Cocoa yield, nutrients and shade trees in traditional cocoa agroforests in a climate change context: a case study in Bahia, Brazil

Lauranne Aude Marina Gateau

Gonville and Caius College

University of Cambridge

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Title: Cocoa yield, nutrients and shade trees in traditional cocoa agroforests in a climate change context: a case study in Bahia, Brazil

Lauranne Aude Marina Gateau

Abstract

Brazil is the world's sixth largest cocoa producer with 270,000 tonnes of cocoa produced per year. In a world with an increasing demand for chocolate, but with agriculture threatened by climate change, the chocolate industry is worried about a possible shortage of cocoa. Furthermore, growing cocoa is a main cause of deforestation. However, in the state of Bahia, Northeast Brazil, cocoa is grown in traditional agroforests called 'cabrucas' which maintain a forest cover. Cocoa, an understorey crop, is planted under the shade of native Atlantic Forest trees and exotic fruit trees introduced by the farmers. These cabrucas have high conservation value but very low cocoa yield. In my thesis I investigate the factors limiting cocoa yield and how to increase yield in cabrucas. I explore the role of shade trees and the nutrient dynamics in litterfall. Finally, I explore the risk that climate change could represent for cocoa production in the future by looking at the effects of an unexpected drought caused by an El Niño Southern Oscillation (ENSO) event between November 2015 and May 2016. My study is based on data collected in permanent transects in 32 randomly chosen cabruca farms in Barro Preto a municipality of Bahia over a period of three years. I also established littertraps in 10 cocoa farms where I intensively studied nutrient dynamics and cocoa yield per tree over 12 months. My results showed that unproductive trees, low cocoa tree density, high shade cover and high cocoa mortality due to drought were the main factors limiting cocoa yield in cabrucas. Surprisingly, adding fertilisers to the cocoa trees did not increase yield. This suggests that there is no nutrient deficiency in cabrucas. In the farms, I found 69 species of shade trees for an average density of 125 ± 32 trees per hectare. Half of the species of shade trees were Atlantic Forest species of conservation value. The litterfall experiment showed the shade tree species and the quantity of litterfall produced, can affect the number of cocoa pods per tree. In cabrucas, a higher number of cocoa pods was found on cocoa trees under shade trees than under no shade. Finally, I showed that the exceptionally severe ENSO-related drought caused 80% loss in yield and 11% cocoa tree mortality in Barro Preto. Climate models predict an increased frequency of strong ENSO events in the future. Farmers in Bahia are not prepared to face regular drought events. The 2015/16 drought affected the dynamics of cocoa production in Brazil: it accelerated the decrease of extensive wildlife-friendly cocoa production in Bahia whereas it increased the development of cocoa production in intensive low shade plantations in the state of Pará. This suggests that climate change could be a threat to traditional cocoa agroforests in Bahia. Developing wildlife-friendly certification schemes and Payment for Ecosystem Services to internalise the value of forest conservation and to encourage farmers to maintain their shade trees could save cabruca systems from going extinct.

Preface

This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except where specifically indicated in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

This dissertation contains less than 60,000 words of length.

Foreword

To facilitate publication of the thesis, Chapters 2 – 4 are written as manuscripts for peer-reviewed journals and have the following authors:

Chapter 2: Gateau L., Tanner E.V.J., Rapidel B., Marelli J-P., (in preparation). Factors limiting cocoa yield and biodiversity conservation in traditional Brazilian agroforests. Intended journal: Agric. Ecosyst. Environ

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Chapter 4: Gateau L., Tanner E.V.J., Rapidel B., Marelli J-P., Stefan Royaert S., (in review). How climate change could threaten cocoa plantations: effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. PLoS One.

As these papers have multiple authors, I use the pronoun "we" rather than "I" where appropriate. Co-author contributions included supervisory guidance (ET, BR, JPM), help with experimental design (ET, BR, JPM), manuscript review (ET, BR), field assistance (WF, SR), and logistic and administrative support (SR, JPM).

At the time of submission, **Chapters 4** is with reviewers in PLoS One and **Chapter 2 and 3** are under review from MARS lawyers to authorise submission to peer-reviewed journals.

Summary

Brazil is the world's sixth largest cocoa producer with 270,000 tonnes of cocoa produced per year. In a world with an increasing demand for chocolate, but with agriculture threatened by climate change, the chocolate industry is worried about a possible shortage of cocoa. Furthermore, growing cocoa is a main cause of deforestation. However, in the state of Bahia, Northeast Brazil, cocoa is grown in traditional agroforests called 'cabrucas' which maintain a forest cover. Cocoa, an understorey crop, is planted under the shade of native Atlantic Forest trees and exotic fruit trees introduced by the farmers. These cabrucas have high conservation value but very low cocoa yield. In my thesis I investigate the factors limiting cocoa yield and how to increase yield in cabrucas. I explore the role of shade trees and the nutrient dynamics in litterfall. Finally, I explore the risk that climate change could represent for cocoa production in the future by looking at the effects of an unexpected drought caused by an El Niño Southern Oscillation (ENSO) event between November 2015 and May 2016. My study is based on data collected in permanent transects in 32 randomly chosen cabruca farms in Barro Preto a municipality of Bahia over a period of three years. I also established littertraps in 10 cocoa farms where I intensively studied nutrient dynamics and cocoa yield per tree over 12 months. My results showed that unproductive trees, low cocoa tree density, high shade cover and high cocoa mortality due to drought were the main factors limiting cocoa yield in cabrucas. Surprisingly, adding fertilisers to the cocoa trees did not increase yield. This suggests that there is no nutrient deficiency in cabrucas. In the farms, I found 69 species of shade trees for an average density of 125 ± 32 trees per hectare. Half of the species of shade trees were Atlantic Forest species of conservation value. The litterfall experiment showed the shade tree species and the quantity of litterfall produced, can affect the number of cocoa pods per tree. In cabrucas, a higher number of cocoa pods was found on cocoa trees under shade trees than under no shade. Finally, I showed that the exceptionally severe ENSO-related drought caused 80% loss in yield and 11% cocoa tree mortality in Barro Preto. Climate models predict an increased frequency of strong ENSO events in the future. Farmers in Bahia are not prepared to face regular drought events. The 2015/16 drought affected the dynamics of cocoa production in Brazil: it accelerated the decrease of extensive wildlife-friendly cocoa production in Bahia whereas it increased the development of cocoa production in intensive low shade plantations in the state of Pará. This suggests that climate change could be a threat to traditional cocoa agroforests in Bahia. Developing wildlife-friendly certification schemes and Payment for Ecosystem Services to internalise the value of forest conservation and to encourage farmers to maintain their shade trees could save cabruca systems from going extinct.

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Chapter 1 | Cocoa production and sustainability: the Brazilian context

1.1 Cocoa and biodiversity conservation -Brazil case

1.1.1 Brazilian cocoa: origins and background

Brazil is the world's sixth largest cocoa producer with 270,000 tonnes of cocoa harvested per year. Cocoa (*Theobroma cacao*) is an understorey tree originally from the Amazon. Cocoa was first introduced in the state of Bahia (on the Atlantic coast) in 1747 as a cash crop for exporting to Europe. Bahia became the world's largest cocoa exporter in 1905-06. In 1957, the Executive Commission of the Cocoa Farming Plan (CEPLAC) was created to provide the cocoa farmers with technical support and to do applied research on cocoa agronomy (e.g fertiliser use, grafting, clonal selection). Most Bahian cocoa is produced in the traditional plantations called 'cabrucas'. Cabrucas are "cocoa planted under large trees retained from the original forest" (Johns, 1999). Most cabruca plantations do not receive any fertiliser or any technical management except manual harvesting. Bahian farmers own large plantations (150 ha on average) and rely on numerous low-paid workers. One of the main drawbacks of the cabrucas are their low cocoa yields with approximately 150 kg/ha of dry cocoa beans per year, compared to 300 kg/ha in West Africa. In the 90's the Bahian cocoa production collapsed due to increasing price of labour, disease pressure and instability of Brazil currency while cocoa prices are established in dollars (cf. Fig. 1.1 Cocoa prices)

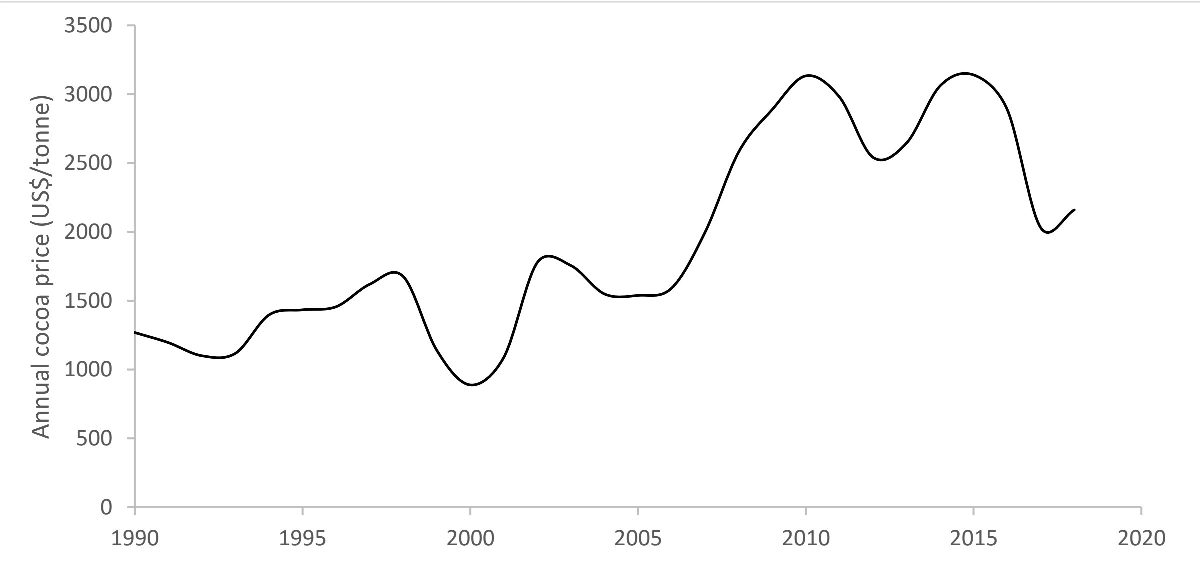

Figure 1-1. World cocoa prices in US dollars (adjusted for inflation) since 1990.

The arrival of a fungal disease known as witches' broom (*Moniliophthora perniciosa*) in 1989 caused a 70% loss of production in 10 years (ICCO, 2013). Twenty years later, the cocoa industry in Bahia is still in crisis: low cocoa yield in aging extensive plantations, low prices for low quality cocoa, almost no support from the authorities and debts which prevent the cocoa farmers investing in the local economy.

1.1.2 Cocoa agroforests as tools for the conservation of the Brazilian Atlantic Forest

In Brazil, 63% of the cocoa is produced in a region where the Atlantic Forest ecosystem is the native vegetation (CEPLAC 2012). The Atlantic Forest is considered as one of the most diverse biodiversity hotspots but also one of the most threatened ecosystems: 93% of the original Brazilian Atlantic Forest has been deforested (Da Fonseca, 1985; Myers et al., 2000). Nature reserves only preserve 9% of the remaining forest and 1% of the original forest (Ribeiro et al., 2009). In Brazil, remnants of Atlantic Forests are preserved under two categories of protected area: public preservation areas (state/national parks, biological reserves and ecological stations) or private preservation areas. Private areas of preservation can be optional or compulsory: optional areas include the Private Reserves of Natural Heritage (RPPN) which are privately protected forests maintained by concerned land-owners interested in conservation; compulsory preservation areas include Legal Reserves (LR) corresponding to 20% of the farmland spared for biodiversity including riparian areas and hilltops and steep slopes (areas of permanent preservation APP) which are required by the 1965 Forest Code (Schroth et al., 2011). All cocoa plantations are located on private land. In the cacao region of Bahia, a survey of three municipalities found that 93% of the land holdings did not have their legal reserves registered by any legal authorities as required by law, even if they had forest remnants in their properties (Fernandes et al., unpublished data in Schrotz 2011). Cocoa landlords were responsible for the clearing of remnants of the Atlantic Forest in the South of Bahia to compensate low cocoa prices (Alger and Caldas, 1994). However, traditional cocoa plantation are also recognised as valuable to protect endangered wildlife such as the golden lion tamarind (*Leontopithecus rosalia*) (Mittermeier et al., 1982), bats (Faria and Baumgarten, 2007) or endemic tree species (Sambuichi et al., 2012). The conservation value of shaded cocoa has been gaining considerable attention in recent years (Parrish et al. 1999; Reitsma et al. 2001; Greenberg et al. 2000). In 1998, the value of shaded cocoa and agroforests for sustainable production and conservation was recognised in a workshop organised by the Smithsonian Tropical Research Institute called ‘Shade Grown Cacao Workshop’ in Panama. Recent studies showed that shaded cocoa production can be associated with a high diversity of species compared to cocoa production in monoculture (Clough et al. 2011; Jagoret et al. 2014; Deheuvels et al. 2014). Currently, cabruca is promoted by the CEPLAC and the Bahian chocolate industry through the name of 'productive conservation' (Setenta and Lobão 2012). However, the yield in cabrucas are low (from 50 to 750 kg/ha/year) compared to the potential yield observed in optimum systems (2-3000 kg/ha/year) (Viana et al. 2011).

