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COFFEE CROP SUSTAINABILITY IN MOZAMBIQUE AND QUALITY UNDER AGROFORESTRY SYSTEM ON GORONGOSA MOUNTAIN

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Abstract

This dissertation provides newly and timely data related to crop management involving *Coffea arabica* L. cv. Costa Rica grown under the full sun (FS) exposure and under Agroforestry System (AFS) management systems, the latter considering moderate (MS) and dense (DS) shade levels in Gorongosa Mountain, highland of Gorongosa National Park. In this area the studies considered as well in three altitudes (650, 825, and 935 m a.s.l). The existence of suitable cropping areas under AFS *vs*. FS systems were also evaluated through a modelling approach for the entire area of Mozambique and for the Gorongosa Mountain until 2100, in a context of predicted climate changes and global warming (CC). Therefore, climate models use, along with field and laboratory experiments were performed to investigate the agronomic, environmental and socio-economic implications to the coffee crop (*C. arabica* L.) under the prevalent and estimated environmental conditions at the whole country level of Mozambique, and in particular, in the Gorongosa mountain. A distribution modeling approach revealed that actual suitable areas for *C. arabica* in Mozambique will be negatively affected under future scenarios (SSP126 to SSP585) in both systems (AFS and FS), worst under for FS. Under AFS are predicted the reduction of suitable areas below 50% by 2040, and between 53% and 82% by 2080 (depending on the scenarios) at the whole country level, whereas in the Gorongosa Mountain all scenarios point to area losses between 27% (2040) and 50% (2080). However, under the FS system it was predicted an absence of suitable cropping areas at the entire country by 2040 and onwards, including at the Gorongosa Mountain. Regarding to beans quality, AFS associated to altitude effect suggested the positive changes on some of the physical (bean mass) and chemical attributes (trigonelline, glucose and fructose) of coffee beans which are very important for the improvement of sensory profile. Finally, the Internal rate return (IRR) indicated that coffee agroforestry in the Gorongosa Mountain is economically viable under farmer´s land and Park´s land management.

Overall, implementation of coffee production under AFS can be crucial for mitigate future CC and for guarantee the livelihood of smallholder and conservation and restoration of rainforest in the Gorongosa Mountain.

Keywords: Agroforestry, Altitude; Bean quality, Climate change, Crop management, Economic feasibility, Light/Shade environment, Temperature.

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ACRONYMS

AFS - Agroforestry System

AUC - Area under the curve

CGA - Chlorogenic acid

CQAtotal - Total caffeoylquinic acids

Ci - internal CO2 concentration;

CGA - ácidos clorogénicos

CQA - ácidos cafeoilquínicos

3-CQA - 3-O-caffeoylquinic acid

4-CQA - 4-O-caffeoylquinic acid

5-CQA - 5-O-caffeoylquinic acid

diCQA - ácidos dicafeoilquínicos

3,4-diCQA - 3,4-O-dicaffeoylquinic acid

3,5-diCQA - 3,5-O-dicaffeoylquinic acid

4,5-diCQA - 4,5-O-dicaffeoylquinic acid

diCQAtotal - Total dicaffeoylquinic

E - Transpiration Rate

ESA CCI – European Space Agency,

FAO - Food and Agricultural Organization

FAOSTAT - FAO statistical databases

FQAtotal - Total feruloylquinic acid

FQA ácidos feruloilquínicos

3-FQA 3-O-feruloylquinic acid

5-FQA 5-O-feruloylquinic acid

GPS Global Positioning System

GIS - Geographic Information System

GNP - Gorongosa National Park

gs - Stomatal conductance

ICO - International coffee organization

ICC - International Coffee Council

ICO - International Coffee Organization

ISO - International Organization for Standardization

IPCC - Intergovernmental Panel on Climate Change

LULC - Landuse and Landcover

MaxEnt - Maximum Entropy

PAR - Photosynthetic active radiation µm Micro mole

P_n - net CO2 assimilation rate

PPFD - photosynthetic photon flux density

RS - Remote Sensing

SDMs - Species Distribution Models

SLA - Specific leaf area

TLA- total leaf area;

TSS - total soluble sugars;

USGS - United States Geological Survey

UTM - Universal Transverse Mercator

WUE - Water use efficiency

CHAPTER I

GENERAL INTRODUCTION AND CONCEPTUAL APPROACH

1. GENERAL INTRODUCTION

1.1. Agro-ecological requirement and production system of Coffea arabica L.

The *Coffea* genus represents around 130 species (Davis and Rakotonasolo, 2021) and is widespread and adapted to tropical and subtropical areas, where suitable habitats and climate conditions occur (Anthony et al., 2010; Davis et al., 2019; Morvaridi et al., 2020), The main cropped species are *Coffea arabica* L. and *Coffea canephora* Pierre ex A. Froehner, which are cultivated in more than 80 countries in the tropical region (Läderach et al., 2017; Hunt et al., 2020). These two species support more than 99% of world coffee trade, with *C. arabica* contributing with approximately 60-65% of global production, while *C. canephora* is responsible for the remaining part (ICO, 2020; Campuzano-Duque et al., 2021), despite the presence of a few other species with local economic value (Anthony et al., 2010; Davis et al., 2019).

Native populations of *C. arabica* coffee are restricted to the highland forests of Ethiopia at altitudes of 1600−2800 m above sea level (DaMatta et al., 2018), but this species typically grows well at altitudes between 400 to 1200 m.a.s.l in the tropical regions with latitudes 9-27 º N/S (Ovalle-Rivera et al., 2015) or altitude between 1000 m to 2100 m.a.s.l in equatorial regions (Ovalle-Rivera et al., 2015; Nugroho et al., 2016) and sunlight between 2200 and 2400 hours per year (Descroix and Snoeck, 2004).

The species is a sensitive crop to temperature changes and requires optimal conditions of year mean temperatures ranging between 18 ºC to 22 ºC (DaMatta et al., 2018; Gomes et al., 2020). Under rainfed conditions, the annual rainfall is decisive for crop development and Arabica coffee is well adapted to 1200-1500 mm, although may also tolerate lower values for 3 to 4 months (DaMatta et al., 2018). On the other hand, high temperature and lack of rain over long periods can promote branch death and defoliation, impairing coffee beans development and leading to a reduction in their size, weight and quality (DaMatta et al., 2018). Temperatures below 15 ºC can also affect the plant growth and abnormal development of coffee crop (Ramalho et al., 2014; Craparo et al., 2015), although some genotypes can endure low positive temperatures for short periods of time, with a moderately fast recover at leaf level after two weeks under adequate temperature (Ramalho et al., 2013; Fortunato et al., 2010; Batista-Santos et al., 2011; Ramalho et al., 2014).

Arabica plants require is a soil with a proportion of organic matter around 2 to 5 %, 45 % of mineral proportion and a pH ranging from 5 to 7. This crop also prefers well-drained soil and with, at least, 1 meter dipper (UCDA, 2019).

Overall, as for other crops, coffee strongly depends from the agro-ecologic condition, namely as regards their physiologic processes. Photosynthesis is one of the most vital processes, by which the plant uses sunlight, water and CO_2 to produce sugars and, thereafter, new biomass, determining crop production. However, too low or too high sunlight irradiance can limit photosynthesis activity. Due to its original understory evolution, coffee is a quite efficient shade species as regards light use, showing a photosynthetic saturation for quite low values of photosynthetic photon flux density (PPFD), usually well below 1000 µmolQ m^{-2} s^{-1} (DaMatta & Ramalho, 2006), thus with potential to grow and produce beans under a certain shade density.

Some controversy still remains regarding the impact of shade in terms of potential yield reduction (namely associated to lower flower numbers and lowered photosynthetic rates), as well as a potential increase of pest and disease incidence (Martins et al., 2014; Koutouleas et al., 2022a), even more because a large proportion of crop genotypes was selected/improved for full sun mono-crop systems, which dominate in large coffee producing areas (DaMatta et al., 2018). However, coffee has a marked phenotypic plasticity to cope with light availability at both the leaf and whole-plant levels allowing him to grow in diverse light environments (DaMatta et al., 2018).

1.2. Status of Coffee production in Mozambique: The context of Coffee Agroforestry system in the Gorongosa Mountain

It is estimated that coffee provides employment for more than 25 million smallholder farmers, with a tendency to increase with this crop expansion in the tropical and sub-tropical countries (ICO, 2019; 2021). However, coffee was one of the cash crops with low impact in the socio-economic sector in Mozambique, it has some areas with suitable agro-ecological condition, similar to its neighbors coffee producing countries, such as, Zimbabwe, Malawi and Tanzania (Global Coffee Report, 2021). Historically, coffee is believed to have been introduced on a small scale in Mozambique by Portuguese colonists. Nevertheless, according to Medina et al. (1955), the existence of limited areas with optimal environmental conditions and frequent management needs has promoted greater interest in other crops, such as tea. Thus, a political decision was made that choose Angola (another Portuguese territory at that time) for coffee production, whereas

Mozambique was devoted to the tea crop (Global Coffee Report, 2021).

The Portuguese agronomic service mapped in 1955 areas of Mozambique with presence of *C. arabica* (and their wild relatives), together with suitable areas for growing this crop (Medina et al., 1955). Those maps showed the distribution for 4 coffee species (*C. arabica, C.canephora, C. racemosa and C. liberica*), and were quite similar to the map of racemosa species distribution recently performed by David et al. (2021). The most common wild species was *C. racemosa*, with a distribution in the coastal area of Inhambane province and Ibo Island, but *C. racemosa* was recognized as indigenous in central and southern Mozambique, as well as in northern South Africa and eastern Zimbabwe. (Davis et al., 2019). Regarding *C. arabica*, the optimal agro-ecologic conditions identified in 1955 showed parts of highland above 900 masl., in the Zambezia province (Alto-Molocue and Milange), Niassa (Maniamba and Unango) and border zone between Manica and Zimbabwe. In the Sofala province the suitable area was restricted to the Gorongosa Mountain, where the altitude and the rainfall amount are remarkable higher compared to whole district of Gorongosa.

Notably, coffee production at commercial level has shown a slow but steadily decline for decades. After, the independence of the country (1975), the coffee sector remained mostly excluded from the Mozambican economic structure as result of civil war and political conflict. These caused devastation of farms, including coffee plantation and displacement of farmer around of district (Schuetze, 2015). Still, in recent years, some old plantations of indigenous/wild species have restored and are being explored in Cabo Delgado (Ibo Island) and Niassa provinces (Mahua district). Additionally, other coffee projects have been implemented throughout the country. Zambézia province (Alto Molocué and Gurue districts), Tete (Tsangano and Angónia districts), Niassa (Muenda and Sanga district) and Manica provinces (Chimanimani zone) are some of lands with small coffee plantation (Mozambique Good Trade, 2020). Finally, in the last 10 years it was started an implementation and production coffee plantations in medium scale of *C. arabica* in the Gorongosa Mountain initiative, associated with the Gorongosa National Park (GNP). Currently, coffee is being implemented under Agroforestry System (AFS) (with indigenous tree species) in the Gorongosa Mountain under the scope of a project that aims at to improve the farmer's incomes, while promotes environmental benefits through the restoration of the tropical rainforest that was devastated during the civil war and due to anthropogenic pressure in the mountain. In fact, deforestation on the upper slopes of the Mountain region was happening at an alarming rate, namely due to intensive farming for cultivating the annual crops associated with fire practices, and the collection of wood for cooking, in a Mountain with an significant presence of communities within or in the surroundings (Müller et al., 2012; Stalmans & Victor, 2020).

Over the past years, traditional reforestation of degraded land or in protected areas have revealed low efficiency in restoring forestry and biodiversity (Foley et al., 2005; Locatelli et al., 2017). Currently, rehabilitation of degrading ecosystem of natural systems, takes into account the involvement of surrounding community with other options for their livelihood in the conservated areas. A leading example of this perspective is the Gorongosa Mountain. Despite, Gorongosa Mountain being (in part) a protected area, and the source of the park's rivers, a significant surrounding community converts substantial forestry areas into agricultural land in the mountain. Facing these challenges, coffee AFS simultaneously responds to the dire environmental, social and economic conditions on Gorongosa Mountain. Degraded land is restored with support of the community, when coffee is planted forest tree is also planted. The coffee crop was described by Bliska, (2013) as an agricultural commodity most promising on the composition of the AFS, especially in regions where the natural landscape was highly disturbed and dominated by family farms.

Therefore, the purpose of coffee AFS is to optimize the productivity of coffee under shade, while actively promote the reforestation with native shade tree and restores flora and fauna, while brings alternatives for livelihood of the community living inside of the Mountain. The number of smallholders farmers deeply involved in coffee grown has increased, with an important social-economic impact, while the cropped coffee area is spreading, aiming at reach 1000 ha by 2025 (Mongabay, 2020)

1.3. The role of Agroforestry System management for coffee in the context of climate changes

Coffea arabica has been widely grown under a monocrop management system. Monocrop system managements and deforestation require attention in most tropical countries, and in the face of global climate change these practices have reached an alarming rate of environmental degradation (Läderach et al., 2017; Ovalle-Rivera et al., 2015).

Under the scope of climate change, temperature and rainfall patterns are the main climate drivers to crop suitability, affecting the biodiversity, plant development, and physiological process

(Gomes et al., 2020; Martins et al., 2016). According to some modelling studies the area suitable for coffee cultivation is expected to strong decrease (more than 50 % in a pessimistic scenario) along this century (Bunn et al., 2015; Ovalle-Rivera et al., 2015), associated with an annual temperature increase of 2 ºC and significant variation of the rainy season (Ovalle-Rivera et al., 2015). Nevertheless, on the other hand, most of recent studies show the positive effects of atmospheric carbon dioxide concentration ([CO2]) rising in crop performance (DaMatta et al., 2019; Avila et al., 2020). According to Ainsworth and Rogers (2007), plants can increase in net photosynthesis rate under atmospheric [CO2] rising. Thus, considering the above benefits of atmospheric [CO2] rising, the impact of global warming might be less harmful than most of climate change impact prediction in coffee crop.

Regional studies on the impact of climate change on coffee crop have shown future loss of suitability for the coffee crop in actual cropping areas, particularly for *C. arabica*, with a greater impact at lower altitude (Läderach et al., 2017). Several regions of America (particularly in Brazil, Mexico, Nicaragua and Costa Rica), and Africa (*e.g.*, in Tanzania, Ethiopia and Zimbabwe), were predicted to suffer substantial losses of suitable areas and considerable shifting on rainfall regime (Bunn et al., 2015; Craparo et al., 2015; Ovalle-Rivera et al., 2015; Chemura et al., 2016; Imbach et al., 2018). These scenarios show the crucial role of developing the new approaches of land management and models that lead the prediction of natural resources management in the future, as well as the need to breed new and more resilient cultivars to environmental constraints.

Generally, area suitability analyses are tools used to represent the spatial distribution of natural resources, especially forestry, crops and animal distribution or growing systems. In this regard, model selection is one of the first steps towards the study of crop management under climate change. The International panel on Climate Change has great confidence in the ability of Global climate Models (GCMs) to simulate future climate, and attribute observed climate change to anthropogenic greenhouse gases (GHGs) emissions (IPCC, 2018). The GCMs predict the climate change, however, its accuracy involves combinations of different models, showing different scenarios. GCM under the SSP (Shared Socioeconomic Pathway) framework provide adequate projections of dynamic vegetation (Qian et al., 2021). Thus, through the Maximum entropy (Maxent) Species distribution modeling (SDM) is projected based on selected bioclimatic variables (non- correlated variables) (Elith & Leathwick, 2009; Yi et al., 2016). To estimate how plant suitability responses to the climate changes impact in the current and future time and to assess the contribute of bioclimatic variables, different sets of GCMs are developed (IPCC, 2018). Currently, models are developed considering different land management. Thus, in the context of climate change, Agroforestry Systems (AFS) are highlighted as sustainable management of natural ecosystems (Muschler, 2016). Therefore, AFS is a land use that is becoming increasingly important in conservation, socio-economic sustainability and restoration of natural and protected areas.

Coffee is one agricultural component widely used in AFS, as an intercropped systems involving coffee shaded by forestry trees (Gomes et al., 2020). The AFS has promising potential to store carbon and remove atmospheric CO_2 through enhanced growth of trees and shrubs. In Central America it has been reported that coffee under AFS had a greater annual atmospheric carbon sequestration than the coffee monocropping system (Harmand et al., 2007). Also, a part of climatic changes mitigation, AFS can enhance biodiversity conservation and ecosystem services, particularly in protected areas (De Camargo, 2010).

In another respect AFS are widely adopt to improve the microclimatic conditions to coffee plant. AFS can improve soil physical and chemical properties, and reduce crop physiology stress, since temperature and radiation effects are most relevant in this crop (Moreira et al., 2018; Anhar et al., 2021). Shade trees reduce the temperature and direct light irradiance in coffee, and promotes an air humidity increase (Oliosi et al., 2016; DaMatta et al., 2018; Koutouleas et al., 2022),

*C. arabic*a plant growth and productivity and physiological process are remarkably affected under warming condition mostly as a monocrop (DaMatta & Ramalho, 2006). Yet, coffee branches growth, bean yields and photosynthesis rate, may be altered by the forestry shade tree. Coffee AFS and mostly associated to altitude management (topographic component) becomes the coffee ecosystems more suitable, even under adverse weather conditions (Cerda et al., 2017; Oliosi et al., 2016). Several findings show the positive effect of temperature and rainfall partners on coffee growth rate, and productivity and photosynthesis performance along the altitude (Koutouleas et al., 2022). Some experiments conducted in Brazil have shown positive effect of shade and altitude on beans yield and net photosynthesis as a result of lower temperature and increased rainfall frequency along of altitude (Ricci et al., 2006).

In line with this, the contribution of AFS in coffee crop is even more than crop productivity, but also in the quality of the coffee bean improvement. Some studies have shown positive effects of shade on bean size and biochemical composition, which interfere with beverage quality (Mintesnot et al., 2018; Ramalho et al., 2018). The role of biochemical composition in the quality of the beverage is determined by the presence and the proportion of some acids, trigonelline, chlorogenic acids (CGAs), and caffeine (Tolessa et al., 2017; Naik et al., 2021).

Green coffee beans are known to contain, among others, trigonelline, chlorogenic acids (CGAs), and caffeine, which are important quality bean constituents for the coffee industry (Bicho et al., 2013; Naik et al., 2021). CGA isomers are phenolic compounds with quite known antioxidant activity against free radicals and metal ions, and contributing to the final acidity, aroma, flavour, bitterness, and astringency of the coffee beverage (Upadhyay & Rao, 2013). This important group of non-volatile compounds in green coffee beans includes the main subgroups of monocaffeoylquinic acids (CQA), feruloylquinic acids (FQA), dicaffeoylquinic acids (diCQA) and, in smaller amounts, *p*-coumaroylquinic acids. Coffee is also a rich source of another major class of phenolic compounds, the hydroxycinnamic acids that include caffeic, ferulic, and *p*-coumaric acids (*p*-CQA) (Farah et al., 2006; Romero-González & Verpoorte, 2009; UpadhyayBe & Rao, 2013; Girma et al., 2020).

The reduction of irradiance at leaf level caused by shade greatly depends on the density and species of the shading trees. Still, although AFS practices have been proposed as a nature-based strategy for coffee farmers to mitigate and adapt to future climate conditions (Koutouleas et al., 2022b), there are somewhat contradictory reports as regards the potential benefits of shade on coffee productivity. In fact, shade can both decrease (Chen et al., 2019), or increase (Bote & Struik, 2011) yields, as well as to alter green bean size and biochemical compounds (Vaast et al., 2006). Additionally, the effect of altitude on the chemical composition of coffee beans, disease incidence, etc., is also in some aspects divergent. For instance, lower contents of phenolic compounds were reported with increased altitude (Hagos et al., 2018; Worku et al., 2018), while others studies pointed to opposite findings (Avelino et al., 2005). Also, high chlorogenic acids contents (CGA) have been associated with either low (Farah & Donangelo, 2006) or high (Yeager et al., 2021) quality coffee.

In general, despite quite numerous studies are related to AFS, most of them are focused in the perspective of forestry component contribution within the system. In the coffee AFS is mostly described the forestry influence in the perspective of shading effect on coffee production or quality with low negative impact to the environment. Nevertheless, few studies show also another approach, in which agricultural components plays a fundamental contribution in the forestry improvement. Coffee crop as shown the have a great potential contribute to help restoring the forest in the degraded areas and the biodiversity of natural ecosystem (Bliska, 2013). Coffee grown in AFS was also reported to provide higher pollination habitat activity (Cerda et al., 2017; Harvey et al., 2021), positive effect in birds abundance (Bakermans et al., 2012) and increased diverse bee communities in the tropical forests, especially nearby crops (Schroth et al., 2016) in comparison to coffee in monocropping system. Moreover, some studies have shown how coffee production can promote the forestry restoration and expand the forest plantation through the strengthening of socio-economic component in the AFS (Bliska, 2013).

Thus, coffee AFS can surely configure an alternative for restoration and enhancement of forest biodiversity, further addressing issues regarding the livelihood and food security of smallholder farmers.

1.4. Coffee Agroforestry System in the context of socio-economic benefits

As compared to full Sun/monocrop management, AFS provide more environmental friendly way for land use. The AFS is recognized as a ecological alternative for connecting the agricultural activity to the conservation of areas or buffer zone of conservated areas (Bliska, 2013). Almost all conservation areas in Africa are characterized by human presence inside or their surroundings, frequently with a high environmental pressure (Abukari & Benedict, 2020). This includes agricultural activities, which play a crucial role in the rural areas, especially in poor countries, where most local people have agriculture as unique alternative for their livelihoods. AFS practices can offer a combination of land for agriculture, and the use of forest resources, such as local charcoal production, timber, together with other fruits and edible plants (Kalaba et al., 2010). However, the conflict of interests between increased human presence (and the use of land for crops), and conservation purposes may become hard to combine, namely as regards the use of land in the medium and long term. For instance, there is a strong need to increase crop food and feed products related with an increasing human population to unprecedent numbers. This must occur under challenging conditions associated with harsher climate changes and global warming, what would increase actual risks and create new ones (see Powell et al., 2012; FAO, 2016; Pais et al., 2020), thus turning the conservation of natural resources even more important. In this aspect AFS can constitute a valuable tool evaluated in terms of multiple ecosystem services provision, although, questions concerning the trade-offs between economic and ecological benefits remain poorly addressed (Bacon et al., 2012).

Economic analysis is fundamental for the comprehensive economic feasibility of AFS in medium and long term. The coffee management under AFS can thus go beyond the perspective of conservation, adding a perspective of sustainable socio-economic development in the conservation areas (Molua, 2014). AFS can be optimal for the ecological stability with deep integration of economic, social and environmental approach. Perez-Soba (2018), reported that the involvement of all stakeholders, with focus in local communities, makes the whole AFS chain more efficient and sustainable. The implementation of AFS provides also new job opportunities in the coffee farming of people living around or inside of conservation area. In Gorongosa Mountain more than 300 local workers are presently deeply involved in forestry plantation and coffee growing based on AFS management. Thus, currently, coffee AFS in the mountain are about 181 ha and it expected to expand to 1000 hectares over the next decade (Mongabay, 2020). Actually, more than 800 families have their income based on coffee grown under agroforestry system.

1.5. Motivation of the dissertation

Gorongosa Mountain is highland part of the iconic Gorongosa National Park (GNP) in Mozambique. This mountain, as well as the entire National Park of Gorongosa, is a wildlife sanctuary with an extraordinary biodiversity of flora and fauna species, some of which are endemic. Moreover, the mountain plays an important role in ensuring wildlife in the park's lowlands by providing the water resources from the Mountain River (Murombodzi River). On the other hand, the large number of people living in the mountain have been used practices that greatly promoted deforestation and loss biodiversity, and a major interference with water flow, all of which might compromise the conservation objectives of GNP. These aspects must therefore be compatibilized, turning the research for understanding the mechanism of improvement and restoring of conserved areas clearly relevant (social, economic, and environmentally). In line with this, the GNP has implemented coffee AFS in the Gorongosa Mountain, aiming at to promote the recovery of degraded rainforest, while improves the livelihoods of local population. AS regards AFS, optimal light conditions (shade density) and altitude, and their implications to coffee yield and quality, and the socio-economic implication are poorly understood. The present study aims at to help to fill these gaps, addressing the optimal growth and crop management (and to reduce the impact of future climate change conditions), to address quality issues regarding the coffee beans, while ensuring the promotion of the biodiversity and socio-economic components in AFS, reducing negative agricultural practices (thus, reducing deforestation) and guarantee income to the farmers, all under a system with environmental and economic feasibility.

1.6. Objectives of the Dissertation

In this thesis was intended to provide knowledges about the influence of AFS associated to altitude in the coffee climatic changes mitigation, crop development and beans quality and its economic feasibility of arabica coffee growing under AFS in the Gorongosa Mountain.

In the above mentioned context, the specific objectives in this thesis are:

(i) To modelling the climatic change suitable areas for *Coffea arabica* under best and worse scenarios and assess the AFS contribution to the strengthen crop sustainability.

(ii) To evaluate the effect of shade density and altitude on the green coffee beans physical and biochemical attributes.

(iii) To assess the economic feasibility of coffee growing under AFS in the short and medium term in the Gorongosa Mountain.

1.7. Outline of the dissertation

To comply with the above objectives, this work evaluated the role of AFS on *C. arabica* crop as follows:

Chapter I described a brief introduction, including different topics about coffee agro-ecologic requirement, the status of coffee production in Mozambique and context of Gorongosa Mountain region, The role of agro forestry systems (AFS) in the climatic change impacts mitigation and economic feasibility on coffee production.

Chapter II provided an overview on the impacts of climatic changes in the future coffee climatic suitability of coffee in Mozambique under full Sun or AFS systems, both considering the whole

Mozambique territory and, more in detail, in the Gorongosa Mountain, thus underlining the potential contribution of AFS to strengthen crop sustainability. We estimated the losses for *C. arabica* suitable cultivation areas under two cropping system management by modelling the climatic changes assuming optimistic and pessimistic scenarios (SSP126, SSP245, SSP370 and SSP545) from 2040 to 2100.

Chapter III In the Gorongosa Mountain it was established an experiment considering coffee plants in three altitudes (650, 825, and 935 m a.s.l), and three light conditions (full Sun, moderate shade, dense shade). The fruits produced under such conditions were collected fully maturated, and the obtained green coffee beans were characterized as regards their physical (*e.g.*, colour, density), and chemical (*e.g.*, chlorogenic acids, sugars) attributes, associated with quality. These analyses assessed the influences of shade and altitude are factors of evaluation the quality of green coffee beans. We hypothesized that shade and altitude provide microclimatic conditions for increasing the coffee beans quality.

