productivity since coffee, namely *C. arabica,* can only grow in a relatively narrow climatic range. However, recent works have demonstrated an important intrinsic resilience to heat and drought in some elite cultivars, being much greater than earlier assumed (DaMatta et al., 2018, 2019; Dubberstein et al., 2020), and a positive role of elevated air [CO_2] that can strength coffee plant resilience (Rodrigues et al., 2016; Avila et al., 2020a; b; Semedo et al., 2022; Marques et al., 2020). Including elevated CO_2 (eCO_2) in the modeling studies showed that CC might have a much less dramatic impact than previously thought, with yield increasing at higher altitudes (Rahn et al., 2018) or if irrigation is implemented (Verhage et al., 2017), but particularly if shading strategies are adopted (Rahn et al., 2018). Still, ongoing CC is already imposing deleterious impacts on the coffee crop in many tropical areas (van der Vossen et al., 2015). These climatic impacts are even expected to escalate in the future, especially in already marginal climatic areas/regions for this and other crops if anthropogenic greenhouse gases (GHG) emissions are not adequately controlled, which could be even worse in the tropical region which is considered particular vulnerability to CC and food insecurity, especially due to a greater impact on rainfall patterns (Pais et al., 2020).

Supra-optimal temperatures and lowered water availability can have detrimental impacts on coffee potential yields (DaMatta and Ramalho, 2006). Restricted water supply (Vinecky et al., 2017) and heat (Ramalho et al., 2018) can also affect coffee bean quality, with the possibility of further negative interactions between these environmental variables under field conditions. This highlights the need to implement mitigation management practices, such as shade from neighboring tree species in Agroforestry Systems (AFS), or intercropping associations. One of the definitions of AFS is a land management system in which forest trees or shrubs are integrated with crops, with benefits from the resulting ecological and economic interactions (Burgess et al., 2019). This can be explored as a CC adaptation strategy (Rahn et al., 2018). AFS is one of the few crop management strategies widely used for optimizing coffee production, having the advantage to integrate the environment and socio-economical components. AFS implementation can improve water use and maintain a more suitable microenvironment, concerning both air temperature and humidity. In fact, by managing shade density at the coffee plant level, AFS reduces incident solar radiation, and air temperature, while promoting water use efficiency, branch growth, and better microenvironment conditions, concerning both air temperature and humidity (Partelli et al., 2014; Oliosi et al., 2016; Dubberstein et al., 2018; Moreira et al., 2018), thus mitigating warming without decreasing yield (Moreira et al., 2018; Koutouleas et al., 2022b), while promoting coffee bean quality (Kath et al., 2021). Furthermore, it prevents large reductions in night temperatures at high elevations, or lower latitudes, thus reducing chilling, and eventually damages produced by frost (Koutouleas et al., 2022b). Additionally, some studies reported that AFS can have a positive impact by increasing natural biodiversity, improving soil chemical and physical properties, sequestering aboveground and soil carbon and organic matter, and enhancing water use efficiency (WUE) (Souza et al., 2012; Martins et al., 2015; Araújo et al., 2016; Moreira et al., 2018). In fact, optimized use of water resources by crops is of utmost importance in the context of predicted CC. WUE would rise as air and leaf temperature decreases while air humidity increases around the coffee plants. This results in a lower vapor pressure deficit (VPD) between the leaf and the air, and a decline in evapotranspiration (although net photosynthesis can be reduced, depending on shade density), in comparison with full sun conditions. This is particularly important in regions experiencing prolonged droughts and/or high evaporative demand, where a higher long-term WUE, should be translated into advantages to the production of coffee plantations (DaMatta et al., 2004; Rodríguez-López et al., 2013). However, although AFS practices have been proposed as a nature-based strategy for coffee farmers to mitigate and adapt to future climate conditions, there are some contradictory reports on the potential benefits of shade. This promotes some uncertainty regarding the use of AFS, due to the possibility of negative impacts on coffee growth and yield, in physical and chemical attributes of green beans, as well as in their potential to exacerbate biotic stressors. Such contrasting findings are dependent on the local environment, shade density, crop management practices, and the cropped *C. arabica* cultivars that respond differently to shade (Koutouleas et al., 2022a; b).

Coffee production under AFS has been implemented in the Americas (*e.g.*, Costa Rica, El Salvador, Guatemala, Mexico, and Colombia), as well as in Africa (Gomes et al., 2020; Haggar et al., 2021; Leijster et al., 2021). In Africa, Ethiopia is one of the main countries using this system, which can be found also in Zimbabwe, Malawi, and Madagascar (Anthony et al., 2010; Chemura et al., 2016). Recently, Arabica coffee was established under AFS management in the Gorongosa Mountain, which is part of the Gorongosa National Park (GNP), in Central Mozambique, one of the most biodiverse places in the world (Tinley, 1977; Bouley et al., 2018). This is part of an approach to simultaneously improve the socio-economic conditions of the populations living on the mountain, whilst reducing forest loss and degradation that results mainly from logging and slash and burn agriculture practices. Thus, while contributing to restoring the degraded rainforest through the re-introduction of native forestry trees, coffee production under AFS (under such native trees) also contributes to improving the livelihoods of smallholder farmers with a significant additional income to local communities (Cassamo et al., 2022). Indeed, deforestation on the upper slopes of Gorongosa Mountain was happening at an alarming rate due to the anthropogenic pressure associated with civil war and detrimental agricultural practices (Schuetze, 2015), with satellite images showing a forest loss of more than 300 ha per year in the last 5 years (Stalmans and Victor, 2020). Although there is still an ongoing loss of wooded areas, more than 800 smallholder farmers are engaged in the rainforest restoration project, deeply involved in coffee production, with an important social and economic impact. Currently, coffee plantations cover about 181 ha and are expected to expand to 1000 ha over the next decade (Mongabay Series, 2020).

Taking into account the increasing interest in expanding Arabica coffee production in Mozambique towards the sustainability of local ecosystems and socio-economic development, the objective of this study was to identify currently suitable areas for *C. arabica* production and to estimate the future trend in these areas, with a particular emphasis in the AFS established in Gorongosa Mountain. The identification of suitable crop distribution areas by environmental niche modeling (ENMs) is an increasingly promising approach (Guo et al., 2019; Chemura et al., 2021), which has been used in Mozambique neighboring countries producing *C. arabica* (Chemura et al., 2016), and to identify future suitable production areas, namely in China (Zhang et al., 2021). The modeling of suitable areas for coffee production at a national scale, both under AFS and a full Sun (FS) cropping system will contribute to comprehensively understanding the potential of coffee AFS in a wider global context. Overall, our modeling approach reveals that AFS management has a greater potential to adapt the coffee crop to CC while contributing to restoring rainforests and biodiversity, associated with the sustainable development of local communities.

2. Materials and methods

2.1. Study and target areas

Mozambique is located on the east coast of southern Africa, between latitudes 10º 27′S and 26º52′S and longitudes 30º12′W and 40º51′W. The country is bordered by South Africa in the south, Swaziland in the southwest, Tanzania in the north, Zimbabwe, Zambia, and South Africa in the west, and Malawi in the northwest (Fig. 1a). The terrain is mostly coastal lowlands with 2515 km of coastline, uplands in center, high plateaus in northwest and mountains in the west (FAO, 2005; Cabral et al., 2017). Some endemic coffee species occur throughout the country (Hallé and Faria, 1973; Davis et al., 2021), with a quite small production of *C. arabica* in its center and northern regions (Anon, 2020). The present modeling study considered the whole Mozambican country and included a part of the Zimbabwean Manicaland province, which is very connected to the Mozambican Manica province in terms of environment, natural habitats, and socio-economic cohesion (Timberlake et al., 2020), where coffee plantations are presently being established. Both provinces share a chain of mountains, including conservation areas (Chimanimani Park), where coffee is cultivated (Fig. 1a).

A more detailed study was done in Gorongosa Mountain, part of which is integrated into the Gorongosa National Park (GNP), located in the south of the Great Rift Valley system, between Manica and Sofala Provinces (Fig. 1a) (Müller et al., 2012). Gorongosa Mountain occupies the central position of the midlands of the mountain and covers an area of 42,698 ha (Fig. 1b), above the 700 m elevation contour, where the coffee crop under AFS was established. The mountain is characterized by a distinctive combination of temperature, radiation, rainfall, and wind compared with lowlands at the same latitude (Stalmans and Beilfuss, 2008).