1.2 The trends in research on cocoa agroforestry

1.2.1 Trends in research

The value of shade cocoa to provide ecosystem services has been gaining considerable attention (Vaast and Somarriba 2014). The cocoa agroforests provide i) provisioning services: the cocoa beans but also timber and non-timber forest products (fruits and medicinal plants); ii) supporting services such as primary production, plant diversity, nutrient cycling though litterfall or N-fixing trees (Beer 1987); iii) regulating services such as carbon sequestration, water and erosion regulation, pest and disease regulation and provision of habitat for pollinators, and iv) aesthetic service: farmers develop cocoa agrotourism and use aesthetic value of cabrucas as marketing arguments (Bright and Sarin 2003). Cocoa agroforests could also contribute to preserving endangered tree species in the long term (Saj et al., 2017a). Shade tree cocoa plantation are known to have a higher diversity of fauna and flora than any other cocoa production system; however, a review showed that shade cocoa is similar to a degraded form of natural forest (Greenberg, 1998).

Shade trees account for 82% to 86% of total carbon stocks in cocoa agroforests whereas cocoa trees account for 14 to 18% (Saj et al. 2013; Somarriba et al. 2013). Soil organic carbon (SOC) also contributes to C sequestration under cacao agroforests. Soil carbon stock to the depth of 1 m was 320 Mg/ha in 30-year-old cacao agroforestry systems in Brazil (Gama-Rodrigues et al. 2010) and 719 Mg/ha to 1221 Mg/ha to 179-cm depth in 9 cabrucas in Bahia (Araujo et al. 2013). In South America and West Africa, carbon sequestration in agroforests, carbon sequestration trading and REDD+ schemes could increase income in communities of cocoa farmers and indigenous populations (Dawoe et al., 2016; Somarriba et al., 2017; Waldron et al., 2015).

Recent literature on agroforests focuses on the relationships (trade-offs or synergies) between yield and biodiversity conservation. Biodiversity decreased while cocoa yield increased over a threshold of 600 kg/ha in a study in four Latin American countries (Rapidel et al., 2015). Highest yields are found in cocoa plantations with low shade and low diversity (monocultures). Partial win-win scenario for very low cocoa yield (< 250 kg/ha) and high tree diversity has also been found in Ecuador (Waldron et al., 2012). However, other studies have showed that cocoa grown under shade trees have high yields and support high biodiversity in Indonesia (Abou Rajab et al., 2016; Clough et al., 2011) and profitable yields without fertiliser and with high biodiversity in Cameroon (Jagoret et al., 2011). Finally, cocoa productivity is more affected by spatial structure and basal area of the shade trees than species composition (Deheuvels et al., 2012; Saj et al., 2017a).

The relationships between cocoa trees and shading are complex in agroforests. A recent development program promoted agroforestry and encouraged farmers to plant shade trees as a climate resilience strategy (Dinesh et al., 2017). However, the benefit of shade trees for cocoa tree growth and nutrition is still under studied. As opposed to common monocultural crops, in polyculture, other shade tree species could benefit or compete with cocoa trees. Recent studies showed no significant or even negative effects of shade trees on cocoa trees. No significant effect of shade trees on soil fertility was found in cocoa agroforests in Ghana (Blaser et al., 2017) and Indonesia (Wartenberg et al., 2017). Shade trees negatively affected cocoa trees by increasing water competition during drought events in Ghana (Abdulai et al., 2018). Furthermore, shade affected cocoa physiology: in an experiment on young cocoa trees in Ghana, cocoa leaf area was lower under shaded condition; cocoa trees under light shade also had higher photosynthetic rates in the rainy seasons whereas in the dry season there was a trend of higher photosynthetic rates under heavy shade (Acheampong et al., 2013); in another study on 7-years old trees at Ceplac in Brazil, shaded cocoa leaves had lower lifespan than unshaded cocoa leaves. The results of studies on soil fertility, water and light competition need to be seen in local context. However, there are not enough studies to be able to make meaningful generalizations about the effect of shade trees on cocoa trees in agroforestry systems.

1.2.2 Trends in the cocoa industry

Low cocoa yield compared to other commodities remain an issue for the cocoa industry. The Intensification of cocoa plantations to increase yield is possible with modern agronomic approaches: fertiliser, fungicides, pesticides, herbicides, combined with high yielding and disease resistant cocoa varieties. Most chocolate companies invest in supporting farmers to intensify their cocoa production using technological packages through farm schools and development programs: e.g. Cocoa Plan for Nestle, CocoaLife for Mondelez and Sustainable Cocoa Initiative for MARS. Chocolate companies also invest in research on large-scale, mechanised, no shade, irrigated cocoa monoculture. However, less than 30% of farmers plant high yielding genetic varieties in their cocoa plantations in West Africa (Vaast and Somarriba, 2014). Most cocoa farmers do not use fertiliser on their cocoa trees. It is estimated that 21,000 km^2 of deforestation could have been avoided if inputs had been applied to cacao systems in West Africa since the 1960s (Gockowski and Sonwa, 2011).

Cocoa is responsible for deforestation in West Africa, Indonesia and Brazil, which has helped to maintain low chocolate price in the western countries (Sonwa 2004). The chocolate industry and governments of Ghana and Cote d'Ivoire (60% of the world cocoa production is grown in these two countries) launched the Cocoa and Forest Initiative: they pledged to eliminate illegal cocoa production in natural parks and emphasised "growing more cocoa on less land" (http://www.worldcocoafoundation.org/cocoa-forests-initiative/).

1.2.3 Knowledge gap

- *Cocoa and climate change*

Cocoa agriculture is responsible for some climate change through deforestation and direct and indirect greenhouse gas (GHG) emissions (Bennetzen et al., 2016). However, climate change is also a threat to cocoa production by reducing the area climatically suitable for growing cocoa in West Africa (Schroth et al., 2016b). In a study in Bahia, cabrucas are described as climate-friendly systems: they emit low amounts of GHG, sequestrate a large amount of carbon while providing acceptable cocoa yield (50 -750 kg/ha/year) (Schroth et al., 2016a). In a recent review on the effect of abiotic stress (drought, high temperature, increase in CO_2 concentrations) on cocoa trees and the role of genetic biodiversity in building a resilience to climate change, Medina and Laliberte (2017) suggest that there is limited information available and more research is needed on cocoa and climate change.

- *Fertiliser and nutrient dynamic: recent reviews*

The highest cocoa yields can be obtained in systems with low shade and high rates of fertilisers. In shaded agroforests, cocoa yields respond less strongly to fertiliser and the differences in response are poorly understood (van Vliet et al., 2015). Brazilian cocoa farmers, like most cocoa farmers, usually use low amounts of fertiliser or none at all on their cocoa plantations. In a recent review, Snoeck et al. (2016) explored how to increase farmers' acceptance to fertiliser their crop. The authors recommended calculating fertiliser doses based on soil and foliar analyses rather than using a single fertiliser formula. Furthermore, the authors identified a knowledge gap on nutrient flux in cocoa plantations and on the effect of shade trees in fertiliser use. In traditional cocoa agroforest, yield can be maintained for more than 70 years at a level of 350 kg/ha without fertiliser (Jagoret et al., 2011). In a cocoa plantation shaded by *Gliricidia* (a potentially N-fixing tree), yield can be maintained at the level of 700 kg/ha without fertiliser (Bastide et al., 2008). These two studies suggest that shade trees play a role in maintaining cocoa nutrition in agroforestry systems. A harvest of 240 kg/ha/year of cocoa beans corresponds only to 5 kg N, 1 kg P and 4 kg K per hectare being removed each year. However, data are limited on the effect of shade trees on nutrient dynamics in cocoa agroforests.

- *Factors limiting yield (light, unproductive trees, drought, pollinators, self-incompatibility)*

The main environmental factors known for limiting cocoa production include diseases (Bowers et al., 2001), water stress (de Almeida et al., 2002), shade (Ahenkorah et al., 1987), pollination (Groeneveld et al., 2010) and poor genetic material (unproductive cocoa trees) (Jagoret et al., 2017; Wibaux et al., 2017). In a production model fed with field data from 30 locations in 10 cocoa producing countries, Zuidema et al. (2005) showed that weather conditions (rain and radiation) explained 70% of the yield variation. Disease are also responsible for 30% loss in cocoa yield. Most cocoa diseases are due to fungi (*Moniliophthora spp*, *Phytophthora spp)* and there are almost no effective fungicidal treatments. Research institutes and chocolate companies have invested in selecting disease-resistant clones (MARS, 2017), a limited number of which are available to farmers. However, there is no drought-resistant genetic material available for farmers in Brazil. Furthermore, high-yielding clones are selected in optimum conditions, with high inputs and little shade. This genetic material does not perform well in heavily shaded conditions in agroforests. There is a necessity to select shade-tolerant cocoa material adapted to cabrucas. Pollination often limits yield in cocoa: increasing pollination success from 10% to 40% could increase yield by 200% (Groeneveld et al., 2010). Cocoa pods grow from flower cushions located on the trunk (cauliflory) and result from pollination by midges (mainly Diptera*: Ceratopogonidae* and *Cecidomyiidae*). However, the ecology of cocoa pollinator is still poorly understood (Toledo-Hernández et al., 2017). Additionally, the genetic self-compatibility status of the cocoa trees also affects the pollination success: self-compatible trees have been observed to produce 66% more fruits than self-incompatible trees; reducing the proportion of self-incompatible trees could increase yield (Lanaud et al., 2017). Finally, the high tree-to-tree variability in cocoa plantation could limit yield. In a study on 10,000 trees in Cote d'Ivoire, it was found that 20% of the trees accounted for 3% of the production and 20% of the most productive trees were responsible for 46% of the total production (Wibaux et al., 2017). More research is needed to increase yield at individual tree scale and reduce the percentage of unproductive trees in cocoa plantations.

1.3 Thesis aims

1.3.1 *Collaboration and Barro Preto project*

This research is the result of a collaboration between three organisations MARS, the confectionary company through its centre for Cocoa Sciences; CIRAD, the French Agricultural Research Centre for International Development through its “Tropical and Mediterranean cropping system functioning and management” joint research unit (UMR System); and the Department of Plant Sciences at the University of Cambridge, through its tropical ecology group.

My PhD study was within the scope of the Barro Preto project, a five-year development project co-run by the MARS Centre for Cocoa Sciences, the Executive Commission of the Cocoa Farming Plan and farmers from the municipality of Barro Preto, in southern Bahia. The objective of the project in Barro Preto was to enhance cocoa production and Atlantic Forest conservation in traditional agroforestry systems. Since 2011, 11 farmers and one ‘assentamiento’ (smallholder settlement) have been receiving technical assistance and subsidies from MARS and the Executive Commission of the Cocoa Farming Plan to improve their cocoa production. My research aimed to contribute to the science in the project.

1.3.2 *Scientific question*

In this study, I explore the sustainability (the long-term production with limited negative impacts on the local environment) of cocoa production in Barro Preto, Bahia and Brazil, in terms of i) yield and income for the farmers, ii) forest conservation and iii) resilience to climate change. I use on-farm field data collected in the municipality of Barro Preto in the historic cocoa growing area of Bahia state. I address four key questions which aim to understand the functioning of traditional Brazilian cocoa agroforests.

1. What are the factors limiting cocoa yield in cabrucas? (Chapter 2)

2. How can farmers increase income without decreasing the biodiversity? (Chapter 2 and Chapter 5)

3. What are the effects of shade trees on nutrient dynamic and yield in cocoa agroforests? (Chapter 3)

4. How will climate change and particularly increased frequency of severe climatic events affect cocoa production. (Chapter 4)

In Chapter 2, I describe the factors limiting cocoa yield in cabrucas based on my field data but I also look at yield gaps in cocoa. In Chapter 3, I discuss the relationships between shade tree species, litterfall, soil fertility and cocoa yield. In Chapter 4, I explore the effect of climate on cocoa production. More specifically I describe the effect of a severe drought due to the 2015-16 El Niño Southern Oscillation on cocoa plantations based on monitoring within field plots. Finally, in Chapter 5, I discuss my main findings, limitations and propose future work to understand the dynamic of cocoa agroforests and the sustainability of cocoa production in Brazil.

To facilitate publication of the thesis, Chapters 2 – 4 are written as manuscripts for peer-reviewed journals and have the following authors:

Chapter 2: Gateau L., Tanner E.V.J., Rapidel B., Marelli J-P., (in preparation). Factors limiting cocoa yield and biodiversity conservation in traditional Brazilian agroforests. Intended journal: Agric. Ecosyst. Environ

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As these papers have multiple authors, I use the pronoun "we" rather than "I" where appropriate. Co-authors included the co-supervisors of this thesis: EVJ. Tanner (University of Cambridge), B. Rapidel (CIRAD) and J-P. Marelli (MARS) and MCCS staff who contributed to field assistance (W. Farias) and administrative support (S. Royaert) in Brazil.

At the time of submission, **Chapters 4** has been published in PLoS ONE and **Chapter 2 and 3** are under review from MARS lawyers to authorise submission to peer-reviewed journals.

Chapter 2 | Factors limiting cocoa yield and biodiversity conservation in traditional Brazilian agroforests

Abstract

Cocoa yield varies from 40 to 4000 kg/ha depending on the location and the production systems in which it is grown. This study aimed to analysis the cocoa yield gap due to variables at farm, plot and tree scale in traditional cocoa agroforests, Brazil. We surveyed 32 traditional cocoa farms in the municipality of Barro Preto in the state of Bahia, Northeast Brazil. We also collected data in 800 m^2 plots in each farm on environmental, physical and agronomical factors which could limit cocoa yield. Cocoa pod counts made during the peak harvests between March 2015 and December 2017 were used as a proxy for yield. We assessed biodiversity conservation on the farm by measuring the shade tree species diversity. Barro Preto farms were categorised in three groups: 1. 'diversified' farms with lower cocoa yield compensated by greater cattle production and 2. specialised cocoa farms with maximum cocoa yield and 3. high-yielding cocoa farms with higher use of labour. We analysed factors limiting cocoa yield and yield gap using a boundary line approach to predict the potential maximum yield. The average yield for the region, 260 kg/ha/year, was very low probably due to a drought event in late 2015. The yield gap 1 was 176 ± 38 kg/ha, 181 ± 76 kg/ha and 111± 32 kg/ha for farms type 1, 2 and 3 respectively. We found that the main yield-limiting factors were the fungal diseases, the high tree mortality of cocoa trees, the shade and the low density of cocoa trees in the cabruca farms. Biodiversity assessment showed a Shannon diversity index ranging from 0.38 to 2.47. Half of the 69 shade tree species identified in the cocoa farms were Atlantic Forest species of conservation value. Shade tree density and shade level (GSF) were factor limiting yield which suggest a trade-off between cocoa yield and tree conservation. To close the yield gap, unproductive cocoa trees should be replaced by high yielding trees at single tree scale. However, cocoa farmers are facing economic difficulties and cannot invest in rejuvenating and densifying their cocoa plantations. Developing rainforest friendly certification scheme advocating cabrucas' biodiversity to increase the very low value of cocoa beans could help the farmers to maintain these aging agroforests.