Chapter IV presented a comprehensive assessment of economic feasibility analysis of growing arabica coffee under AFS on Gorongosa Mountain, which is the actual choosen management system. This chapter explored the potential socio-economic advantages of AFS coffee project on Gorongosa Mountain, shifting from intensive farming to a more sustainable farming. Specifically, the internal return rate (IRR) was assessed at the level of smallholders and at the level of Gorongosa National Park involved in coffee growing in the Gorongosa Mountain.

Chapter V summarized and integrated the main findings of mentioned chapters/studies, highlighting implications to the coffee crop.

1.8. References

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CHAPTER II

IMPACT OF CLIMATE CHANGES IN THE SUITABLE AREAS FOR *Coffea arabica* L. PRODUCTION IN MOZAMBIQUE: AGROFORESTRY AS A MANAGEMENT SYSTEM TO STRENGTHEN CROP SUSTAINABILITY

Abstract

Climate changes (CC) are a main global phenomenon, with 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 success ecosystems restoration, including the rain forest from Gorongosa Mountain. Additionally, the 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. Projections were supported through bioclimatic and biophysical variables (Elevation), with *Coffea arabica* L. being modelled under the current conditions and under four global climate models (GCMs) using four Shared Socio-economic Pathways (SSPs). Temperature, precipitation, and altitude are the most important variables influencing the suitability areas in Mozambique. The analysis revealed that actual suitable areas for *C. arabica* 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 of the actual suitable areas by 2060, and up to 91% by 2100 (depending on scenarios) at the whole country level. Additionally, in the Gorongosa Mountain almost all scenarios point to area losses below 30% by 2060, and lower than 50% by 2100 in SSP126 and SSP245 scenarios. In sharp contrast, at the whole country level the FS system is predicted to be unsuitable for most Mozambique territory, with area losses close or above two thirds already in 2040, and greater than 80% by 2080. Under this system, the predictions are even more dramatic, by pointing to a total absence of adequate areas at the Gorongosa Mountain already by 2040. Overall, our study provides clear evidence that the implementation of AFS greatly reduce CC deleterious impacts, being crucial to guarantee this crop sustainability in a near future and along the present century.

Keywords: Agroforestry systems, Climate change, *Coffea arabica* L, Gorongosa Mountain, Sustainable development

2.1. 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* was recently updated a regards the number of species, which is now of 130 (Davis & Rakotonasolo, 2021), widespread and adapted to tropical and subtropical areas, with their the center of endemism in Africa, particularly in Madagascar (Anthony et al. 2010; Davis et al. 2019; Davis & Rakotonasolo, 2021). However, only two of those species, *Coffea arabica* L. (Arabica coffee) and *Coffea canephora* Pierre ex A. Froehner (Robusta coffee) support to *ca*. 99% the coffee trade, and the coffee global economy (DaMatta et al. 2007; Anhar et al. 2021).

Agriculture production closely depends directly on natural resources, as well to climate and weather conditions, thus keeping agriculture production as a whole in a CC scenario configures an urgent and challenge (FAO 2016). The 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, despite the adequate agro-ecological conditions in some areas and the existence of native coffee species (Almeida 2013; O'Sullivan 2017). Arabica coffee grows at optimal temperatures of about 20 ºC and needs over 1200 mm of rainfall annually (or irrigation), and temperatures over 30 ºC for extended periods can promote negative implications to yields (DaMatta 2004; DaMatta & Ramalho 2006; Ovalle-Rivera et al. 2015). In Mozambique, the worst case scenarios predict that increase in temperature may vary from 0.9 to 4.47 ºC and the precipitation may decrease under scenarios RCP4.5 and 8.5, particularly in the inner country side (Mavume et al. 2021). Within the coffee genus, *C. canephora* and, particularly, *C. arabica* have been pointed as quite sensitive to climate changes (CC), namely as regards excessive heat and water shortage, what could lead to important losses of cropping areas, reduced bean yield and quality, and greater pest incidence (van der Vossen et al., 2015; Magrach & Ghazoul 2015; Davis et al. 2019). These predictions show how deeply the climatic changes and global warming might affect the crop distribution and productivity, since coffee, especially *C. arabica,* can only grow in a relatively narrow climatic range. However, recent works have demonstrated an important intrinsic heat and drought resilience displayed by some elite cultivars, 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 strengths coffee plant resilience (Rodrigues et al. 2016; Avila et al. 2020a, b; Semedo et al. 2021). Furthermore, by including elevated CO_2 (eCO_2) in the models it become clear that CC might have a much less dramatic impact than previously predicted, and even yield can increase at higher altitudes (Rahn et al. 2018), if irrigation is implemented (Verhage et al. 2017), or shading strategies are adopted (Rahn et al. 2018). Still, ongoing CC are already imposing deleterious impacts in 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, what could be even worse in the tropical region which is considered particular vulnerability to CC and food insecurity, namely 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), and 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 the use of shade with 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 benefit from the resulting ecological and economic interactions (Burgess et al. 2019). The use of shade tree management can be explored as a CC adaptation strategy (Rahn et al. 2018). In fact, agroforestry system (AFS) is one of the few crop management strategies widely used for optimizing coffee production, having the advantage that can integrate the environment and socio-economical components. AFS implementation can improve an efficient 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 reduce 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 promote coffee bean quality (Kath et al. 2021). Furthermore, it prevent large reductions in night temperatures at high elevations, or at lower latitudes, thus reducing chilling, and eventually frost, damage (Koutouleas et al. 2022b).

Additionally, AFS was reported to increase the natural biodiversity, to improve the soil chemical and physical properties, to sequester soil carbon and organic matter, and to enhance water use efficiency (Souza et al. 2012; Araújo et al. 2016; Moreira et al. 2018). Although AFS practices have been proposed as a nature-based strategy for coffee farmers to mitigate and adapt to future climate conditions, there are somewhat contradictory reports as regards the potential benefits of shade on coffee. This promoted some uncertainty regarding the use of AFS, due to the possibility of negative impacts on coffee growth and yield, in green bean physical and chemical attributes, as well as their potential to exacerbating biotic stressors. In fact, contrasting findings are dependent on local environment, shade density and other crop management practices, and the cropped C. arabica cultivars that intrinsically respond differently to shade, from yield to quality aspects (Koutouleas et al., 2022a, b).

Coffee production under AFS has been implemented in Americas (*e.g*., Costa Rica, El Salvador, Guatemala, Mexico, Colombia), as well as in Africa (Gomes et al. 2020; Haggar et al. 2021; Leijster et al. 2021). In Africa, Ethiopia is one of main countries using this system, which can be found also in Zimbabwe, Malawi, 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), Central Mozambique, one of the most biodiverse places in the world (Tinley 1977; Bouley et al. 2018). This forms part of an approach to simultaneously improve the socio-economic conditions of the populations living on the mountain, whilst reduce forest loss and degradation that results mainly from logging and slash and burn agriculture practices. Thus, while contributing to restore the degraded rainforest through the re-introduction of native forestry trees, coffee production under AFS (under such native trees) also contributes for additional income of local communities. Indeed, deforestation on the upper slopes of Gorongosa Mountain was happening at an alarming rate due to anthropogenic pressure, formerly associated with civil war and detrimental agricultural practices (Schuetze 2015), with the assessment of the satellite imagery showing a forest loss of more than 300 ha per year in the last 5 years (Stalmans & Victor 2020). Although there is still an ongoing loss of wooded areas, more than 800 smallholder famers are engaged in the rainforest restoration project, deeply involved in coffee production, with an important social and economic impact. Currently, the coffee plantations are about 181 hectares and it expected to expand to 1000 hectares 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 current suitable areas for *C. arabica* production and to estimate the future trend to this crop areas, with a particular emphasis in the AFS established in Gorongosa Mountain. The identification of suitable crop distribution areas by species distribution models (SDMs) is an increasingly promising approach (Guo et al. 2019; Chemura et al. 2021). This approach had been also used in *C. arabica* neighbouring countries (Chemura et al. 2016), and to identify future suitable areas, namely in China (Zhang et al. 2021). The modelling of suitable areas for coffee production at a national scale, both under AFS and full Sun (FS) cropping system will contribute to comprehensively understand the potential of coffee AFS in a wider global context. Overall, we provide evidence that AFS greatly mitigate CC impacts on coffee crop in years to come, while contributing to restore the rainforest areas and biodiversity, associated with the sustainable development of local communities.

2.2. Materials and methods

2.2.1. 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 centre, high plateaus in northwest and mountains in west (FAO 2005; Cabral et al. 2017). This country has an occurrence of wild and endemic coffee species to some extent throughout the country (Campa et al. 2008; Bunn et al. 2015) and a small production of Arabica coffee in the center and north of the country (Mozambique Good trade 2020). This modelling study considered the whole Mozambican country, and included a part of the Zimbabwean Manicaland province, which is very connected to Mozambican Manica province in terms of natural habitats and socio-economic cohesion (Timberlake et al. 2020). 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 in the Gorongosa National Park (GNP), located in the southern of the Great Rift Valley system, a central region of Mozambique 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 hectares (Fig. 1b), above the 700 m elevation contour, where the coffee crop under AFS was established. The mountain is characterized by a rather distinctive combination of temperature, radiation, rainfall, and wind compared with lowlands at the same latitude (Stalmans & Beilfuss 2008).

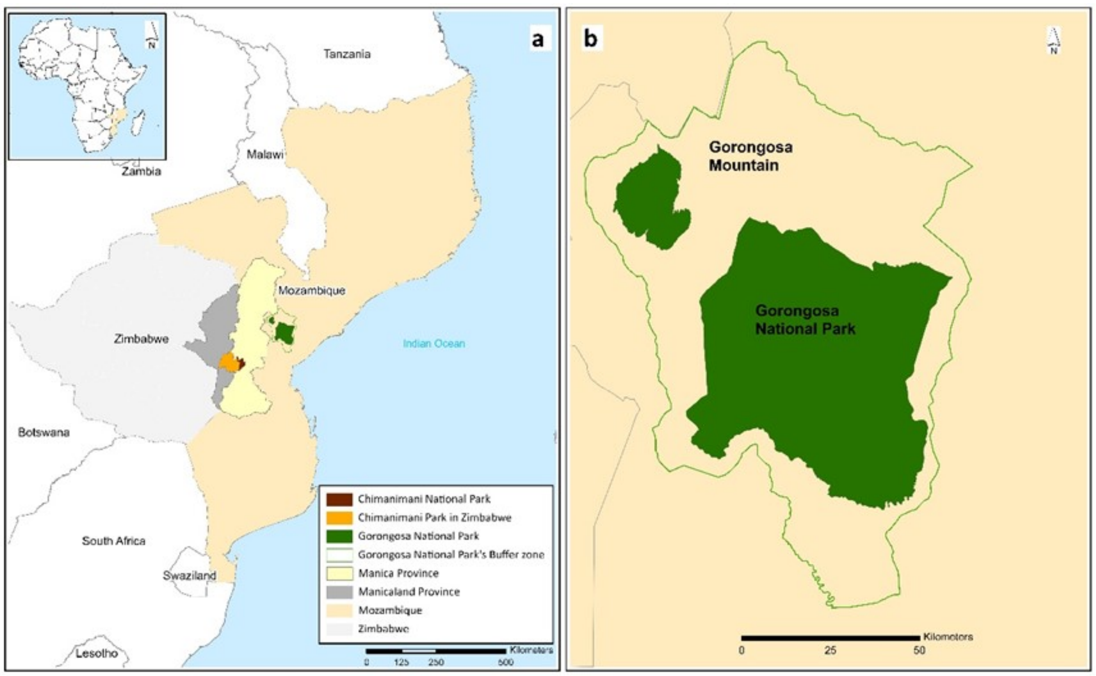

Figure II 1 Maps showing the location of the study area, regarding the entire country of Mozambique (a), and the Gorongosa Mountain area (b).

2.2.2. *Coffea arabica* L. cropping system and data collection

In this study, coffee-AFS was defined as a management in which the coffee plants are grown under 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 micrantha* (Hochst.) In the full Sun (FS) management system the 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 to 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. The *C. arabica* distribution was mostly obtained through field surveys (85%) of the sites with coffee plantations (Fig. 2). Records were grouped by crop system management type, identifying each record as FS or AFS (Table S1).

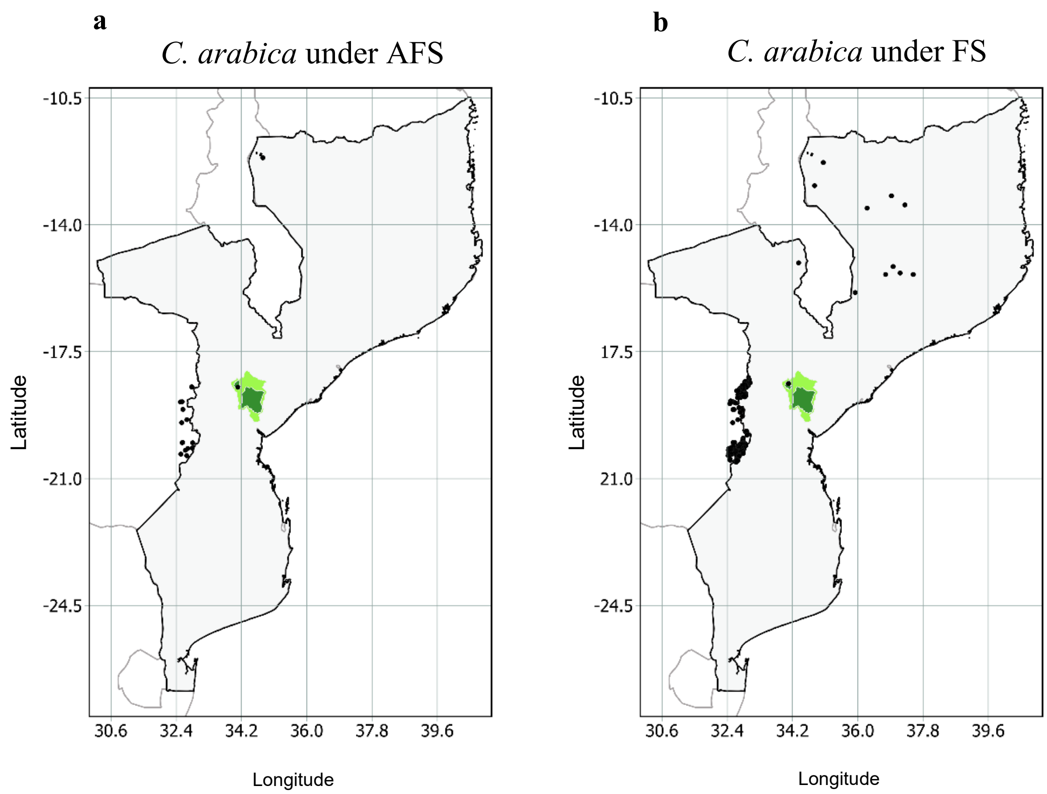

Figure II 2 - Compilation of Coffea arabica records considered for modelling covering the entire country and some adjacent areas of Zimbabwe, separated for agroforest (AFS) (a) or full Sun (FS) (b) management systems. Coloured areas correspond to the target area of the Gorongosa National Park (dark green)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

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), a number of Zimbabwean records were also considered as input data. Zimbabwean records were reinforced by literature review, particularly from Kutywayo et al. (2013).

2.2.3. Environmental variables

The climatic variables of temperature, and rainfall water availability are the most relevant to coffee plant growth and production (DaMatta and Ramalho 2006; Gomes et al. 2020). The most meaningful climatic variables for ecological niche modelling (Läderach et al. 2017) were downloaded from the WorldClim website (https://www.worldclim.org/). Due 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-250m-digitalelevation-database-v4-1/) at a resolution of 250 m (Reuter et al. 2008). In total, twenty environmental variables were considered for modelling 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 a correlation analysis ($r \geq 0.7$; Pearson coefficient) to avoid model over fitting (Abolmaali et al. 2018). Only the most biologically relevant and non-correlated variables were subsequently used for modelling, resulting in six selected variables (Table 1; Fig. S1).

To evaluate the future projections of *C. arabica* cropping, 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). Afterwards, 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 Wm^2 by 2100; SSP245 represents a nominal 4.5 Wm^2 radioactive forcing level by 2100; SSP370 is a medium-high reference scenario within the socio-economic family; and SSP585 represents the last scenario spectrum in a high fossil-fuel development (Meinshausen et al. 2019). The models were run for 2040, 2060, 2080, and 2100, for scenarios projections from a pessimist to optimist conditions, considering the expected future changes (Gidden et al. 2019; Schwingshackl et al. 2019).

Finally, the gridded maps were overlaid to determine the areas where coffee production under different growth scenarios and systems (AFS or FS) is projected to decrease, increase, or remain stable (Ochola et al. 2022). Computation of the percentage of the geographic shift in each region was determined without discriminate the coffee suitability categories (high, medium and low).

To reinforce the variation between AFS and FS influence on the microclimatic modification, shade affects in the daily temperature and Sun radiation were monitored in plants of both systems in the 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.

Table II 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	⁰C	https://www.WorldClim/.org
BIO02	**Mean Diurnal Range (Mean of monthly (max temp - min temp))**	⁰C	
BIO03	**Isothermality (BIO2/BIO7) (* 100)**	%	
BIO04	Temperature Seasonality (standard deviation *100)	⁰C	
BIO05	Max Temperature of Warmest Month	⁰C	
BIO06	Min Temperature of Coldest Month	⁰C	
BIO07	Temperature Annual Range (BIO5-BIO6)	⁰C	
BIO08	Mean Temperature of Wettest Quarter	⁰C	
BIO09	Mean Temperature of Driest Quarter	⁰C	
BIO10	Mean Temperature of Warmest Quarter	⁰C	
BIO11	Mean Temperature of Coldest Quarter	⁰C	
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-250m-digitalelevation-database

2.2.4. Environmental niche modelling

The Maxent algorithm (Phillips et al. 2006; Phillips 2008) was used to evaluate the current, and predict the future suitability areas for *C. arabica*. We applied the kuenm package in R (Cobos et al. 2019) for model calibration and selection. 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). A total of 18,183 candidate models were obtained for each combination. Resulting models were evaluated with 500 interactions based on significance of partial receiver operating characteristic (ROC), and 50% of data for bootstrapping, omission rate (OR), and the corrected Akaike information criterion (AICc) (Warren & 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 & 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 Maxent output grids were thresholded above the 10^{th} percentile training presence and were classified as High, Medium and Low suitability using a natural break (Abolmaali & Bashari 2018).

2.3. Results

2.3.1. Model selection and evaluation

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

Among the studied variables, elevation was selected in both systems. Models of *C. arabica* under FS also included the effect between day-to-night temperatures oscillation relative to the summer-to-winter (annual) oscillations (BIO03) (Table S3). On the other hand, *C. arabica* under AFS reveals a strong dependency of precipitation under different forms (Annual Precipitation (BIO12), Precipitation of Driest Month (BIO14), and Precipitation of Warmest Quarter (BIO18)) (Table S4).

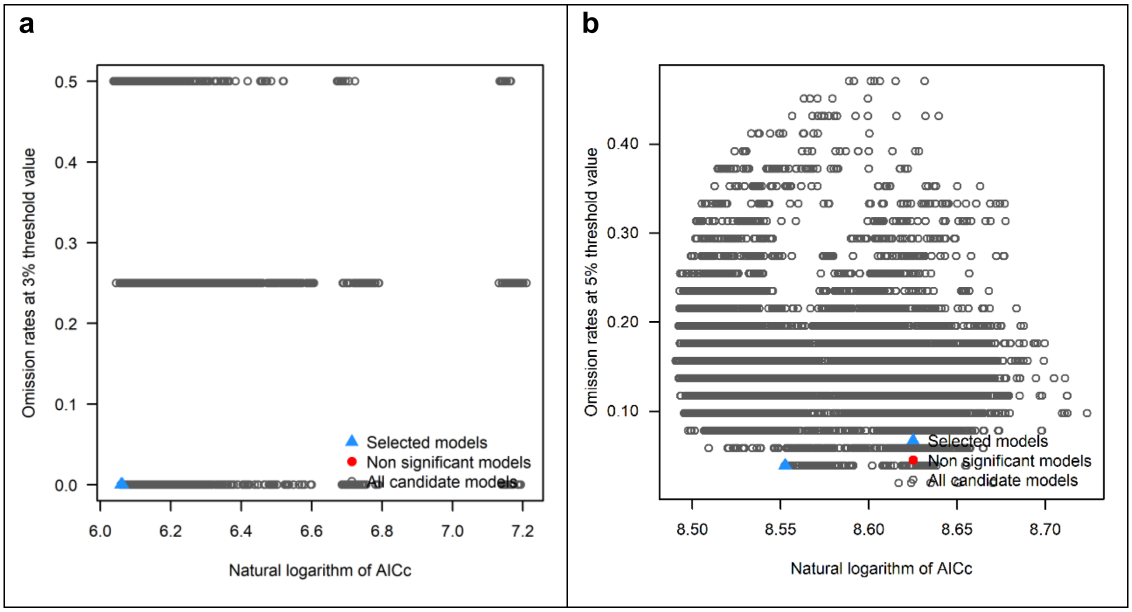

Figure II 3 - Omission rates (OR) and Akaike information criterion (AICc) values for all, non-significant, and selected "best" candidate models *Coffea* arabica under agroforest (AFS) (a) or under full Sun (FS) (b) management systems.

Table II 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

2.3.2. Current coffee suitability of areas for the coffee crop

The northern and central part of Mozambique, namely areas in the Manica, Sofala, Zambézia and Nampula provinces, were identified as suitable areas for *C. arabica* (Fig. 4). The model identified more central, north and interior regions for AFS (Fig. 4a) or FS (Fig. 4b), but there was a spatial segregation between these management systems. All suitable areas for both models are located in the country highlands. Limited areas in the centre of the country are currently suitable for *C. arabica* under AFS, and are restricted to the Gorongosa Mountain, and the chain of mountains between Manica and Zimbabwe. According to the maps obtained through GIS tools, the actual suitable areas for *C. arabica* production in and around the GNP are restricted to the elevations of the Gorongosa Mountain above 700 m for both management systems. Still, a higher environmental quality for coffee crop was found under AFS (Fig. 5).

Based on the data retrieved from the temperature sensors along 14 months (from September 2019 until October 2020), the monthly diurnal mean temperature in the Gorongosa Mountain was usually lower in the area with coffee under AFS than under FS. Differences up to 1.7, 0.4 and 2.9 ºC were observed at the elevations of 650, 825 and 935 m, respectively (data not shown).

Favourable conditions for the growth of *C. arabica* occur at one of the extremes of this climatic range, 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.

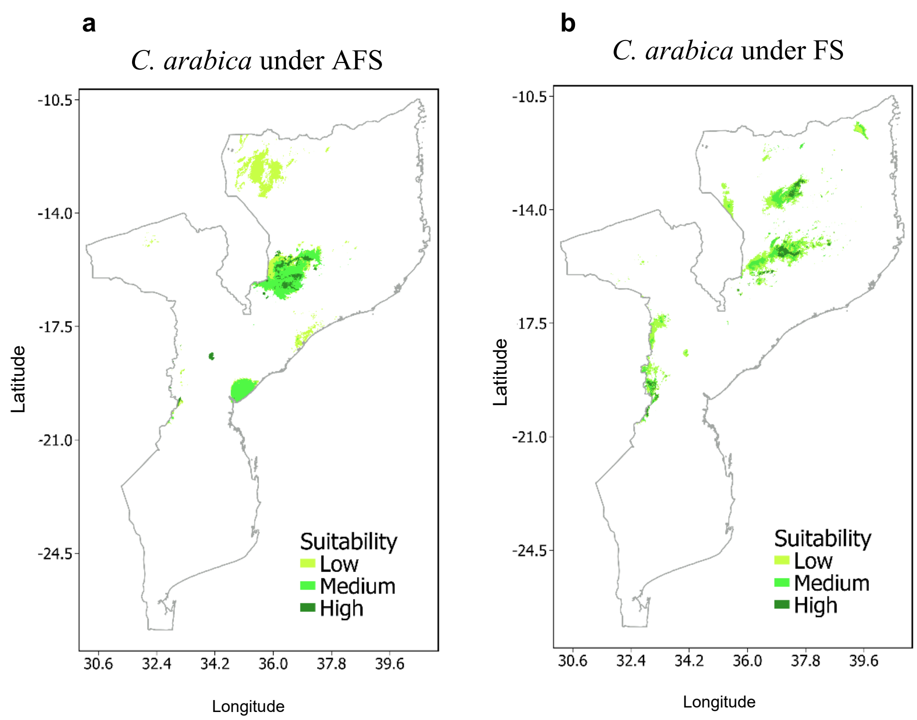

Figure II 4- Actual suitable areas for *Coffea arabica* at the whole country level of Mozambique, considering the use of agroforest (AFS) (a) or full Sun (b) management systems. Applied models were scaled within low, medium and high suitability.

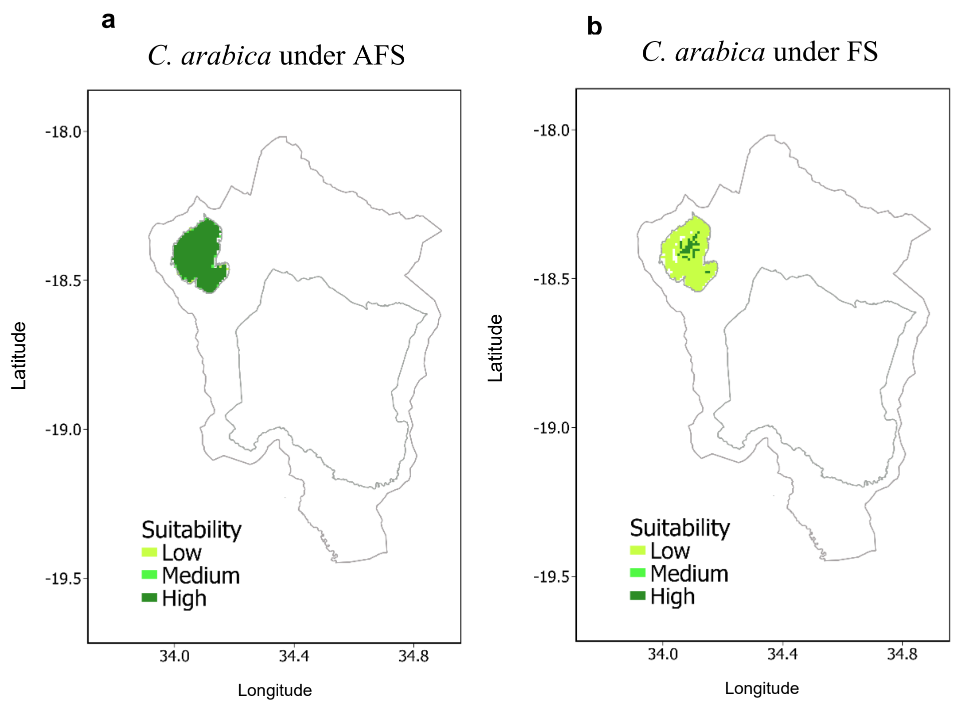

Figure II 5- Actual suitable areas for Coffea arabica in the Gorongosa National Park, Mozambique, considering the use of agroforestry (AFS) (a) or full Sun (b) management systems. Applied models were scaled within low, medium and high suitability.