2.2. Coffea arabica cropping system and data collection

In this study, coffee-AFS was defined as a management system in which the coffee plants are grown under the shade provided by native forest trees, mainly *Khaya anthotheca* (Welw.) C.DC, *Erythrina lysistemon* Hutch., *Albizia adianthifolia* (Schumach.) W. Wight, *Breonadia salicina* (Vahl) Hepper & J.R.I. Wood, *Millettia stuhlmannii* Taub., and *Bridelia*

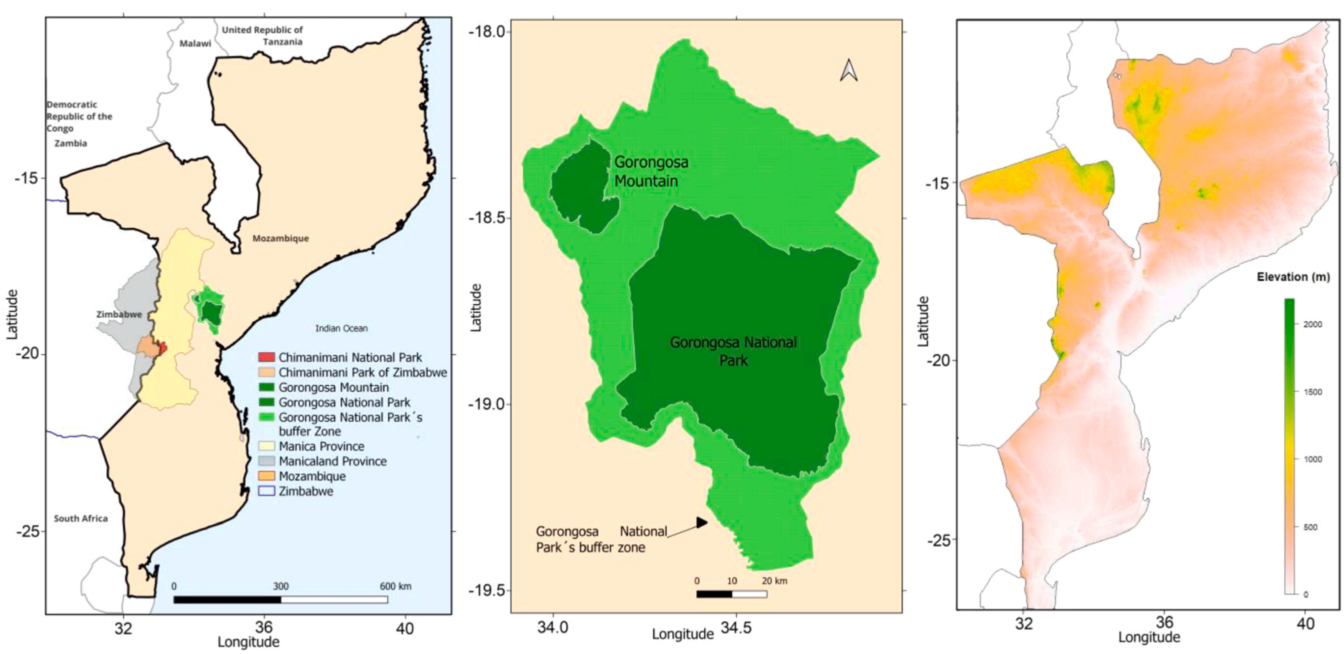

Fig. 1. Maps showing the location of the study area, regarding the entire country of Mozambique (a), and the Gorongosa Mountain area (b), elevation map of Mozambique (c).

micrantha (Hochst.) Baill. In the full Sun (FS) management system, coffee plants were grown under a mono-crop system without any shade.

Previous records of *C. arabica* distribution in Mozambique and Zimbabwe were collected from the GBIF database (Global Biodiversity Information Facility, https://www.gbif.org/). We also incorporated into the record list, a set of occurrences from the LISC herbarium (University of Lisbon). Other databases such as PROTA4U (http://www.prota4u.org/), and the African Plant Database (http://www.tropicos.org/) were used to locate current plant populations. *Coffea arabica* distribution was mostly obtained through field surveys (85%) in the sites with coffee plantations (Fig. 2). Records were grouped by the system management type, identifying each record as FS ($n = 328$) or AFS ($n = 27$) (Table S1). As mentioned above, due to the ecological unit formed by the mountains between Manicaland province (Zimbabwe) and Manica province (Mozambique) (Fig. 1a) (Timberlake et al., 2020), some Zimbabwean records were also considered as input data. Zimbabwean records were reinforced by a literature review, particularly from Kutywayo et al. (2013).

2.3. Environmental variables

Temperature and rainfall are considered the most relevant climatic factors to coffee plant growth and production (DaMatta and Ramalho, 2006; Gomes et al., 2020). The most meaningful climatic variables for ecological niche modeling (Läderach et al., 2017) were downloaded from the WorldClim website (https://www.worldclim.org/) (Fick and Hijmans, 2017). Due to its influence on the climatic variables (Cerda et al., 2017), information related to elevation was also downloaded from CGIARCSI Consortium for Spatial Information (https://cgiarcsi.community/data/srtm-250 m-digitalelevation-database-v4–1/) at a resolution of 250 m (Reuter et al., 2008). In total, twenty environmental variables were considered for modeling the suitable areas of *C. arabica* in Mozambique (Table 1). All environmental variables were resampled to the same pixel size (30 s, ~1 km^2) and projected into the same Geographic Coordinate System (WGS 1984). Variable selection was performed using correlation analysis (r ≥ 0.7; Pearson coefficient) to avoid model overfitting (Abolmaali et al., 2018). Only the most biologically relevant and non-correlated variables were subsequently used for modeling, resulting in six selected variables (Table 1; Fig. S1; Table S3).

To evaluate the future projections of *C. arabica*, four global climate models (GCMs) were used: BCC-CSM2 (Wu et al., 2019), CNRM-ESM2–1 (Gregory et al., 2004), CanESM5 (Swart et al., 2021) and MIROC6 (Tatebe et al., 2019). The selection of GCM was supported by previous models on *C. arabica* (Zhang et al., 2021) and other those that present better behavior in neighboring areas (Ongoma et al., 2019). Afterward, four future Shared Socio-economic Pathways (SSPs) scenarios (SSP126, SSP245, SSP370, and SSP585) were considered for each GCM. The SSPs covered a wide set of future considerations: SSP126 is a scenario that leads to a radioactive forcing level of 2.6 W m^{-2} by 2081–2100; SSP245 represents a nominal 4.5 W m^{-2} radioactive forcing level by 2081–2100; SSP370 is a medium-high reference scenario within the socio-economic family; SSP585 represents the last scenario spectrum in a high fossil-fuel development (Meinshausen et al., 2019). The models were run for the periods of 2021–2040, 2041–2060, 2061–2080, and 2081–2100 (hereinafter referred to as 2040, 2060, 2080, and 2100 periods, respectively), for scenarios projections from pessimist to optimist conditions, considering the expected future changes (Gidden et al., 2019; Schwingshackl et al., 2019).

To reinforce the influence of AFS and FS on the microclimatic modification, shade effects in the daily temperature and Sun radiation were monitored in plants of both systems in Gorongosa Mountain. Temperature variation was estimated by the sensors (Onset HOBO Data Loggers, Bourne, MA, USA) installed in the coffee plantations at three elevations (650, 825, and 935 m a.s.l.) between September 2019 and October 2020 (Cassamo et al., 2022).

2.4. Environmental niche modeling (ENM)

The Maxent algorithm (Phillips et al., 2006; Phillips, 2008) was used to evaluate the current, and to project future suitability areas for *C. arabica*. Several authors propose the use of several models in an

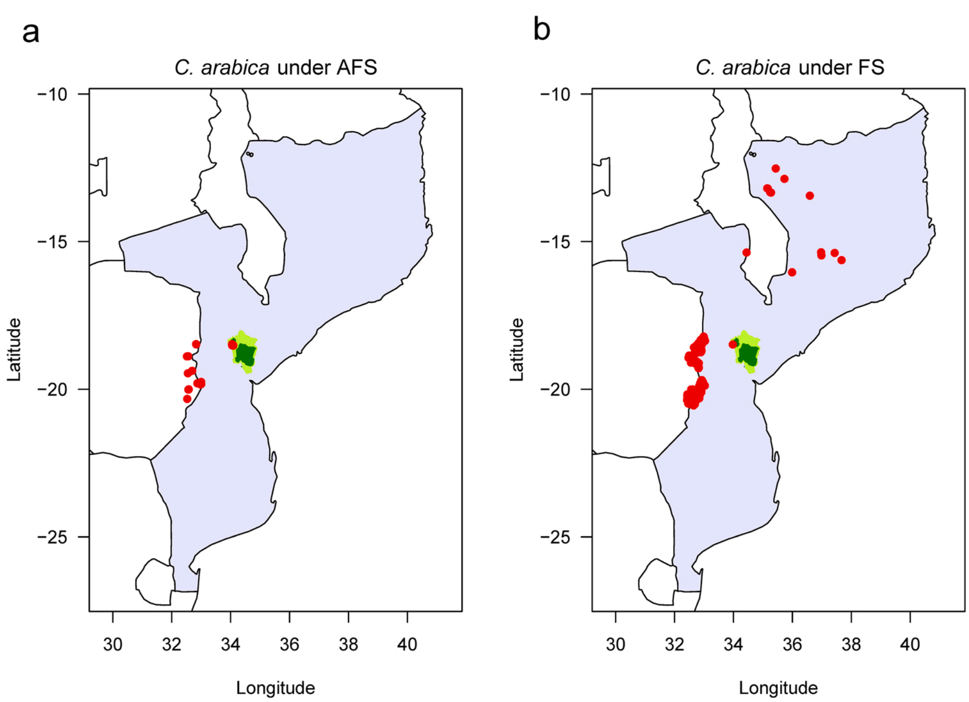

Fig. 2. Compilation of *Coffea arabica* records (in red) considered for modelling covering the entire country and some adjacent areas of Zimbabwe, separated for agroforest (AFS, n = 27) (a) or full Sun (FS) (n = 328) (b) management systems. Coloured areas correspond to the target area of the Gorongosa National Park (dark green) and buffer areas (light green).