2.1 Introduction

Cocoa is the raw material for chocolate, an industry worth $98.3 billion in 2016 (Potts et al., 2014). Originally from the Amazonian forest, cocoa trees (*Theobroma cacao*) are often grown in cocoa AgroForestry Systems (cAFS) in the tropics. Cocoa agroforests are agricultural systems mixing cocoa trees with other species. They range from low diversity such as cocoa mixed with banana, rubber or coconut, to high diversity when cocoa is mixed with native forest species and planted species. In Brazil, the world's sixth largest cocoa producer, cocoa is grown in cabruca agroforests, a type of agroforestry system where cocoa is shaded by a mixture of remaining native Atlantic Forest species of conservation interest and introduced exotic tree species which provide fruits, timber and N-fixation (Lobão et al., 2004). Cabrucas have been recognized to have high environmental and cultural value (Lobão, 2007; Martini et al., 2007). In the cabrucas, the diversity of shade trees provides a range of benefits such as carbon sequestration (Schroth et al., 2015), soil preservation (Araujo et al., 2012), pest regulation (Sperber et al., 2004) and biodiversity conservation (Sambuichi et al., 2012). Cabrucas create corridors or stepping stones for endangered species between highly fragmented remnants of Atlantic Forests (Cassano et al., 2009; Schroth et al., 2011). However, since the end of the 60's, aging cabrucas systems have been slowly disappearing and are often replaced by pasture (Johns, 1999; Rolim and Chiarello, 2004).

One of the main drawbacks of these traditional agroforests are their low cocoa yields. The average yield in Brazilian cabrucas is approximately 150 kg/ha of dry cocoa beans per year, compared to 300 kg/ha in West Africa, where most cocoa is grown, to over 4000 kg/ha in highly intensified plantations in Asia or Central America. The highest yielding cabrucas produce 585 kg/ha (Schroth et al., 2016a), so there is a great difference between maximum attainable yield and observed yield (i.e. a 'yield gap', van Ittersum et al. (2013)). This variability in yield is due to spatial variability of factors affecting yield such as management practices and environmental variables. The main limiting factors in cocoa can be identified using yield gap analysis (Lobell et al., 2009).

Heavy shade due to the high density of shade trees is thought to be the main factor limiting yield in cabrucas (Wessel, 1985). However, several studies have shown that shade tree density and species composition is not a main limiting factor in cocoa agroforests. Cocoa trees can reach high yield (> 700 kg/ha) while co-existing with a high density and diversity of shade trees (Abou Rajab et al., 2016; Kieck et al., 2016; Saj et al., 2017b). There is a need to identify the relationship between biodiversity conservation and yield in cabruca systems in order to preserve these unique agroforestry systems.

There is a high variability between cabruca farms. This diversity is due to several factors including: the environmental context of the farm (location, typography, soil, access to water), the socio-economical context (property type, size of the farm, labour, age and history of the farm, diversity of income) and the management practices (shade trees, varieties of cocoa, densities of trees, regular management such as pruning or weeding). This diversity between farms affects the cocoa production: all farms cannot be considered as similar entities when considering yield. Furthermore, there is a high variability in cocoa production from one harvest to another and from one year to another.

This study uses farm typology and biodiversity assessment combined with yield gap analysis to identify the factor(s) limiting cocoa yield in cabrucas. We used a typology, a comparative framework to classify farming systems based on socio-economic and agronomic criteria to cluster farms with similar agricultural practices and similar yield.

Our study aimed to i) identify the main factors limiting yield in cabrucas; ii) assess the biological diversity of the cabrucas in Barro Preto, Bahia; iii) identify trade-offs and opportunities to increase yield while maintaining shade tree biodiversity.

2.2 Materials and methods

2.2.1 Study area and selection criteria for the farms

The study area was the municipality of Barro Preto (14.05° S, 39.04°W, 16,000 ha, c. 150 m a.s.l.) in the Southern region of Bahia State, Brazil. The climate is tropical with a mean annual temperature of 26°C and an annual rainfall of 1608 mm per year with May and September being the driest months, with, respectively, 110 mm and 67 mm (tropical moist forest). The soils are highly weathered reddish-yellow Ferralsols (USDA classification: Oxisols) with predominance of low-activity clays, such as kaolinite and gibbsite, and iron oxi-hydroxides (Sambuichi et al. 2012).

The study was conducted on 35 cocoa farms with homogeneous traditional agroforestry systems (cabruca), randomly selected from the 333 farms identified in the 2014 agricultural census from the Executive Commission of the Cocoa Farming Plan (CEPLAC) for Barro Preto. For each farm, the study included one socio-economic assessment based on semi-structured interviews with the administrator of the farm and one agro-environmental assessment based on permanent transects in the plantation. Three farms were removed from the analysis for logistic reasons: two farms were sold to new landlords during the study and one landlord asked to be removed from the study (Fig. 2.1).

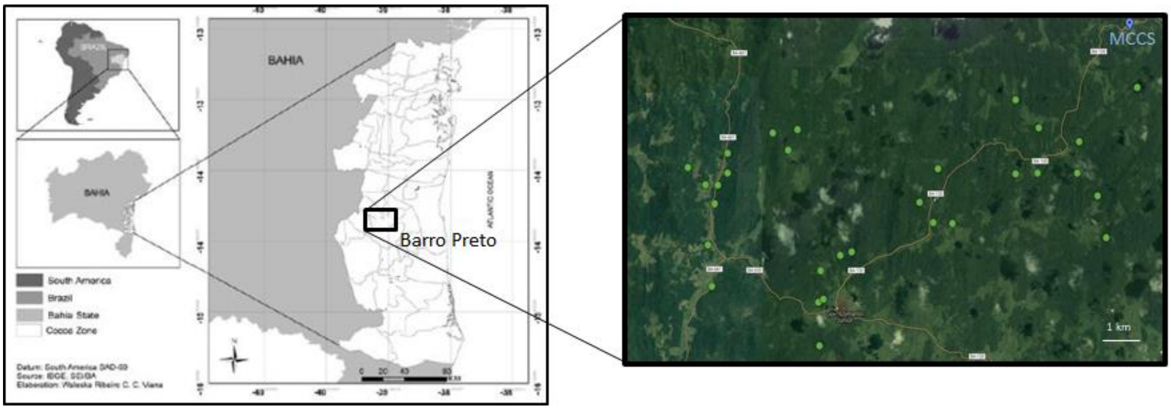


Figure 2-1. Cocoa farms in Barro Preto in the cocoa producing region of Bahia state, Brazil.

A framework of three sub-systems (biophysical, technical, and decisional) can be used to describe and improve agricultural production systems (Le Gal et al., 2010). Data collected in each cocoa farm described the decisional sub-systems (at farm scale) and the technical and biophysical sub-systems (at plot scale) cf Fig. 2.2.

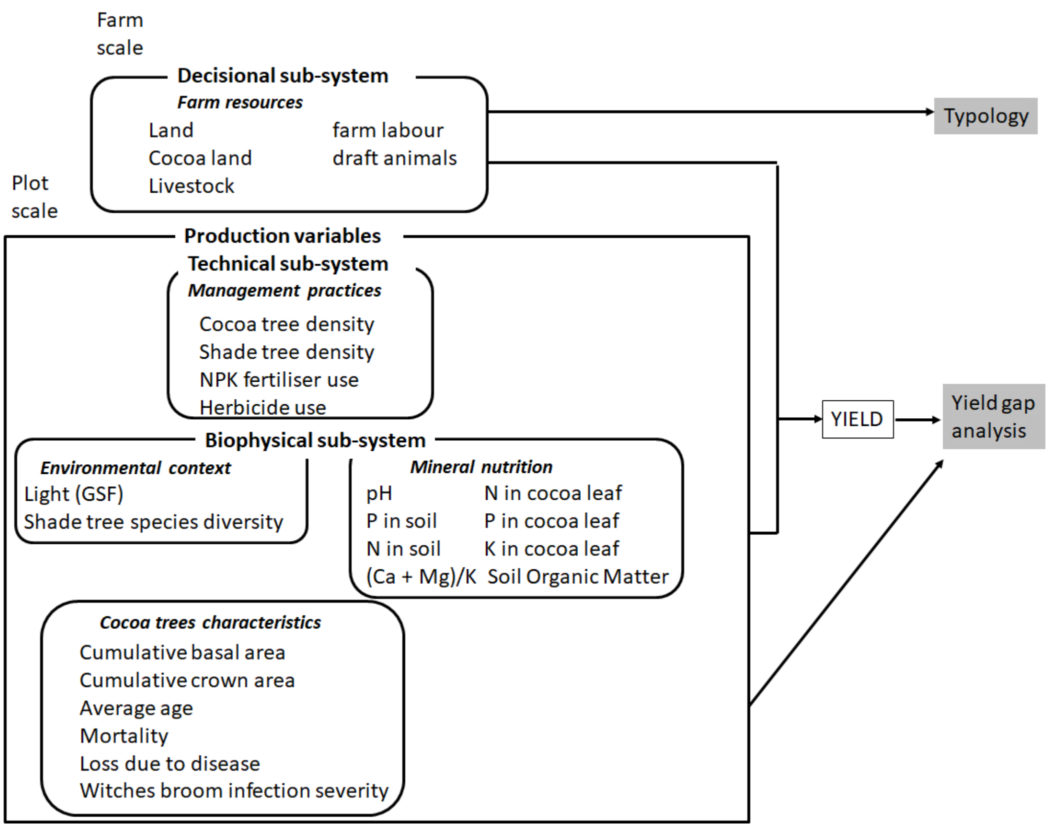


Figure 2-2. Data collected on-farm to describe three agricultural sub-systems: decisional, technical and biophysical

We combined farm typology with yield gap analysis.

2.2.2 Farm typology

Farm typology was based on data at farm scale collected using semi-structured interviews with the farm administrator between March and June 2015. Data collected included the characteristics of each cocoa farm (total area of the farm, percentage of area cultivated for cocoa, quantities of fertiliser and herbicide (glyphosate) use per ha) and socio-economic data (labour in workers per ha, draft animal per ha and livestock production in Tropical Livestock Unit (TLU). TLU is a livestock grazing unit used by the FAO corresponding to an animal of 250 kg liveweight, "tropical cows" being considered smaller than cows in Europe (600kg) (Jahnke, 1982). see Table 2.1.

Table 2-1. Variables used to create a typology of farms

Variable	Abbreviation	Unit
Total farm area	TotalArea	ha
Percentage of area planted with cocoa	PerCocoaArea	%
Livestock	TLU	Tropical Livestock Unit
Total labour for cocoa	LabourHa	worker/ha
Draft animal	AniLabHa	animal/ha
Intensity of NPK* fertiliser use	FertiHa	kg/ha
Intensity of herbicide use	GlyphoHa	kg/ha of glyphosate

* as N, P_2O_5 and K_2O that is 16% N, 24% P and 16% K

Annual cocoa production for the farm was calculated as an average of the total farm harvest for the two previous years (i.e. 2014 and 2015).

We used Principal Component Analysis (PCA) on the farm variables followed by a hierarchical cluster analysis (HCA) to identify a typology for the 32 agroforests following the approach described by Blazy et al. (2009). Performing a PCA allowed us to reduce the weight of outliers before performing the HCA. Data were analysed using FactoMineR and factoextra packages in Rstat (R Development Core team, 2008).

2.2.3 Variables considered in the yield gap analysis

The yield gap is the difference between the actual farm yield and the maximum yield that could be achieved under the same agro-environmental conditions. Identifying the variables responsible for this yield gap (limiting factors) can help the farmers increase their productivity (van Ittersum et al., 2013). We studied the possible factors limiting cocoa yield in each farm using 800 m^2 permanent transects (100 m x 8 m) in the area of the agroforest defined as representative of the farm by the farm administrator (the landlords usually live in bigger cities distant from their farms). Transects were installed in March 2015. We explore variables limiting yield at plot scale.

2.2.3.1 Plot scale measurement

Data collected at plot scale are summarized in Table 2.2. and included: cocoa tree density, shade tree density and species composition identified by their colloquial name by local experts (used for calculation of Shannon H'), percentage of amelonado (an Amazonian forastero, the historically most common cocoa variety in Bahia) in the plot, cocoa tree mortality (percentage of dead cocoa trees in the transects 6 months after a main drought event) and percentage of pod loss due to fungal disease (percentage of rotten pods, counted on the tree relative to total pod number per transect). The main loss related to fungal disease for the region is due to *Moniliophthora perniciosa* (witches' broom). We described the fungal infection on the vegetative part of the cocoa trees by attributing a score from 0 to 1.5 based on a visual assessment of the infection (0: no visual symptoms and 1.5: maximum symptoms all the tree cover with brooms). We also estimated the production loss due to fungal disease by counting the number of rotten pods per tree during each harvest and converting this pod number into kg/ha. We collected data on shade cover by measuring the gap fraction using hemispherical picture: one picture was taken every 10 m along the transect, above the cocoa tree but below the shade tree canopy to define an average percentage of canopy cover per transect. We used an EOS 5D Nikon camera with a hemispherical lens, attached to a telescopic gimbal. All pictures were analysed using Canopy analyser HEMIv9 (HemiView, delta-T, Cambridge, UK) to produce gap fractions which were converted into Global Site Factor (GSF) which is the proportion of global solar radiation (direct and diffuse) at a given location relative to that in the open and integrated over time.