2.3.3. Spatio-temporal projection of areas suitability *C. arabica*

Future potential distribution for *C. arabica* under both management 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 both in the area and in its suitability for *C. arabica* production under AFS (Fig. 6) and FS (Fig. 7) management systems. This suitability gradual decline from 2040 to 2100 is expected both in the country as a whole, and in the GNP region (Figs. 8 and 9), irrespective of the different scenarios, that is, from SSP126 (optimistic scenario) to SSP583 (pessimist scenarios). However, the strongest impacts were clearer by 2080 and 2100, and under the SSP370 and SSP585 scenarios, and should be emphasized that growing *C. arabica* under FS will be totally compromised for the foreseeable future (Figs. 8 and 9). That is even true for the GNP area, where FS management system should not be used anymore by 2040, despite its use nowadays in some areas (Fig. 5). In contrast, under AFS some suitable areas can still be envisaged by the end of the actual century, both in North of Mozambique and in Gorongosa Mountain area (Figs. 6 and 8).

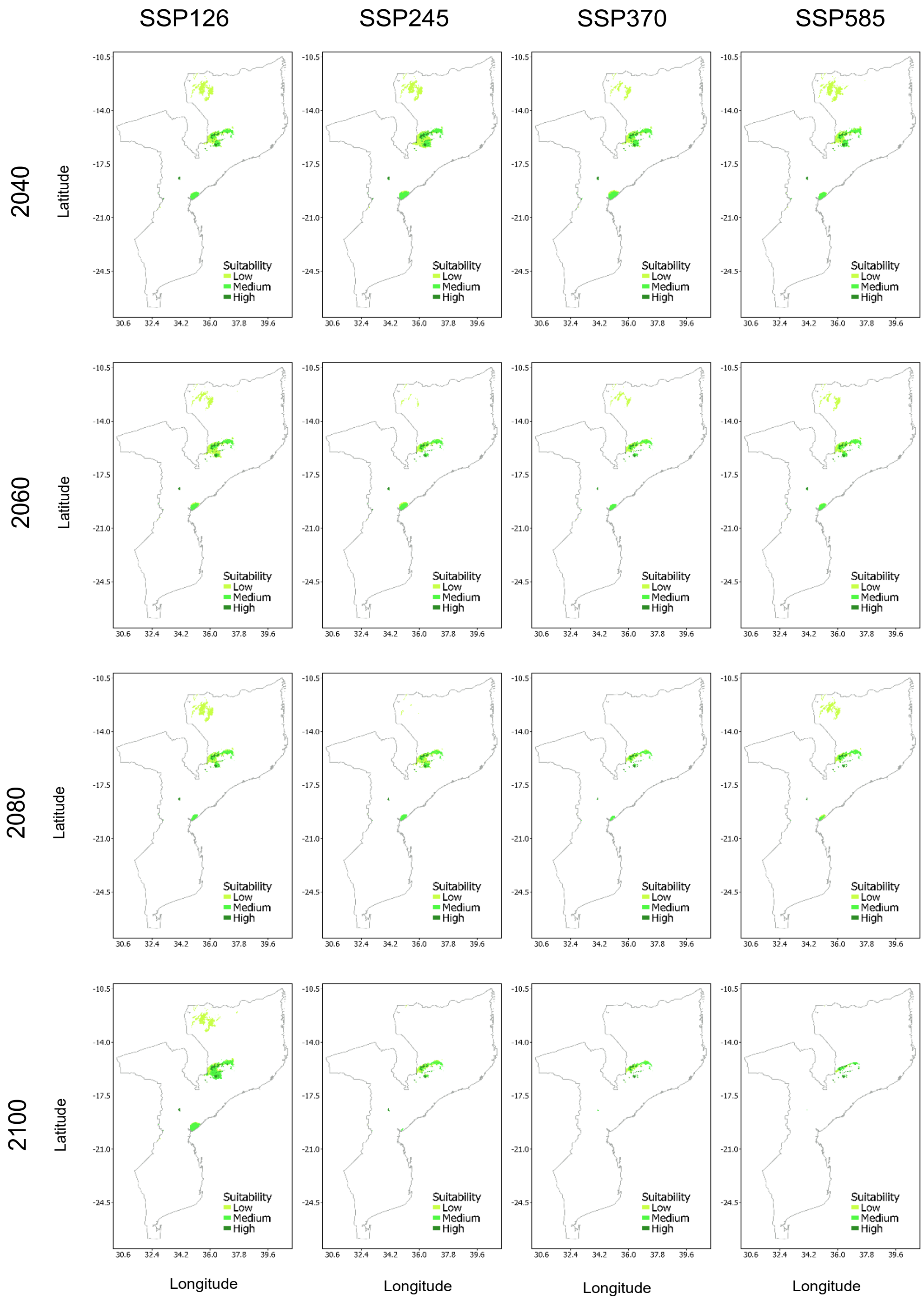

Figure II 6 - Projections for the climatic suitability areas for Coffea arabica in Mozambique under agroforest system (AFS) management, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100). Applied models were scaled within low, medium and high suitability.

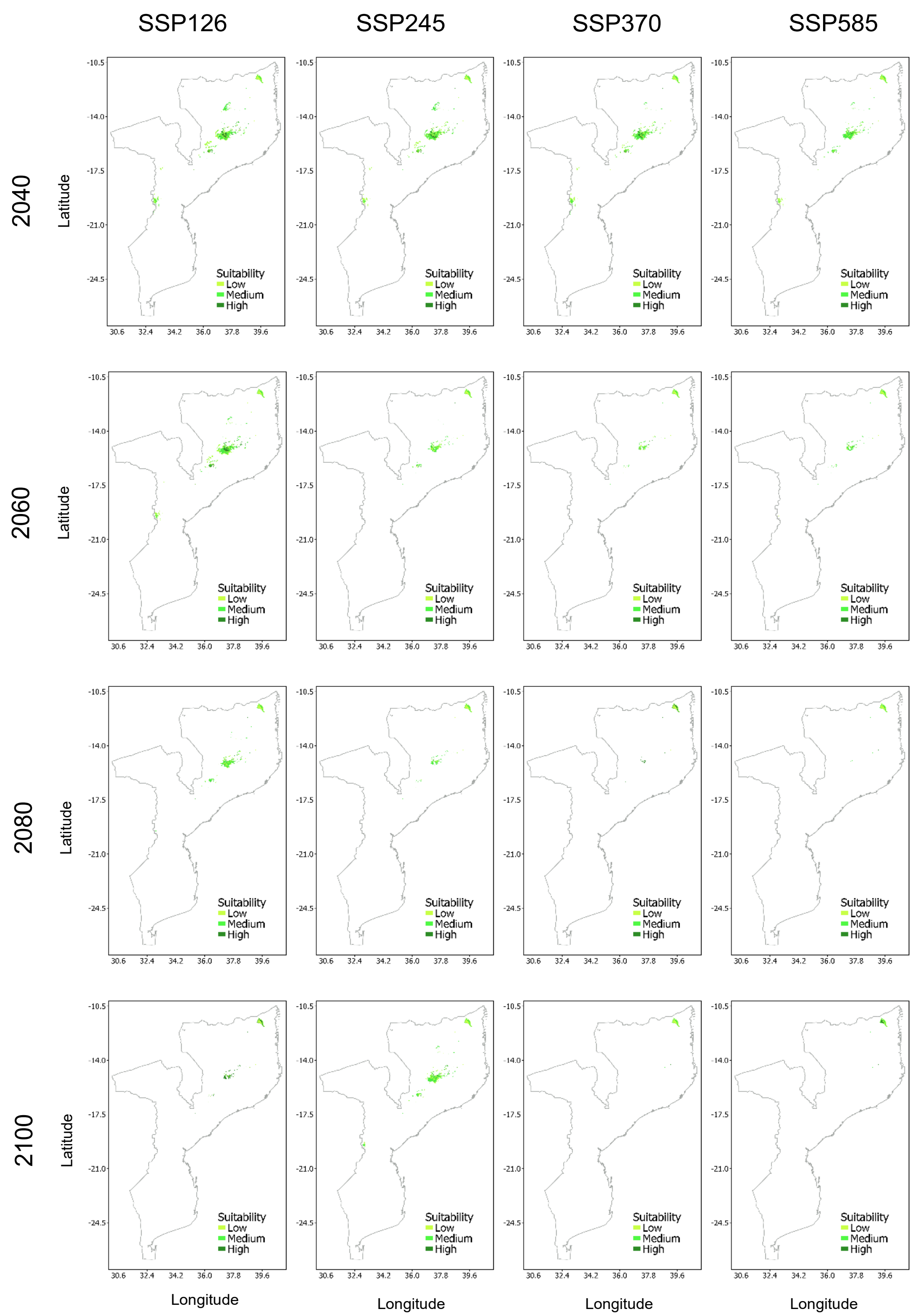

Figure II 7- Projections for the climatic suitability areas for *Coffea arabica* in Mozambique under full Sun (FS) management system, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100). Applied models were scaled within low, medium and high suitability.

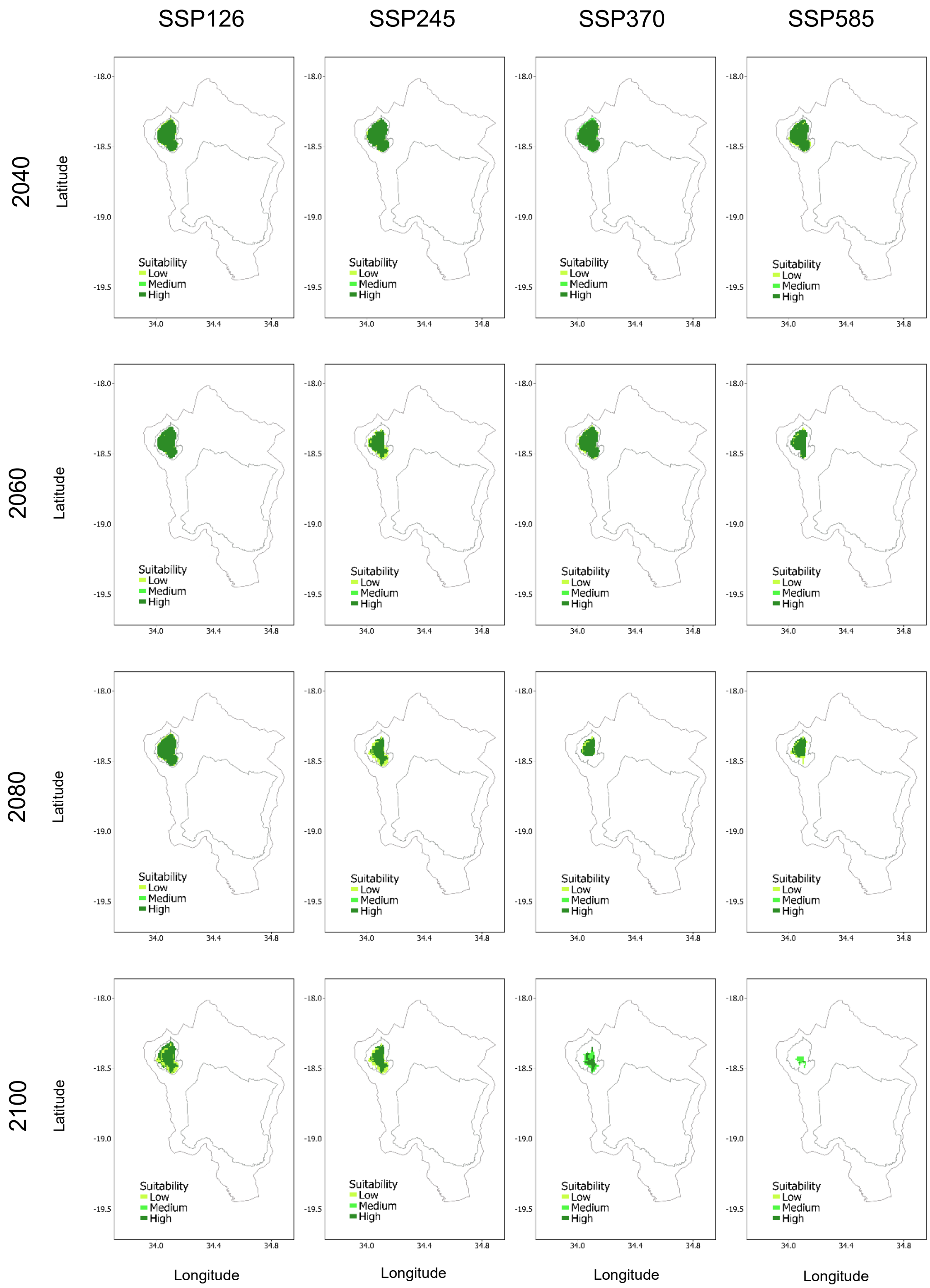

Figure II 8 - Projections for the climatic suitability areas for Coffea arabica in Gorongosa Mountain under agroforestry (AFS) management systems, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100). Applied models were scaled within low, medium and high suitability.

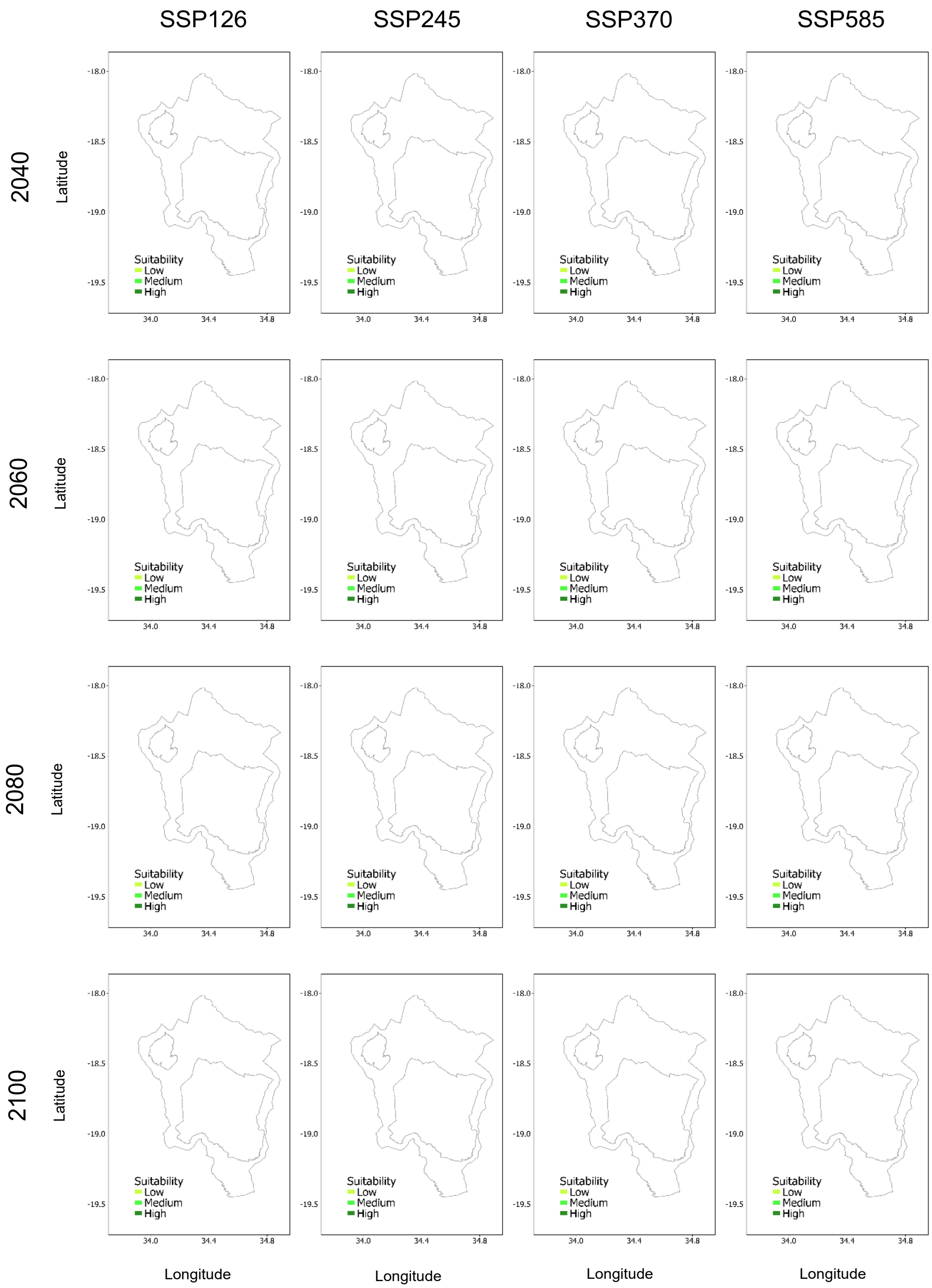

Figure II 9 - Projections for the climatic suitability areas for Coffea arabica in Gorongosa Mountain under full Sun (FS) management systems, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100). Applied models were scaled within low, medium and high suitability.

2.3.4. Loss of climatic suitable cropping areas

All scenarios point to large losses of suitable areas along the century, both under AFS or FS and considering the whole country (Figs. 10 and 11) and the Gorongosa Mountain region (Figs. 12 and 13). Under AFS the suitability of coffee areas at the whole country level was estimated to be reduced between 38.5% (SSP245) and 53.8% (SSP370) already by 2040 (Fig. 10). Over the years, for most scenarios these losses will gradually increase, reaching values of 41.4%, 80.8%, 85.1% and 90.1% by 2100, for SSP126, SSP245, SSP370 and SSP585 scenarios, respectively. In this respect, only under the most favourable scenario (SSP126) the lost area by 2100 will be lower than half of the actual suitable areas.

Still at the whole country level, the projections for coffee cropped under FS (Fig. 11) estimated a substantial greater loss than that under AFS. By 2040 these losses were between 64.9% (SSP126) and 77.2% (SSP585), whereas by 2080 and 2100 most scenarios point to areas losses greater than 80%, with SSP245, SSP370 and SSP585 showing reductions to less than 8% of actual suitable areas by 2100. Looking to the Gorongosa Mountain region belonging to the GNP, it was found a lesser negative impact under AFS (Fig. 12) but a worse one under FS (Fig. 13), as compared with the whole country analysis. Under AFS management, estimates point to area losses between lower than 30% until 2060, with the exception of SSP585 (48.6%) by 2060 (Fig. 12). That was substantially aggravated by 2080 and onwards, with reductions of 28.6%, 44.3%, 68.2% and 89.9% in SSP126, SSP245, SSP370, and SSP585 scenarios, respectively, by 2100.

As stated before, under FS there was no areas with low, medium or high suitability (Fig. 9), thus in line with the results of the total loss of actual area (Fig. 5b) from 2040 and onwards (Fig. 13).

Overall, it was estimated that suitable areas in Mozambique will be lost between half (SSP126) and about two thirds (all other scenarios) under AFS management by 2060, when those values are between 71% and 92% under FS, thus turning this crop unsuitable to be managed under FS in Mozambique as a whole. This impact under FS in Gorongosa Mountain was even clearer, as no area was predicted to be suitable already in 2040 and onwards. However, under AFS management strong decline of suitable areas were estimated to occur mostly in 2080 and afterwards. Therefore, the future of *C. arabica* in the Gorongosa Mountain (and in a few areas at whole country level) can be envisaged only under AFS management when approaching the end of this century (Fig. 14).

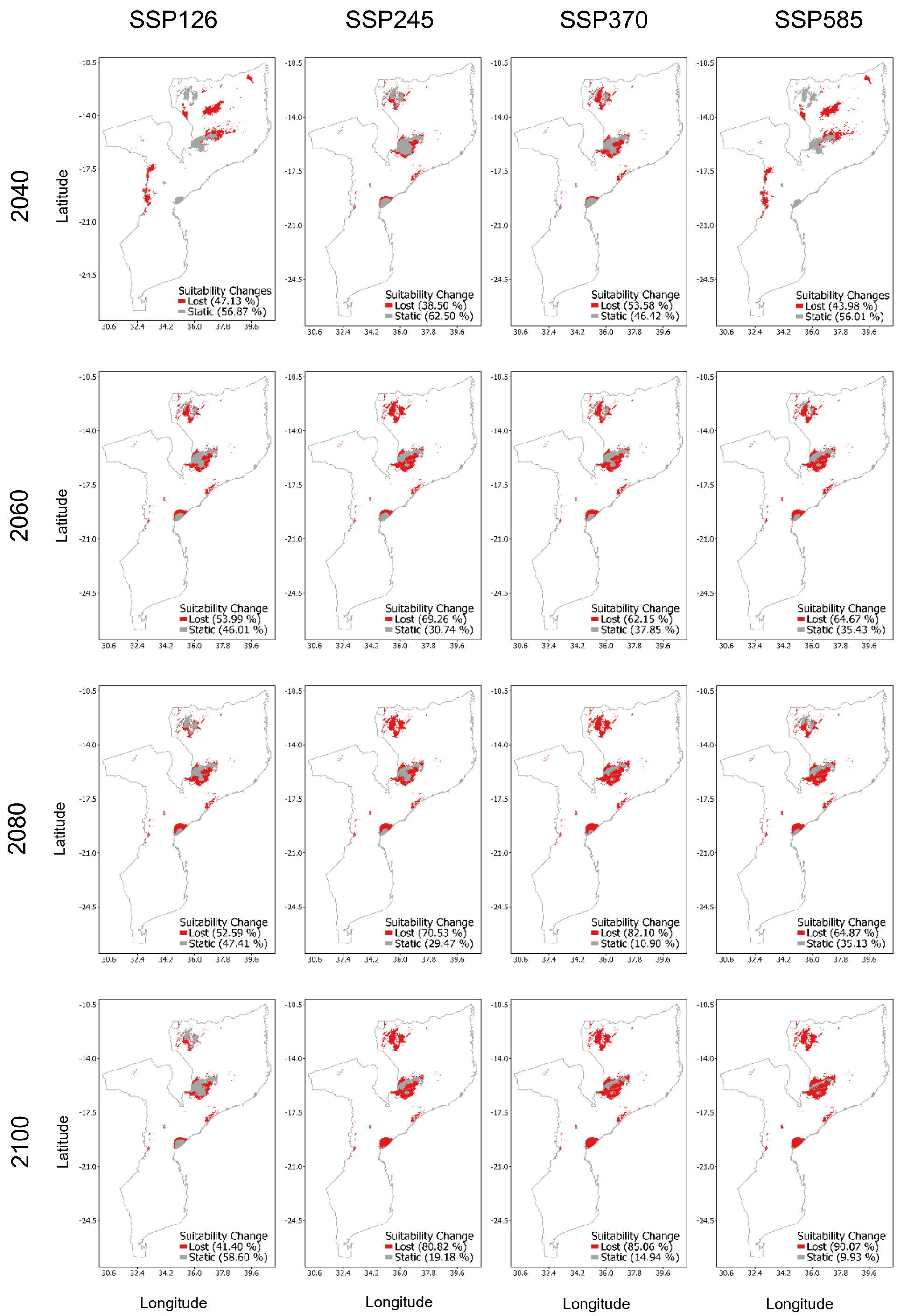

Figure II 10 - Loss and maintenance (Static) of climatic suitability areas for *Coffea arabica* in Mozambique under agroforestry system (AFS) management, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100).

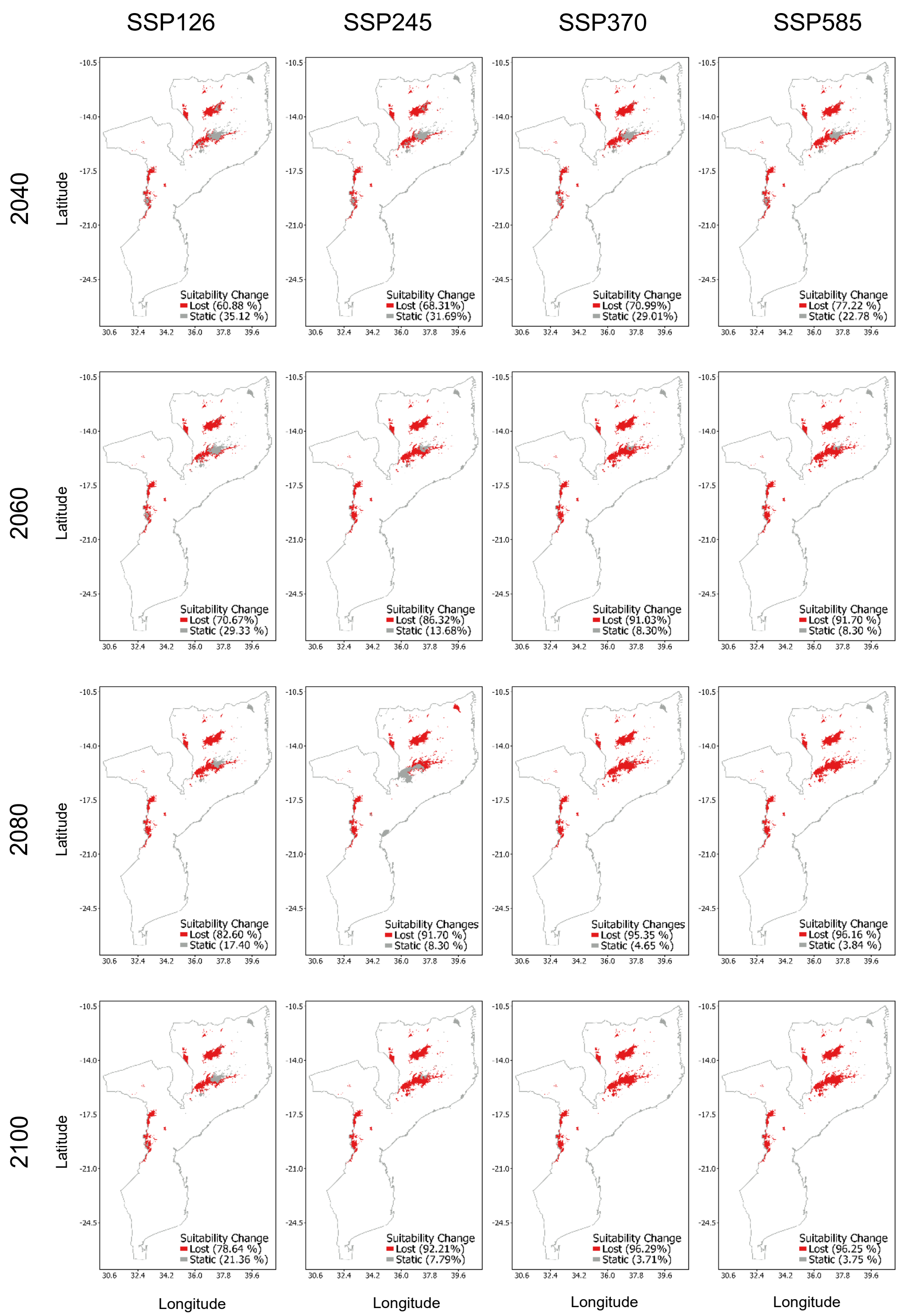

Figure II 11- Loss and maintenance (Static) of climatic suitability areas for Coffea arabica in Mozambique under full Sun management system (FS), considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100).