Table 1
List of environmental variables considered to build the suitability models of *Coffea arabica* in Mozambique. After analysis of collinearity, the most biologically relevant and non-correlated variables were subsequently used for modelling, resulted in the selection of six variables (in bold).

Code	Description	Unit	Sources
BIO01	Annual Mean Temperature	^{0}C	
BIO02	**Mean Diurnal Range (Mean of monthly (max temp - min temp))**	^{0}C	
BIO03	**Isothermality (BIO2/BIO7) (* 100)**	%	
BIO04	Temperature Seasonality (standard deviation *100)	^{0}C	
BIO05	Max Temperature of Warmest Month	^{0}C	
BIO06	Min Temperature of Coldest Month	^{0}C	https://www.WorldClim/.org
BIO07	Temperature Annual Range (BIO5-BIO6)	^{0}C	
BIO08	Mean Temperature of Wettest Quarter	^{0}C	
BIO09	Mean Temperature of Driest Quarter	^{0}C	
BIO10	Mean Temperature of Warmest Quarter	^{0}C	
BIO11	Mean Temperature of Coldest Quarter	^{0}C	
BIO12	**Annual Precipitation**	mm	
BIO13	Precipitation of Wettest Month	mm	
BIO14	**Precipitation of Driest Month**	mm	
BIO15	Precipitation seasonality (CV)	(%)	
BIO16	Precipitation of Wettest Quarter	mm	
BIO17	Precipitation of Driest Quarter	mm	
BIO18	**Precipitation of Warmest Quarter**	mm	
BIO19	Precipitation of Coldest Quarter	mm	
Elev	**Elevation a.s.l.**	m	https://cgiarcsi.community/data/srtm-250 m-digitalelevation-database

ensemble framework to produce an 'ensemble' prediction (Segurado and Araújo, 2004; Araújo and New, 2007; Marmion et al., 2009; Thuiller et al., 2009). But uncertainty remains in the performance of ensemble modeling since model performance is heavily influenced by the choice of the initial species distribution models used for averaging (Araújo et al., 2005; Diniz-Filho et al., 2009; Kaky et al., 2020). Nevertheless, when comparing the performance of the ensemble forecasting and Maxent models, similar results were obtained (Kaky et al., 2020). Thus, we opted to use only Maxent with an exhaustive model calibration and selection using the kuenm package in R (Cobos et al., 2019). A combination of 11 regularization parameter values (0.1, 0.3, 0.5, 0.7, 0.9, 2, 4, 6, 1, 8, 10) was considered, with all possible feature class combinations of linear, quadratic, product, threshold, and hinge responses (29 combinations), and 57 combination sets of the six selected predictors described above (Table S2 and S3) to select the appropriate combination of variables. A total of 18,183 candidate models were obtained for each combination. The resulting models were evaluated with 500 interactions based on the significance of partial receiver operating characteristic (ROC), 50% of data for bootstrapping, omission rate (OR), and the corrected Akaike information criterion (AICc) (Warren and Seifert, 2011). Models were thresholded based on a calibration omission rate of $E = 5\%$ so that models with OR above 0.05 were removed (Peterson and Sober, 2007). The most parsimonious but highly predictive models were selected following the subsequent criteria of statistical significance, with an acceptable low OR, and with lower AICc value. Final statistically significant models meeting omission rate and AICc criteria were created considering 10 replicates and projected to future conditions. The default value of 10,000 background samples was used within a convex hull defined by all observations (Merow et al., 2013). The Maxent output grids were thresholded above the 10th percentile of training presence and were classified as High, Medium, and Low suitability using the Jenks natural break method (Jenks, 1977). This method reduces the variance within classes and maximizes the variance between classes.

Finally, the future gridded maps were overlaid and compared with the current model to determine the areas where coffee suitability under different scenarios and systems (AFS or FS) is projected to decrease, increase, or remain stable (Ochola et al., 2022). Suitable maps were converted to binary maps assuming the threshold above the 10th percentile of training presence as suitable. The computation of the percentage of the geographic shift in each region was determined by merging the coffee suitability categories (High, Medium, and Low).

2.5. Model uncertainty

Statistical methods for species distribution models are the main contributor to uncertainty in the projections (Buisson et al., 2010). Model uncertainty was evaluated by identifying areas of strict extrapolation (Owens et al., 2013). Areas of strict extrapolation in model projections are places with non-analogous conditions to those of the current period (Alkishe et al., 2020). These areas were located using the mobility-oriented parity (MOP) metric (Owens et al., 2013). This method evaluates levels of similarity between calibration and projection areas and identifies areas of strict extrapolation based on calculated similarities (Alkishe et al., 2020). MOP analyses were performed for the area resulting from comparing the GCMs, as well as from the comparison between current and future climate scenarios using the kuenm R package (Cobos et al., 2019).

3. Results

3.1. Model selection and its evaluation

The purpose of this selection was to determine the set of variables that will provide the best fit for the final model so that accurate predictions can be made. The first step was to remove highly correlated variables (see Fig. S1). This selection produced a subset of six predictors [Mean Diurnal Range (Bio02), Isothermality (Bio03), Annual Precipitation (Bio12), Precipitation of Driest Month (Bio14), Precipitation of Warmest Quarter (Bio18) and Elevation (Elev)], which were afterward considered for model selection of each of the management systems (AFS and FS).

Some differences in these variables are expected when comparing their evolution in areas where AFS and FS are currently used, and what is expected to happen in the future (Table S3). Areas currently using AFS are expected to have an average reduction of 100 mm of annual precipitation (Bio12), but only *ca.* 50 mm on FS, for the end of the century (2081–2100) under SSP585. In the same direction, an average reduction of 4 mm is expected during the extreme precipitation period (Bio14) under AFS but only around 1 mm under FS considering the most pessimistic conditions (SSP585). An important reduction in the Precipitation of Warmest Quarter (Bio18) is expected under AFS, changing from 745 mm to 421 mm under the most pessimistic conditions estimated by the SSP585 scenario. An increase of 1 °C of Bio02 under the pessimistic SSP585 is expected for both AFS and FS systems. In parallel, it is expected an average decrease of 5% in isothermality (Bio03), indicating a smaller level of temperature variability within an average month relative to the annual temperature range, also considering both management systems.

All candidate models were significantly better than the null expectations considering *C. arabica* under FS, whereas 90% (16,406) were significant for *C. arabica* under AFS (Fig. 3). Considering the three evaluation criteria together (partial ROC, OR AICc) only one candidate