Data on soil nutrients were collected. Six soil samples (depth = 0–15 cm) were taken in each transect using an auger in zig-zag locations along the 100 m line of the transect and combined to form a composite sample. Five fresh cocoa leaves per tree were sampled in zig-zag locations on 6 cocoa trees along the 100 m line of the transect, oven-dried 5 days at 70°, ground and combined to form one composite leaf sample per farm. All samples were sent to an external Brazilian laboratory for analysis. Soils were analysed for pH, organic matter (oxidation with $Na_2Cr_2O_7$ / 10 M H_2SO_4), 'available' P (Mehlich 0.05 M HCl + 0.0125 M H_2SO_4), exchangeable K, Ca and Mg and total soil N (Kjedahl). The concentration and competition of ions in soil is expressed by the relation (Ca+Mg)/K. Cocoa leaves were analysed for N, P, K content (Kjeldahl method for N and nitro-perchloric decomposition for P and K).

Data on the characteristic of the cocoa trees which could affect the yield were also collected: cumulative basal area of the cocoa tree (calculated from the diameter at breast height of the trees in each transect), cumulative area of the crown of the cocoa trees (each tree crown was calculated from the maximum length times maximum width treated as an ellipse) and the average age of the trees in each plot (estimated based on the average age of the different stems and graftings given for each cocoa trees by the administrator of the farm).

Table.2-2. List of variables collected on the cocoa transects.

Category	Variable	Abbreviation	Unit
	Cocoa tree density	DensityC	unit per ha
	Shade tree density	DensitySh	unit per ha
	Shannon diversity Index	ShannonH	
	Mortality of cocoa tree	Mortality	%
	Production loss due to fungal diseases	ProdLoss	kg/ha
	Witches' broom infection score	WB	0 to 1.5
	Global Site Factor	GSF	%
mineral nutrition	Soil pH	pH	
	Soil P	P	mg/g
	Soil (Ca+Mg)/K	(Ca+Mg)/K	-
	Soil Organic Matter	SOM	mg/g
	N concentration in cocoa leaf	Leaf N	mg/g
	P concentration in cocoa leaf	Leaf P	mg/g
	K concentration in cocoa leaf	Leaf K	mg/g
cocoa tree characteristics	cumulative cocoa tree basal area	BA	cm/ 800m2
	cumulative cocoa tree crown area	Crown	m2/ 800m2
	average cocoa tree age	AverageAge	years
	Yield	yield	kg/ha(/year)

2.2.4 Productivity

The number of pods (>10 cm) per transect were used as a proxy indicator of productivity in kilogram per hectare of dry beans. We assumed 40 g of dry beans per pod as a conversion factor (Appendix 2.1.). Pods were counted during the main peak harvests for Barro Preto, that is between April and June and during the secondary peak harvest, that is between October and December over a period between April 2015 and December 2017. Cocoa pods were counted over three main peak harvests and two secondary peak harvests between April 2015 and December 2017. The secondary peak harvest for the first year (October to December 2015) was not recorded for logistic reasons. Thence, we extrapolated the 2015 secondary peak harvest from the 2015 main peak harvest, based on the assumption that the main harvest and the secondary peak harvest corresponded to 2/3 and 1/3 of the yearly production respectively. This allowed used to compare three years of production: 2015, 2016 and 2017.

2.2.5 Yield gap analysis using the boundary line approach

Yield gaps are the difference between yield potential (modelled or defined) and average farmers' yields over some specified spatial and temporal scale of interest (Lobell et al., 2009). To calculate the cocoa yield gaps (Ygap) over 3 years in Barro Preto, we used the method developed for coffee by Bhattarai et al. (2017) based on the boundary line approach which was first developed by Schnug et al. (1996) to establish critical nutrient values in soil and plant analyses. Later, boundary lines were built using scatter plots with biophysical and environmental factors (x-axis) and crop yield (y-axis) to define which biophysical and environmental factors were limiting yield in cassava (Fermont et al., 2009), banana (Wairegi et al., 2010) and coffee (Bhattarai et al., 2017; Wang et al., 2015) plantations.

In this study, potential yield were estimated using boundary lines drawn using quantile regressions (Egli and Hatfield, 2014; Makowski et al., 2007). Quantile regression is a type of regression analysis which aims at estimating either the conditional median or other quantiles of the response variable and is robust against outliers (Koenker and Hallock, 2001). We used "quantreg" package in R and we chose a quantile parameter value of $\tau = 0.90$. One regression line was built for each variable (Table 2.2) using the three annual yields observed in each of the 32 farms.

Observed yield (Yobs): annual yield observed per farm based on cocoa pods counted over three years (2015, 2016, and 2017). These observations were used to draw the boundary lines.

Attainable yield (Yatt): highest yield observed in each cabruca farm among the tree years of study (2015, 2016 and 2017).

Predicted yield (Y90): yield predicted by the boundary line for each studied variable. It represents the maximum predicted yield for all cabruca farms under the limitation of each variable (cocoa tree density, shade trees, Shannon's H', mortality, soil composition SOM and pH, cocoa leaf composition, GSF, cumulative BA, crown area, average age, yield loss pods and witches' broom score).

Yield gap (Ygap): the difference between the highest attainable yield per farm and the yield predicted by the boundary line for each farm. This corresponds to the difference between attainable yield and maximum yield (Yatt-Y90) for each farm.

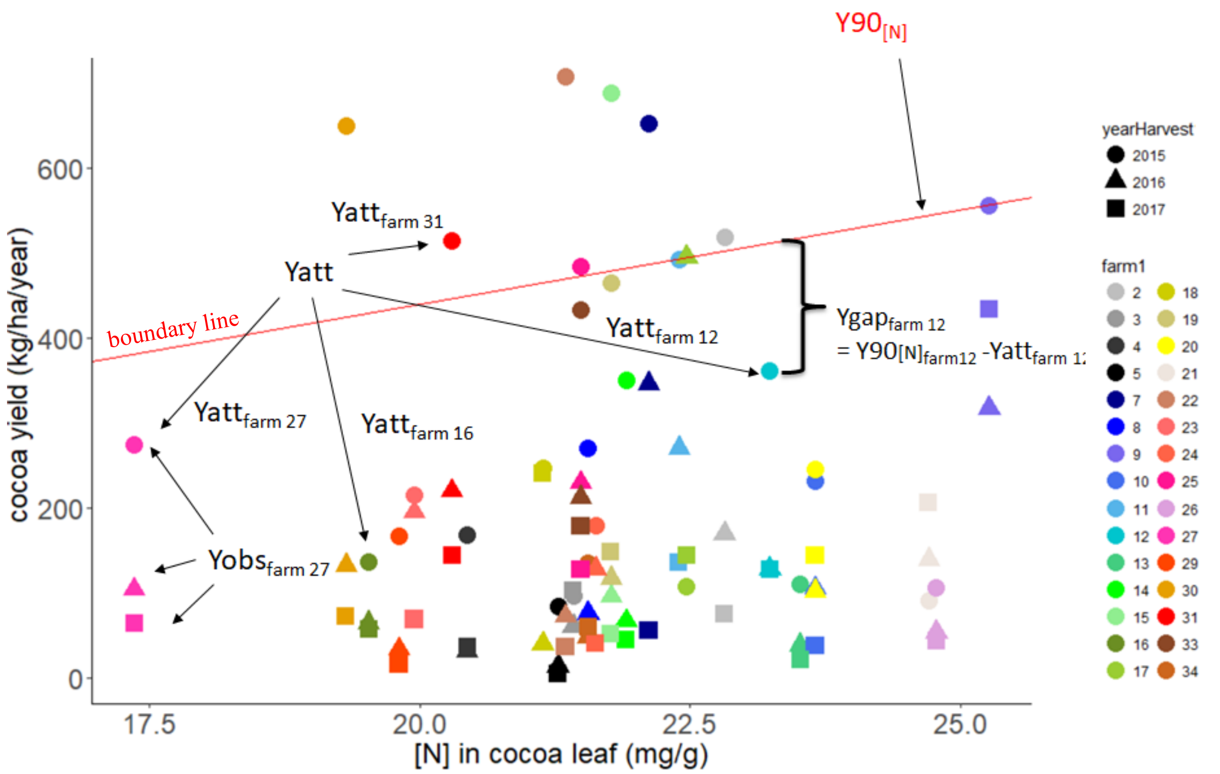


Figure 2-3. Explanation graph for defining: observed yield (Yobs), attainable yield (Yatt), yield predicted by the boundary line (Y90) and the yield gap (Ygap) which is difference between Y90 and Yatt.

Yield gap as percentage of attainable yield

For all 35 farms the attainable yield per farm (Yatt) was identified as the highest observed yield among the 3 annual yields measured between 2015 and 2017. The yield gap of each farm (Y90-Yatt) was expressed as a percentage of the highest observed yield (Yatt) for each variable. Y90 which is the yield predicted by the boundary line corresponding to this farm for each of the 17 variables. For each farm, 17 yield gaps (one for each variable) were calculated. The yield gaps of the 35 farms as a percentage of attainable yield were summarised per variable in a boxplot.

Factor limiting yield per farm type

Initially, the 17 studied variables were all potentially yield limiting factors. We hypothesised that low cocoa tree density, low light (GSF) and low mineral nutrition (low soil P, low Ca+Mg/K, low SOM and low N, P and K in leaves), low pH (high acidity) and small trees (low BA and low crown area) would limit cocoa yield. Conversely, high shade tree density, high diversity (Shannon's H'), high cocoa tree mortality, high loss due to fungal diseases or high witches' boom infection and high age of plantations were also expected to limit cocoa yield.

To identify the variables which were the most yield-limiting, we compared for each farm the maximum yields predicted by the 17 boundary lines: the variable corresponding to the lowest Y90 was the main factor limiting yield for this farm (for example K in leaf is the limiting variable for farm 12 in Fig. 2.4). The frequency each of the 17 studied variables appeared as limiting was summarised using the typology of the farms.

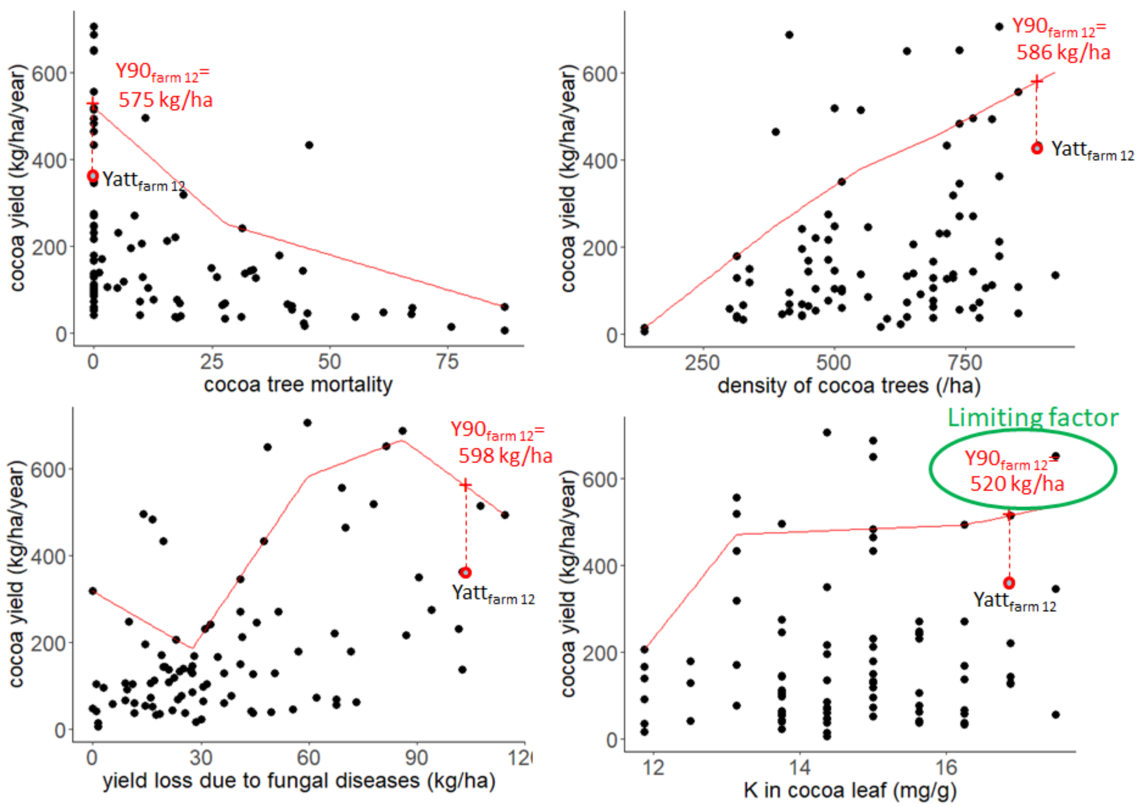


Figure 2-4. Example of identifying the variable limiting yield among 4 studied variables for the cabruca farm 12. The limiting variable for farm 12 is K in cocoa leaf which is associated with the smaller Y90. Red line is the boundary line for each variable. Red circle is the observed yield corresponding to the maximum yield found on farm 12 comparing year 2015,2016 and 2017 (Yatt). Red cross is the yield predicted by the boundary line corresponding to farm 12.