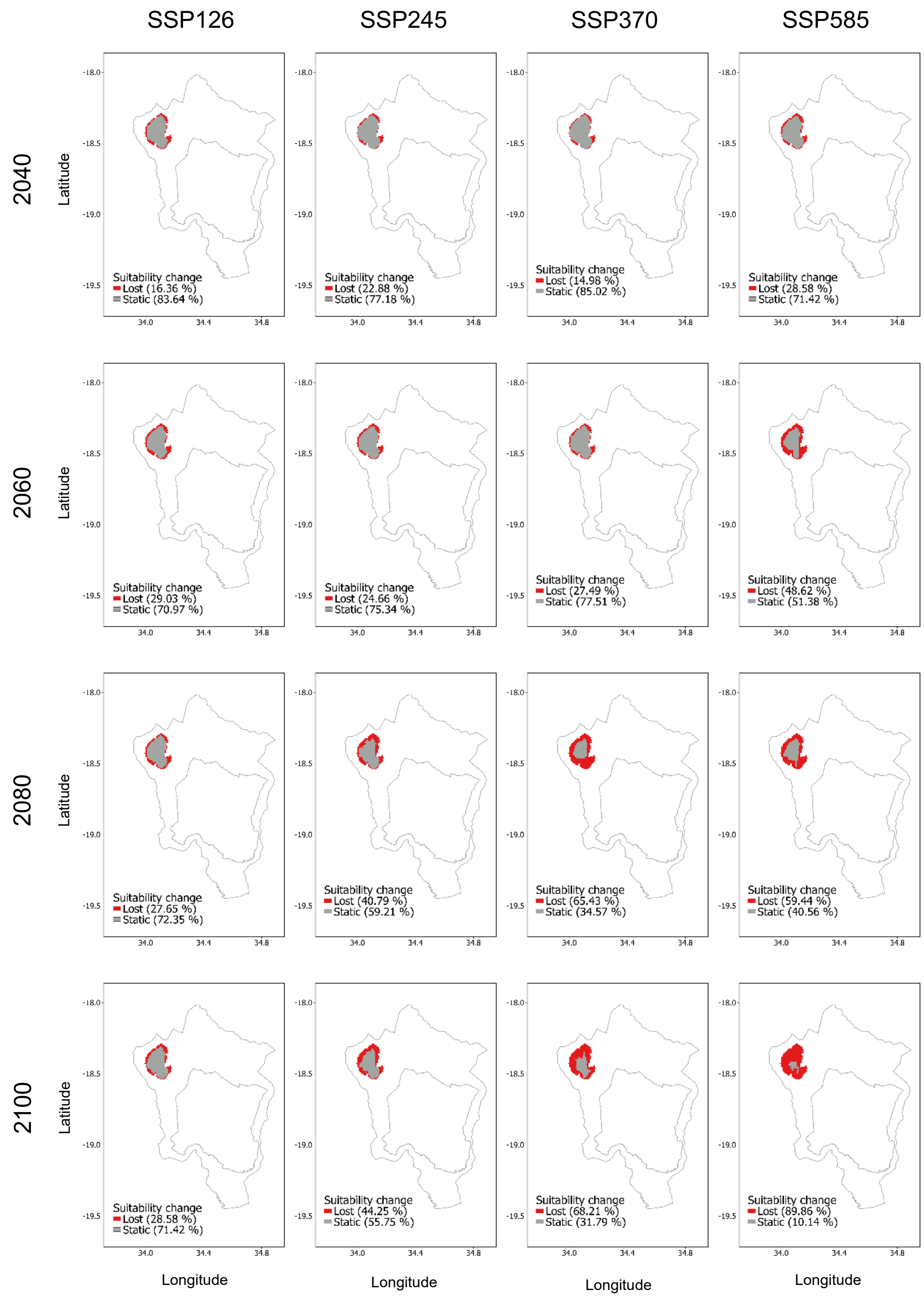

Figure II 12 -Loss and maintenance (Static) of climatic suitability areas for Coffea arabica in Gorongosa Mountain under agroforestry (AFS) management systems, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245, SSP370, and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100).

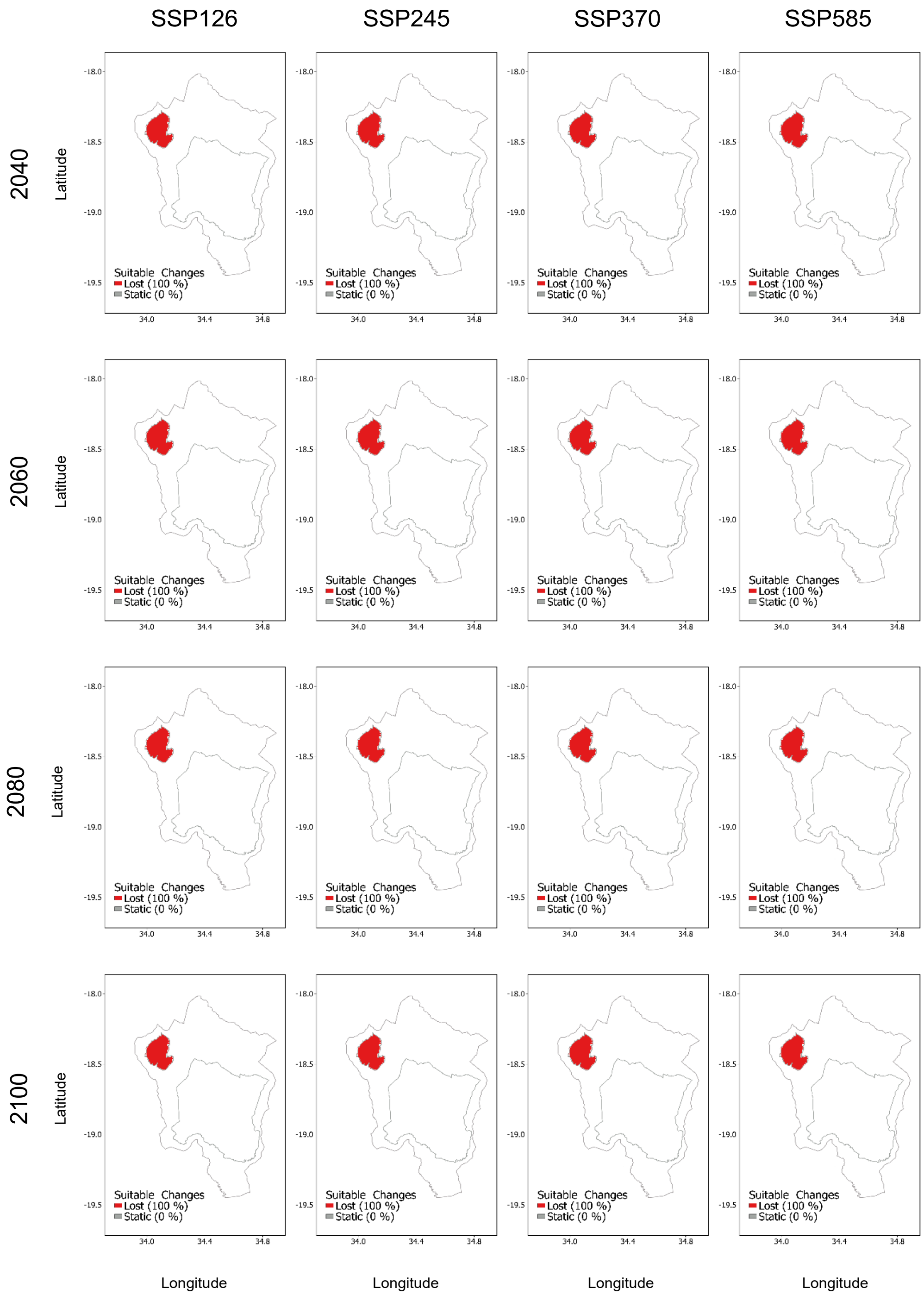

Figure II 13- Loss and maintenance (Static) of climatic suitability areas for *Coffea arabica* in Gorongosa Mountain under full Sun (FS) management systems, considering the average of the four GCMs for each of the SSPs (SSP126, SSP245; SSP370 and SSP585) analysed, and four step periods (2040, 2060, 2080, and 2100).

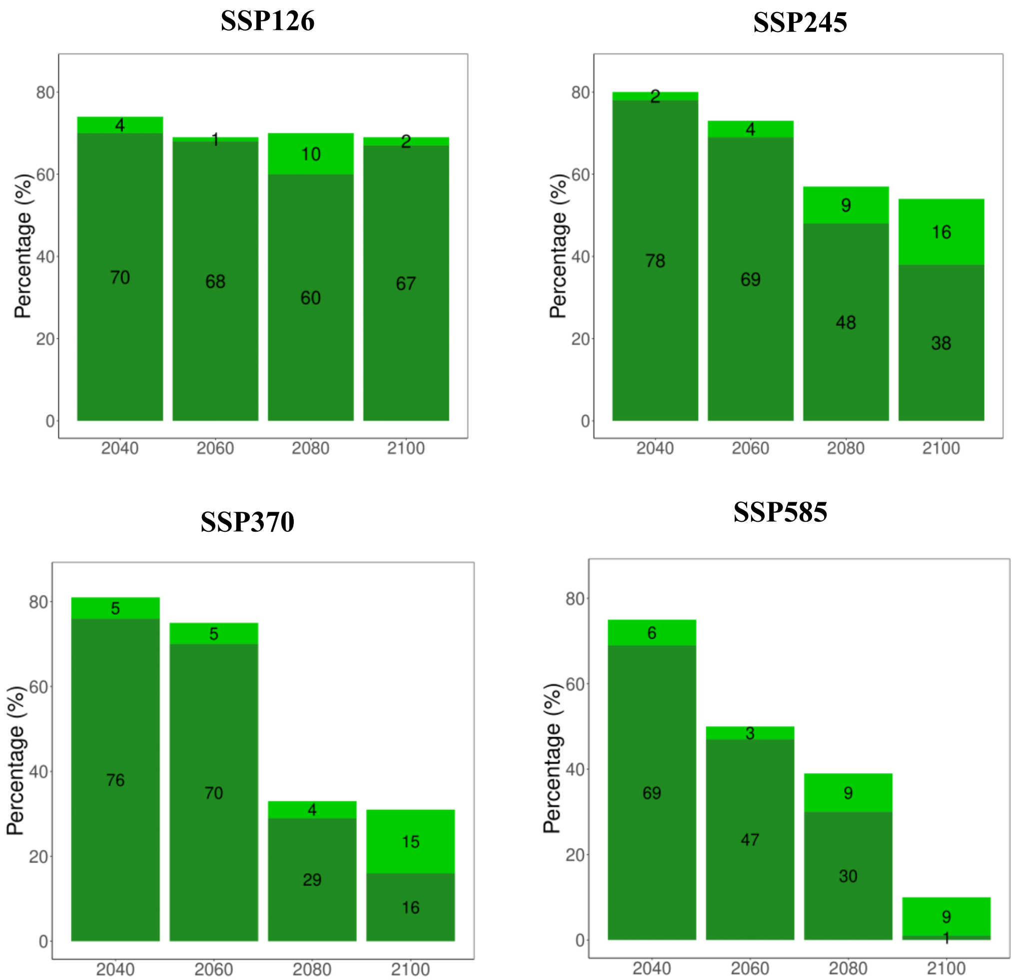

Figure II 14 - Projections for suitable cropping areas (values in %) of Coffea arabica at Gorongosa Mountain under agroforestry system (AFS) considering the scenarios SSP126, SSP 245, SSP370 and SSP585 (See material and Methods) from 2040 until 2100. Low suitability: light green; high suitability: dark green.

2.4. Discussion

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

The distribution model indicated that the best suitable areas for coffee production in the Mozambique highlands, 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). In this way, the landscape along of altitude of Gorongosa Mountain was categorized as a suitable area by the model, since altitude is crucial to coffee performance due to its association with temperature variation (Zhang et al. 2021). Also in accordance, the southern areas of Mozambique are mostly unsuitable, since they are lowlands or medium altitude highlands (< 600 m). Notably, a similar distribution of *C. arabica* was already described by Medina (1955) who reported that the north of Mozambique, restricted areas of Gorongosa, and the border zone of Manica were the most suitable for *C. arabica*. An exception was observed outside the GNP buffer zone (southeast zone), namely in the Cheringoma district, where low to medium suitable areas were predicted. Although the climatic requirements are not optimal for coffee, since the Cheringoma district is typically a lowland and the temperature is relatively higher than in Gorongosa Mountain, such coffee suitability was likely related to temperature mitigation provided by forestry trees and to the vegetation composition of that district (Muller 2012).

In general, the projections for Gorongosa Mountain highlighted that even in a relatively short term (by 2040), the FS system will not be sustainable for coffee production, whereas AFS constitute a better crop management system to face climatic change, allowing the crop to exist in a few areas at the whole country level, especially in Gorongosa Mountain. AFS can also have a potential positive role in pest control, which is crucial for crop sustainability (Kutywayo et al. 2013), although some studies reported greater pest incidence (Koutouleas et al. 2022a).

The temperature (BIO03) (Fig. S2) was also highly relevant descriptors for *C. arabica* distribution in the FS system, with temperature being recognized as a crucial variable that limits the suitability of coffee crop areas (DaMatta & Ramalho 2006; Ramalho et al. 2014; Gomes et al. 2020). While AFS was greatly associated with water availability (precipitation) and altitude (thus, also with the associated temperature variation) (Fig. S3), the suitable area for FS conditions 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 to 2.9 ºC higher than those found in the corresponding elevation areas under shaded AFS conditions. Additionally, extreme temperatures associated with rainfall deficit can favour a decline in the suitability for coffee cultivation (DaMatta & Ramalho 2006; Oliosi et al. 2016; Benti et al. 2022). This situation is more prone to occur in lowlands, where rainfall patterns in amount and frequency, 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 own findings due to the similar edaphic and climatic features in both provinces along the border, where the crop is cultivated (Timberlake et al. 2016, 2020), despite the potential presence of other variables that contribute to the geographic shifts of agricultural crops (Ochola et al. 2022).

2.4.2 Climate change and elevated air [CO_2]: a double-edged sword to coffee

Temperature and precipitation variations (and balance) are considered the most relevant factors determining the future distribution of species under new climate scenarios (Román-Palacios & Wiens 2020). Still, upon climate changes (CC) conditions other limiting factors, such as solar radiation (Yilmaz et al. 2017) or land use type (Tilman & Lehman 2001) can strongly contribute to 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 air [CO_2] (Rahn et al. 2018; Schwingshackl et al. 2019). In fact, together with its associated role in global warming, elevated air [CO_2] (eCO_2) promote important physiological impacts on plants. Such eCO_2 frequently lead to reductions on leaf stomatal conductance and, thus, in transpiration, in many species, thus with the potential to promote an increase in leaf temperature surface, particularly during temperature extremes. This 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* spp. genotypes. In fact, eCO_2 was reported to greatly strengthen coffee vigour, growth and yield, closely associated with significant increase in net C-assimilation close or above 50% in the range of 550 to 700 ppm of air CO_2 (Ramalho et al. 2013; Ghini et al. 2015; DaMatta et al. 2018; Avila et al. 2020; Rakocevic et al., 2021). Most important, eCO_2 can additionally promote/reinforce the triggering of protective responses to drought and supra-optimal temperatures, thus 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 new modelling approaches that include eCO_2 to conclude that the increase of air CO_2 might significantly reduce warming impact, particularly if 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* might in fact happens, although gradual decrease of the suitability over time will occur, with significant losses of adequate areas under almost all climate scenarios (Fig. 10).

Under the scenarios considering the lowest (SSP126) and highest (SSP585) GHG emissions, the air mean temperature is estimated to raise 1.5 ºC and 4.1 ºC, respectively, in the region of Gorongosa Mountain. The detected loss of suitable areas for coffee crop was more pronounced below the 935 m of altitude, where the higher temperatures implicate harsher environmental conditions (Fig. 12). Additionally, rainfall shortage (and lower fog persistence) will be more evident at lower elevations, thus increasing the loss of suitability of these areas for coffee (Figs. S2 and S3). Therefore, the projected CC conditions points to a much greater pressure under the FS system, related to higher temperatures (Fig. 11), with AFS associated with elevation (as in the Gorongosa Mountain) becoming the only sustainable management system, both at the whole country level (Figs. 6 and 10), and, especially in the Gorongosa mountain (Figs. 8, 12 and 14), with negligible (or 100% loss of) suitable coffee areas under FS in the latter region already in 2040 and on onwards (Figs. 9 and 13).

These estimates, reporting a much greater impact under FS, are in line with similar findings, namely for Brazil projections where this crop is mainly cropped under FS. This would result in marked shifts (to higher elevation and lower latitudes) of the actual suitable/cropped area due to CC (Bunn et al. 2015, Magrach & Ghazoul 2015). By 2050 some estimates point to area losses of *ca*. 56% for *C. arabica* (with gain of new areas of only 9%), whereas *C. canephora*, despite impacted in actual areas of cultivation, can more than double the actual cultivation area in the future (Magrach & Ghazoul 2015). Still, in some areas the projected 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). This strongly highlights the urgent need to implement adaptiation strategies, such as AFS due to the long-time needed to be fully established (Läderach et al. 2017), although with promissing results, as here clearly showed when comparing AFS with FS results in the 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 system may interfere for 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 in the tropical rainforest ecosystem, 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 the smallholder farmers. Such annual crops are essential for local food security in remote areas, with maize and cassava assuming a particular importance for more than 2000 families in the 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, which simultaneously promote afforestation, could be more effective in land restoration, while bringing additional benefits to the mountain communities. In fact, from 2010 to 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*), but in some areas included also some 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 along this century (FAO 2022). New smallholder farmers have their income from coffee production or from job opportunities in coffee plantations in Gorongosa Mountain, representing about 40% of the families living in the area. In 2022 and in the following years, additional families will be involved, to fulfil the demand for coffee under AFS, which has the objective to reach *ca*. 1000 ha in coming years (Mongabay 2020).

Overall, in Mozambique under AFS management the coffee crop will be affected (regarding the loss of suitable cropping areas) in a much lower extent than in FS. Additionally, AFS offer a better support to the livelihoods of local populations, while improves the recovery/conservation of native rainforest (in Gorongosa Mountain) and promotes plant, animal and microbiological biodiversity, thus constituting a more sustainable management strategy for this crop for the coming years.

2.5. Conclusions

Bioclimatic modelling is a powerful tool to predict species distribution and estimate the impact of CC on crop production both at global and regional level. Modelling the current distribution and future suitable areas of *C. arabica* in Mozambique provide a clear understanding about the trends of environmental limitations to coffee whereas also allows to identify areas with a mid- or long-term future to implement this crop. 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. Associated with CC, according to four scenarios (SSPs) projection, temperature and precipitation ("hidden" also in the altitude) 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 actually and, especially, in terms of future, consistently for all SSP scenarios.

As main findings, under AFS, at the whole country level reductions of suitable areas are estimated to be between about half and two thirds of the actual suitable areas by 2060, and between 41% and 91% by 2100 (depending on the scenarios), whereas in the Gorongosa Mountain almost all scenarios point to area losses below 30% by 2060, and lower than 50% by 2100 in two of the scenarios (SSP126 and SSP245). In sharp contrast, at the whole country level, the FS system is predicted to become unsuitable for most Mozambique territory, due to losses close or above two thirds of the actual suitable areas already in 2040, and greater than 80% by 2080. Even more striking, the predictions for this system point to a total absence of adequate areas at the Gorongosa Mountain already by 2040 and afterwards. Overall, our study strengthens the knowledge regarding the coffee crop under CC, showing great impacts under FS in a quite near future (2040), and that the implementation of AFS (complemented with other management techniques) greatly reduced CC deleterious impacts and can be crucial to guarantee this crop sustainability in a near future and along the present century.

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Supplementary information II

Table S1. Sites with coffee plantations and grouped by the crop management systems under agroforestry (AFS) and full Sun (FS).

long	lat	System	long	lat	System	long	lat	System	long	lat	System	long	lat	System
32.99	-18.21	Full Sun	32.93	-18.46	Full Sun	32.91	-18.65	Full Sun	32.92	-19.70	Full Sun	32.80	-20.14	Full Sun
33.00	-18.26	Full Sun	32.93	-18.48	Full Sun	32.91	-18.67	Full Sun	32.92	-19.69	Full Sun	32.82	-20.12	Full Sun
33.00	-18.27	Full Sun	32.83	-18.47	Agroforestry	32.91	-18.69	Full Sun	32.92	-19.69	Full Sun	32.82	-20.11	Full Sun
33.00	-18.28	Full Sun	32.83	-18.48	Agroforestry	32.89	-18.70	Full Sun	32.92	-19.69	Full Sun	32.82	-20.11	Full Sun
33.00	-18.31	Full Sun	32.85	-18.50	Full Sun	32.88	-18.68	Full Sun	32.93	-19.69	Full Sun	32.83	-20.10	Full Sun
32.97	-18.31	Full Sun	32.82	-18.48	Full Sun	32.90	-18.71	Full Sun	32.93	-19.69	Full Sun	32.83	-20.10	Full Sun
32.97	-18.32	Full Sun	32.83	-18.48	Full Sun	32.91	-18.71	Full Sun	32.96	-19.78	Full Sun	32.83	-20.09	Full Sun
32.95	-18.31	Full Sun	32.82	-18.49	Full Sun	32.86	-18.68	Full Sun	32.96	-19.79	Full Sun	32.84	-20.13	Full Sun
32.94	-18.33	Full Sun	32.82	-18.43	Full Sun	32.86	-18.67	Full Sun	32.97	-19.79	Full Sun	32.83	-20.14	Full Sun
32.93	-18.34	Full Sun	32.82	-18.44	Full Sun	32.86	-18.67	Full Sun	32.97	-19.78	Full Sun	32.83	-20.14	Full Sun
32.91	-18.32	Full Sun	32.81	-18.52	Full Sun	32.84	-18.68	Full Sun	32.95	-19.80	Full Sun	32.86	-20.13	Full Sun
32.89	-18.33	Full Sun	32.81	-18.52	Full Sun	32.83	-18.67	Full Sun	32.84	-19.89	Full Sun	32.86	-20.13	Full Sun
32.98	-18.36	Full Sun	32.79	-18.53	Full Sun	32.85	-18.70	Full Sun	32.83	-19.94	Full Sun	32.85	-20.14	Full Sun
32.98	-18.35	Full Sun	32.86	-18.51	Full Sun	32.84	-18.73	Full Sun	32.82	-19.96	Full Sun	32.57	-20.11	Full Sun
32.97	-18.35	Full Sun	32.87	-18.54	Full Sun	32.85	-18.73	Full Sun	32.84	-19.97	Full Sun	32.56	-20.11	Full Sun
33.03	-18.35	Full Sun	32.87	-18.56	Full Sun	32.89	-18.75	Full Sun	32.82	-20.01	Full Sun	32.56	-20.15	Full Sun
33.04	-18.36	Full Sun	32.76	-18.50	Full Sun	32.88	-18.74	Full Sun	32.82	-20.01	Full Sun	32.58	-20.19	Full Sun
32.94	-18.37	Full Sun	32.74	-18.51	Full Sun	32.56	-18.88	Agroforestry	32.83	-20.02	Full Sun	32.54	-20.19	Full Sun
32.94	-18.38	Full Sun	32.76	-18.54	Full Sun	32.61	-18.91	Full Sun	32.84	-20.03	Full Sun	32.56	-20.24	Full Sun
32.93	-18.37	Full Sun	32.77	-18.56	Full Sun	32.64	-18.92	Full Sun	32.85	-20.01	No data	32.59	-20.24	Full Sun
32.91	-18.37	Full Sun	32.72	-18.55	Full Sun	32.52	-18.89	Agroforestry	32.86	-20.02	Full Sun	32.72	-20.21	Full Sun
33.00	-18.38	Full Sun	32.72	-18.56	Full Sun	32.49	-18.86	Full Sun	32.87	-20.03	Full Sun	32.75	-20.20	Full Sun
32.99	-18.39	Full Sun	32.72	-18.57	Full Sun	32.48	-18.91	Full Sun	32.86	-20.04	Full Sun	32.77	-20.20	Full Sun
32.96	-18.40	Full Sun	32.72	-18.59	Full Sun	32.47	-18.93	Full Sun	32.85	-20.04	Full Sun	32.83	-20.20	Full Sun
32.96	-18.42	Full Sun	32.71	-18.57	Full Sun	32.77	-19.07	Full Sun	32.90	-20.04	Full Sun	32.86	-20.18	Full Sun
32.96	-18.42	Full Sun	32.70	-18.58	Full Sun	32.83	-19.12	Full Sun	32.90	-20.07	Full Sun	32.87	-20.17	Full Sun
32.95	-18.42	Full Sun	32.66	-18.58	Full Sun	32.72	-19.04	Full Sun	32.91	-20.07	Full Sun	32.86	-20.14	Full Sun
32.94	-18.41	Full Sun	32.70	-18.69	Full Sun	32.72	-19.05	Full Sun	32.91	-20.09	Full Sun	32.84	-20.16	No data
32.93	-18.41	Full Sun	32.75	-18.69	Full Sun	32.72	-19.04	Full Sun	32.76	-20.04	Full Sun	32.82	-20.18	Full Sun
32.91	-18.39	Full Sun	32.75	-18.74	Full Sun	32.76	-19.17	Full Sun	32.78	-20.05	Full Sun	32.79	-20.18	Full Sun
32.90	-18.39	Full Sun	32.81	-18.73	Full Sun	32.56	-19.10	Full Sun	32.77	-20.04	Full Sun	32.78	-20.18	Full Sun
32.89	-18.39	Full Sun	32.77	-18.76	Full Sun	32.57	-19.10	Full Sun	32.78	-20.04	Full Sun	32.80	-20.17	Full Sun
32.88	-18.40	Full Sun	32.75	-18.76	Full Sun	32.58	-19.09	Full Sun	32.80	-20.04	Full Sun	32.80	-20.18	Full Sun
32.86	-18.41	Full Sun	32.68	-18.77	Full Sun	32.59	-19.10	Full Sun	32.81	-20.04	Full Sun	32.80	-20.19	Full Sun
32.88	-18.42	Full Sun	32.86	-18.58	Full Sun	32.59	-19.09	No data	32.82	-20.05	Full Sun	32.75	-20.16	Full Sun
32.88	-18.42	Full Sun	32.85	-18.60	Full Sun	32.57	-19.09	Full Sun	32.82	-20.06	Full Sun	32.77	-20.15	Full Sun
32.90	-18.43	Full Sun	32.87	-18.61	Full Sun	32.58	-19.09	Full Sun	32.79	-20.10	Full Sun	32.78	-20.15	Full Sun

32.91	-18.43	Full Sun	32.90	-18.64	Full Sun	32.83	-19.27	Full Sun	32.69	-20.11	Full Sun	32.77	-20.14	Full Sun
32.92	-18.43	Full Sun	32.87	-18.64	Full Sun	32.81	-19.28	Full Sun	32.69	-20.11	Full Sun	32.74	-20.14	Full Sun
32.89	-18.41	Full Sun	32.86	-18.64	Full Sun	32.82	-19.29	Full Sun	32.71	-20.11	Full Sun	32.73	-20.15	Full Sun
32.87	-18.41	Full Sun	32.85	-18.63	Full Sun	32.69	-19.38	Agroforestry	32.72	-20.11	Full Sun	32.75	-20.15	Full Sun
32.87	-18.41	Full Sun	32.85	-18.63	Full Sun	32.55	-19.46	Agroforestry	32.75	-20.12	Full Sun	32.74	-20.16	Full Sun
32.90	-18.46	Full Sun	32.84	-18.64	Full Sun	32.90	-19.71	Full Sun	32.76	-20.12	Full Sun	32.74	-20.17	Full Sun
32.86	-18.48	Full Sun	32.84	-18.63	Full Sun	32.93	-19.71	Full Sun	32.77	-20.12	Full Sun	32.76	-20.17	Full Sun
32.86	-18.48	Full Sun	32.83	-18.65	Full Sun	32.93	-19.71	Full Sun	32.77	-20.12	Full Sun	32.73	-20.14	Full Sun

Table S2. Candidate sets of environmental predictors tested for model calibration used to model *C. arabica*, in full Sun and *C. arabica* under agroforestry systems.