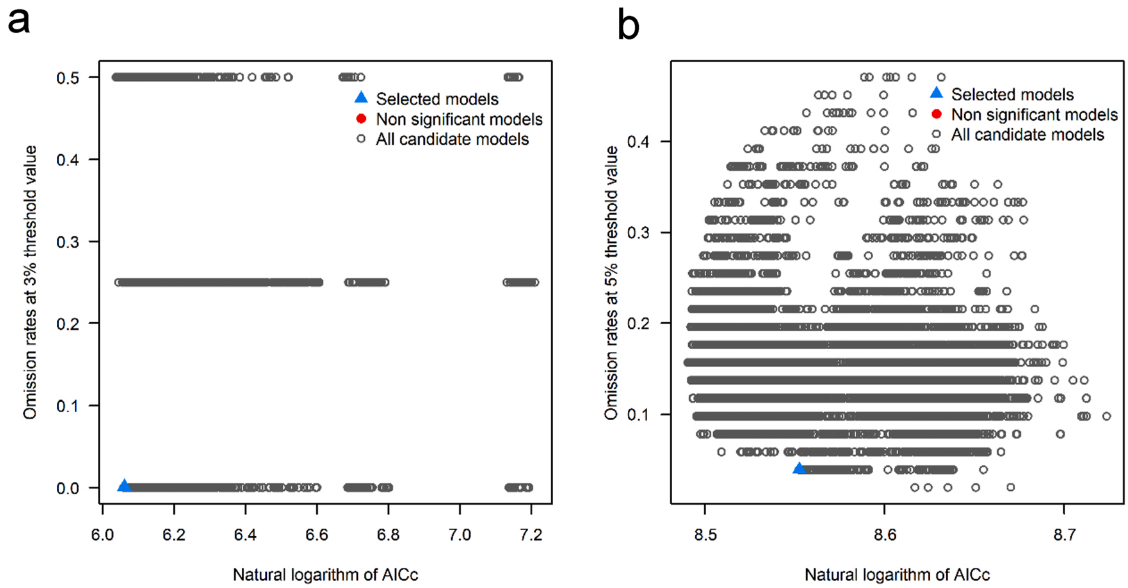

Fig. 3. Omission rates (OR) and Akaike information criterion (AICc) values for all, non-significant, and selected "best" candidate models *Coffea arabica* under agroforest (AFS) (a) or under full Sun (FS) (b) management systems.

model for each *C. arabica* set meet the full suite of selection criteria (Table 2). The two ENMs meet both the statistical significance and the OR criteria after the final model evaluation.

Among the previously selected predictors, the finally used combination for AFS and full Sun were Set_50 and Set_9 respectively (Table S2; Fig. S2, S3). Elevation was selected in both systems. Models of *C. arabica* under FS also included the effect between day-to-night temperature oscillation relative to the summer-to-winter (annual) oscillation (Bio03) (Table S4). On the other hand, *C. arabica* under AFS reveals a strong dependency on precipitation under different forms: Annual Precipitation (Bio12), Precipitation of Driest Month (Bio14), and Precipitation of Warmest Quarter (Bio18) (Table S5). The mean Diurnal Range (Bio02) was not included in either of the two final models. The MOP analysis excludes large suitable regions where strict extrapolation occurs. Only potential distributional areas with higher levels of certainty between GCMs were considered.

3.2. Current suitability of areas for the coffee crop

The northern and central part of Mozambique, namely areas in the Manica, Sofala, Zambézia, and Nampula provinces, showed suitable areas for *C. arabica*, although depending on the management system (Fig. 4). The suitability threshold above the 10th percentile of training presence was reported as 0.465 and 0.218 for AFS and FS, respectively. Below these values, the model is unsuitable for each management system. Ranges of AFS suitability were classified between 0.465 and 0.602 as Low, 0.602–0.793 as Medium, and higher than 0.793 as High. For FS, the ranges of suitability were 0.218–0.489, 0.489–0.712, and 0.712 – 1, in the same order.

The model identified mainly central, north, and interior regions for AFS (Fig. 4a) and FS (Fig. 4b), but with a spatial/areas segregation for each management system, that is, AFS and FS systems can be suitable for the coffee crop although in different cropping areas. Current models (Fig. 4), identify areas in the center of the country highly suitable for *C. arabica* under AFS, which are restricted to the Gorongosa Mountain (Fig. 4a), while the most favorable conditions for FS are identified on the chain of mountains of Manica, at the border between Mozambique and Zimbabwe (Fig. 4b). A similar segregation is observed at the north of the Zambezi River, despite the results of the two management systems tend to point out the great interior plateau and mountain ranges. The results also indicate similar segregation in the north of the Zambezi River. The highest suitability areas under AFS are the mountains around Montes Mabu and Namul, while for FS the best suitable areas extend between Mount Namul and north of Ribáuè , and along the Mozambique plateau.

Currently suitable areas for *C. arabica* production in and around the GNP are restricted to Gorongosa Mountain above 700 m for both management systems. Still, a better environmental condition for the coffee crop was found under AFS as compared with FS (Fig. 5).

Based on the data retrieved from the temperature sensors for 14 months (from September 2019 until October 2020) in three altitudes of coffee areas of Gorongosa Mountain, the monthly diurnal mean temperature was usually lower in the areas under AFS than under FS. Differences up to 1.7, 0.4, and 2.9 °C were observed at the elevations of 650, 825, and 935 m, respectively, between AFS and FS management systems, based on the measured values. Favorable conditions for the growth of *C. arabica* occur at all three altitudes, with low-temperature oscillation throughout the year and high rainfall, but with a dry interval of a few months, a situation restricted to the GNP mountains.

3.3. Spatial-temporal projection of areas suitability for C. arabica

Future potential distribution for *C. arabica* under both management

Table 2
Model performance that met the statistical significance and omission rate criteria during evaluation with data of the *Coffea arabica* under agroforestry system (AFS), or full Sun (FS) management using the regularization multiplier (RM), feature classes (FC), sets of predictors (Pred. Sets), partial receiver operating characteristic (ROC), omission rate (OR), corrected Akaike information criterion (AICc) (See Table S2 for details on the sets).

System	RM	FC	Pred. Sets	partial ROC	OR 5%	AICc	Weight AICc	Number of parameters
AFS	0.9	lqt	Set_50	0.00	0.00	427.64	0.56	7
FS	1	pt	Set_9	0.00	0.04	5178.93	0.29	25

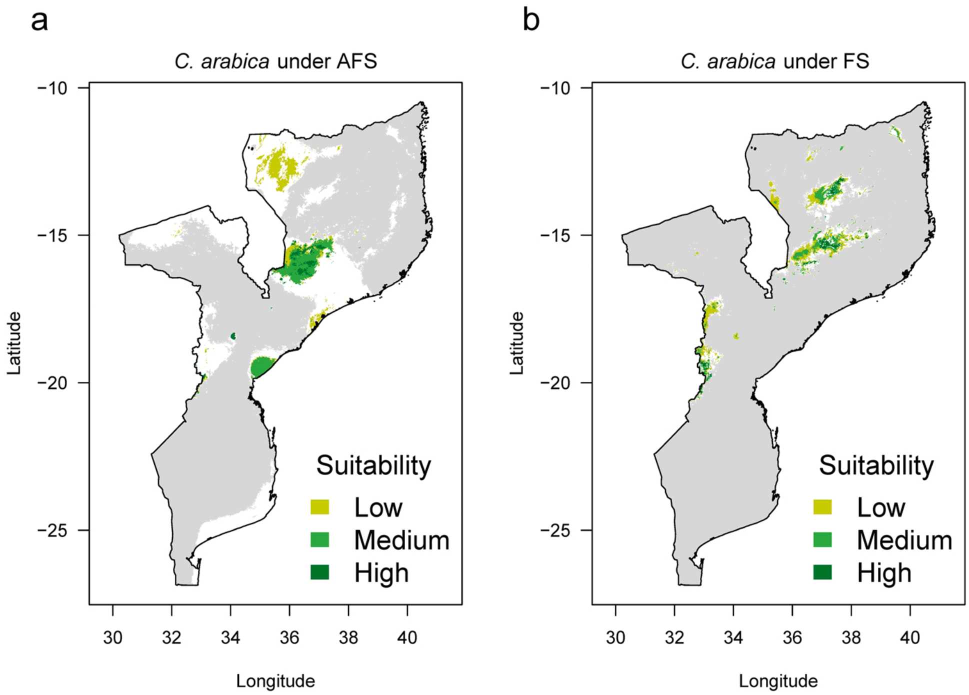

Fig. 4. Actual suitable areas for *Coffea arabica* at the whole country level of Mozambique, considering the use of agroforest (AFS) (a) or full Sun (FS) (b) management systems. Applied models were scaled within Low, Medium and High suitability (areas of strict extrapolation in grey).