2.2.6 Biodiversity inventory

We made the hypothesis than high diversity of shade tree species was not the main limiting factor and that high yield could be compatible with high diversity. In this section we described the diversity of shade trees species found in the 32 cabruca farms. In cocoa agroforests, the diversity of the shade trees and plants intercropped with the cocoa trees could be used as a proxy indicator for biodiversity (Rice and Greenberg, 2000; Steffan-Dewenter et al., 2007). Our assessment included exotic and endemic Atlantic Forest species. Non-woody species such as banana trees were excluded. In the 800 m^2 plots we identified the species and we assessed the density of shade trees, their DBH, height and age. We calculated the Shannon index H for species diversity based on the number of tree species and individuals per farm plots. We established a species accumulation curve of the shade tree species based on the 800 m^2 plots in the 32 farms using "vegan" package in R. This species accumulation curve was compared to accumulation curved found for cocoa plantations in five Latin American countries (Somarriba et al., 2013).

2.3 Results

2.3.1 Agroforests structure and typology

The first two axes of the PCA contain 53.1% of the variation in the sample (Fig. 2.5). Cocoa farms separated into three groups: in group 1 (in green), cocoa plantations associated with lowest livestock production and largest farm area. In group 2 (in blue) cocoa farms were associated with highest fertiliser use. In group 3 (in purple) cocoa farm had the lowest fertiliser use and smallest area but highest labour input. One unique farm (2) with highest Tropical Livestock Unit (TLU), draft animal labour and total farm area was not part of the 3 clusters. The use of herbicide did not contribute to the 2 first axes of the PCA.

Figure 2-5. Principal component analysis of 32 cocoa farms in Barro Preto. The correlations between 7 variables describing the farms management and characteristics: annual cocoa yield per ha (yield), farm size (TotalArea), percentage of cocoa area (PerCocoaArea), livestock (TLU), draft animal labour (AniLabHa), labour (LabourHa), fertiliser use (FertHa), herbicide use (GlyphHa) are projected on the two first axes explaining 50.1% of the variation. The two colours define the three groups of farms: group 1 in blue and group 2 in green and group 3 in purple.

Average variables for each of the three farm types are summarised in Table. 2.3.

Table 2-3. Average characteristic for each farm category. Different letters indicate significant differences (Tukey's HSD, P<0.05) between groups.

	Group 1		Group 2		Group 3		Significant difference
Labour (unit/ha)	0.1	± 0.0	0.1	± 0.0	0.2	± 0.1	
Total area (ha)	146.0	± 24.8	52.8	± 14.8	50.4	± 8.7	*
Percentage of area planted with cocoa	67.6	± 5.5	80.0	± 7.6	62.7	± 5.6	
Animal labour (numbers of donkeys and horses)	4.8	± 1.4	1.0	± 0.3	1.6	± 0.3	*
Tropical Livestock Unit (TLU)	60.8	± 26.7	0.0	± 0.0	5.4	± 1.8	*
Herbicides (kg/ha glyphosate)	3.8	± 1.9	4.2	± 2.1	4.0	± 1.1	
Fertiliser (kg/ha NPK)	14.0	± 9.5	119.2	± 9.5	3.7	± 3.7	*

These three groups corresponded to different decisional and technical farm managements which affected the cocoa yield.

2.3.2 Productivity and yield gap

2.3.2.1 Yield variability

The average cocoa yield calculated from the pod counts in the 32 transects during the peak harvests between April 2015 and December 2017 in kg/ha of dry cocoa beans are summarized in Table 2.4. The yields were significantly higher for group 3 than for group 2 and for group 2 than group 1 (Tukey's HSD, $P < 2.10^{-6}$).

Table 2-4. Average yield in kg/ha/year for three annual harvests: sum of main peak harvest (April) and second peak harvest (November) per year.

Year of harvest	Group 1		Group 2		Group 3	
2015	264.6	± 55.0	317.7	± 110.4	378.8	± 49.3
2016	118.4	± 23.3	142.3	± 69.0	158.7	± 28.8
2017	75.9	± 22.2	92.1	± 43.5	124.0	± 24.9

2.3.2.2 Yield limited factors and yield gap analysis

The relationships between cocoa yield and potentially yield-limiting variables and their boundary lines are shown Fig. 2.6.

Two boundary lines had negative slopes which suggest that the maximum yield was reach for the minimum values of the variable: cocoa trees' mortality, witches' broom score and Shannon's H'. Most mineral nutrition variables (Ca+Mg/K and N, P, K in leaf) and cocoa tree density had boundary lines with positive slopes, which suggest that increasing mineral concentrations and increasing the density of cocoa trees, increased yield. Soil organic matter and pH had flat boundary lines. The boundary lines for the variables soil P, BA area and crown area, had positive slopes before decreasing. Two variables related to shade tree reached a plateau before decreasing: density of shade trees and GSF. The boundary line for the average age of the cocoa trees decreased up to 20 years before increasing again. Finally, the boundary line for the yield loss due to fungal disease first decreased before increasing up to a peak before decreasing again.

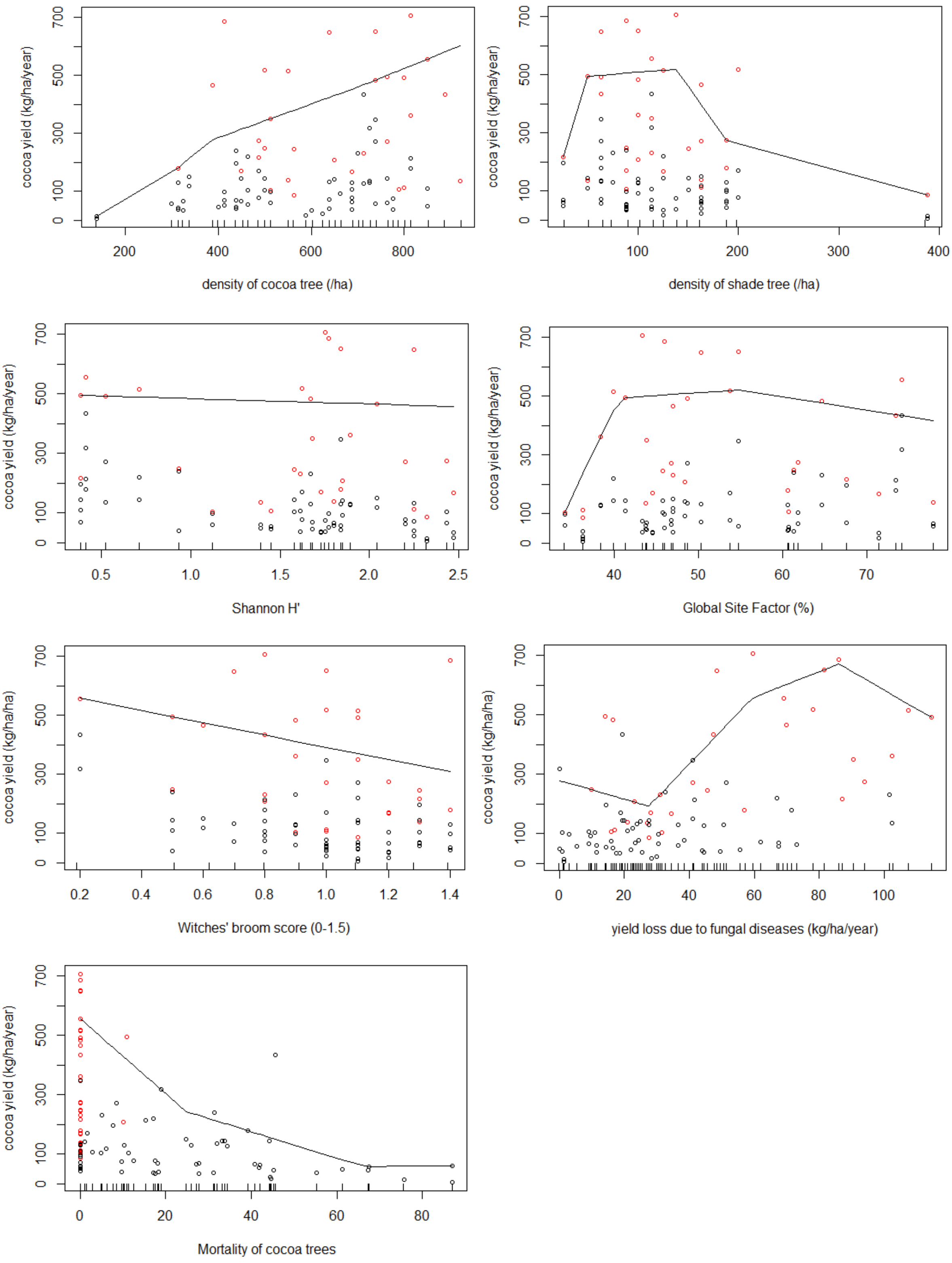


Figure 2-6. Quantile regressions(τ = 0.90) between annual cocoa yield per farm (2015, 2016 and 2017) and potentially yield-limiting production variables including: management variables (cocoa and shade tree densities, Shannon's H and average GSF), mineral nutrition variables (pH, Soil organic matter, soil P, Soil Ca+Mg/K and leaf NPK), other biophysical variables (cocoa tree mortality due to drought, yield loss due to fungal disease, witches' broom score) and cocoa trees characteristic (basal area, crown area and age). Red points represent the maximum attainable yield among the 3 years for each farm (Yatt).

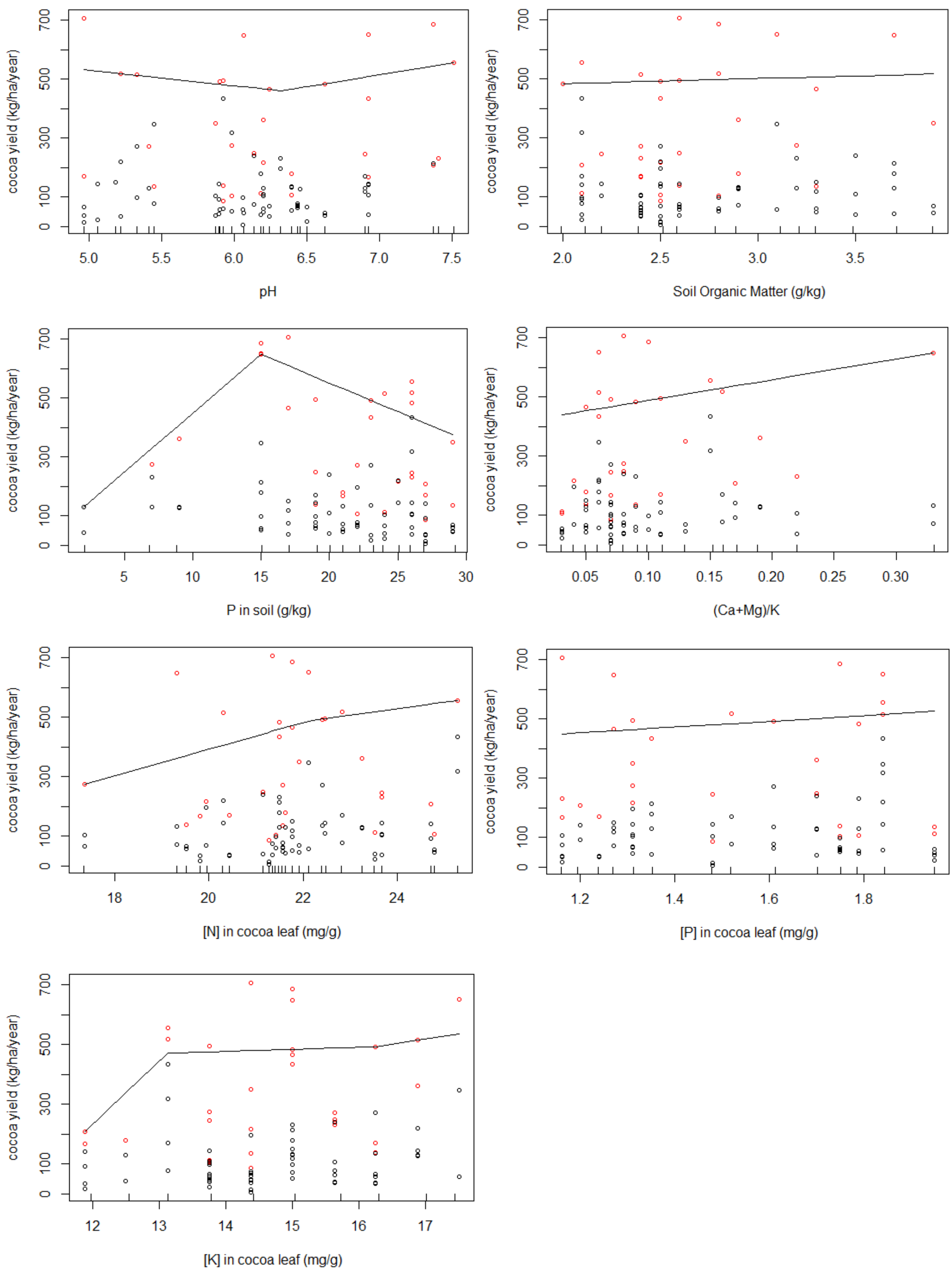


Figure 2-6 cont. Quantile regressions (τ = 0.90) between annual cocoa yield per farm (2015, 2016 and 2017) and potentially yield-limiting production variables including: management variables (cocoa and shade tree densities, Shannon's H and average GSF), mineral nutrition variables (pH, Soil organic matter, soil P, Soil Ca+Mg/K and leaf NPK), other biophysical variables (cocoa tree mortality due to drought, yield loss due to fungal disease, witches' broom score) and cocoa trees characteristic (basal area, crown area and age). Red points represent the maximum attainable yield among the 3 years for each farm (Yatt).