Pred. Sets	Environmental predictors
Set_1	Bio02, Bio03
Set_2	Bio02, Bio12
Set_3	Bio02, Bio14
Set_4	Bio02, Bio18
Set_5	Bio02, Elev
Set_6	Bio03, Bio12
Set_7	Bio03, Bio14
Set_8	Bio03, Bio18
Set_9	Bio03, Elev
Set_10	Bio12, Bio14
Set_11	Bio12, Bio18
Set_12	Bio12, Elev
Set_13	Bio14, Bio18
Set_14	Bio14, Elev
Set_15	Bio18, Elev
Set_16	Bio02, Bio03, Bio12
Set_17	Bio02, Bio03, Bio14
Set_18	Bio02, Bio03, Bio18
Set_19	Bio02, Bio03, Elev
Set_20	Bio02, Bio12, Bio14
Set_21	Bio02, Bio12, Bio18
Set_22	Bio02, Bio12, Elev
Set_23	Bio02, Bio14, Bio18
Set_24	Bio02, Bio14, Elev
Set_25	Bio02, Bio18, Elev
Set_26	Bio03, Bio12, Bio14
Set_27	Bio03, Bio12, Bio18
Set_28	Bio03, Bio12, Elev
Set_29	Bio03, Bio14, Bio18
Set_30	Bio03, Bio14, Elev
Set_31	Bio03, Bio18, Elev
Set_32	Bio12, Bio14, Bio18
Set_33	Bio12, Bio14, Elev
Set_34	Bio12, Bio18, Elev
Set_35	Bio14, Bio18, Elev
Set_36	Bio02, Bio03, Bio12, Bio14
Set_37	Bio02, Bio03, Bio12, Bio18
Set_38	Bio02, Bio03, Bio12, Elev
Set_39	Bio02, Bio03, Bio14, Bio18
Set_40	Bio02, Bio03, Bio14, Elev
Set_41	Bio02, Bio03, Bio18, Elev
Set_42	Bio02, Bio12, Bio14, Bio18
Set_43	Bio02, Bio12, Bio14, Elev
Set_44	Bio02, Bio12, Bio18, Elev
Set_45	Bio02, Bio14, Bio18, Elev
Set_46	Bio03, Bio12, Bio14, Bio18
Set_47	Bio03, Bio12, Bio14, Elev
Set_48	Bio03, Bio12, Bio18, Elev
Set_49	Bio03, Bio14, Bio18, Elev
Set_50	Bio12, Bio14, Bio18, Elev
Set_51	Bio02, Bio03, Bio12, Bio14, Bio18
Set_52	Bio02, Bio03, Bio12, Bio14, Elev
Set_53	Bio02, Bio03, Bio12, Bio18, Elev
Set_54	Bio02, Bio03, Bio14, Bio18, Elev
Set_55	Bio02, Bio12, Bio14, Bio18, Elev
Set_56	Bio03, Bio12, Bio14, Bio18, Elev
Set_57	Bio02, Bio03, Bio12, Bio14, Bio18, Elev

Table S3. Contributions of bioclimatic variables to the MaxEnt model's performance under full Sun management system.

Variable	Percent contribution	Permutation importance
Elev	58.7	73.6
Bio03	41.3	26.4

Table S4. Contributions of bioclimatic variables to the MaxEnt model's performance under Agroforestry system.

Variable	Percent contribution	Permutation importance
Bio12	42.9	10.7
Elev.	23.7	64.9
Bio14	16.9	10.7
Bio18	16.4	13.7

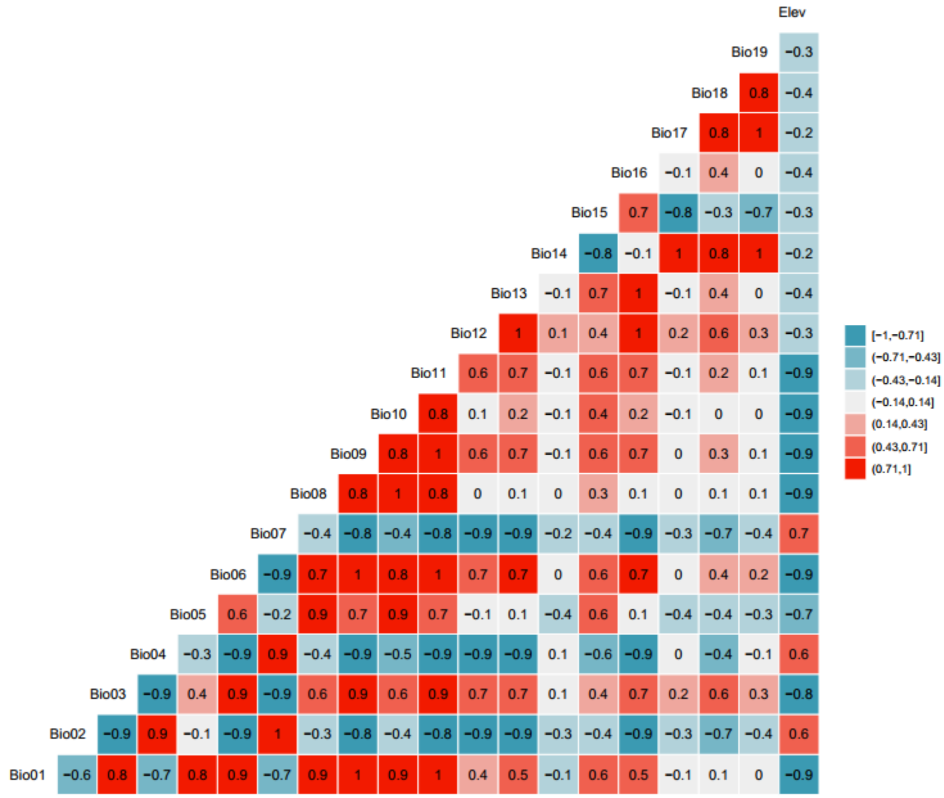

Figure S1. Correlation matrix of environmental predictors considered to build the suitability models of *Coffea arabica* in Mozambique (Bio02, Mean Diurnal Temperature Range; Bio03, Isothermality; Bio12, Annual Precipitation; Bio14, Precipitation of Driest Month; Elev, Elevation).

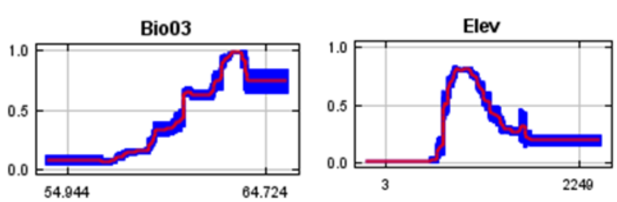

Figure S2. Response curves for important environmental predictors (Bio03 (Isothermality (BIO2/BIO7) (* 100)) and Elev (Elevation)) in MaxEnt model for *C. arabica* under full Sun management system in Mozambique.

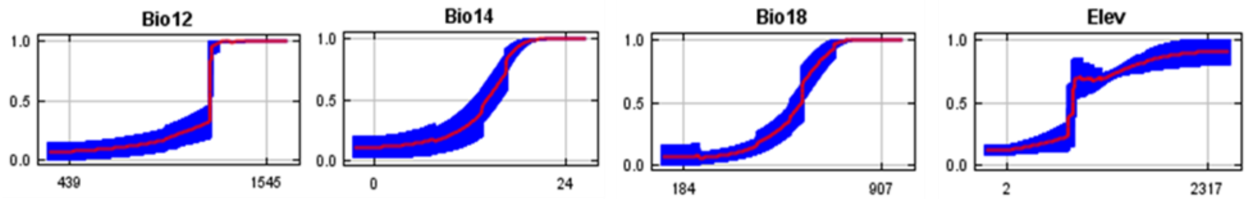

Figure S3. Response curves for important environmental predictors (Bio12 (Annual Precipitation), Bio14 (Precipitation of Driest Month), Bio18 (Precipitation of Warmest Quarter)) in MaxEnt model for *C. arabica* under agroforestry management system in Mozambique.

CHAPTER III

SHADE AND ALTITUDE IMPLICATIONS ON THE PHYSICAL AND CHEMICAL ATTRIBUTES OF GREEN COFFEE BEANS FROM GORONGOSA MOUNTAIN

Abstract

Coffea arabica L. is as a tropical crop that can be grown under monocrop or agroforestry (AFS) systems, usually at altitudes greater than 600 m, with suitable environmental conditions to bean quality. This study aimed to assess the effect of altitude (650, 825, and 935 m) and light conditions (deep shade - DS, and moderate shade - MS provided by native trees, and full Sun - FS) on the physical and chemical attributes of green coffee beans produced in the Gorongosa Mountain. Regardless of altitude, light conditions (mainly MS and FS) barely affected most of the studied physical and chemical attributes. Among the few exceptions in physical attributes, bean mass tended to lower values under FS in all three altitudes, whereas bean density increased under FS at 650 m. As regards the chemical compound contents, sporadic changes were found. The rises in trigonelline (MS and FS at 935 m), glucose and fructose (FS at 935 m), and the decline in *p*-coumaric acid (MS and FS at 825 m), may indicate an improved sensory profile, but the rise in FQAs (FS at 825 m) could have a negative impact. These results highlight a relevant uncertainty of the quality changes of the obtained bean. Altitude (from 650 to 935 m) extended the fruit maturation period by four weeks, and altered a large number of bean attributes. Among physical traits, the average sieve (consistent tendency), bean commercial homogeneity, mass, and density increased at 935 m, whereas the bean became more yellowish and brighter at 825 and 935 m (b*, C* colour attributes), all of which pointing to an increase in bean trade quality, usually as compared with beans from 650 m. Furthermore, at 935 m trigonelline, and 5-CQA (both under MS and FS) increased, whereas FQAs and diCQAs isomers declined (in all light conditions). Altogether, these changes likely contributed to improve the sensory cup quality. Caffeine, *p*-coumaric acid, and soluble sugars showed mostly inconsistent variations. Overall, light conditions (FS, MS, or DS) did not greatly and consistently altered bean physical and chemical attributes, whereas altitude (likely associated with lower temperature, greater water availability (rainfall/fog), and extended maturation period) was a major driver for bean changes and improved quality.

Keywords: Agroforestry system; Altitude; Chlorogenic acids; Coffee; Colour parameters; Full Sun; Green bean; Quality; Shade; Soluble sugars

3.1. Introduction

To date, at least 130 coffee species have been identified (Davis and Rakotonasolo, 2021), although only two have been largely exploited for commercial purposes. These are *Coffea arabica* L., representing approximately 60-65% of global production, and *Coffea canephora* Pierre ex A. Froehner contributing with the remaining 35-40% (Santos et al. 2015; ICO 2020; Campuzano-Duque et al. 2021). Coffee is widely consumed as a beverage and its annual global production is close to 9 million tons (DaMatta et al. 2018; Saud & Salamatullah, 2021), generating an income of *ca*. USD 200.0000 million (ICO 2021). This crop is spread across more than 80 countries from the tropical regions of America, Africa and Asia, supporting the livelihoods of about 25 millions of smallholder farmers (Tolessa et al. 2017; Semedo et al. 2018; DaMatta et al. 2019; Tsegay et al. 2020; Hall et al. 2022) who are estimated to account for *ca*. 60 % of the coffee farms (Koutouleas et al. 2022b). Additionally, the entire value chain of coffee might involve up to 125 million people worldwide (Osorio 2002; Herrmann & Schober 2019). The two main producing coffee species, *C. arabica* and *C. canephora*, with emphasis in the first, have been pointed as highly sensitive to climate changes (CC) and global warming, what could lead, among others, to important losses of suitable cropping areas, decreased bean yield and quality, and greater pest incidence (Magrach & Ghazoul 2015; van der Vossen et al. 2015; Davis et al. 2019). Importantly, such problems can lead to reduction of coffee quality in a context where consumer awareness has increased the demand for better product quality (Mussatto et al. 2011), thus imposing a continuous need of this (and other) crop improvement. Despite such estimated impacts, recent reports have highlighted a greater intrinsic resilience to some abiotic stresses than earlier assumed displayed by some elite cultivars (DaMatta et al. 2018; 2019; Dubberstein et al. 2020). Furthermore, the "C-fertilization" effect, promoted by the rising air [CO_2], can benefit coffee growth and photosynthetic performance regardless of the light availability (Ramalho et al. 2013; DaMatta et al. 2019; Marçal et al. 2021). Additionally, elevated air [CO_2] was found to mitigate the negative impacts of supra-optimal temperatures and drought (Rodrigues et al. 2016; Avila et al. 2020; Semedo et al. 2021), while preserving coffee bean production and quality (Ramalho et al. 2018; Rakocevic et al. 2021). Still, it is expected that CC can have some degree of deleterious impacts in the coffee crop, especially in actual marginal areas/regions. In fact, adverse thermal and water availability are the key environmental factors that limit coffee potential yields (DaMatta & Ramalho 2006). Also, given that water supply *per se* might affect coffee bean quality (Vinecky et al. 2017), it is anticipated that a negative interaction between water supply and temperature may occur under field conditions, which would ultimately exacerbate the impairments on coffee bean quality. This highlights the urgent need to implement mitigation management practices, such as the use of shade with tree species in Agroforestry Systems (AFS), or intercropping associations. These could contribute to a more efficient use of water, to reduce warming at the plant level, and to avoid large drops of night temperatures at high elevations, or at lower latitudes, thus reducing chilling and, eventually, frost damage. Overall, a more suitable microenvironment, concerning both air temperature and humidity, will be obtained for the plants (DaMatta & Ramalho 2006; Oliosi et al. 2016; Dubberstein et al. 2018; Koutouleas et al. 2022b).

Green coffee beans are known to contain, among others, trigonelline, chlorogenic acids (CGAs), and caffeine, which are important quality bean constituents for the coffee industry (Bicho et al. 2013; Naik et al. 2021). CGA isomers are phenolic compounds with quite known antioxidant activity against free radicals and metal ions, and contributing to the final acidity, aroma, flavour, bitterness, and astringency of the coffee beverage (Upadhyay & Rao 2013). This important group of non-volatile compounds in green coffee beans includes the main subgroups of monocaffeoylquinic acids (CQA), feruloylquinic acids (FQA), dicaffeoylquinic acids (diCQA) and, in smaller amounts, *p*-coumaroylquinic acids. Coffee is also a rich source of another major class of phenolic compounds, the hydroxycinnamic acids that include caffeic, ferulic, and *p*-coumaric acids (*p*-CQA) (Farah et al. 2006; Romero-González & Verpoorte 2009; Upadhyay & Rao 2013; Girma et al. 2020).

The coffee bean quality is largely associated with their physical and chemical attributes. In turn, these are closely dependent on the coffee species/genotype, microclimatic (temperature, water availability, irradiance) conditions along the fruit/bean maturation process, soil characteristics, as well as of agricultural crop management practices (*e.g.*, fertilization, irrigation), and post-harvest processing, with prevalent environmental conditions during fruit development playing a crucial role in the final bean quality (DaMatta et al. 2006; Carelli et al. 2006; Vaast et al. 2006; Joët et al. 2010a; Barbosa et al. 2012; Bertrand et al. 2012; Cheng et al. 2016; Ramalho et al. 2018). Among the environmental conditions, those related with shade and altitude are often pointed to have beneficial effects on coffee bean quality, and might be key factors to produce specialty or high-quality coffee in the future. Furthermore, the reduction of irradiance at leaf level caused by shade greatly depends on the density and species of the shading trees. Higher altitudes and shade at lower altitudes might improve the physical and chemical traits of beans, associated with lower temperatures and higher air humidity (Decazy et al. 2003; Joët et al. 2010b; Bertrand et al. 2012; Oliosi et al. 2016; Paudel et al. 2021). Such cooler weather conditions can prolong the coffee fruit/and bean maturation period, promoting greater accumulation of sugar and aroma-related phenolic compounds (Vaast et al. 2006; Tolessa et al. 2017).

Although AFS practices have been proposed as a nature-based strategy for coffee farmers to mitigate and adapt to future climate conditions (Koutouleas et al. 2022b), there are somewhat contradictory reports regarding the potential benefits of shade on coffee productivity and quality. In fact, shade was reported to reduce (Chen et al. 2019), increase (Bote & Struik, 2011), or unaffect (Ehrenbergerová et al. 2021) coffee yields. Also, shade can alter green bean size and biochemical compounds (Vaast et al. 2006). However that was found to have negative influence on sensory attributes (Bosselmann et al. 2009), or to improve bean quality (Bote & Struik, 2011). Finally, other studies point that irradiance/shade by itself seems to have little effect on organoleptic bean quality if nitrogen is not limiting to the plant, revealing that crop management practices can be a greater determinant factor to quality than the genetic factors (Bote & Vos 2017). Much of these apparently contradicting findings generate controversy about the use of AFS, due to the possibility of negative impacts on coffee growth, yield, and the potential to exacerbate biotic stressors (Bosselmann et al. 2009), what is also greatly dependent on local environment, shade level/density type of shading trees, and other crop management practices (Koutouleas et al. 2022b).

The effect of altitude on the chemical composition of coffee beans, disease incidence, etc., is also in some aspects divergent. For instance, altitude positively influenced the physical attributes of the bean (Bosselmann et al. 2009), and with higher yield, better quality and fewer defects were reported (Paudel et al. 2021). However, lower contents of phenolic compounds associated with aroma and bitterness were reported with increased altitude (Worku et al. 2018), while others studies pointed to opposite findings (Avelino et al. 2005). Also, high chlorogenic acids contents (CGA) have been associated with either low (Farah & Donangelo 2006) or high (Yeager et al. 2021) quality coffee. This uncertainty is further exacerbated by the fact that altitude has been studied alone without no great impact (Worku et al. 2018), or increasing (Avelino et al. 2005) bean acidity, or together with AFS with results pointing to greater cup acidity at greater altitude (Worku et al. 2018).

Finally, most of the apparent contradictory findings would result from the fact that studies used distinct *C. arabica* cultivars that intrinsically respond differently to shade/altitude, from yield to quality aspects (Koutouleas et al. 2022a,b), and other management conditions that can strongly determine the final outcome (Bote & Vos 2017).

In our case, in addition to the previously mentioned advantages of AFS, the use of this strategy to produce coffee in the Gorongosa Mountain, greatly contributes to the restoration of the degraded rainforest, and its associated biodiversity within the Gorongosa National Park (GNP), while contributes to increase the income and livelihoods of the local farming communities. Located in the center of Mozambique, GNP is one of the most biodiverse places worldwide, with an outstanding history of wildlife restoration. The Coffee-AFS system with native trees is being implemented in degraded rainforest landscape, above of 700 m (protected area of GNP), but it is essential to find a combination of adequate light condition (shade density under AFS) and/or altitude that provide greater productivity and better bean quality. In this context, the present work aims at to evaluate the impacts of altitude and/or light irradiance on the physical and chemical attributes of green coffee.

3.2. Materials and Methods

3.2.1. Experimental design

Four year-old coffee plants (*Coffea arabica* cv. Costa Rica 95, from Catimor group) cropped at the Gorongosa Mountain, part of the Gorongosa National Park, Mozambique (Lat. 18º14' and 18º42' South and Long. 33º50' and 33º13' East), were used to study the impact of light conditions and altitude on the bean physical and chemical parameters associated with quality. The plants were implanted 1.5 m apart within the row and 3 m between rows, for an approximate density of *ca*. 2222 plants ha^{-1}, similarly to all light treatments.

For each of the light and altitude treatments.

To assess the impact of altitude and light conditions on bean traits, five plants were randomly selected across the crop area for each treatment. For altitude it was considered three levels: 650 (18° 30' 53"S, 34° 3' 5"E), 825 (18° 30' 4"S, 34° 2' 58"E), and 935 m above sea level (a.s.l.) (18° 28' 54"S, 34° 2' 43"E). Within each of the three altitudes, the irradiance studies comprised deep shade (DS), moderate shade (MS), and full Sun (FS). These conditions corresponded to an average diurnal PPFD of 127 ± 28 μmol m^{-2} s^{-1} (DS), and 725 ± 48 μmol m^{-2} s^{-1} (MS), and 1268 ± 52 μmol m^{-2} s^{-1} (FS), thus with the PPFD of DS and MS representing *ca*. 10% and 57% of that observed in FS. These values represent the average of six months (April, May, June, July and September) of 2020 and were obtained through measurements of PPFD four times along daytime (9-10 h; 11-12 h; 13-14 h; 15-16 h) using the light sensor from an infrared gas analyzer (IRGA) system, model LI-6400 (LI-COR Biosciences, Lincoln, NE, USA).

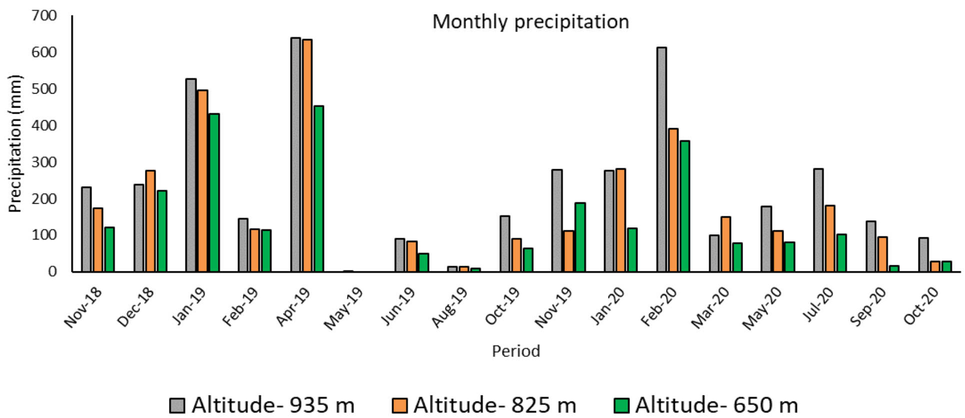

Figure III 1 - Monthly precipitation rainfall at three altitudes (935 m, 825 m, 650 m) in the experimental area of Gorongosa Mountain.

Shade was provided by native forest trees, namely *Khaya anthotheca* (Welw.) C. DC., Erythrina *lysistemon* Hutch., *Albizia adianthifolia* (Schumach.) W. Wight., *Bridelia micrantha* (Hochst.) Baill., *Annona senegalensis* Pers., and *Bridelia micrantha* (Hochst.) Baill, exposing the underneath coffee plants to the mentioned irradiation values.

As the system was rainfed, the water availability was obtained by monitoring precipitation through pluviometers installed in the three altitudes (Fig. 1).

Air temperature values were obtained with Temperature External Data Logger devices (ONSET, Pro v2 Logger U23-00x), installed in each of the three altitudes and three light conditions (Fig. 2).

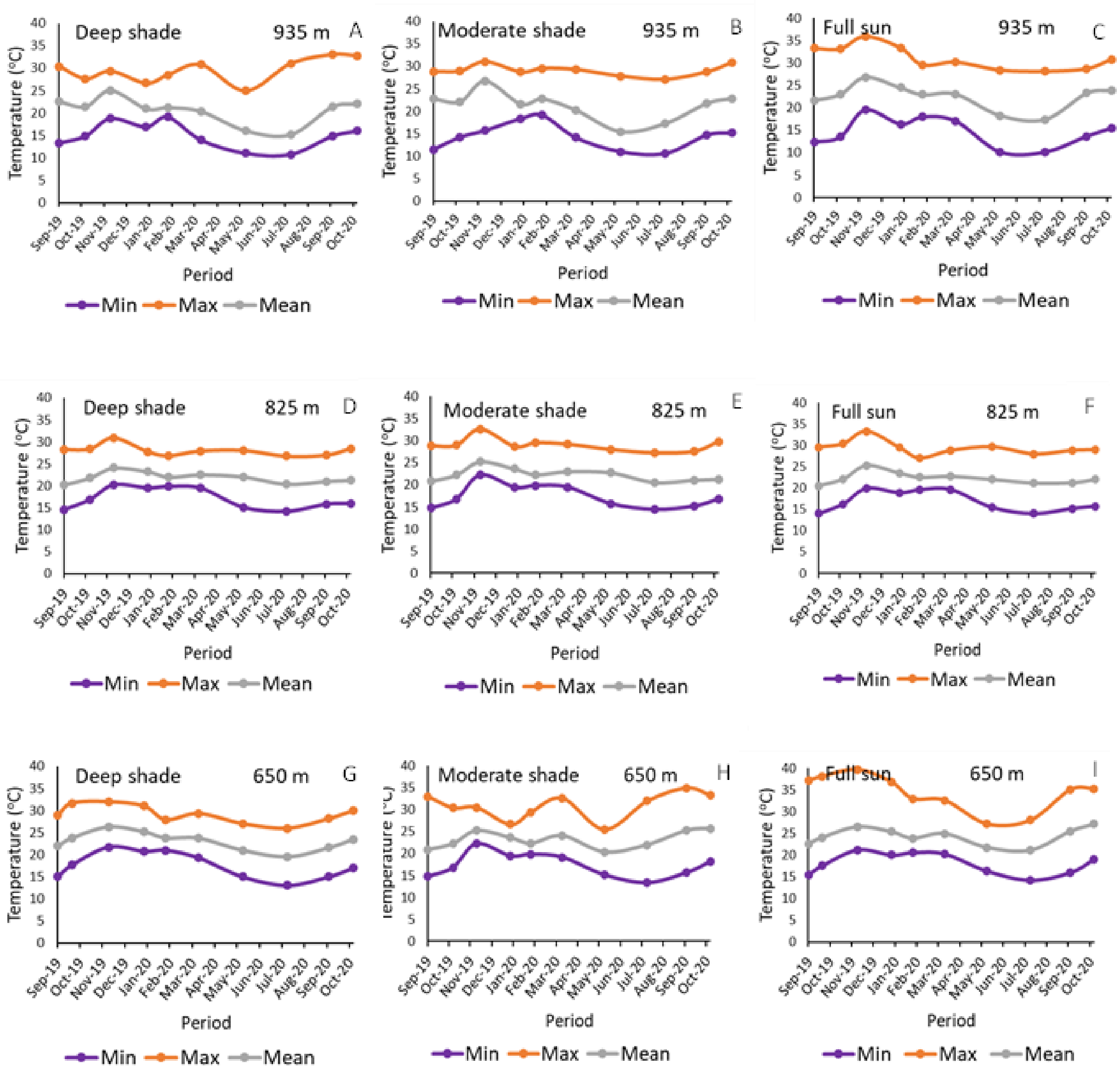

Figure III 2 - Maximum, mean and minimum air temperature measured, under three light exposure conditions (deep shade, moderate shade and full Sun) and three altitudes (650 m, 825 m and 935 m) in the experimental area of Gorongosa Mountain.