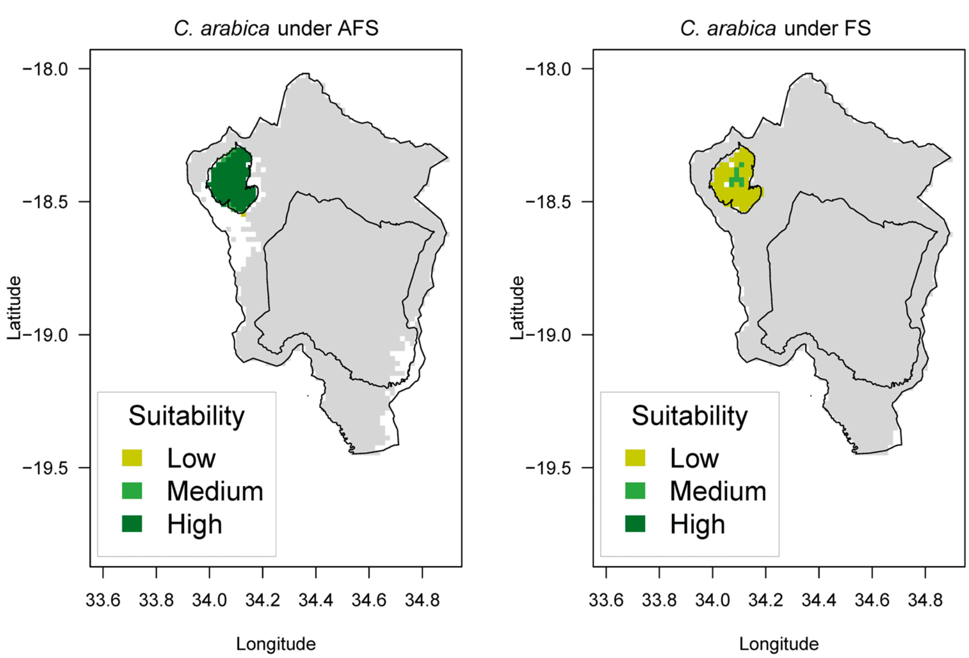

Fig. 5. Actual suitable areas for *Coffea arabica* within the Gorongosa National Park, Mozambique, considering the use of agroforestry (AFS) (a) or full Sun (b) management systems. Applied models were scaled within Low, Medium and High suitability, areas of strict extrapolation are represented in grey.

systems can be envisaged in the highest lands in the North of the country. The projection in space and time under four SSPs (SSP126, SSP245, SSP370, and SSP585) revealed a reduction in the area and its suitability for *C. arabica* production under AFS (Fig. S4) and FS (Fig. S5) management systems. This gradual decline from 2040 to 2100 is expected both in the entire Mozambique area and in the GNP region (Figs. S6), irrespective of the different scenarios, that is, from SSP126 (optimistic scenario) to SSP585 (pessimist scenario). However, the strongest impacts were reported by 2080 and 2100, under the SSP370 and SSP585 scenarios, emphasizing that growing *C. arabica* under FS will be compromised for the foreseeable future in Mozambique (Fig. S5). It seems noteworthy that, according to our climate models, the current newly cropping area in Manica, close to the Zimbabwe border, does not show high suitability for this crop, whereas the areas in the northern region will lose their suitability, particularly when considering the SSP370 and SSP585 scenarios (from 2060 onwards) under FS (Fig. S5), although maintaining relevant areas under AFS (Fig. S4).

Differences between FS and AFS management systems were also very clear for the GNP area, with a total loss of suitable areas already by 2040 under FS, regardless of the applied scenarios (graphs not shown because it will be all white, without any suitable area), although some of these areas are suitable (Fig. 5), being used nowadays (Fig. 2).

Contrasting with the mentioned absence of future adequate areas in Mozambique under FS, under AFS some suitable areas can still be envisaged by the end of the current century, both in the north of Mozambique (Fig. S4) and in Gorongosa Mountain (Fig. S6), even under the harsh conditions predicted by the SSP370 scenario.

3.4. Loss of climatically suitable cropping areas

All scenarios point to large losses of suitable areas along the century, both under AFS and FS, when considering the whole country (Figs. 6 and 7) and the Gorongosa Mountain region (Fig. 8). Under AFS, suitable areas at the whole country level will be reduced between *ca.* 39% (SSP245) and 54% (SSP370) already by 2040 (Fig. 6). Over the years, losses will gradually increase for most scenarios, reaching values of *ca.*

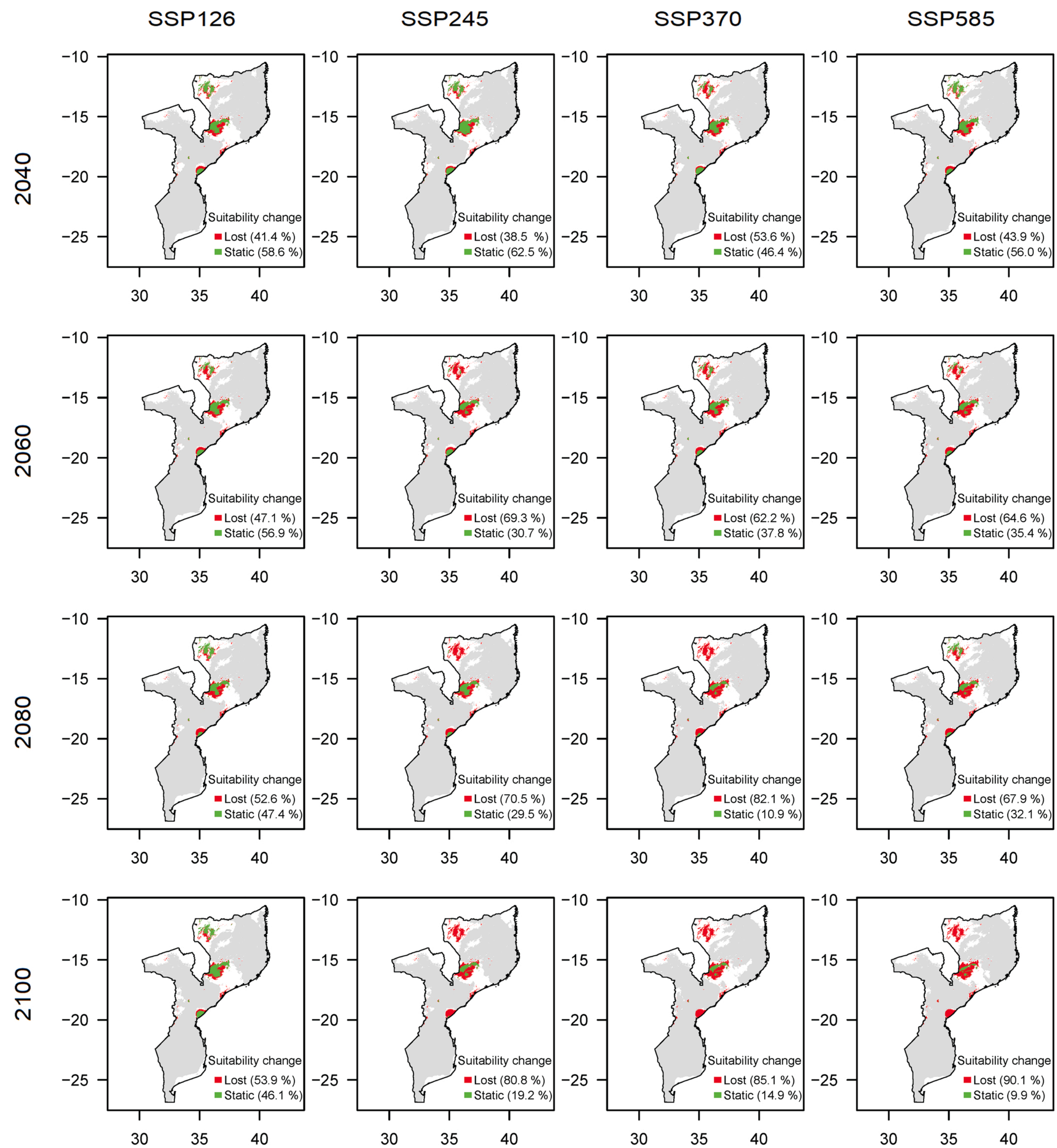

Fig. 6. Loss and maintenance (Static) of climatic suitability areas for *Coffea arabica* in Mozambique under the agroforestry (AFS) management system, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100) (areas of strict extrapolation in grey).