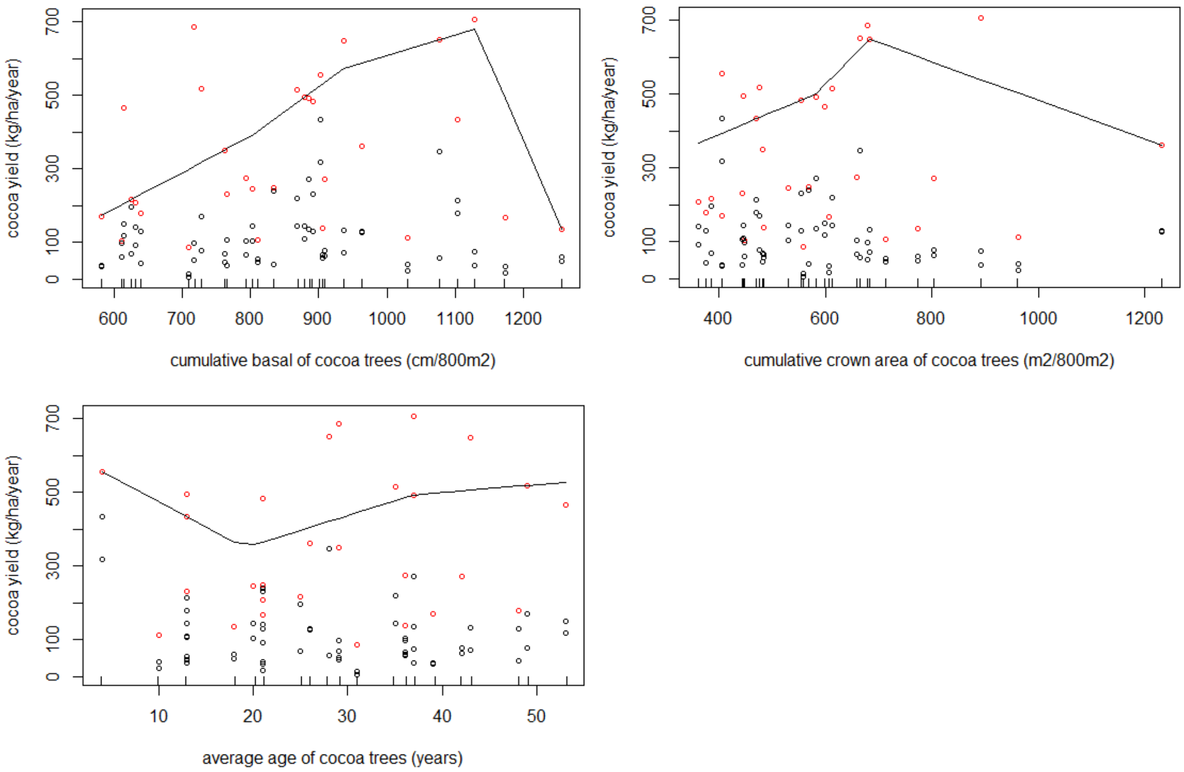


Figure 2-6 cont. Quantile regressions (τ = 0.90) between annual cocoa yield per farm (2015, 2016 and 2017) and potentially yield-limiting production variables including: management variables (cocoa and shade tree densities, Shannon's H and average GSF), mineral nutrition variables (pH, Soil organic matter, soil P, Soil Ca+Mg/K and leaf NPK), other biophysical variables (cocoa tree mortality due to drought, yield loss due to fungal disease, witches' broom score) and cocoa trees characteristic (basal area, crown area and age). Red points represent the maximum attainable yield among the 3 years for each farm (Yatt).

We performed a quantile regression (τ = 0.90) to assess the interaction effects. Cocoa yield in the cabruca farms was significantly affected by the variables: yield loss, the interaction yield loss and witches' broom score, yield loss and sum of basal area of cocoa trees, yield loss and soil organic matter (cf Appendix 2.2).

Yield gap as percentage of attainable yield

The limiting variables for which the yield gap corresponded to the highest percentage of the attainable yield (Yatt) included: yield loss due to disease (c. 40%), density of cocoa tree, cocoa tree mortality, witches' broom score and cocoa tree basal area (c. 30%) (Fig. 2.7).

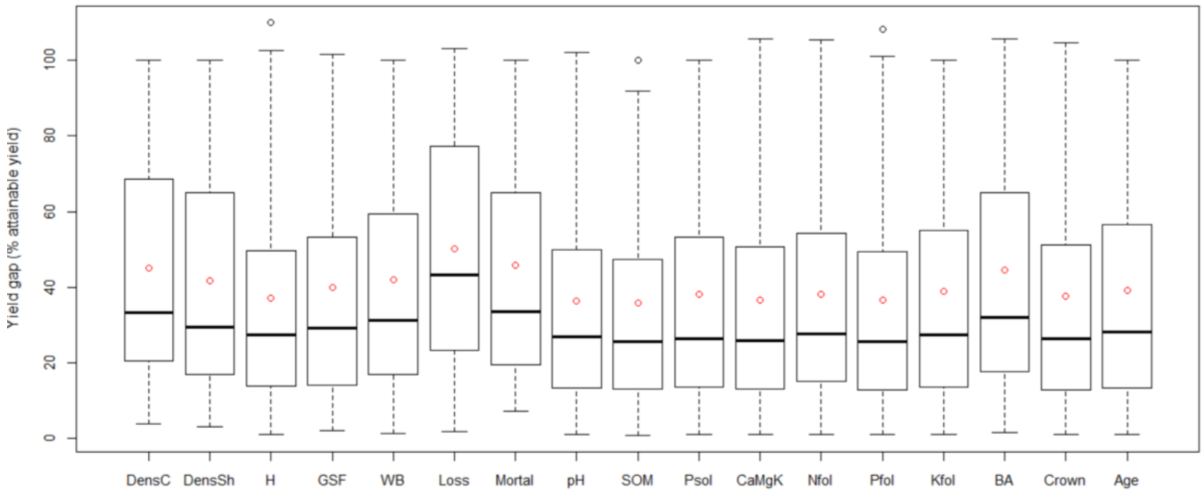


Figure 2-7. Yield gap as percentage of attainable yield explained for 17 studied variables. Red dot represent means.

The average yield gaps (Ygap) by farm type were obtained by the subtracting the yield predicted by the boundary lines (Y90) with the maximum yield observed across the three annual harvests (Yatt). Across all variable and all farms, average yield gap was 176 ± 38 kg/ha for group 1 farms (cattle intensive), 181 ± 76 kg/ha for group 2 farms (cocoa intensive) and 111 ± 32 kg/ha for group 3 farms.

Yield limiting factor per farm type

We identified the main yield limiting factors per farm and per year - the factors corresponding to the minimum value predicted by the boundary lines (Y90) after comparing across the 17 variables. The main limiting factor in the group 1 farms were yield loss due to fungal diseases, cocoa tree mortality, soil P and leaf K. The main limiting factor in the group 2 farms were high witches' broom infection score, yield loss due to fungal diseases, cocoa tree mortality and low cocoa density. The main limiting factor for group 3 were yield loss due to fungal diseases and cocoa tree mortality (Fig. 2.8).

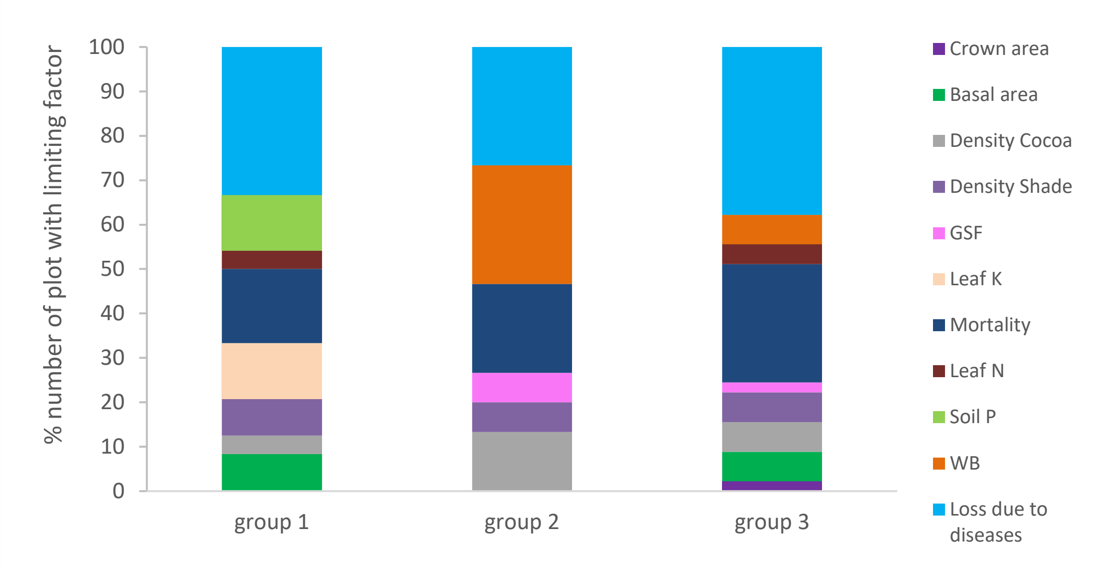


Figure 2-8. The main yield limiting factors per group of farms: cocoa tree density, shade tree density, Global Site Factor (GSF), cocoa tree mortality, leaf K, soil P, leaf N, cocoa basal area, crown area of cocoa trees, witches' broom score (WB) and yield loss due to fungal disease. Group 1, 2 and 3 are based on the typology of the 32 farms.

2.3.3 Biodiversity

We identified at least 69 species of shade tree and 343 individuals in the 32 plots (see appendix 2.3. List of species). Shannon's diversity index (H) was on average 1.55 ($e^{1.55}$= 4.7 species equivalent) for the 32 farms and ranging from 0.38 to 2.47 (1.5 to 12 species equivalent). Half of these shade tree species were native Atlantic Forest trees. The most abundant were introduced species: *Artocarpus heterophyllus*, *Citrus spp* and *Erythrina spp*. Endangered and vulnerable IUCN red-list species were identified such *Dalbergia nigra*, *Plathymenia foliosa* and *Cariniana legalis*.

Accumulation curves plot the number of species as a function of the number of samples. The accumulation curve for the 32 transects did not reach a plateau which suggests that a larger number of species would be identified if more farms were sampled (Fig. 2.9). Compared to five other Latin American cocoa growing regions, Brazilian cabrucas reached higher shade tree diversity than Guatemala agroforests, but lower than in Panama or Honduras.

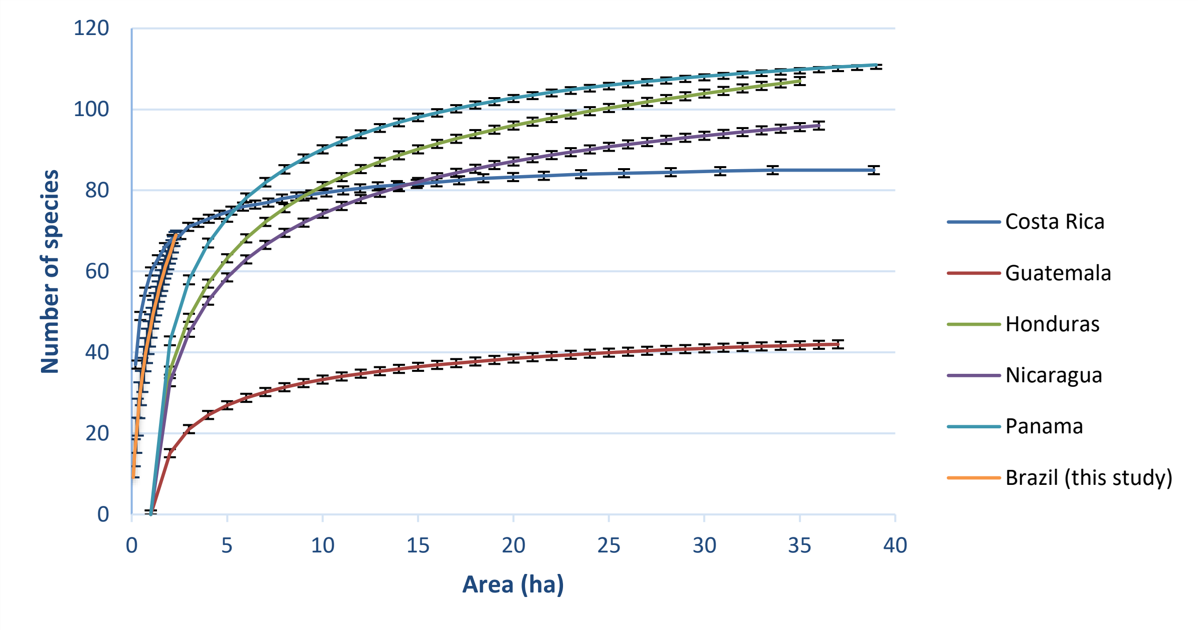


Figure 2-9. Species accumulation curve for the 32 cocoa agroforestry plots in Barro Preto in orange compared to accumulation curves for 5 Latin American countries (modified from Somarriba et al., 2013)

2.4 Discussion

2.4.1 Farm typology

The three groups of farms were mainly defined by their yield, the size of the farm, the labour, the percentage of farm area dedicated to cocoa and the size of the cattle herd: group 1, ‘diversified’ farms, had the largest farm area, with larger cattle production and lowest cocoa yield; group 2 farms ‘intensive cocoa’, had the largest percentage of the total area planted with cocoa, no cattle production, higher fertiliser use and intermediary cocoa yield; group 3 farms ‘labour-intensive’, had the larger use of labour per hectare, marginal cattle production and the highest cocoa yield. All types of farms have similar level of shade over cocoa (35% shade cover). Surprisingly greater use of fertilisers was not associated with higher yield. This could be due to the effects of a severe drought which happened during the study (2015-2016). In the three groups, labour was unusually low compared to the needs to maintain large plantations: the Bahian historic production model relies on high number of low-paid workers maintaining large domains. This model is no longer viable in Brazil due to the increasing price of the labour and yield declines due to the witches’ broom outbreak and despite a marginal increase in the cocoa prices for the past 25 years. Other studies on cocoa agroforests have established farm typologies based on the structure and diversity of the species associated with the cocoa trees (Deheuvels et al., 2012) or based on the farm structure and the age of the plantation (Fahmid, 2013). In Barro Preto, we found that smaller farms with larger percentage of area for cocoa production (higher density of cocoa trees, larger cocoa trees and lower tree mortality) had greater cocoa yields per area. In Bahia, larger farms with cattle production as a diversified sourced of income are more likely to preserve their remnant patches of forest and their cabrucas systems compared to smaller 'cocoa intensive' farms (Alger and Caldas, 1994). In our typology, farms with lower yield and smaller cocoa area had larger quantity of livestock. It is possible that the farmers compensated their lower cocoa production by diversifying the farm income.