3.2.2. Fruit post-harvest processing

At full maturation stage (red cherries), approximately 1 kg of fruits were harvested from each of the five plants in each treatment (three altitudes and three light conditions). After manual fruit depulping, the obtained coffee beans were placed in water for 24 h for slight fermentation and mucilage removal. Seeds were then sundried until a moisture content of *ca*. 11-12% was reached, as evaluated by a moisture meter (TG Pro, Coffee and Cocoa, Draminski, Poland). Finally, the parchment was removed, and the few defective coffee beans (broken, atypical colour and/or form) were discarded in each sample according to ISO (2005), before physical and chemical analyses.

3.2.3. Physical attributes of green coffee beans

Coffee beans with a moisture of *ca*. 11-12% were used for this analysis.

3.2.3.1. Bean mass of 100 beans, apparent density and size

Samples of 100 beans per plant were taken and weighed to obtain their mass (Esteves & Oliveira, 1970; Bicho et al., 2014).

The apparent density was determined as the ratio between the weight and the volume occupied by the coffee beans (Esteves & Oliveira, 1970; NP 2285, 1991; Bicho et al., 2014).

Bean size was assessed based on ISO 4150 (2011), using different sieves with gradual decreasing diameter: number 20 (8.00 ± 0.19 mm), 19 (7.50 ± 0.18 mm), 18 (7.10 ± 0.18 mm), 17 (6.70 ± 0.17 mm), 16 (6.30 ± 0.17 mm), 15 (6.00 ± 0.16 mm), 14 (5.60 ± 0.16 mm), 13 (5.00 ± 0.15 mm), 12 (4.75 ± 0.14 mm), and 10 (4.00 ± 0.13) (Kath et al., 2021). Samples of 100 g of each plant were weighted in portion retained per sieves, and the weight retained in each sieve were converted to percentage of 100 g of bean.

The commercial homogeneity was evaluated by the sum of the percentages from the two most represented sieves.

3.2.3.2. Colour analysis

Determination of colour attributes of ground coffee bean globally followed the procedures previously reported (Bicho et al., 2014; Ramalho et al., 2018). Briefly, colour parameters, lightness (L), and chromaticity (coordinates a * and b *) were obtained with a Minolta CR 400 colourimeter (Minolta Corp., Ramsey, NJ, United States) coupled with a glass container for solid samples (CR-A504). Measurements were performed for illuminant D65 based on Commission Internationale de l'Éclairage (CIE) L *a *b * system. The colourimeter was first calibrated to white Yxy coordinates (Y = 93.10, x = 0.3161, y = 0.3326). L * measures the lightness of a colour and ranges from black (0) to white (100); a * indicates the contribution of red or green (when its value is positive or negative, respectively); and b * the contribution of blue or yellow (when its value is negative or positive, respectively). The elements of perceived colour lightness (L *), Hue angle (H◦), chroma (C, saturation), and CI were determinate from the L *a *b * coordinates. Calculation of H◦ (= (arctg (b * /a *)), in degrees, sets the kind of colour (starting at red, 0 º, yellow, up to 90 º, green, up to 180 º, and blue, up to 270 º). C* (= (a $*^2$+b $*^2$) $^{1/2}$) is a measure of colour saturation or purity, were calculated following (Silveira et al. 2007), whereas CI (= (1000a *)/ (L *b *)) (Sdiri et al., 2017) ranges between −20 (green) and +20 (orange) with 0 representing yellow.

3.2.4. Chemical characterization of green coffee beans

To express the data in dry weight, the moisture content of the coffee bean samples was determined according to AOAC (1995) procedures (Geromel et al., 2008). For each plant, 100 green coffee beans were selected, weighed, and dried in an oven at 105 ºC for 24 h. After cooling in a room temperature (*ca*. 20 ºC), the samples were weighed and the percentage of moisture was calculated.

3.2.4.1. Chlorogenic acids, *p*-coumaric acid, caffeine, trigonelline

For chemical analysis, green beans were grounded (< 500 µm size), using a grinder (Pulverisette 14, Fritsch, Germany), vacuum packed, and stored at 4 ºC until analysis.

Monocaffeoylquinic acids (3-CQA, 4-CQA, 5-CQA), and *p*-coumaric acid, as well as trigonelline and caffeine were analyzed based on Alves et al. (2006). In detail, an aliquot of 500 mg ground beans from each sample/plant was extracted with 30 mL of acetonitrile/water (5:95, v/v) for 10 min, at 80 ºC, and filtered through Whatman Paper No. 1. A 5 mL aliquot was then diluted to a total volume of 25 mL with the same acetonitrile/water extracting solution, and filtered (nylon, 0.45 µm). A 20 µL aliquot was then injected into an HPLC Beckman System Gold (USA) equipped with a DAD (model 168), and a solvent module (model 126).

For separation a reversed-phase HPLC analysis was performed using an end-capped, C18, 5 µm Spherisorb ODS2 column (250 x 4.6 mm) (Waters, USA), and a mixture of acetic acid/water (5:95, v/v) as eluent A, and acetonitrile as eluent B, at a flow rate of 1 mL min^{-1}, at *ca*. 25 ºC. A gradient program was used: 5% B during 5 min; from 5 to 13% B during 5 min; 13% B during 35 min, and returned to initial conditions after 1 min. The trigonelline and caffeine compounds detection was performed at $Abs_{272\ nm}$, whereas for *p*-coumaric, 3-CQA, 4-CQA, and 5-CQA acids the $Abs_{320\ nm}$ was used.

Additionally, the chlorogenic acids 3-FQA, 4-FQA, 5-FQA, 3,4-diCQA, 3,5-diCQA and 4,5-

diCQA were analysed as previously described (Bicho et al., 2012; 2013). Samples of 1 g of ground green bean per plant were added to 40 mL of a methanol-water (40:60) solution, stirred for 1 h, and centrifuged (9400 *g*, 5 min, 20 ºC), and the supernatant decanted. For samples clearing were added 1 mL of Carrez solution I (aqueous solution of zinc acetate dihydrate and glacial acetic acid, 10.95 g and 1.5 mL, respectively, to a final volume of 50 mL), 1 mL of Carrez solution II (aqueous solution of 5.3 g of potassium hexacyanoferrate II trihydrate in a final volume of 50 mL), and a methanol-water (40:60, v/v) solution to obtain the final volume of 100 mL. After 15 min, the mixture was filtered using the Whatman paper filter nº 1, and an aliquot of 10 mL was filtered (nylon, 0.45 µm). The samples were then analysed using the same HPLC system and column used for chlorogenic acids. The elution of a 20 µL injection was performed at *ca*. 25 ºC, over 45 min, with a 1 mL min^{-1} flow rate, using an optimized linear gradient 20-70% of B (solvent A tripotassium citrate buffer solution 10 mM, pH 2.5; solvent B methanol 100%). Detection of 4-FQA, 5-FQA, 3,4-diCQA, 3,5-diCQA, and 4,5-diCQA were performed at $Abs_{330\ nm}$. The identification and quantification of all CQAs and FQAs were carried out using 5-CQA as a standard, following the equation proposed by Trugo and Macrae (1984), whereas standard curves were used for caffeine, trigonelline and *p*-coumaric acid as previously described (Ramalho et al., 2018).

3.2.4.2. Soluble sugars

Soluble sugars were evaluated in *ca*. 400 mg of ground green coffee beans, after extraction according to Medlicott and Thompson (1985), following Lidon et al. (2018). Briefly, sample aliquots of 40 µL were injected in a HPLC system (Waters, USA), coupled to a refractometric detector (Waters 2414), and the separation of sugars was performed using a Sugar-Pak 1 column (300 x 6.5 mm; Waters) at 90 ºC, with H_2O as eluent (containing 50 mg EDTA-Ca L^{-1} H_2O) and a flow rate of 0.5 mL min^{-1}. Sugars were identified and quantified, using the individual standard curves for sucrose, glucose fructose and arabinose.

3.2.5. Statistical analysis

Coffee bean physical and chemical parameters data were analysed using a two-way ANOVA, considering the effects altitude and/or light conditions, followed by a Tukey's HSD test for mean comparison using the software R studio v3.1. A 95% confidence level was adopted for all tests.

3.3. Results

3.3.1. Physical characterization of green coffee beans

The physical attributes of green coffee beans harvested in Gorongosa Mountain were slightly modified by the altitude and shading. Increasing altitude favoured a decrease in temperature and an increase in water availability (greater rainfall, together with frequent fog persistence) (Figs. 1 and 2), enabling just a few changes in granulometry, mass and apparent density of green beans.

Most of green coffee beans, regardless of altitude or shade density and full Sun, presented granulometry around 6.70 m, which corresponds to sieve number 17 (Fig. 3). However, the beans obtained in plants at 935 m of altitude tended to have a greater presence in the sieves 18, 19 and 20, thus showing somewhat larger sizes as compared to those obtained at 650 m and 825 m. On the other hand, a considerable % of beans were found in sieve 17 for 825 m, whereas at 650 m that happened in sieve 16, with some beans found even below sieve 12, thus reflecting a higher proportion of smaller beans at the lowest elevation.

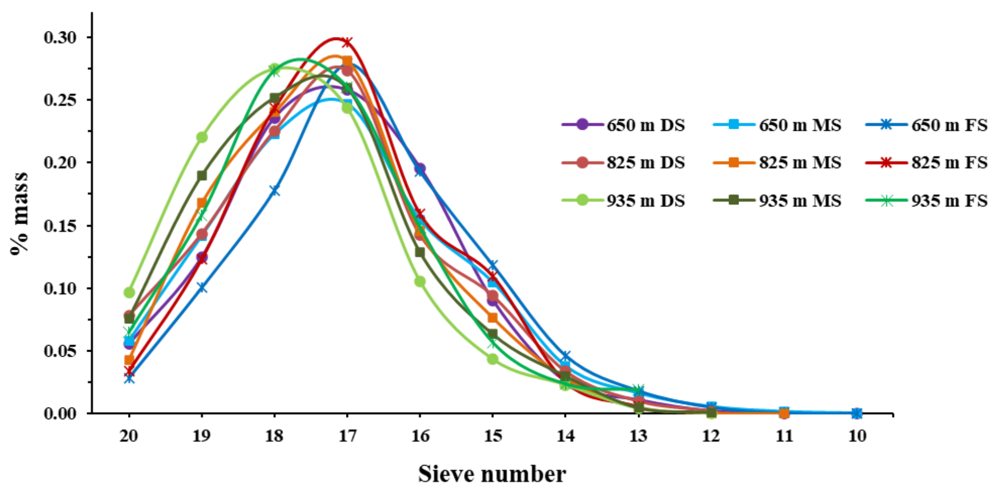

Figure III 3 -Distribution of green coffee beans according to their size, obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS) and three altitudes (650 m, 825 m and 935 m).

These finding were partly in line with the consistent tendency to greater values of the commercial homogeneity (given by the maximum sum of the percentages of the two most representative sieves) at 935 m and 825 m, whereas the beans from 650 m exhibit values always below 50% (Table 1). Notably, light conditions promoted only minor (if any) changes in commercial homogeneity at 650 m under MS and FS, that is, under harsher environmental conditions of lower water availability (Fig. 1), together with higher temperature (Fig. 2).

Table III 1 - Variation of the most frequent sieve, average sieve and commercial homogeneity for green coffee beans obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS), and three altitudes (650 m, 825 m and 935 m).

Attributes	Light condition	Altitude		
		650 m	825 m	935 m
Frequent sieve	DS	17.0 ± 0.3 Aa	17.0 ± 0.5 Aa	18.0 ± 0.3 Aa
	MS	17.0 ± 0.3 Aa	17.0± 0.3 Aa	17.0 ± 0.4 Aa
	FS	17.0 ± 0.2 Aa	17.0 ± 0.2 Aa	18.0 ± 0.3 Aa
Average sieve	DS	17.1 ± 0.0 Aa	17.1 ± 0.0 Aa	17.9 ± 0.0 Aa
	MS	16.9 ± 0.0 Aa	17.3 ± 0.0 Aa	17.6 ± 0.0 Aa
	FS	16.2 ± 0.0 Aa	17.1 ± 0.0Aa	17.5 ± 0.0 Aa
Commercial homogeneity	DS	0.49 ± 0.02 Aa	0.52 ± 0.02 Aa	0.52 ± 0.01 Aa
	MS	0.46 ± 0.02 Ab	0.54 ± 0.01 Aa	0.51 ± 0.02 Aa
	FS	0.45 ± 0.01 Ab	0.54 ± 0.01 Aa	0.53 ± 0.02 Aa

*Mean values ± SE (n = 5) followed by the same letter, comparing light conditions within each altitude (A, B, C) or altitude treatments within each light condition (a, b, c), are not significantly different according to the Tukey's HSD for mean comparison ($p < 0.05$), always separately for each attribute.

The mass of 100 coffee beans and apparent density showed maximal values always at the greater altitude, as compared with 650 and/or 825 m (Table 2). Also, bean mass showed a tendency to lower values under FS in all altitudes (significantly only at 935 m), whereas apparent density showed significant differences among light conditions only at 650 m, with greater values under FS.

Table III 2 - Mass of 100 green coffee beans and apparent density (g cm^{-3}) of green coffee beans obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS) and three altitudes (650 m, 825 m and 935 m).

Attributes	Light condition	Altitude		
		650 m	825 m	935 m
Mass of 100 beans (g)	DS	16.0 ± 0.5 Aab	14.3 ± 0.2 Ab	17.2 ± 0.4 ABa
	MS	15.1 ± 0.2 Ab	14.5 ± 0.2 Ab	18.5 ± 0.7 Aa
	FS	14.3 ± 0.4 Ab	13.2 ± 0.2 Ab	16.0 ± 0.5 Ba
Apparent density (g cm^{-3})	DS	0.62 ± 0.02 ABb	0.65 ± 0.02 Aab	0.69 ± 0.00 Aa
	MS	0.61 ± 0.02 Bb	0.67 ± 0.01 Aa	0.69 ± 0.01 Aa
	FS	0.67 ± 0.01 Aab	0.62 ± 0.01 Ab	0.69 ± 0.00 Aa

*Mean values ± SE (n = 5) followed by the same letter, comparing light conditions within each altitude (A, B, C) or altitude treatments within each light condition (a, b, c), are not significantly different according to the Tukey's HSD for mean comparison ($p < 0.05$), always separately for each attribute.

Table III 3 - Colour analysis considering colour lightness (L*), a*, b*, Chroma (C*), Hue angle (Hº), and colour index (CI) attributes of grounded green coffee beans from *C. arabica* obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS) and three altitudes (650 m, 825 m and 935 m) in Gorongosa Mountain.

Attribute	Light condition	Altitude		
		650 m	825 m	935 m
L*	DS	87.7 ± 0.2 Aa	87.7 ± 0.4 Aa	88.6 ± 0.3 Aa
	MS	87.7 ± 0.3 Aa	88.2 ± 0.2 Aa	88.6 ± 0.6 Aa
	FS	87.7 ± 0.2 Aa	87.5 ± 0.1 Aa	88.3 ± 0.2 Aa
a*	DS	-3.05 ± 0.06 Aa	-3.05 ± 0.06 Aa	-3.07 ± 0.04 Aa
	MS	-2.97 ± 0.10 Aa	-3.16 ± 0.04 Aa	-2.99 ± 0.08 Aa
	FS	-3.02 ± 0.06 Aa	-2.92 ± 0.04 Aa	-3.01 ± 0.06 Aa
b*	DS	17.2 ± 0.22 Aa	16.3 ± 0.1 Ab	16.2 ± 0.1 Ab
	MS	17.3 ± 0.19 Aa	16.3 ± 0.2 Ab	16.2 ± 0.2 Ab
	FS	17.4 ± 0.26 Aa	16.4 ± 0.2 Ab	16.3 ± 0.1 Ab
C*	DS	17.7 ± 0.2 Aa	16.6 ± 0.1 Ab	16.4 ± 0.1 Ab
	MS	17.5 ± 0.2 Aa	16.6 ± 0.2 Ab	16.5 ± 0.3 Ab
	FS	17.7 ± 0.3 Aa	16.7 ± 0.2 Ab	16.6 ± 0.1 Ab
Hº	DS	99.9 ± 0.2 Ab	101 ± 0 Aa	100 ± 0 Aab
	MS	99.7 ± 0.4 Aa	101 ± 0 Aa	100 ± 0 Aa
	FS	99.8 ± 0.2 Aa	100 ± 0 Aa	100 ± 0 Aa
CI	DS	-1.99 ± 0.04 Ab	-2.20 ± 0.04 Aa	-2.14 ± 0.02 Aa
	MS	-1.96 ± 0.07 Aa	-2.20 ± 0.04 Aa	-2.08 ± 0.03 Aa
	FS	-1.98 ± 0.05 Aa	-2.03 ± 0.03 Aa	-2.09 ± 0.04 Aa

*Mean values ± SE (n = 5) followed by the same letter, comparing light conditions within each altitude (A, B, C) or altitude treatments within each light condition (a, b, c), are not significantly different according to the Tukey's HSD for mean comparison ($p < 0.05$), always separately for each attribute.

Colour attributes of green beans showed some changes among the altitudes, but were never modified by the light condition, irrespective of the altitude (Table 3). The negative a* values (denoting the strong contribution of the green colour in the bean), and the L* (lightness close to white), were not modified neither by altitude nor by light condition. The positive b* values (reflecting a greater yellow contribution), and C* (measuring light saturation), showed the same pattern of variation, being reduced in the two highest altitudes for all light conditions, as compared with 650 m. In agreement with the yellow colour depicted by b*, both the Hue angle (Hº) and colour index (CI) values point to a yellow (/greenish) colour in all treatments, with a slightly greater yellow component only in DS at 650 m as compared to the other two altitudes.

3.3.2. Chemical coffee green bean characterization

Several changes related with altitude and/or light condition were observed in the several studied compounds associated with bean quality, phenolic acids (CQAs, diCQAs, FQAs, *p*-coumaric acid), and nonphenolic compounds (caffeine, trigonelline, sugars) (Table 4).

Trigonelline content showed one of the most striking responses, since it was markedly modified at the highest altitudes, under MS and FS conditions, showing 126% and 170% increases, respectively, as compared to their respective treatments at 650 m. Furthermore, such increased MS and FS values were also significantly higher than that under DS at 935 m. Notably, no differences were observed between light conditions at 650 and 825 m.

Caffeine and *p*-coumaric acid contents showed mostly small, non-significant, changes, although a reduction of the latter compound was observed under MS and FS at the intermediate elevation.

The contents of the mono CQA isomers, 3-CQA and 4-CQA, showed only minor changes under the studied conditions, with just a minor tendency to lower values at 935 m, and without implications of light conditions in any of the altitudes (Table 4). On the other hand, the most representative CQA (5-CQA) presented consistent tendencies to increase with altitude in all light treatments (but without any difference between light conditions). Maximal values of 5-CQA (as well as of Total CQA) were found under FS at 825 m and MS at 935 m (significantly for the last, as compared to the lowest altitude). Overall, these mono CQA changes modified the proportion of individual CQAs in Total mono CQA content, which in 5-CQA gradually increased from *ca*. 79% to 83% and to 85%, at 650, 825 and 935 m, respectively. Similar values were obtained for all light conditions within each altitude.

Table III 4 - Characterization of chemical composition, regarding the contents of trigonelline, caffeine, p-coumaric acid, monocaffeoylquinic acids (CQAs), feruloylquinic acids (FQA), and dicaffeoylquinic acids (diCQA) in green coffee beans from C. arabica obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS) and three altitudes (650 m, 825 m and 935 m) in Gorongosa Mountain.

Atributtes	Light condition	Altitude		
		650 m	825 m	935 m
Trigonelline ($mg\ g^{-1}$ DW)	DS	11.1 ± 0. 3 Aa	10.4 ± 0.3 Aa	9.37 ± 1.01 Ba
	MS	11.4 ± 0.6 Ab	9.91 ± 0.8 Ab	25.8 ± 0.2 Aa
	FS	11.9 ± 0.5 Ab	9.63 ± 0.6 Ab	32.1 ± 1.4 Aa
p-coumaric acid ($mg\ g^{-1}$ DW)	DS	0.41 ± 0.01 Aa	0.57 ± 0.01 Aa	0.43 ± 0.07 Aa
	MS	0.43 ± 0.01 Aa	0.30 ± 0.03 Ba	0.42 ± 0.04 Aa
	FS	0.41 ± 0.01Aa	0.42 ± 0.04 Ba	0.33 ± 0.04 Aa
Caffeine ($mg\ g^{-1}$ DW)	DS	16.2 ± 0.2 Aa	13.8 ± 0.4 Aa	14.7 ± 0.5 Aa
	MS	15.9 ± 0.2 Aa	14.2 ± 0.2 Aa	15.1 ± 0.3 Aa
	FS	15.2 ± 0.4 Aa	13.6 ± 0.3 Aa	14.8 ± 0.2 Aa
3-CQA ($mg\ g^{-1}$ DW)	DS	2.42 ± 0.13 Aa	2.52 ± 0.26 Aa	1.92±0.18 Aa
	MS	2.41 ± 0.09 Aa	2.24 ± 0.19 Aa	2.35±0.07 Aa
	FS	2.50 ± 0.05 Aa	2.62 ± 0.07 Aa	2.17±0.12 Aa
4-CQA ($mg\ g^{-1}$ DW)	DS	3.32 ± 0.09 Aab	3.61 ± 0.11 Aa	2.67±0.31Ab
	MS	3.51 ± 0.15 Aa	3.24 ± 0.10 Aa	3.34±0.11 Aa
	FS	3.60 ± 0.19 Aa	3.60 ± 0.24 Aa	3.08±0.14 Aa
5-CQA ($mg\ g^{-1}$ DW)	DS	21.6 ± 0.6 Aa	28.2 ± 1.2 Aa	25.8± 0.8 Aa
	MS	21.8 ± 1.3 Ab	25.9 ± 0.9 Aab	32.0 ± 0.8 Aa
	FS	24.9 ± 2.3 Aa	30.0 ± 1.9 Aa	28.4 ± 0.9 Aa
Total CQAs ($mg\ g^{-1}$ DW)	DS	27.4 ± 0.5Aa	34.3 ± 1.4 Aa	30.4 ± 3.3 Aa
	MS	27.7 ± 1.4 Ab	31.3 ± 1.1 Aab	37.7 ± 1.0 Aa
	FS	31.1 ± 2.7 Aa	36.2 ± 2.3 Aa	33.7 ± 1.2 Aa
4-FQA ($mg\ g^{-1}$ DW)	DS	0.32 ± 0.04 Aa	0.16 ± 0.01 Bb	0.16 ± 0.04 Ab
	MS	0.31 ± 0.02 Aa	0.18 ± 0.02 ABb	0.18 ± 0.01 Ab
	FS	0.25 ± 0.02 Aa	0.23 ± 0.02 Aa	0.17 ± 0.01 Aa
5-FQA ($mg\ g^{-1}$ DW)	DS	2.79 ± 0.16 Aa	1.84 ± 0.07 Bb	1.79 ± 0.29 Ab
	MS	2.82 ± 0.09 Aa	2.13 ± 0.21 ABb	2.16 ± 0.14 Ab
	FS	2.55 ± 0.14 Aab	3.14 ± 0.20 Aa	2.11 ± 0.14 Ab
3,4-diCQA ($mg\ g^{-1}$ DW)	DS	0.98 ± 0.08 Aa	0.65 ± 0.03 Aab	0.34 ± 0.11 Ab
	MS	1.17 ± 0.10 Aa	0.44 ± 0.15 Ab	0.54 ± 0.03 Ab
	FS	1.02 ± 0.09 Aa	0.56 ± 0.03 Ab	0.60 ± 0.03 Ab
3,5-diCQA ($mg\ g^{-1}$ DW)	DS	3.03 ± 0.10 Aa	2.04 ± 0.08 Aab	1.26 ± 0.42 Ab
	MS	3.42 ± 0.28 Aa	1.49 ± 0.15 Ab	1.83 ± 0.55 Ab
	FS	2.90 ± 0.29 Aa	1.76 ± 0.47 Aa	1.69 ± 0.07Aa
4,5-diCQA ($mg\ g^{-1}$ DW)	DS	0.80 ± 0.06 Aa	0.48 ± 0.04 Aab	0.37 ± 0.11 Ab
	MS	1.08 ± 0.10 Aa	0.23 ± 0.03 Ab	0.53 ± 0.04 Ab
	FS	0.82 ± 0.07 Aa	0.40 ± 0.10 Ab	0.45 ± 0.11 Aab

*Mean values ± SE (n = 5) followed by the same letter comparing light conditions within each altitude (A, B) or altitude treatments within each light condition (a, b) are not significantly different according to the Tukey's HSD for mean comparison ($p < 0.05$), always separately for each attribute.

Table III 5 - Mean values for soluble sugars of green coffee beans from C. arabica obtained under three light exposure conditions (deep shade, DS; moderate shade, MS; full Sun, FS) and three altitude (650 m, 825 m and 935 m). in Gorongosa Mountain.