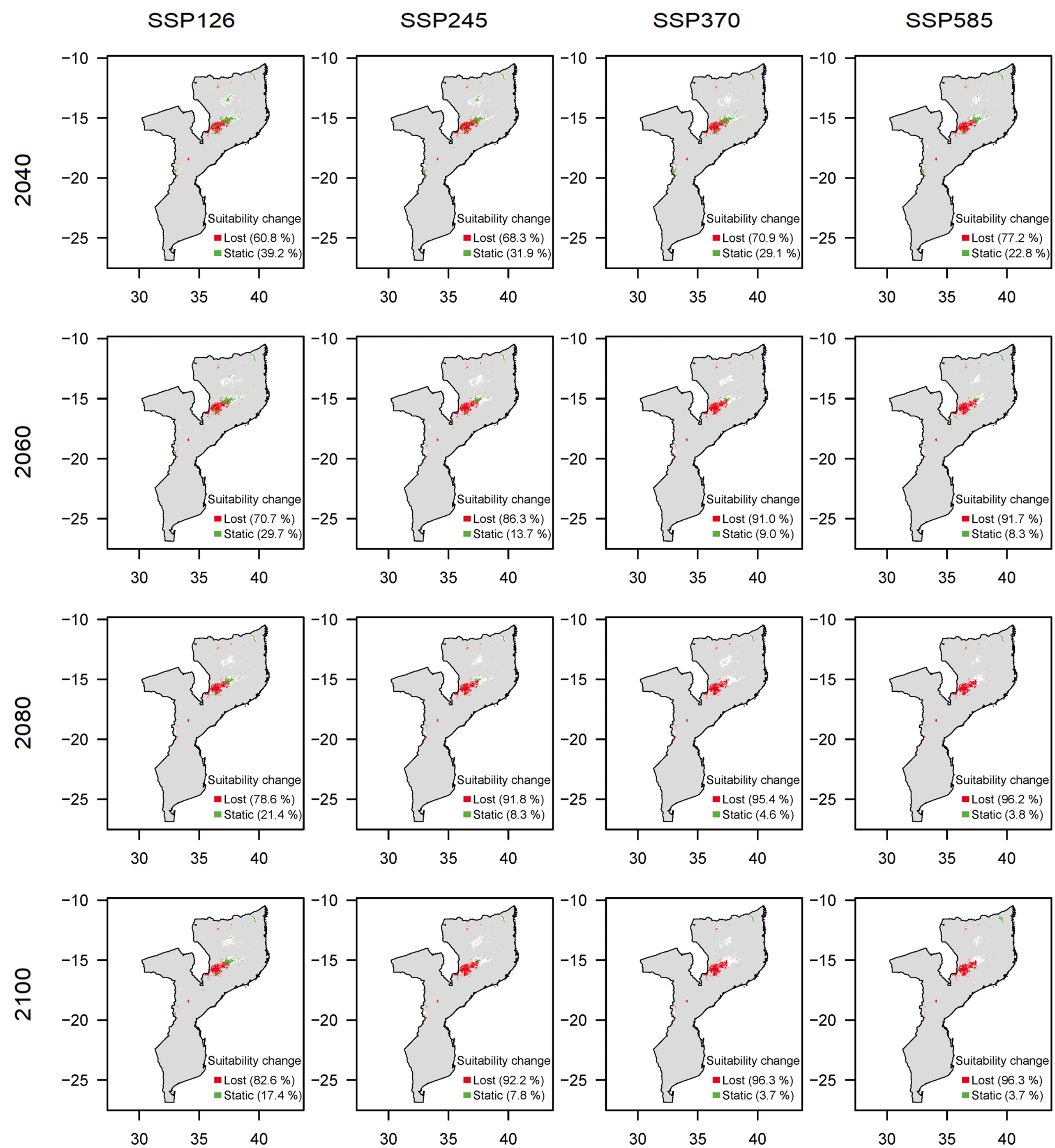

Fig. 7. Loss and maintenance (Static) of climatic suitability areas for *Coffea arabica* in Mozambique under the full Sun (FS) management system, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100) (areas of strict extrapolation in grey).

41%, 81%, 85% and 90% by 2100, for SSP126, SSP245, SSP370, and SSP585 scenarios, respectively. Even under the most favorable scenario (SSP126) the lost area by 2100 will decrease to almost half of the currently suitable areas. Still, at the whole country level, the projections under FS (Fig. 7) estimate a greater loss than under AFS. By 2040, these losses fall within the range between *ca.* 65% (SSP126) and 77% (SSP585), whereas by 2080 and 2100 most SSP245, SSP370, and SSP585 scenarios point to losses greater than 91%.

Looking at the Gorongosa Mountain region belonging to the GNP, a much lesser negative impact was found under AFS (Fig. 8) but a worse one under FS, compared with the whole country. Under AFS management, estimates point to losses between 30% until 2060, except for SSP585 (49%) (Fig. 8). This will be substantially aggravated by 2080 and onwards, with reductions of *ca.* 29%, 44%, 68% and 90% in SSP126, SSP245, SSP370, and SSP585 scenarios, respectively, by 2100. However, it is noteworthy to underline the complete lack of suitable conditions

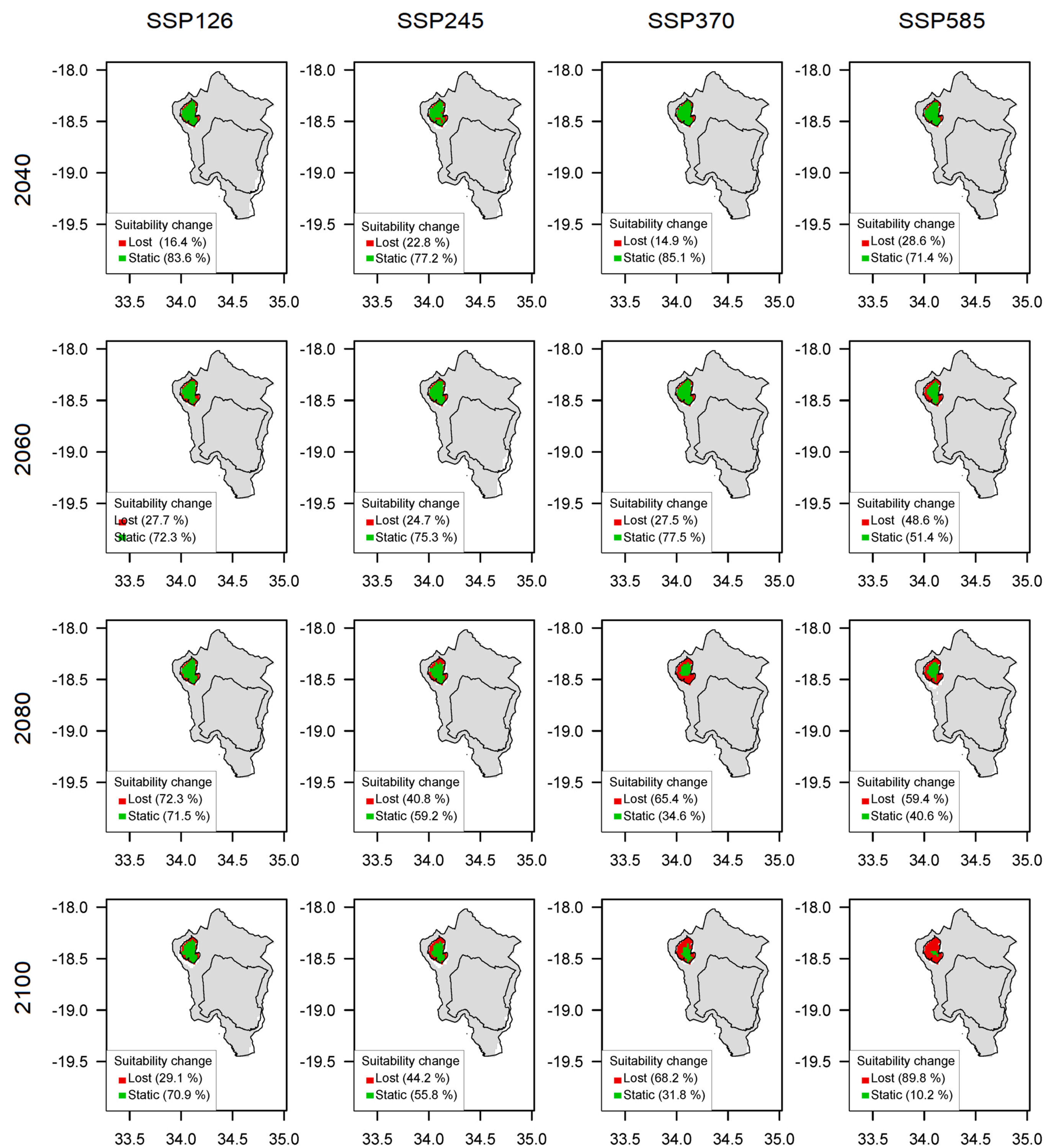

Fig. 8. Loss and maintenance (Static) of climatic suitability areas for *Coffea arabica* in Gorongosa Mountain under the agroforestry (AFS) management system, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100) (areas of strict extrapolation in grey).

under FS from 2040 and onwards in the GNP region.

Overall, suitable areas in Mozambique will be lost between half (SSP126) and about two-thirds (all other scenarios) under AFS management by 2060, with losses between 71% and 92% under FS. The impact under FS was even clearer in Gorongosa Mountain, as no area was projected to be suitable already in 2040 and onwards. Under AFS management a strong decline of suitable areas was estimated to occur mostly in 2080 and afterward in GNP. Therefore, the future of *C. arabica* in Gorongosa Mountain (and in a few areas in the whole country) can be envisaged only under AFS management at the end of this century (Fig. 9).