2.4.2 Cocoa yield gap and factors limiting yield

Cocoa yield gap

The average yield gap (Y90-Yatt) found in Barro Preto was 153 ± 24 kg/ha. That is 64% of the average annual yield in Barro Preto (average yield was 240 kg/ha). By comparing the maximum annual yield observed (707 kg/ha) in the most productive farm for Barro Preto, the farm yield gap is 467 kg/ha. In another yield gap analysis in Ghana, (Aneani and Ofori-Frimpong, 2013) found a yield gap of 1,537 kg/ha per year by comparing the maximum observed yield and the average yield of the studied region. This large difference in yield gap suggests that Ghanaian farms had higher potential to increase their yield than Bahian cabrucas. Cabrucas were closer to the maximum yield they could reach than cocoa farms in the Ghanaian study, this is possibly because the variables used to estimate yield gaps in Brazil were mostly environmental variables whereas the variables used in Ghana were mostly socio-economic variables. However, there is still a large margin of manoeuvre to increase yield in cabruca farms.

The maximum yield attainable (707 kg/ha) in cabrucas was low compared to yield observed in intensive cocoa plantations, which can reach up to 4000 kg/ha (Jagoret et al., 2017). This corresponds to a potential yield difference of 3293 kg/ha. Cocoa yields in Barro Preto were 20% lower than the Brazilian national average (300 kg/ha) in 2015. However, increasing yield in cabrucas would require large investments (fertiliser, labour, highly productive seedlings, shade tree removal) from the cocoa farmers. Most Brazilian cocoa farmers are in debt and cannot afford to rejuvenate and intensify their large cocoa domains (90 ha per farm on average). Extensive cocoa production in Bahia is slowly decreasing and being replaced by intensive high-yielding cocoa plantations in new agricultural frontier in the state of Pará (FAOSTAT, 2017). Low-yielding cabrucas are not competitive production systems with cocoa prices remaining the same (approximately $2,000 per tonne) for high quality organically-grown rainforest friendly Brazilian cocoa and 'bulk quality' cocoa produced in high-yielding production systems. However, increasing the value of the cocoa grown in cabrucas by using rainforest friendly certifications could make the Bahian cocoa sector more profitable (Rezende, 2012).

Factors limiting yield

The main limiting factors (average yield gap c. 40% of attainable yield) in decreasing order were: high yield loss due to fungal diseases, high cocoa tree mortality, low cocoa tree density, small basal area of cocoa trees, high witches' broom infection score, high density of shade trees and heavy shade (low GSF).

Fungal diseases are common factors limiting yield in cocoa producing countries. Bahian plantations have been infected by the chronic fungal disease witches' broom (*Moniliophthora perniciosa*) since the end of the 90's (Pereira et al., 1996). Cabruca conditions (heavy shade, low management) favour the infection of witches' broom, causing a decrease in yield (cocoa production decreased by 70% in 10 years in Bahia following the first outbreak of witches' broom) without killing the trees. In our study, rotten pods infected by witches' broom accounted for an average per harvest of 31% of the pods produced by the trees. Furthermore, witches' broom affects the vegetative growth of the cocoa tree, reducing net primary productivity and decreasing the cocoa yield indirectly. Pests and diseases are the main limiting factors accounting for 30% to 40% loss of the world's cocoa production (Bowers et al., 2001). Agronomical institutes and chocolate companies are addressing this limiting factor as a priority to increase yield using integrated management: chemical treatments, biological treatment and resistant genetic material. However, none of the treatments developed so far have been successful in significantly reducing the damage causes by witches' broom in Bahia (Purdy and Schmidt, 1996; Teixeira et al., 2015).

The exceptionally high mortality of cocoa trees observed was a main limiting factor. Between November 2015 and May 2016 a severe drought due to El Niño caused an 11% cocoa tree mortality and 80% yield loss in Barro Preto (Chapter 4). Additionally, we showed that shade (GSF) and high shade tree density, were limiting factors: the yield gap due to GSF and shade tree density represented 40% and 42% of the highest yield attained by the farmers. In a production model fed with field data from 30 locations in 10 cocoa producing countries, Zuidema et al. (2005) showed that weather conditions (rain and radiation) explained 70% of the yield variation. Zuidema's production model also showed that heavy shade could decrease yield by 33% whereas low shade did not affect the yield. The relationship between light and cocoa yield is well-known (Ahenkorah et al., 1987); lower yields are found in heavily shaded cocoa plantations. Shade trees in cabruca could be pruned to reduce their shade, however the high cost of the labour to reduce the canopy of trees 30-40 m tall prevents any management of the shade trees in the cabrucas.

We also found that the low cocoa tree density had a strong limiting effect. Aging cabrucas have low cocoa tree density (620 trees/ha on average) compared to commercial cocoa plantation which can reach 1111 trees/ha. Cocoa yield could be increased by increasing cocoa tree density up to 800-900 cocoa trees/ha depending on the spatial distribution of the shade trees. Finally, we found that small cocoa trees (basal and crown area) were limiting yield. In Cameroon, Jagoret et al. (2017) found that cocoa basal area and unproductive trees were key factors in productivity and recommended removing cocoa trees with basal area < 19 cm^2.

Finally, by using quantile regression we found that interactions between factors (particularly between yield loss, witches' broom infection, basal area of cocoa trees and soil organic matter) affected yield and were limiting. However, it was not possible to include these interactions while calculating the yield gaps.

Solution to increase yield

Limiting factors were related to the individual cocoa tree productivity. Unproductive cocoa trees (trees producing less than 3 pods per year) resulted from the combination of the different limiting variables. In Ivory Coast, (Wibaux et al., 2017) found that the 20% most productive trees produced 46% of the pods. An even higher ratio was observed in Barro Preto plantations with 20% of the most productive trees produced 70% of the pods (among a total of 1606 cocoa trees). The most productive tree produced 167 healthy pods per harvest. In a scenario where all cocoa trees of a plot were as productive as this tree, the yield per hectare (560 trees/ha) per harvest would reach 3,740 kg/ha of dry beans, which is still below the 4000 kg/ha maximum suggested by Jagoret et al., (2017). Better management, including grafting and replacing old unproductive trees with productive genetic material of high-yielding varieties, which are self-compatible, tolerant to disease and high-yielding, would increase yield in cabrucas by reducing the percentage of unproductive trees. However, there is still uncertainty about the role of the unproductive trees. They could have positive effects e.g: be a source of compatible pollen for highly productive trees. More research is needed to understand the relationship between productive and unproductive trees (e.g to establish an experiment where unproductive trees would be cut and remaining trees would be monitored on a long-term).

2.4.3 Biodiversity conservation

We showed that tree diversity in private land outside national parks in Bahia, i.e. cabrucas in Barro Preto, is still high (half the species found in cabrucas are Atlantic Forest species, density ranged from 25 to 387 with an average 126 ± 12 trees/ha) and Shannon diversity Index H ranged from 0.38 to 2.47. A previous study on the species biodiversity in cabrucas farms showed even higher values for Shannon's H (2.21 to 3.52) and density ranging from 43 to 284 (average 121 ± 73) trees/ha (Sambuichi et al., 2012). However, the species diversity in neighbouring protected Atlantic forest (Serra do Conduru State Park) was higher with 2530 trees/ha and 144 trees species in 0.1 ha of old growth forest (Martini et al., 2007). Other studies emphasize the role of cabrucas in preserving and connecting remnant patches of Atlantic Forest (Schroth et al., 2011). However, our study suggests that cabruca farms are slowly losing their biodiversity. Cabrucas have not been renewed because of economic pressure on the farmers: no shade tree seedlings have been planted to replace the aging trees. Additionally, laws protecting the remaining 5% of pristine Atlantic Forest are one of the reasons no new cabrucas have been established. Cabrucas will slowly go extinct if nothing is done to densify, renew and replant cocoas tree and Atlantic Forest species (Ganzhorn et al., 2015). This cannot be done without increased cabrucas' profitability, for example by increasing the cocoa value by including the price of conserving the forest (rainforest friendly certification at landscape scale (Tscharntke et al., 2015)). After ENSO 2015-16, 47400 ha of cabrucas (9.5% of the estimated total area of cabruca) were lost in Bahia (http://www2.sidra.ibge.gov.br) mainly due to the severe drought, often replaced by pasture for cattle ranching, which generated higher profitability for the farmers. If cabrucas were to be abandoned as cocoa production systems to be turned into protected area instead of pasture, they would present highly favourable conditions for the regeneration of Atlantic Forest (Rolim et al., 2017). However, this environmentalist approach does not provide incomes to farmers (establishing a system of subsidies/payment of the land for farmers willing to abandon cocoa production for biodiversity conservation could be an option to explore). Maintaining and renewing cabrucas remains the best option to obtain both farmers' livelihood and biodiversity conservation.

2.4.4 Trade-offs between yield and tree diversity

Shade tree diversity and density were yield limiting factors in our study. Most studies in cocoa agroforests showed that increasing shade tree diversity and density decreases cocoa yield mainly due to the competition for light (Steffan-Dewenter et al., 2007; Bisseleua et al., 2013;

Kieck et al., 2016). However, other authors showed that it is possible to reach high yield (>700kg/ha) while maintaining the biodiversity in cocoa agroforests (Abou Rajab et al., 2016; Deheuvels et al., 2012; Schroth et al., 2016a). In cabrucas, the shade tree density was low resulting in only 35% shade cover; this could explain why cocoa yield were less limited by the shade than by other variables (disease, tree mortality).

Our results suggest that cabrucas maintain Atlantic forest species and provide low cocoa yields with reduced farm investments (almost no inputs, low labour). The cocoa yields (260 kg/ha) were lower than in intensive plantations (4000 kg/ha) and the diversity of shade trees in cabruca was lower than in protected Atlantic Forest (Martini et al., 2007). The rewilding of land sharing agriculture with low yield such as these wildlife-friendly cabrucas can contribute to regenerate the Atlantic forest (Rolim et al., 2017). Some researchers are advocating a land sparing strategy to produce more cocoa on smaller land area to spare and protect larger area of untouched ecosystems (Phalan et al., 2011). However, in practice it is difficult to implement the legal environmental framework required to enforce the 'land sparing' strategy, that is, actually protecting the areas that are designed as "spared". Despite a clear Brazilian environmental law which requires the farmers to spare 20% of their farms for biodiversity conservation ('Legal Reserve'), this measure is often not implemented in Bahia were environmental agencies have extremely limited means to enforce the law. Additionally, cabruca land could be purchased for conservation purpose only, (privately-owned reserved, 'Private Reserves of Natural Heritage' are commonly found in Brazil), however studies on the effectiveness of privately-own parks in the tropics on forest conservation remains scarce (Langholz and Lassoie, 2001). Finally, when farmers decide to abandon cocoa production, they often remove the shade to get a short-term peak of production (5-10 years) before removing the cocoa trees. The forest cover of the cabruca is finally replaced by pasture for extensive cattle ranching. Replacing cabruca by pasture could increase greenhouse gas emissions by removing shade trees, releasing stored soil C and increasing methane production from the cattle (Cohn et al., 2014). Cabrucas, beside the cultural heritage they represent for the region, provide a range of ecosystem services (maintain soil fertility, create corridors between remnant patches of forest reserves, sequestrate carbon) but they are slowly disappearing.

2.5 Conclusion

Traditional cabruca farms in Bahia state were separated into three groups: farms specialised in cocoa production with intermediate to high yield; farms with high yield and high labour; and farms producing lower cocoa yield but compensated for by raising cattle. Fungal diseases, tree mortality, shade and low cocoa tree density were the main factors limiting yield. The yield gap could be closed by replacing unproductive cocoa trees by high yielding clones (self-compatible, disease tolerant) and increasing cocoa tree density. However, most farmers have debts and the price of the labour required to replace cocoa trees is too high. Shade trees limited yield in cabrucas but also contributed to maintaining a forest cover in Bahia. Cabrucas also create corridors between remaining patches of endangered Atlantic Forest. Increasing the value of cocoa beans on the market by using rainforest friendly certification, advocating the originality and richness of cabrucas, could help to maintain and renew these aging agroforests.

Chapter 3 | Cocoa agroforests in Bahia, Brazil - shade tree species affect yield but fertiliser did not.

Abstract

Cocoa is a major crop usually grown under shade trees. Production is sometimes limited by light, nutrients, pests and diseases, but the degree of limitation has rarely been investigated in traditional cocoa agroforests – it has usually been studied in research stations under highly controlled conditions, but most cocoa is still grown by small holders in traditional agroforests. We investigated whether nutrients and shade tree species were factors limiting yield on traditional agroforests (cabrucas) on 10 farms in Bahia, Brazil. We assessed the effect of seven species of common shade trees on cocoa tree nutrition over a period of 12 months. We measured: cocoa leaf nitrogen (N) and phosphorus (P) concentrations, soil N, P and potassium (K) concentrations under the cocoa trees, light above the cocoa trees, litterfall, and litterfall nutrients. We also carried out a bioassay using cocoa seedlings grown in soils collected under the different shade tree species. In a separate experiment we added fertilisers to 20 adult trees on each of 10 cocoa farms and measured pod production per tree over 15 months. All our research was carried out immediately after a strong drought.