Attributes	Light condition	Altitude		
		650 m	825 m	935 m
Sucrose ($mg\ g^{-1}$ DW)	DS	44.3 ± 0.48Aa	43.3 ± 2.10ABa	43.1 ± 0.53 Aa
	MS	44.6 ± 1.76Aa	40.7 ± 1.31Ba	42.9 ± 0.84 Aa
	FS	42.9 ± 0.74Aa	46.2 ± 0.76Aa	44.7 ± 0.65 Aa
Glucose ($mg\ g^{-1}$ DW)	DS	1.77 ± 0.21 Aa	1.22 ± 0.07 Aa	0.66 ± 0.05 Bb
	MS	1.74 ± 0.12 Aa	1.25 ± 0.09 Ab	0.84 ± 0.06 ABc
	FS	1.28 ± 0.05 Ba	0.88 ± 0.10 Ab	1.05 ± 0.12 Aab
Fructose ($mg\ g^{-1}$ DW)	DS	0.65 ± 0.05 Aa	0.96 ± 0.1 Aa	0.51 ± 0.06 Ba
	MS	0.64 ± 0.03 Aa	0.76 ± 0.09 Aa	0.76 ± 0.17 Ba
	FS	0.71 ± 0.03 Ab	0.69 ± 0.08 Ab	1.22 ± 0.22 Aa
Arabinose ($mg\ g^{-1}$ DW)	DS	0.96 ± 0.09 Aa	0.92 ± 0.09 Aa	0.92 ± 0.02 Aa
	MS	1.07 ± 0.15 Aa	0.93 ± 0.10 Aa	0.93 ± 0.12 Aa
	FS	0.98 ± 0.05 Aa	0.70 ± 0.08 Aa	1.00 ± 0.07 Aa
Total sugars ($mg\ g^{-1}$ DW)	DS	47.7 ± 0.8 Aa	46.4 ± 2.05 ABa	45.2 ± 0.50 Aa
	MS	48.1 ± 1.7 Aa	43.6 ± 1.13 Bb	45.4 ± 0.88 Aab
	FS	45.9 ± 0.7 Aa	48.4 ± 0.80 Aa	48.0 ± 0.51 Aa

*Mean values ± SE (n = 5) followed by the same letter comparing light conditions within each altitude (A, B) or altitude treatments within each light condition (a, b) are not significantly different according to the Tukey's HSD for mean comparison ($p < 0.05$), always separately for each attribute.

The values of FQAs were mostly responsive to altitude (Table 4), with 4-FQA and 5-FQA being reduced at 935 m in comparison with 650 m. Moreover, at 825 m both FQA isomers increased from DS to FS.

As regards the diCQAs, despite some content fluctuations, light conditions did not promote any significant change, regardless of altitude. In sharp contrast, the green bean content of all diCQA isomers (3,4-diCQA, 3,5-diCQA, 4,5-diCQA) greatly declined at the two higher altitudes, frequently to values below half at 935 m, as compared with those found at 650 m.

Soluble sugars did not reveal consistent changes among altitudes and light conditions in the coffee beans (Table 5). Still, under FS sucrose showed greater values at 825 and 935 m (significant for the first). In fact, at 935 m all sugars tended to greater contents under FS. In contrast, FS plants showed a consistent tendency to lower values of sucrose, glucose and total sugars at 650 m. Noteworthy is also the fact that sucrose represented the large majority of soluble sugars, between 92 and 95% of their total content.

3.4. Discussion

Coffea arabica is a widely known tropical crop, which can be grown under monocrop or under agroforestry (AFS), and intercropped systems, at altitudes between 600 and 2500 m (Ovalle-Rivera et al., 2015; Ahmed et al., 2021). There are still some controversies regarding the potential positive impact on bean quality traits promoted by higher altitude and/or shading, both of which presumably associated with lower air temperature and longer fruit maturation periods. In a quite recent and comprehensive review it was shown that some authors pointed to lower yields and unaffected quality, while other suggested that AFS could improve bean quality traits (Koutouleas et al., 2022). Such quality enhancement was associated with altered bean chemical composition, namely of CGAs that are naturally occurring bioactive compounds that accumulate in the bean as the coffee fruit matures (Bertrand et al., 2003; Oestreich-Janzen, 2013; Yeager et al., 2021). In this context, we aimed to evaluate the impact of altitude and light conditions in crucial physical and chemical traits, associated with coffee green bean (and, thereafter, cup) quality from a new coffee cropping area in the Gorongosa Mountain, Mozambique.

3.4.1. Coffee bean physical attributes

Our findings highlighted that altitude driven most of the observed changes of physical characteristics of coffee bean, whereas only minor impacts were promoted by the irradiance conditions. The apparent density values were close to other field collected beans of *C. arabica* cultivars (*ca*. 0.63 - 0.68 g mL^{-1}) (Molin et al. 2008; Bicho et al. 2014), similarly to the usual range observed for the mass of 100 beans (*ca*. 15-20 g) yielded from both under Sun or shade management systems (Ricci et al. 2006; Bicho et al. 2014).

Frequent sieve number, average sieve and commercial homogeneity are good indicators for green coffee bean quality, as well as for commercial quality assessment (Esteves & Oliveira, 1970). The Gorongosa Mountain coffee presented a frequent sieve number around 17 for most treatments (Fig. 3), in line with the values obtained in *C. arabica* (Bicho et al. 2014). Nevertheless, a modest number of smaller beans were still found in samples harvested at the lowest altitude. In contrast, larger beans (with greater presence in sieves 18, 19 and 20) were obtained at 935 m (Fig. 1), whereas average sieve, commercial homogeneity (Table 1), bean mass and bean apparent density increased with altitude (Table 2). This is in line with the reports of maximal bean weight, and density at greater altitudes (1400-1500 m) (Kamal et al. 2021), and of a rise of the 100 beans weight from 1600-1680 to 1950-2100 m (Tolessa et al. 2017). In our case, the positive altitude impact on these traits might be related with the favourable environment conditions, which were associated with greater water availability (higher rainfall amounts and fog presence, the latter mostly at the greater studied elevation) (Fig. 1), together with somewhat lower temperature, particularly in the dry period from May-to-September (Fig. 2). Such lower temperature was pointed as an important factor that causes slower maturation process and an extended time period for bean filling, with beneficial impact on physical (*e.g.*, size and weight) and biochemical (*e.g.*, sugar and acids content) coffee bean attributes (Muschler 2001; Vaast et al. 2006; Joët et al. 2010; Tolessa et al. 2017; Hall et al. 2022). In fact, such delayed maturation was evident in Gorongosa Mountain, with a drift of *ca*. two (825 m) and four (935 m) weeks of the harvest date, as compared with 650 m (data not shown).

The commercial homogeneity is quite important for trade assessment. Although our data shows lower values (< 55 %) than previously reported for *C. arabica* from Angola (Esteves & Oliveira 1970), only altitude exerts a positive influence in this attribute that significantly increased (at 825 and 935 m) under MS and FS conditions.

Light regime *per se* had no relevant impacts on any of the attributes mentioned above when comparing DS and FS conditions (regardless of altitude), in line with unaltered values of yield per plant and weight of 100 fruits in a Cambodia study (Ehrenbergerová et al. 2021). Only FS beans showed a systematic tendency to lower mass values (Table 2), what attenuated the bean mass increase due to altitude. Notably, bean mass showed maximal values under the moderate environmental conditions regarding light irradiance (MS) at 935 m. These findings agree with the observed absence of impact of shade level in the 100 bean weight, and a tendency to lower levels under FS irrespective of the altitude (Tolessa et al. 2017), although this same *C. arabica* cultivar (Costa Rica 95) showed greater bean size under shade conditions (Koutouleas et al. 2022b).

Colour features can also be used to assess bean quality, allowing a fast, reliable, low cost, and non-destructive analysis (Borém et al. 2013; Ramalho et al. 2018), being dependent of (and reflecting), among others, the genotype and environmental conditions (Bicho et al. 2014; Cheng et al. 2016). A few colour attributes were significantly modified by altitude, but were almost irresponsive to light conditions, without any significant associated modification (Table 3). Altitude, promoted some decline in b* and C* (regardless of the light condition), and slight increases in H° and CI in beans from DS plants. These findings are partly in line with the findings that higher temperature (here associated to the lower elevation of 650 m) increased C*, CI, and L*, and reduced Hº, suggesting some degree of altered bean quality (Ramalho et al. 2018). Reflectance measurements indicating greater colour intensity (darker) were associated with a quality decline, due to phenol oxidation, thus with impact on flavour and aroma precursors (Afonso & Corrêa 2003; Borém et al. 2013). Additionally, the maintenance of bean quality was related with the stability of colour attributes of blue-green or green tones (Borém et al. 2013), as it was the case in our samples where the negative a* values reflected a strong contribution of the green colour to the bean, regardless of treatments. In fact, the observed increases with altitude in b* just emphasises a moderate decrease in the yellow tone, whereas the increase in C* still maintained the value close to 17 that was reported in non-defective *C. arabica* green beans (Mendonça et al. 2009). In this way, the few minor changes in colour attributes pointed to an absence of a clear impact of altitude and, particularly, light regime, on bean quality.

Overall, the studied physical attributes showed that Gorongosa Mountain beans have an appreciable quality, similar to other *C. arabica* cropped genotypes. Additionally, a few physical attributes (larger beans, with greater mass and density, commercial homogeneity) suggested a quality increase at higher altitude, but these attributes were mostly unresponsive to the light regime.

3.4.2. Chemical compounds involved in bean quality

The coffee quality is closely associated with biochemical transformations that occur in the seed, during the roasting process, depending on the precursors existing in the green bean, namely as regards aroma and flavour. Such aroma precursors vary with plant genetic characteristics, geographical factors, agricultural and post-harvest management practices, which interfere with the profile of volatile and non-volatile compounds that are directly related to coffee flavour formation (Bertrand et al., 2006; Farah et al., 2006; Lemos et al., 2020; Martins et al., 2020). The contents of several compounds of beans from Gorongosa Mountain has fallen within or close to the ranges previously observed in cropped *C. arabica* genotypes, namely for caffeine and trigonelline, although somewhat below for total mono CQAs (Malta & Chagas, 2009; Mussatto et al., 2011; Bicho et al., 2013; Ramalho et al., 2018). However, some changes were promoted almost exclusively by altitude in our experimental conditions.

Among the studied compounds, trigonelline showed one of the more striking changes with altitude, with increases to *ca*. 2.3 (MS) and 2.7 (FS) fold at 935 m when compared to their respective values at 650 m (or even at 825 m), in contrast with the almost stable values from 900 to 1450 m reported by Bertrand et al. (2006). This compound is a known precursor of volatile compounds that contribute to the aroma and taste after roasting (Malta & Chagas, 2009; Barbosa et al., 2012). As reported by Farah et al. (2006), improved cup quality can be sensed with relatively small increases from 9.6 to 13.4 mg g^{-1} DW in the green bean, thus suggesting that the bean harvested at 935 m would have a significant increase in cup aroma and taste under MS and FS (but not in DS) conditions. This is in line with lower trigonelline values under shade for this genotype (Koutouleas et al., 2022b), as well as with a greater quality for specialty coffee observed under high altitude combined with full Sun or medium shade level, including greater quality scores for total specialty cup quality, overall cup preference, acidity, body, flavour, and after taste (Tolessa et al., 2017).

Caffeine is a very important compound to flavour and is also a bioactive element (Godos et al., 2014). The patterns of accumulation of this compound are highly variable, and have been reported to slightly increase with increasing elevation above 1200 m (Bertrand et al., 2006), to decrease at 1400-1500 m (Kamal et al., 2021) or 1950-2100 m with moderate shade of 40-55% (Tolessa et al., 2017), or even to remain unaffected by altitude or shading (Mintesnot & Dechassa, 2018). Caffeine and polyphenol *p*-coumaric acid, together with CGAs, contribute to coffee bitterness, and their rise under higher temperature conditions was suggested to result in poor bean quality (Joët et al., 2010; Santos et al., 2015). That was not the case in our study, since caffeine and the hydroxycinnamic *p*-coumaric acid, showed only marginal changes regardless of altitude or light (Table 4).

The mono CQAs isomers are the most represented subgroup of CGAs and are bioactive compounds (Godos et al., 2014) that greatly participate to the development of coffee cup flavour (Avelino et al., 2005; Mintesnot & Dechassa, 2018; Worku et al., 2018). In our case, mono CQAs showed an absence of changes with light conditions, and some divergent tendencies with altitude, dependent of the considered isomer. Among 3-CQA and 4-CQA contents, a consistent tendency to decrease was observed for both compounds at 935 m, although only 4-CQA showed a significant change under DS (Table 4). By opposition 5-CQA (and the total of mono CQAs) tended to greater values at 825/935 m (as compared with 650 m), although significantly only under MS at the highest elevation. Additionally, 5-CQA, which constitutes by far the largest fraction of total CGAs, increased its proportion in in the total mono CQA content, similarly in all light conditions. This result was in line with the reduction of 5-CQA promoted by supra-optimal temperatures (Ramalho et al., 2018), here associated with the lower values at the lowest altitude. Coffee berries grown at high altitude experience lower temperatures, conditions that increase the period of fruit maturation, as observed also in our case. Such extended period can allow a higher accumulation of phenolic compounds, among them chlorogenic acids. Still, there are contrasting reports regarding the impact of elevation on mono CGAs, which concentration can tend to lower values (1950-2100 m *vs*. 1600-1680 m) (Tolessa et al., 2017), or to increase (Bertrand et al., 2006; Martins et al., 2020) at greater altitudes, particularly 3-CQA and 5-CQA. In fact, the rise of 5-CQA has been associated with first grade coffee beans, both under shaded and unshaded conditions (Mintesnot & Dechassa, 2018), since this compound has been characterized as low acidic, with a small amount of bitterness (Yeager et al., 2021). Additionally, 5-CQA in stored green coffee was also pointed as responsible for sensory perception of coffee freshness (Rendón et al., 2014). Still, a certain degree of uncertainty still remains regarding the 5-CQA impact on the sensory properties of expresso coffee beverage. As highlighted in a recent review (Yeager et al., 2021), this compound might not contribute substantially to sensory beverage quality by itself, since its large enzymatic degradation (98%) in brewed coffee did not significantly change the beverage flavour (Sieber et al., 2019). Degrading chlorogenic acid lactones to CGAs induced a decline in the bitterness attributed to lactones, although that did not promote other sensory attributes. Yet, when 5-CQA was hydrolyzed to caffeic acid, the drink was found to be more sour, bitter, and burnt (Kraehenbuehl et al. 2017; Siebert et al., 2019). Hence, CGAs seemed to have a limited direct contribute to coffee flavour after roasting, while their derivatives did (Yeager et al., 2021).

As for mono CQAs, also the FQAs were moderately impacted by the light conditions, except at 825 m, where beans collected from FS plants showed a greater 4-FQA and 5-FQA contents (Table 4). These results somewhat agree with the significantly higher values of FQAs present in unshaded than in shaded coffee bean samples (Mintesnot & Dechassa, 2018). On the other hand, the impact of altitude was clearer with both compounds showing declines at 825 and 935 m, corroborating earlier findings of greater FQA values in beans from lower altitudes (Mintesnot & Dechassa, 2018). Such lower FQAs values at higher elevation (and in DS and MS at 850 m) would have the potential to improve the sensory quality of this coffee, since high FQA contents were observed in coffees with poor cupping scores after roasting (Farah et al., 2006). However, it seems likely that the FQAs specific negative/positive role on the beverage will be largely dependent of some interactions with other chemical components of each specific coffee (Yeager et al., 2021).

As for most compounds previously discussed, all diCQA isomers (3,4-diCQA, 4,5-diCQA and 3,5-diCQA) did not show any significant change with the light conditions within each altitude, but where clearly reduced at the two highest altitudes. Similar absence of shade effect on diCQAs, as well as lower 3,4-diCQA and 4,5-diCQA contents at high than at low altitude were previously reported (Mintesnot & Dechassa, 2018). Such, diCQAs reduction at higher altitudes might benefit cup quality, since diCQA mixtures were suggested to present a greater bitterness, together with ametallic taste and astringency (Clifford, 1985; Upadhyay & Rao, 2013). Nonetheless, much remains to be elucidated due to contradictory reports. In fact, 3,4-diCQA was associated with sweetness and full body, and 3,5-diCQA with astringency and immature bean taste (Maria et al., 1994), but 3,5-diCQA and 4,5-diCQA contents were also positively associated with higher cup quality scores (Scholz et al., 2018).

Another group of important compounds are sugars, since they undergo complex changes during the roasting that contribute to the cup organoleptic profile (Redgwell & Fischer, 2006). For instance, sucrose degradation during roasting play a major role in flavour formation through Maillard reactions, although its relation with sensory characteristics was unclear in some cases (Avelino et al., 2005). As for CGAs, an extended period of fruit maturation due to lower temperature/higher altitude can promote important increase in coffee bean sugars and lipids (Vaast et al., 2006; Tolessa et al., 2017; Worku et al., 2018). Interestingly, a recent report point that the sucrose content of coffee beans from low altitude was significantly higher than those from middle and high altitudes (Mintesnot & Dechassa, 2018). In our case, sucrose was by far the most represented soluble sugar irrespective of the environmental conditions, but did not show any consistent pattern of variation (similarly to all sugars), although at 935 m the FS condition showed always a greater absolute value than MS and DS for all sugars, significantly only for the minor represented glucose and fructose

3.5. Conclusions

The present study highlights the impact of light conditions (full Sun and agroforestry system managements) and altitude (associated with temperature and water availability) on the physical and chemical attributes of *C. arabica* green coffee beans in Gorongosa Mountain.

Light conditions (mainly MS and FS) barely affected most of the studied physical and chemical attributes of the green coffee bean regardless of the altitude level, in line with the findings that a number of *C. arabica* cultivars responded either positively or neutrally to shaded environments in terms of yield, among them Costa Rica 95 (Koutouleas et al., 2022a). Among the few physical traits exceptions, the bean mass consistently tended to lower values under FS in the three altitudes (significantly only as compared with MS at 935 m), and the density was greater under FS at 650 m, whereas colour attributes were irresponsive to light conditions. As regards the chemical compound contents, significant impacts were observed sporadically. An improved sensory profile might be expected (after roasting) in the beans regarding the rises of trigonelline (FS and MS at 935 m), glucose and fructose (FS at 935 m), and *p*-coumaric acid decline (MS and FS at 825 m). On the other hand, the FQAs rise (FS at 825 m) could have a negative impact, thus adding a greater uncertainty regarding potential quality modifications of the yielded bean.

Contrasting with light conditions, altitude promoted changes in a large number of attributes with potential implications to bean quality. Altitude extended the fruit maturation period by four weeks from 650 to 935 m. Among the physical attributes, average sieve (consistent tendency), bean commercial homogeneity, mass, and density significantly increased at 935 m, whereas the beans became more yellowish and brighter at 825 and 935 m (b*, C*), usually as compared with the beans from 650 m elevation, all of which pointing to increased bean trade quality. As regards the studied compounds at 935 m, increases of trigonelline and 5-CQA (both under MS and FS) were observed, whereas FQAs and diCQAs isomers declined (regardless of the light condition), all of which likely contributing to improve the sensory cup quality. Other major compounds such as, caffeine, *p*-coumaric acid, and soluble sugars showed mostly inconsistent variations.

Overall, light (full Sun and shade under AFS) did not greatly and consistently modify the bean quality physical and chemical attributes. In contrast, altitude, likely associated with lower temperature, greater water availability through rainfall and fog, and extended fruit maturation period, was a major driver for bean attribute modifications, ultimately improving coffee green

3.6. References

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CHAPTER IV

ECONOMIC FEASIBILITY ANALYSES OF COFFEE GROWN UNDER AGROFORESTRY SYSTEM IN THE GORONGOSA MOUNTAIN, GORONGOSA NATIONAL PARK IN MOZAMBIQUE

Abstract

The implementation of Agroforestry Systems (AFS) is widely used strategy to promote of ecosystem conservation, while maximizing ecosystem services. This is a particularly important approach in developing countries where the livelihoods of millions of people depend on natural resources. The objective of this study was to assess the economic feasibility of coffee grown under AFS in the Gorongosa Mountain considering the land directly manage by the Gorongosa National Park (GNP) and land manage by the smallholder farmers. GNP, one of the most outstanding cases of success integrating conservation and human development. Internal Rate Return (IRR) was the economic metric used to estimate the feasibility of the system, particularly from the perspective of smallholder farmer's livelihood. Our results showed relatively high IRR values under condition of land directly manage by the GNP. However, in both land management, the project is feasible even in the condition of lower price in the international market.

Overall, the study suggests that selling price in the international market is crucial for net income trends of this crop and the selling price forecast by the International Organization of Coffee predicted a promising future regarding the economic benefits for coffee growing in the Gorongosa Mountain.

Keywords: Coffee production; Economic feasibility; Internal Rate Return; Smallholder farmers

4.1. Introduction

Over the last 40 years, coffee production, one of the most widely traded commodities worldwide, has been driven by intensification strategies aiming to maximizing short-term yields through the use of purchased inputs in full-sun production systems (Mbow et al., 2014; Dumont et al., 2019). The sustainability of intensive coffee monocultures, mostly grown on land recently converted from natural forests or located near conservation hotspots, has been increasingly questioned because of their environmental cost and the economic vulnerability of coffee farmers affected by fluctuating coffee prices (Philpott et al., 2003; Soto-Pinto et al., 2022). Agroforestry Systems (AFS) are among the few options available to protect the forests and, additionally, lift people out of the poverty trap (Rahman, 2011; Pantera et al., 2021). One of the definitions of AFS is a land management system in which forestry trees or shrubs are integrated with crops and/or animals to benefit from the resulting ecological and economic interactions (Burgess et al. 2019). Coffee naturally grows in shade, and coffee agroforestry practices around the world sit along a gradient of complexity from simple mixtures involving one or two companion tree species in regular arrangements to several species in diverse multistrata systems, which can increase nutrient cycling, biodiversity, carbon storage, and provide a moderate microclimate (Thang et al., 2015; Haggar et al., 2021). A basic assumption is that short-term financial benefits from planting tree species in combination with row crops will improve productivity over traditional monocrops and hence increase financial returns to farmers.

In the Gorongosa Mountain, a coffee AFS has been implemented to counteract the effect of the massive destruction of the rain forest while improving the livelihoods of local communities. Gorongosa Mountain is part of the Gorongosa National Park (GNP). Coffee Agroforestry System Program is an agroforestry initiative within Gorongosa Mountain. The program aims to restore the degraded forestry above 700 m.a.s.l, while simultaneously is improving the economic conditions of farmers living in different locals of the Mountain.

Through this project it is expected, in medium and long term, to reduce and even to stop the deforestation and ensure the involvement of more than 2,000 families living inside of Gorongosa Mountain in coffee plantations. Currently more than 800 smallholder farmers have shifted about 181 ha from traditional land uses to coffee AFS management. This process includes employment of the local communities into the project. More than 300 seasonal workers and about 17 permanent workers ensure operations in the company's farming communities and agriculture (Mongabay, 2020). In this regard, this study intends to estimate the economic feasibility of the project after shifting from traditional land management to coffee AFS management. Therefore, when restoring the forestry, estimates of how coffee AFS could effectively improve the community livelihoods is crucial for the sustainability of the system.

Coffee trade is an essential component of the AFS as it should generate income for smallholders, particularly those living in and in the surrounding of Gorongosa Mountain, contributing to food security through direct food acquisition or expansion of the farming lands outside the protected areas (Duguma et al., 2001; Abebe, 2013; Soto-Pinto et al., 2022). To properly address the socioeconomic value of AFS, parameters such as the Internal Rate of Return (IRR) or economic rate of return, and Net income (NI), must be assessed (Bijarpas et al., 2015). The IRR is one of the most popular metrics used to measure the economic return on investment in agriculture. According to Evison (2008), IRR is a powerful metric for comparing the economics of competing land uses, as well as the realized and unrealized gains, providing a basis for comparing investments. This investmens analysis is particularly important for commodities due to the export volatile prices. In this study we have determined the IRR based on green coffee bean export prices over a 30 year production interval (2021-2051) under two different scenarios, direct management by the GNP structure and direct management by the smallholders.

4.2. Material and methods

4.2.1. Study Area

The Gorongosa Mountains region (Lat. 18°14' and 18°42' South and Long. 33°50' and 33°13' East) is located in the southern of the Great African Rift Valley in the heart of central Mozambique, and is part of the Gorongosa National Park of (GNP), which is an important biodiversity hotspot of the country (Figure 1). The conserved area of Gorongosa Mountain is the upland area of GNP with elevations varying from 700 m.a.s.l to 1.863 m.a.s.l (Müller et al., 2012). The mountain is an important part of the ongoing ecological functioning of the lowland areas of the Gorongosa National Park, as it provides the water flow to its rivers, lakes, and wetlands. Both sections of the park have a wide range of flora and fauna habitats, including endemic species (Müller et al., 2012)

The Mountain covers 42698 ha, where currently 181 ha consists of coffee plantations under Agroforestry System. There are 625000 coffee plants in which 40 % of them are producing the green coffee bean. *C. arabica* is the species grown in the Mountain and the main variety is Costa Rica 95 imported from coffee producing regions of other countries (Mongabay, 2020).