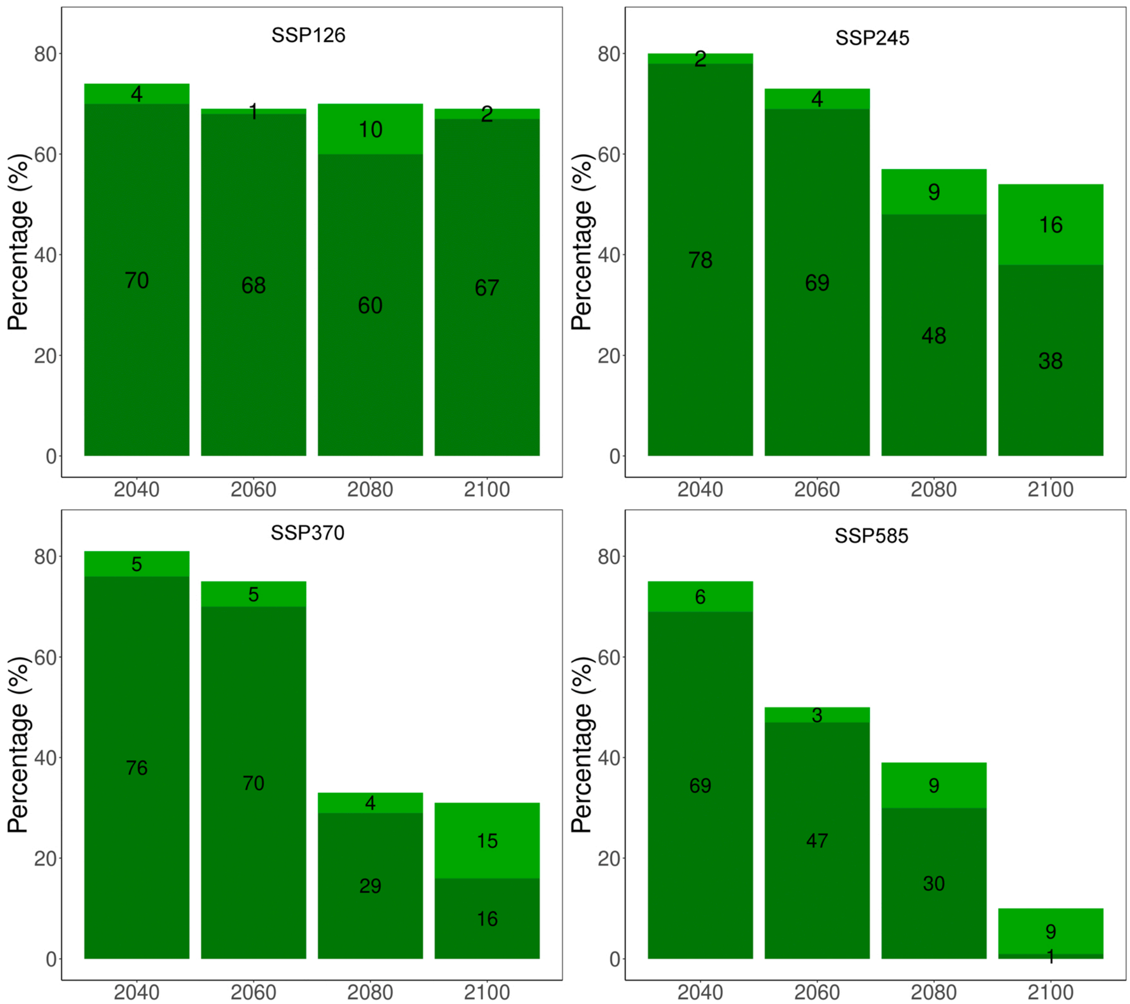

Fig. 9. Projections for suitable cropping areas (values in %) of *Coffea arabica* at Gorongosa Mountain under the agroforestry (AFS) management system, considering the scenarios SSP126, SSP245, SSP370 and SSP585 (See material and Methods) from 2040 until 2100. Values are related to the Gorongosa Mountain area. Medium suitability: light green; High suitability: dark green (note the lack of Low suitability in Gorongosa Mountain at any time slice).

4. Discussion

4.1. *Coffea arabica* cropping at the whole country level and in the Gorongosa Mountain

The distribution model indicated that the best currently suitable areas for coffee production in Mozambique are located above 600 m, in line with recent findings associated with other mountain regions with adequate environmental conditions for *C. arabica* (Ahmed et al., 2021; Anhar et al., 2021), since the altitude is crucial to coffee performance due to its association with temperature variation (Zhang et al., 2021). In accordance, the southern areas of Mozambique are mostly unsuitable since they are lowlands or medium-altitude hills (< 600 m). This suitable distribution was already described by Medina (1955) who reported that the north of Mozambique, some restricted areas of Gorongosa Mountain, and the border zone of Manica were the most suitable areas for *C. arabica*. Here, an exception was observed outside the GNP buffer zone (southeast zone), namely in the Cheringoma district, where low to medium suitable areas were projected. Although the climatic requirements are not optimal for coffee, since the Cheringoma district is typically lowland and the temperature is relatively higher than in Gorongosa Mountain, such suitability is likely related to the mitigation of temperatures provided by the forestry and the vegetation composition of that district (Müller, 2012).

In general, the projections for Gorongosa Mountain highlighted that, even in a relatively short term (*e.g.*, 2040), the FS system will not be sustainable for coffee production, whereas AFS constitutes a better management system to face CC, allowing the production of this crop in a few areas at the whole country, especially in Gorongosa Mountain. The better microclimate conditions provided to the crop by shading systems are associated with an improved physiological performance of coffee plants (Rodríguez-López et al., 2013; Oliosi et al., 2016; Koutouleas et al., 2022a; b). Additionally, AFS management might also have a potential positive role in pest control, which is crucial for crop sustainability (Kutywayo et al., 2013), despite some studies also pointing to greater pest incidence (Koutouleas et al., 2022a).

The temperature descriptor (Bio03) (Fig. S2) was highly relevant to determine *C. arabica* distribution under the FS system, in line with the fact that temperature is recognized as a crucial variable that limits the suitability of coffee distribution (DaMatta and Ramalho, 2006; Ramalho et al., 2014; Gomes et al., 2020). While AFS was greatly associated with water availability (precipitation) and altitude (Fig. S3), the suitable area for FS was mostly determined by temperature. Notably, along the year, the monthly diurnal average temperatures recorded in FS areas in Gorongosa Mountain were *ca.* 0.4–2.9 °C higher than those found in the corresponding elevation areas under shaded AFS conditions. Extreme temperatures associated with rainfall deficit can favor a decline in the suitability for coffee cultivation (DaMatta and Ramalho, 2006; Oliosi et al., 2016; Benti et al., 2022). This situation is more prone to occur in lowlands, where the amount and frequency of rainfall patterns are usually lower. In agreement, precipitation and temperature were reported as the most important variables for the coffee climatic suitability in Manica region (Chemura et al., 2016), thus, reinforcing our findings due to the similar edaphic and climatic features along the border of both provinces, where the crop is cultivated (Timberlake et al., 2016, 2020), despite the potential presence of other variables that contribute to the geographic shifts of crops (Ochola et al., 2022). According to our findings, Manica region seems to be more suitable for coffee under FS management, covering a major suitable area than under AFS, which would be barely located in the Chimanimani region (Figs. 4a and S4). However, when analyzing the future evolution only a very few areas maintain the suitability in this region. Still, although the area suitable for AFS is very small in Manica, greater resilience to CC is expected under this management system than under FS. In fact, our results indicate that favorable conditions for AFS in Manica may occur until the end of the century, although only considering SSP126 and SSP245 scenarios, and until 2080 under SSP370 (Fig. 6). On the other hand, it will hardly be possible to cultivate coffee under FS beyond 2080 when the SSP245 scenario is considered (Fig. 7). However, it should be highlighted that a major limitation when modeling a recent event, such as the introduction of a new crop system as AFS, is the few available records and their spatial aggregation. The evident spatial segregation obtained from our results between the two management systems may be due to the reduced and localized implementation of the AFS in Mozambique. Despite our efforts on sampling and bootstrapping the currently available data, and that our results are sustained by strong statistical procedures, we are aware that these results may not identify all the suitable places for AFS. In other words, the results are consistent but there may be other suitable areas that we cannot identify under the currently available information.

4.2. Climate change and elevated air [CO_2]: a double-edged sword for coffee

Variations and the balance between temperature and precipitation are considered the most relevant factors determining the future distribution of species under new climate scenarios (Román-Palacios and Wiens, 2020). Still, under CC conditions, other limiting factors such as solar radiation (Yilmaz et al., 2017) or land use type (Tilman and Lehman, 2001) can strongly influence the future distribution of plant species. The relevance of considering future situations based on SSPs is that they are inherently contemplating a wide set of derived variables, such as GHG (Riahi et al., 2017), including the increase in the air [CO_2] (Rahn et al., 2018; Schwingshackl et al., 2019). Together with the associated role in global warming, elevated air [CO_2] (eCO_2) promotes important physiological impacts on plants, frequently leading to reductions in leaf stomatal conductance and, thus, in transpiration, in many species. This has the potential to promote an increase in leaf temperature, particularly during high-temperature events, which was recently envisaged as an additional detrimental impact that could result in an underestimation of the negative impacts of temperature associated with global warming (Schwingshackl et al., 2019). However, several works point to a minor (if at all) impact of eCO_2 on stomatal conductance in *Coffea* genotypes. In fact, eCO_2 was reported to greatly strengthen coffee vigor, growth, and yield, closely associated with significantly increases in net C-assimilation close to or above 50% in the range of 550–700 ppm of air CO_2 (Ramalho et al., 2013; Ghini et al., 2015; DaMatta et al., 2018; Avila et al., 2020a; b; Rakocevic et al., 2021). Most importantly, eCO_2 can promote/reinforce the triggering of protective responses to drought and supra-optimal temperatures, improving coffee plant resilience against environmental constraints (Martins et al., 2016; Rodrigues et al., 2016; Avila et al., 2020a; b; Fernandes et al., 2021; Marques et al., 2021; Semedo et al., 2021). Altogether, these findings led to new modeling approaches that included eCO_2 concluding that it might significantly reduce the warming impact, particularly if adequate irrigation (Verhage et al., 2017) or shade (Rahn et al., 2018) conditions are granted to the coffee plants. Overall, a less dramatic decline regarding the suitable areas estimated for *C. arabica* is likely to occur, although with an unquestionably gradual decrease of suitability areas, over time, for the whole country (Fig. 6).

The scenarios considering the lowest (SSP126) and highest (SSP585) GHG emissions estimated an increase in the air mean temperature of 1.5 ºC and 4.1 ºC, respectively, in the region of Gorongosa Mountain. Under AFS, the detected loss of suitable areas for the coffee crop was more pronounced below 935 m, where higher temperatures implicate harsher environmental conditions (Fig. 8). Additionally, rainfall shortage and lower fog persistence (thus, without the positive impact of a reduced temperature, higher air humidity, and improved leaf/plant hydration) will be more evident at lower elevations, increasing the loss of suitability (Figs. S2 and S3). Therefore, the projected CC conditions show a much greater pressure under the FS system, related to higher temperatures, while the AFS associated with elevation becomes the only sustainable management system, both for the whole country (Figs. S4 and 6) and, especially, in the Gorongosa mountain (Figs. S6, 8 and 9), with 100% loss of suitable areas under FS in GNP region already in 2040 and on onwards, regardless of the considered scenario. These estimates, reporting a much greater impact under FS, are in line with similar findings found for Brazil where coffee is mainly cropped under FS. This would result in marked shifts (to higher elevations and lower latitudes) of the actual suitable/cropped area due to CC (Bunn et al., 2015; Magrach and Ghazoul, 2015). By 2050, some estimates point to area losses of *ca.* 56% for *C. arabica* (with a gain of new areas of only 9%), whereas *C. canephora*, can more than double the current cultivation area despite an impact in current areas of cultivation (Magrach and Ghazoul, 2015). Still, in some areas, decreases in suitability can hit more than 90% of the current growing areas (as we found for Mozambique as a whole from 2060 onwards), with greater impacts in the lower altitudes (below 800 m). Although these studies did not integrate the potential positive impact of eCO_2 in the mitigation of warming (as mentioned above), they strongly highlight the urgent need to implement adaptation strategies, such as shading/AFS due to the long-time needed to be fully established (Läderach et al., 2017). This strategy shows promising results (Koutouleas et al., 2022a; b), as clearly shown here when comparing AFS with FS results in Gorongosa Mountain, without suitable areas for coffee cultivation already in 2040 for the latter management system.

Another dimension included in the AFS approach from Gorongosa Mountain was how the management system may interfere with the socio-economic development of the region. In fact, currently and in the future, different management systems (under different climate scenarios) will likely have contrasting socio-economic implications. The adoption of coffee under AFS, closely associated with the recovery of biodiversity and the tropical rainforest ecosystem itself, will support changes in the actual degraded ecosystem structure, function, and services, being likely to concomitantly (and positively) affect the livelihoods of the human communities (Manish et al., 2016). Coffee AFS management is quite new in Mozambique and is sometimes understood as competing with short-term annual crops grown by smallholder farmers. Such annual crops are essential for local food security in remote areas, with maize and cassava assuming particular importance for more than 2000 families in Gorongosa Mountain (Mongabay Series, 2020). However, annual crop production with intensive land use and burning practices is one of the main causes of land degradation and biodiversity loss (Müller et al., 2012). In this context, coffee management under AFS using native trees could be more effective in land restoration, while bringing additional benefits to the mountain communities. Still, it should be underlined that a parallel survey of the effect of CC on native species used for shade, as well as their resilience over time, must be considered. The impact of future environmental conditions on the shading species should also be envisaged for a full and accurate comprehension of CC impacts on the coffee crop sustainability. From 2010–2019, the AFS coffee plantation increased from 43 ha to 181 ha, being implemented with native forest trees (*Khaya anthotheca*, *Erythrina* *lysistemon*, *Albizia adianthifolia*, *Breonadia salicina*, *Millettia stuhlmannii,* and *Bridelia micrantha*), with some areas also including typical fruit trees (*Annona senegalensis* Pers. and *Vangueiria infuausta* Burch.). This is even more important when considering that a greater socio-economic pressure for food security will be expected, considering the estimates of a growing human population in this century (Anon, 2022). New farmers have their income from coffee production or job opportunities in coffee plantations in Gorongosa Mountain, representing about 40% of the families living in the area. In 2022 and the following years, additional families will be involved, to fulfill the demand for coffee under AFS, which has the objective to reach *ca*. 1000 ha in coming years (Mongabay, 2020).

In sum, under AFS, the coffee crop will be affected in Mozambique to a much lower extent than under FS. AFS offers better support to the livelihoods of local populations while improving the recovery/conservation of the native rainforest and promoting plant, animal, and microbiological biodiversity, thus constituting a more sustainable management strategy for this crop for the coming years.

5. Conclusions

Bioclimatic modeling is a powerful tool to project species distribution and estimate the impact of CC on crop production both at global and regional levels. Modeling the current distribution and future suitable areas of *C. arabica* in Mozambique provides a clear understanding of the trends of environmental limitations and also allows us to identify suitable areas where in the mid- or long-term future this crop can be implemented. Therefore, this study provides a scientific reference to assist the decision-making process regarding the selection of suitable agro-ecological sites for coffee plantations, and the type of crop management system to be used. According to four scenarios (SSPs), temperature, and precipitation are and will be the main variables affecting the suitable areas for *C. arabica* production. We clearly show that, for rainfed coffee, the AFS is the best management strategy, both currently and, especially, in terms of future SSP scenarios.

As the main findings, under AFS, reductions of suitable areas in the whole country are estimated to occur between about half and two-thirds of currently suitable areas by 2060, and between 41% and 91% by 2100 (depending on the scenarios). In Gorongosa Mountain, almost all scenarios point to 30% losses by 2060, reaching 50% by 2100 in two of the four analysed scenarios (SSP126 and SSP245). In sharp contrast, in the whole country, the FS system is projected to become unsuitable for most territory, due to losses close to or above two-thirds of the currently suitable areas already in 2040, and greater than 80% by 2080. Projections for this system reveal a total absence of adequate areas at Gorongosa Mountain already by 2040. Overall, our study strengthens the knowledge regarding the coffee crop under CC, showing great impacts under FS in a near future (2040). The implementation of AFS (complemented with other management techniques) greatly reduced CC deleterious impacts and can be crucial to guarantee the sustainability of this crop in the future.

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CRediT authorship contribution statement

David Draper, Crimildo T. Cassamo, Fábio L. Partelli, Ana Ribeiro-Barros, José C. Ramalho contributed to the study conception and design. Material preparation, data collection and analysis were performed by David Draper, Crimildo T. Cassamo and Maria M. Romeiras. The first draft of the manuscript was written by Crimildo T. Cassamo, David Draper. All authors commented the following versions of the manuscript, and read and approved the final version.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ana I. Ribeiro-Barros Jose C. Ramalho reports financial support was provided by Camões-Instituto da Cooperacao e da Língua. Ana I. Ribeiro-Barros Jose C. Ramalho Crimildo Cassamo reports financial support was provided by Fundação para a Ciência e a Tecnologia, I.P. Fabio L Partelli reports financial support provided by Agência Brasileira de Cooperação.

Data availability

No data was used for the research described in the article.

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Declarations

Ethical approval: This research did not require ethical approval.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108341.

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