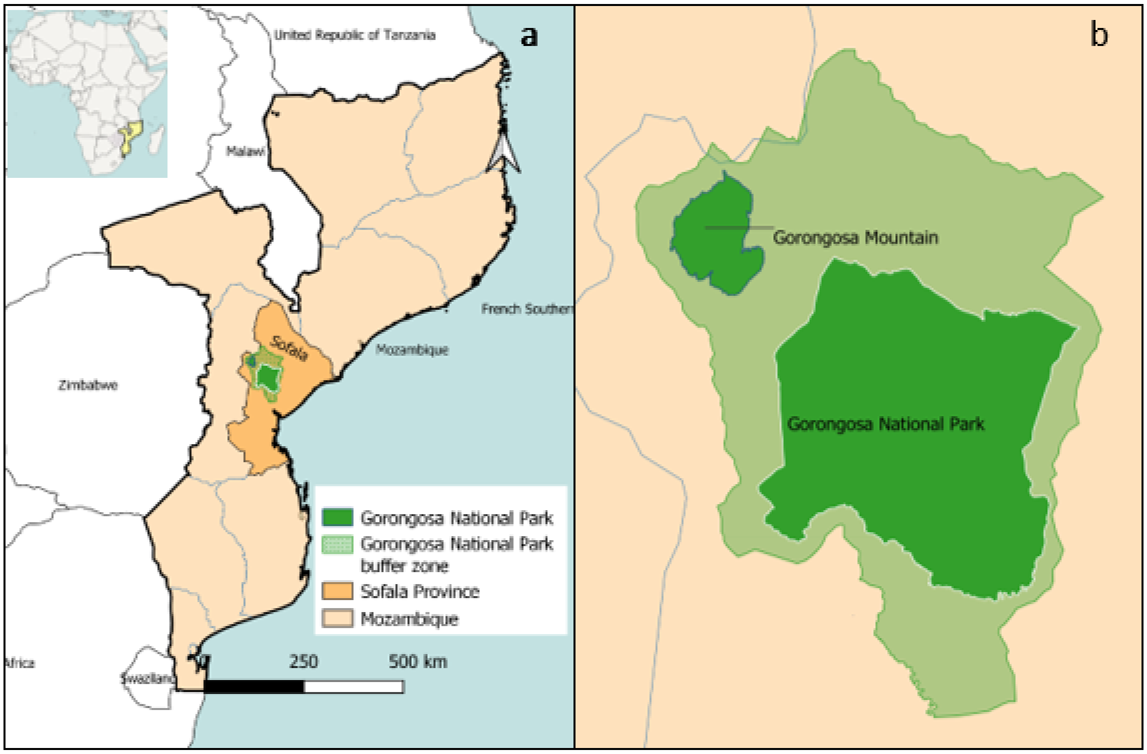

Figure IV 1 Map showing the location of the study area in Mozambique (a) and Gorongosa National Park (b)

4.2.2. Project Description

Coffee AFS Project in an agroforestry initiative with enduring socio-economic and environmental benefits. The program's vision is to improve the socio-economic conditions of smallholder living in the mountain, particularly in localities above of 700 m altitude. Canda, Santugira and Tambarara are the localities above 700 m altitude deeply involved in the production of high quality shade-grown coffee for the national and international markets. Lands are being re-forested using native trees to restore forest fragmentation.

Coffee is grown on GNP lands and adopted by smallholder in their lands, under GNP management. The production of coffee seedling and native forestry trees is the first step in this program, grown in nurseries, using permanent and seasonal workers employed by the GNP.

Then, from the establishment of the nursery to obtaining green coffee beans, the inputs and main operation costs are fully covered by the GNP, and the smallholder farmers are only responsible for managing their lands from planting the seedling to harvesting the red cherries. In this process the seedlings are grown and transported by GNP to the lands of smallholder famers, promoting the inclusion of new members in the project through the transfer of traditional land uses to AFS. The smallholder farmers receive the coffee and native trees seedlings for the establishment of AFS, and are planted at a density of around 2000 coffee seedling and around 300 native forestry trees per hectare of land.

For the smallholder, minimum slashing, chemical fertilizer application, pruning and harvesting are the main operation carried out in their lands and in most cases with the support of family members.

The GNP management is more complex and involves nurseries management, own plantations, transport, training and technical assistance, coffee processing and the sale of green coffee beans. In this context, GNP provides continuous training for technical staff and of smallholder so that, they can increase the yield and coffee quality, while ensuring the forestry tree plantation. Besides providing all the inputs, technical assistance, transportation of inputs, the GNP buys and red coffee (red cherries) harvested by the smallholder The final stage is coffee processing of red cherries into green coffee beans which consists in, wetting and drying the beans, both of which are the responsibility of the GNP.

Currently, the project involves more than 800 family members covering more than 181 ha and it is expected for the next decades to reach 1000 ha of AFS.

Overall, coffee is an alternative income for the communities, with important social and economic impact, while it is addressing the environmental conservation through the promotion of coffee growing under native forest trees (Mongabay, 2020).

4.2.3. Data Collection Methods.

The data was collected through field survey and observations of coffee grown under AFS management in the Gorongosa Mountain and in the enterprise facilities including the coffee processing factory. Field survey was carried out between 2020 to 2021 in order typify the all stakeholders in the system, including the staff, smallholder farmers and management of nurseries lands. On the ground we observed the all the components of AFS and all the stakeholders (GNP staff and smallholder). Through observations and participatory rapid appraisal (PRA) all operations were recorded, from the seed acquisition to red cherries. All the process involved in farming operations, material and equipment and all the inputs necessary to run the project were also analysed. However, most of coffee production unit costs were provided by GNP, referring to one hectare of production.

4.2.4. Assessment of the economic feasibility

The economic feasibility was analysed in the context of coffee AFS in the Gorongosa Montain between 2020 to 2021. The study used two approaches: i) economic feasibility of coffee AFS under direct land management of GNP and ii) the smallholder growing coffee in their lands. Both approaches were analysed based on the Internal Rate Return (IRR) calculation for growing coffee in Gorongosa Mountain. IRR is a mean annual return derived from an investment and expressed in percentage (Graves et al., 2007) IRR value indicates an interest rate that can be paid by a business, or in other words, the ability to gain income from the cost invested. In other words, IRR is the discount rate that makes the net present value (NPV) of a project zero (Evison, 2008).

The NPV represent the present worth of the net cash flow (Björnsdóttir, 2010). The NPV simply describes the present worth of the income stream from an investment.

a) $NPV = 0 = \sum_{i=1}^{t} \frac{NI}{(1+IRR)^t}$

Where:

NI- Net Income

IRR- internal rate return

t - period (first year to thirty years)

The Net income (NI) was estimated as total revenues after taking total cost production deductions into account.

$$b)\ NI = TR - TC$$

Where:

NI - Net Income

TR - Total Revenues

TCP - Total costs of production

The total costs of production were estimated as all the costs from nursery grown to obtaining of green coffee beans (inputs, material, salary, operations, processing) for both stakeholders (enterprise and smallholder farmer). For the cost determination we considering a set of assumptions described as follows:

i) The investment costs were not taken into account in this study
ii) We assumed no depreciation cost of material and equipment
iii) Transport costs incurred in coffee exporting, packing materials were not considered in the analyze
iv) Current devaluation and economy inflation were not taken into account
v) The land cost was not included in this study
vi) We assumed the salary costs for only the local labours and smallholder farmers
vii) The green coffee production per hectare reaches the full production and does not change from the 5 years to the 30 years of coffee grown
viii) We considered in this study, all green coffee was exported, excluding coffee sales in the domestic market.

ix) The Mozambique Prime Rate (20.60%) was used as a proxy for the cost of capital in this study (BM, 2022). The prime rate is the interest rate charged by commercial banks to their most creditworthy business clients.

4.3. Results

The IRR for coffee grown under direct GNP management was positive under different scenarios of green coffee beans selling price (Table 1).

Since the cost of capital is 20,60%, the investment for GNT is only economically viable when the price of coffee is equal to or greater than $2.00. In contrast, the project is only viable for Smallholder farmers when the price of coffee on the international market exceeds $2.50. In other words, the IRR for coffee grown under direct GNP management was positive under five different selling price of green coffee beans (Table 1). However, considering coffee grown on smallholder land, the IRR is no longer positive below the export price of $3.00/Kg of green coffee bean.

Table IV 1 - Simulation of Internal Rate Return (IRR) of coffee production under GNP and smallholder land management along of 30 years of production in different scenarios of selling price of green coffee bean

GNP & SMALLHOLDER FAMERS PRODUCTION								
OPERATIONS	Stakeholder	EXPORT PRICE OF GREEN COFFEE (USD)						
		$4.00	$3.50	$3.00	$2.50	$2.00	$1.50	$1.00
IRR	GNP	59%	53%	46%	39%	27%	13%	
	SmallholderFarmers	49%	38%	24%	-4%			

Cost of production is very determinant for the economic feasibility and obviously for the IRR of the project. In both types of land management, whether it is in the GNP land or smallholder farmers. NI is greater as expected, for higher prices of selling green coffee bean (Tables 2 and 3).

The results in Table 2 and 3 shown that NI is higher when coffee is grown under GNP land (Table 2) than when it is grown on smallholder land (Table3).

Table IV 2 - GNP and Smallholders Net Income (NI) from producing green coffee beans under GNP land management in the different scenarios for green coffee bean selling prices. *(The production condition assumes that GNP provides all the inputs, pays labour and sells the green coffee in the market)*

NET INCOME OF OPERATORS ON A FULL PRODUCTION YEAR (USD)	**PRICE OF GREEN COFFEE (USD)**						
	$4.00	$3.50	$3.00	$2.50	$2.00	$1.50	$1.00
GNP	4,881.47	4,024.32	3,636.47	2,779.32	1,922.17	1,066.10	207.87
FARMERS LABOUR	1,111.27	1,111.27	1,111.27	1,111.27	1,111.27	1,111.27	1,111.27

On the other hand, the tables (2 and 3) show that, smallholders obtain a higher NI when they manage production in their lands themselves (Table 3) than when they only provide the labour force in GNP lands (Table 2).

Additionally, the results in Table 3 also show that when coffee beans are produced in smallholder land, if the selling price falls to $2.00, production is no longer viable, as GNP obtains a negative NI. For the benefits of all stakeholders, the selling price of green coffee beans should be more than 2.5 USD. Green coffee beans at a price below 2.5 USD, NI is negative for GNP (Table 3).

Table IV 3- GNP and Smallholder farmers Net Income (NI) from producing green coffee beans under smallholder farmers land management in the different scenarios for green coffee beans selling prices. *(The production condition assumes that GNP provides all the inputs and Smallholder Farmers provide management, labour and sell the red coffee to the GNP)*

NET INCOME OF OPERATORS ON A FULL PRODUCTION YEAR (USD)	**PRICE OF GREEN COFFEE (USD)**						
	$4.00	$3.50	$3.00	$2.50	$2.00	$1.50	$1.00
GNP	2,625.26	1,768.11	910.96	53.81	-803.04	-1,660.49	-2,517.64
	PRICE OF RED COFFEE (USD)						
(Selling price of red coffee to the GNP kept constant at 20 MZN/kg)	$0.28	$0.28	$0.28	$0.28	$0.28	$0.28	$0.28
FARMERS	3,367.48	3,367.48	3,367.48	3,367.48	3,367.48	3,367.48	3,367.48

4.4. Discussion

Coffee grown under AFS project has the main purpose of restoring the degraded forest in the mountain and limiting the progress of forestry losses by creating a new alternative for the livelihood of local communities living in and around of upper land (Gorongosa Mountain) of the GNP. Therefore, it should be noted that the economic profits are not the priority in this project, but rather, economic benefits for the local population is the main focus.

Coffee grown under AFS is a great challenge for the farmers since the green coffee production takes four years to generate income. While the smallholder farmers practicing the traditional agriculture (e.g., maize, cassava) can get revenues within three months to 1 year. Food crop is very important for the food security and they can immediately sell the production in the village. According to the IRR indicator, for a green coffee selling price between $1.50/kg and $1.00/kg, production is no longer strictly economically attractive under the GNP system (Table 1). Nevertheless, better price policies for the red coffee (red cherries) may encourage smallholder to shift from intensive slashing for food crops to coffee production under AFS. The Economic analyses performed in coffee production in Nepal emphasize that coffee can provide high income to the farmers than cereals and vegetables (Sharma et al., 2016).

Considering all the costs (package, transport, depreciation, etc.) that have not included in this study the economic feasibility of coffee production is substantially reduced for low selling prices of the beans. Similarly, the IRR for the smallholder for coffee production is noticeable less attractive for a selling price of green coffee between \$3.00/kg and \$2.50/kg, but relatively greater than it is expected in the GNP system (Table 1). However, at selling price greater than \$2.50/kg it may still be competitive, when compared to the IRR found in other studies. The economic viability performed in Espírito Santo state in Brazil showed that IRR values ranging from 16 % to 8 %, for identical selling prices, where an IRR above 8% is reached using mechanic process for harvesting the green coffee (Galeano & Krohling, 2019). Our findings reinforce that price volatility should be considered in economic viability studies and for decision making, particularly for agricultural commodity.

Moreover, the results showed in detail the impact that the selling price has on Net Income (NI) (Table 3). In both land management, simultaneously the selling price of green coffee cannot be less than \$2.50/kg, otherwise, the NI to GNP will be negative, and the Park will not buy the red cherries from the farmers.

Overall, to enhance the economic feasibility of coffee grown under AFS in the mountain, adopting technologies that allow high quality green coffee and increased coffee productivity per hectare at a lower cost can minimize the economic risk. Adopting new short cycle varieties of, improving coffee processing quality to sell the green coffee bean at a high price are some possible alternatives. Since simulations show that production is still viable for sales prices below \$3/kg, the current international market price is still attractive. In fact, in the last two years the selling price has been more than \$3/kg of green coffee (Sachs et al., 2019), so in the context of Gorongosa Mountain, the project is still attractive under both management systems . Moreover, the sales prices predicted by the World Bank (2022) will be above \$4/kg of green coffee for the next 3 years, which means that economic environment will be favourable for coffee grown in the Gorongosa Mountain. Therefore, it is very important to mention that in this study the productive capacity is below the optimum level, since of the 181 ha already planted only 60% of the plantation is actually producing the fruits (red cherries).

Furthermore, coffee grown under AFS is a crop management that benefits from many incentives and certification (Mas & Dietsch, 2004). Certification can favour the sale of coffee at the best prices on the international market. Gorongosa coffee is grown under natural condition and free from the use of chemical products, such as pesticides and fertilizers.

4.5. Conclusion and Recommendations

Coffee grown under AFS project is a sustainable opportunity to supply the national and international market and generate income for the local smallholder.

The high IRR scenarios in this study, especially at a lower selling price than currently observed in the international market suggest the economic feasibility of coffee grown under AFS. According to the World Bank (2022), predicted green coffee selling price for the next 3 years, which is above $4/kg indicates that economic benefits of coffee crop will increase in the future. Nevertheless, the highest incomes for coffee growing under AFS will be achieved by GNP. However, the focus of coffee AFS project is to safeguarding the rainforest, so, the economic externalities may reinforce this purpose. Apart from the economic benefits, the involvement of the smallholder farmers on the local economy, may in the future strengthen local control and management of forestry, leading to increased biodiversity and restauration of degraded forestry.

Overall, to enhance the economic feasibility for growing coffee under AFS in the mountain, the adoption of technologies that promote high quality green coffee and increase coffee productivity per hectare at low cost are the indispensable tool for the economic success of this project.

This study was performed with limited data however, more realist economic analyses should consider all production costs (such as, depreciation, inflation, etc.) and all the elements of price variation.

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Supplementary information III

Table S1- Simulation detailed of Internal Rate Return (IRR) of coffee production under GNP and smallholder farmers land management along of 30 years of production in different scenarios of selling price of green coffee beans

GNP & SMALLHOLDER FAMERS PRODUCTION									
YEAR	OPERATIONS	Stakeholder	NET INCOME (USD)						
			EXPORT PRICE OF GREEN COFFEE						
			$4.00	$3.50	$3.00	$2.50	$2.00	$1.50	$1.00
1	Nursery	GNP	-755.54	-755.54	-755.54	-755.54	-755.54	-755.54	-755.54
		Farmers	-237.99	-237.99	-237.99	-237.99	-237.99	-237.99	-237.99
2	Implantation	GNP	-839.36	-839.36	-839.36	-839.36	-839.36	-839.36	-839.36
		Farmers	-357.81	-357.81	-357.81	-357.81	-357.81	-357.81	-357.81
3	Implantation	GNP	-1,284.18	-1284.18	-1284.2	-1284.2	-1284.18	-1284.2	-1284.18
		Farmers	-839.67	-839.67	-839.67	-839.67	-839.67	-839.67	-839.67
4	Implantation	GNP	-1,284.18	-1284.18	-1284.2	-1284.2	-1284.18	-1284.2	-1284.18
		Farmers	-839.67	-839.67	-839.67	-839.67	-839.67	-839.67	-839.67
5	Implantation	GNP	5,350.77	4,493.74	3,636.47	2,779.32	1,922.17	1,066.10	207.87
		Farmers	2,650.05	1,792.90	935.75	94.84	-778.55	-1,635.68	-2,492.85
6 to 30	Full production	GNP	4,881.47	4,024.32	3,167.17	2,526.50	1,452.87	595.72	-261.43
		Farmers	2,650.05	1,792.90	935.75	94.84	-778.55	-1,635.68	-2,492.85
IRR		**GNP**	**59%**	**53%**	**46%**	**39%**	**27%**	**13%**	
		Farmers	**49%**	**38%**	**24%**	**-4%**			

Table S2- Detailed Net Income (NI) of coffee production under GNP land management in the different stages along of 5 years of coffee production and in the different scenarios of selling price of green coffee beans. The production condition assumes that GNP provides all the inputs, pays labour and sells the green coffee in the market.

YEAR	I. Nursery costs (for coffee and native plants)	Units	Quantity	Unit value	Total value	Total value
				(MZN)		(USD)
1 (Nursery)	Coffee seeds *(pergaminho variety)*	kg	1.50	50.00	75.00	1.05
	Flowerpots for coffee plants	units	3,333.00	1.00	3,333.00	46.77
	Flowerpots for native plants	units	300.00	1.00	300.00	4.21
	Labour	man/month	13.00	2,640.00	34,320.00	481.55
	Nursery maintenance	units	1.00	8,000.00	8,000.00	112.25
	Fertilizer	kg	26.60	30.79	819.01	11.49
	Other costs (Irrigation, hoeing, transport, etc)	units	1.00	7,000.00	7,000.00	98.22
	Total costs					755.54
	NET INCOME					-755.54
	II. Planting of coffee and native plants					
2 (1st year of implantation)	Labour for openinig holes and planting coffee and native plants	man/month	1.00	2,640.00	2,640.00	37.04
	Analysis of soil samples	units	1.00	10,000.00	10,000.00	140.31
	Set of tools (Hoes, catan, rake, etc)		1.00	2,000.00	2,000.00	28.06
	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant)	kg	133.32	38.18	5,090.16	71.42
	Yara Milla Nitrabor fertilizer (40 gr / plant)	kg	133.32	31.34	4,178.25	58.63
	Labour for application of calcareous and fertilizers	man month	12.00	2,640.00	31,680.00	444.51
	Total Production Costs					839.36
	NET INCOME					-839.36
3 (2nd year of implantation)	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man month	12.00	2,640.00	31,680.00	444.51
	Total Production Costs					1,284.18

	NET INCOME					-1,284.18
4 (3rd year of implantion)	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man month	12.00	2,640.00	31,680.00	444.51
	Total Production Costs					1,284.18
	NET INCOME					-1,284.18
5 (4th year of implantation)	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man month	12.00	2,640	31,680.00	444.51
	Acquisition of red fruits	kg	12,000.00	0.00	0.00	0.00
	Labour for harvesting and processing	man month	6.00	2,640	15,840.00	222.25
	Total Production Costs					1,506.43
	Sell of green coffee	kg	1,714.30	285.08	488,712.64	6,857.20
	Total Revenue					6,857.20
	NET INCOME					5,350.77

Table S3- Detailed Net Income (NI) of coffee production under GNP land management, between 5th to 30th year of full production condition in the different scenarios of selling price of green coffee beans. The production condition assumes that GNP provides all the inputs, pays labour and sells the green coffee in the market.

YEAR	OPERATIONS	Units	Quantity	Unit value	Total value	Total value
				(MZN)		$ US
6 to 30	**Production Costs**					
	Yara Milla Winner fertilizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of fertilizers	man month	12.00	2,640.00	31,680.00	444.51
	Labour for pruning, hoeing and disease control	man month	12.00	2,640.00	31,680.00	444.51
	Acquisition of red fruits	kg	12,000.00	0.00	0.00	0.00
	Labour for harvesting and processing	man month	6.00	2,640.00	15,840.00	222.25
	Other costs		6.00	1,000.00	6,000.00	84.19
	Total Production Costs					1,975.73
	Sell of green coffee	kg	1,714.30	285.08	488,712.64	6,857.20
	Total Revenue					6,857.20
	NET INCOME / Ha (green coffee)					4,881.47

Table S4- Detailed Net Income (NI) of coffee production under smallholder farmers land management along of 5 years of production stages in the different scenarios of selling price of green coffee beans. The production condition assumes that GNP provides all the inputs and Smallholder Farmers provide labour and sell the red coffee to the GNP.

year	I. Nursery costs (for coffee and native plants)	Units	Quantity	Unit value	Total value	Total value
				(MZN)		(USD)
1 (Nursery)	Coffee seeds *(pergaminho variety)*	kg	1.50	50.00	75.00	1.05
	Flowerpots for coffee plants	units	3,333.00	1.00	3,333.00	46.77
	Flowerpots for native plants	units	300.00	1.00	300.00	4.21
	Labour	man/month	13.00	0.00	0.00	0.00
	Nursery maintenance	units	1.00	8,000.00	8,000.00	112.25
	Fertilizer	kg	26.60	30.79	819.01	11.49
	Other costs (Irrigation, hoeing, transport, etc)	units	1.00	7,000.00	7,000.00	98.22
	Total Production Costs					273.99
	NET INCOME					-273.99
	II. Planting of coffee and native plants					
2 (1st of implantation	Labour for openinig holes and planting coffee and native plants	man/month	1.00	0.00	0.00	0.00
	Analysis of soil samples	units	1.00	10,000.00	10,000.00	140.31
	Set of tools (Hoes, catan, rake, etc)		1.00	2,000.00	2,000.00	28.06
	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant)	kg	133.32	38.18	5,090.16	71.42
	Yara Milla Nitrabor fertilizer (40 gr / plant)	kg	133.32	31.34	4,178.25	58.63
	Labour for application of calcareous and fertilizers	man/month	12.00	0.00	0.00	0.00
	Total Production Costs					357.81
	NET INCOME					-357.81
3 (2nd year of implantation	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man/month	12.00	0.00	0.00	0.00
	Total Production Costs					839.67
	NET INCOME					-839.67

4 (3rd year of implantation	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man/month	12.00	0.00	0.00	0.00
	Total Production Costs					839.67
	NET INCOME					-839.67
5 (4th year of implantation)	Soil correction with calcareous powder (62.5 g / plant)	kg	208.31	20.32	4,232.91	59.39
	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of calcareous and fertilizers	man/month	12.00	0	0.00	0.00
	Acquisition of red fruits	kg	12,000.00	20.00	240,000.00	3,367.48
	Labour for harvesting and processing	man/month	6.00	0.00	0.00	0.00
	Total Production Costs					4,207.15
	Sell of green coffee	kg	1,714.30	285.08	488,712.64	6,857.20
	Total Revenue					6,857.20
	NET INCOME					2,650.05

Table S5- Detailed Net Income (NI) of coffee production under smallholder farmers land management, between 5th to 30th year of full production condition in the different scenarios of selling price of green coffee beans. The production condition assumes that GNP provides all the inputs and Smallholder Farmers provide labour and sell the red coffee to the GNP.

YEAR	OPERATIONS	Units	Quantity	Unit value	Total value	Total value
	Production Costs			(MZN)		$ US
6 to 30	Yara Milla Winner fertliizer (40 gr / plant) * 6 applications	kg	799.92	38.18	30,540.95	428.52
	Yara Milla Nitrabor fertilizer (40 gr / plant) * 6 applications	kg	799.92	31.34	25,069.49	351.75
	Labour for application of fertilizers	man/ month	12.00	0.00	0.00	0.00
	Labour for pruning, hoeing and disease control	man/ month	12.00	0.00	0.00	0.00
	Acquisition of red fruits	kg	12,000.00	20.00	240,000.00	3,367.48
	Labour for harvesting and processing	man/ month	6.00	0.00	0.00	0.00
	Other costs		6.00	1,000.00	6,000.00	84.19
	Total Production Costs					4,231.94
	Sell of green coffee	kg	1,714.30	285.08	488,712.64	6,857.20
	Total Revenue					6,857.20
	NET INCOME / Ha (green coffee)					2,625.26

V. FINAL CONSIDERATIONS

The work presented here investigated the drivers of Agroforestry system (AFS) role on the sustainable *C. arabica* production in the Gorongosa Mountain and Mozambique as whole country. This study emphasis the role of shading in the context of AFS as an alternative for mitigate the climate change impact on the coffee area suitability and as promoter of beans quality attributes. Another focus of this study was associated with the role of AFS on the conservation of natural resource (flora and fauna) in areas with substantial human presence.

Throughout the second chapter using GCMs models under SSPs scenarios (SSP126, SSP245, SSP370 and SSP585) and four periods (2040, 2060, 2080 and 2100) were estimated the suitable areas for coffee production. Fundamentally, it was reinforced that climate change will have deep negative impact on coffee production either in qualitative or quantitative aspects of area suitability in Mozambique. Our results provide relevant insights by predicting to what extend the loss of suitable area is expected in the future for different scenarios considering different crop management. Therefore, the main innovation of this study was to demonstrate how the crop management can mitigate the impact of climate change in the future. Particularly, in this study has shown in detail comparative approach of two crop systems (AFS and FS) simultaneously in space and time which is not common in most of models of crops area suitability using the species distribution. Overall, the coffee AFS pointed toward a more optimistic scenarios while the coffee under FS pointed toward a more pessimistic scenario (Gomes et al., 2020). AFS is known as a crop management that provide optimal microclimatic condition through temperature decreasing, humidity regulation and carbon sequestration (Harmand et al., 2007; De Camargo, 2010; Muschler,,2016).The main microclimatic effect of both crop system (AFS and FS) is related with temperature in which shade reduce the maximum diurnal temperatures without negative effects on night temperatures (Anhar et al., 2021).

The third chapter was intended in a micro-scale to study the influence of light condition in the coffee beans quality. Experiments under three light condition (DS, MS and FS) and three altitudes were carried out in the Gorongosa Mountain. The assumption was that temperature condition and water availability might be improved by the forestry shade and altitude (Vaast et.al, 2006)

Based in the experiment, shading has any effect on some of bean quality attributes, however, to some extend the results showed to be not consistent in terms of temperature influence on the tendency of chemical compounds changes (Avelino et al., 2005; Vaast et al., 2006; Harvey et al., 2021). Despite, lower temperature under optimal shade is reported as favorable conditions on growth and ecophysiological process in the crop (Ramalho et al., 2018) and on beans biochemical accumulation (Vaast et al. 2006; Rahn et al. 2018). Particularly, in this experiment, altitude was another factor with greater influences on the bean quality attributes. Lower temperature, greater water availability and extended maturation period at the higher altitude might be the major driver for bean changes and improved quality.

AFS implementation could be also too much effective in forest restoration in the Gorongosa Mountain, since the coffee plantation can ensure the smallholder farmers livelihoods and decrease the forest losses. The burning practices for agriculture are the main reason of forest and fauna losses in the conservated areas (Müller et al., 2012; Stalmans et al., 2020).

Furthermore, the economic feasibility for growing coffee in the Gorongosa Mountain is attractive, whether under direct management of the land by the Gorongosa National Park or by the farmers. The high IRR scenarios estimated in this study, showed that even at a lower selling price of green coffee than currently observed in the international market suggest the economic feasibility for growing coffee under AFS.

Overall, the approaches of present study allow to integrate aspects regarding to economic sustainability and conservation of natural resources in the context of climate change mitigation.

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