We found that half of the soils and cocoa leaves sampled in the 10 farms had P and K values lower than the values recommended by the Brazilian Executive Commission of the Cacao Farming Plan (CEPLAC) for optimal cocoa yield in cabrucas. We found an effect of shade trees species on cocoa yield, the quantity of litterfall production, and on the nitrogen and phosphorus concentrations in litters. Cocoa yield was positively correlated with the quantity of litterfall (with high nutrient content) and was maximum under the shade of *Erythrina spp*. Surprisingly, we did not find cocoa yield to be higher in unshaded plots than in shaded plots, which may have been due to the high individual variability between cocoa trees. In the bioassay cocoa seedlings grew more when fertilised, but bioassay seedlings did not respond to the different shade tree species. We found no effect of fertiliser on cocoa yield. The live cocoa leaves collected under different shade tree species did not show significant differences in nutrient concentration between shade tree species.

Our study shows that the species of shade trees affected cocoa yield, but the mechanism for this is unclear. Mature cocoa trees did not respond to fertiliser addition within the 15 months of the study due, very likely, to the post-drought conditions. Overall this suggests that

potentially N-fixing shade trees species (*Erythrina*) had a positive long-term effect whereas NPK fertiliser addition had no positive short-term effect on cocoa yield.

3.1 Introduction

3.1.1. Agroforestry for cocoa production

Cocoa (*Theobroma cacao*) is an understory tree native to the Amazon, it is often grown under the shade of other trees, forming agroforestry systems. Despite the recent development of non-shaded systems (Gockowski and Sonwa, 2011), most cocoa is still produced in some type of agroforestry system. The composition of the shade trees in these cocoa agroforests ranges from one species for temporary shade during the establishment of the plantation (often banana trees), different combinations of economical or agronomical associations (e.g. cocoa-rubber, cocoa-coconut, cocoa-timber, cocoa-*Erythrina*) to multi-species systems that mix native and exotic trees. The general benefits of having shade trees in cocoa plantation has been the subject of detailed studies. These trees provide a wide range of ecosystem services (Mortimer et al., 2017; Obeng and Aguilar, 2015; Tscharntke et al., 2011) including carbon sequestration (Dawoe et al., 2016; Monroe et al., 2016; Saj et al., 2013; Somarriba et al., 2013; Wade et al., 2010) biodiversity conservation (De Beenhouwer et al., 2013), potential for nitrogen fixation (Santana and Cabala-Rosand, 1982) and, to a certain extent, pest control (Sperber et al., 2004). This diversification also provides economic benefit and resilience for smallholders (Jezeer et al., 2017; Cerda et al., 2014). However, other studies also underline the negative effects of shade trees on cocoa yield, for example through resource competition for water and nutrients between cocoa and shade trees (Abdulai et al., 2018; Köhler et al., 2014). Shade trees also reduce the light reaching cocoa leaves and possibly increase pathogen pressure due to high humidity (e.g witches' broom, (Rudgard et al., 1993)), so removing shade in mature plantations can increase yield in the short term (Wessel, 1985). As a consequence, recent studies emphasize the possible trade-offs and benefits (or Ecosystems Services) provided by the shade trees (Saj et al., 2017; Abou Rajab et al., 2016; Rapidel et al., 2015; De Beenhouwer et al., 2013). Our study addresses the possible effects of different shade trees species on cocoa production of single trees, within complex agroforestry systems, by measuring soil fertility, nutrient cycling in litterfall and cocoa yield under different shade tree species.

3.1.2. Nutrient and fertiliser in agroforestry

The relationships between shade trees, nutrient cycling in litterfall, light and soil fertility in cocoa agroforests remains unclear. To assess the possible effects of shade trees on cocoa nutrition, an ideal experimental design would be a long-term study of cocoa trees under different individual species of shade trees compared to non-shaded plots, with and without fertiliser, in farm conditions. To our knowledge, there is no such study published, however some experiments bring some elements to the discussion. Two recent studies looking at the soil and foliar nutrients on a gradient of shade cover (32 individual shade trees across eleven cocoa farms in Ghana and 36 cocoa plots ranging from monocultures to complex agroforestry systems in Indonesia), both without fertiliser addition, showed that shade trees did not increase soil fertility at the plot scale (Blaser et al., 2017; Wartenberg et al., 2017). In a similar kind of field study Hosseini Bai et al. (2017) found higher concentrations of soil nutrients in cocoa plantations with the lowest shade tree densities under two different shade tree species (*Gliricidia sepium* and *Canarium indicum*) (soil nutrients were lower in 8 m × 8 m than in 8 m × 16 m spacing between shade trees), which they ascribed to differences in the nutrient concentrations in the litterfall; but these differences in the soil did not cause differences in mineral concentration of leaves of cocoa trees under the two shade tree species. However, there was no fertiliser treatment to check for potential deficiency. In another 17-year full factorial experiment with fertiliser addition comparing shaded and unshaded plots (but without details on the shade tree species composition) Ahenkorah et al. (1974) found strong gradual decrease in soil C, N, P, K, Ca in both shaded and unshaded plots which were partially compensated by fertilisation. In the first 10 years its seems that removing the shade (with or without fertiliser) results in the highest yields, but *after* 10 years adding fertiliser (with or without shade) results in the highest yield. In the long term keeping the shade trees could (with fertiliser) result in higher yields than removing the shade trees and not adding fertilisers. Thus in that study shade trees seemed to contribute to the maintenance of yield in the long term when associated with fertilisation. However, from the studies mentioned previously it is not possible to conclude whether cocoa yields were limited by nutrient supplies from 'litter' (both above-ground and below-ground) under *specific* species of shade trees. In the current chapter we report the effect of specific shade tree species on soil and cocoa leaf nutrients, and two fertiliser experiments, one on cocoa trees in cabrucas and one in a bioassay.

3.1.3. Yield and shade tree species

The benefit of different shade tree species on cocoa yield remains unclear. In Peru an increase in shade tree species diversity (ranging from 2 to 18 species in 20 m^2 plots) was associated with a decrease in healthy cocoa pods for smallholder cocoa plantation on inceptisols in the department of San Martin (2,400 mm annual average rain) (Kieck et al., 2016). In two experimental sites in Costa Rica and Panama, a 10-year study showed no shade tree species effect on cocoa yield (on fertilised cocoa trees) under intensively managed *Erythrina poeppigiana, Gliricidia sepium, Inga edulis,* and non-legumes *Cordia alliodora, Tabebuia rosea* or *Terminalia ivorensis* (Somarriba and Beer, 2011). Legumes as potentially nitrogen fixing trees, which also have high foliar concentration of other nutrients, have been promoted in different agronomical programs, including cocoa agroforestry. In Costa Rica, in the Central experiment at CATIE (Tropical Agricultural Research and Higher Education Center), Heuveldop et al., (1988) reported a higher mean yield under legume trees *Erythrina* poeppigiana than under *Cordia alliodora* during the first 4 years after plantation. However, in the same experiment Beer et al., (1990) did not find a difference in mean yield between cocoa trees under *E.* poeppigiana or *C. alliodora* when the plantation reached maturity (between 6th and 10th years). It is important to understand whether N-fixing trees, which have been recommended to farmers by agricultural extension officers for decades, have generally positive effect on cocoa yield. Furthermore, there is no published study on the effect of different species of Brazilian Atlantic Forest shade trees, often endangered or vulnerable tree species of conservation interest, on cocoa yields in Bahia state. In this chapter, we report an assessment over one year of cocoa tree pod production under eight different shade types including five Atlantic Forest species and two legumes (*Erythrina spp. -E. fusca* or *E. poeppigiana-* and *Plathymenia foliosa*) commonly found in cabrucas in Bahia, Brazil.

3.1.4. Brazilian cocoa

Brazil is currently the world's sixth largest cocoa producing country with the state of Bahia providing 150,000 metric tonnes of dry beans per year (ICCO 2015). The littoral South of Bahia is the Brazilian historical cocoa producing region. Bahian cocoa is produced in traditional cocoa agroforestry systems called cabrucas, which are a mixture of cocoa with remnant large Atlantic Forest trees (though the individual trees are mostly not literally remnants of the original forests, since the forests have been exploited for centuries) and exotic species were introduced by the farmers for their economic or agronomic value. These systems contribute to the maintenance of emblematic species of conservation concern such golden lion tamarind (*Leontopithecus rosalia*), Brazilian rosewood (*Dalbergia nigra*) and Brazilwood (*Caesalpinia echinata).* In a recent assessment of the municipality of Barro Preto, the number of shade tree species was on average 92 ± 7 species per hectare for a tree density of 126 ± 12 trees/ha (cf Chapter 2). These cabrucas with high species diversity are thus relevant study areas for assessing the potential effect of different species of shade trees on cocoa.

3.1.5. Hypothesis and reason for the Chapter

In this chapter, we addressed three main questions:

(1) Were nutrients a main factor limiting cocoa yield in cabrucas? To assess nutrient status, we fertilised individual cocoa trees and recorded cocoa tree pod production after fertiliser addition for 10 months. We also assessed soil fertility by collecting soils from ten different farms and analysing their chemical composition and their effect on cocoa seedling growth (bioassay).

(2) How do shade trees species (their litterfall and shade cover) affect cocoa yield? We recorded cocoa pod production for one year in plots shaded by different tree species. We assessed the litterfall production for one year under these different shade tree species. We also measured canopy openness (GSF) per different shade tree species plots using hemispherical photographs.

(3) Do different shade tree species affect soil fertility? We assessed shade tree species effect on soil fertility by running a 180-day bioassay using cocoa seedling grown in soils collected under different shade tree species. We also measured the N, P, K concentrations of the leaf litterfall of the different shade tree species.

Finally, to get a better understanding of the system, we tried to summarise the interactions between cocoa yield and shade trees by measuring the relationships between the different variables measured on farm: light, soil fertility, litterfall and pod production.

3.2. Materials and methods

3.2.1. Study site

The study was carried out in Bahia, the major historical cocoa growing state in Brazil. We studied 10 cabruca farms in the municipality of Barro Preto in South of Bahia (14.05° S, 39.040°W, 16,000 ha) located at c. 150 m a.s.l. and one full-sun irrigated highly intensified farm located in the municipality of Uruçuca (14.59° S, 39.28° W, 40,000 ha), 45 km distance from Barro Preto. The bioassay experiment was done in the nursery of the MARS Center for Cocoa Sciences (MCCS) located in Barro Preto. The soils in Barro Preto are classified as Latosol or Argisol Red-Yellow with a moderate clayey-loam texture (Araujo et al., 2013). Mean annual rainfall at MCCS is 1608 mm per year with May and September being the driest months, with, respectively, 110 mm and 67 mm. Mean annual temperature is 26°C. In the region, cabrucas have native tree species from the Atlantic Forest of conservation interest and introduced tree species of economic interest (i.e fruits, timber, rubber) together with cocoa as the main cash crop (Lobão, 2007).

3.2.2. Selection of farms, shade trees plots and measurement of variables

We chose ten cabruca farms with gradient of yield from the 32 farms randomly-chosen from a list of 333 farms in a regional assessment (Chapter 2): three farms with the lowest yield, four farms with intermediate yield and three farms with the maximum yield. To assess the effects of different species of shade trees, we selected three individuals of mature cocoa trees under the canopy of the six most common shade trees species and three individuals mature cocoa trees in one plot in the open without a shade tree (3 x 7 = 21 cocoa trees) in each of the 10 cabrucas farms in Barro Preto.

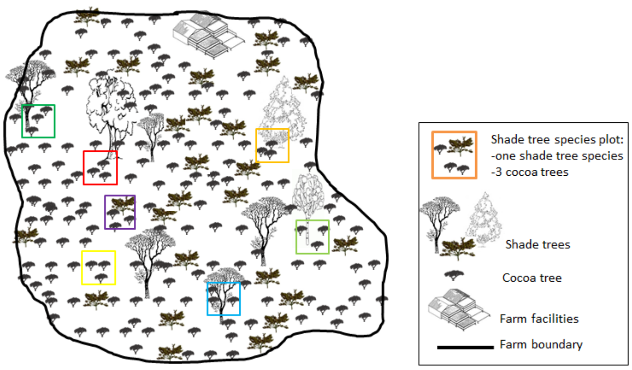


Figure 3-1. Shade tree species plots in each cabruca farm. Dark green: *Erythrina spp*, blue: *Artrocarpus heterophylus*, red: *Spondias mombin*, light green: *Cariniana legalis*, orange: *Lecythis pisonis*, purple: *Plathymenia foliosa* or *Genipa americana*, yellow: no shade.

The plots without shade are referred as 'no shade' plots. The shade tree species were Atlantic Forest species: *Spondias mombin*, *Lecythis pisonis*, *Cariniana legalis*, *Plathymenia foliosa* and *Genipa americana*; and introduced species: *Artocarpus heterophyllus* and *Erythrina spp*. Despite our efforts to try find the same shade tree species in each farm, we did not get perfect species-plot replications for each farm (see Table 3.1 for shade tree species found on each cabruca farm: 3 farms with 6 plots and 7 farms with 7 plots).

Table 3-1 Shade tree species found in each cabruca farms

	Artocarpus	*Cariniana*	*Erythrina*	*Genipa*	*Lecythis*	*Plathymenia*	*Spondias*	No shade
farm 1	x	x	x	x	x		x	x
farm 2	x	x	x	x		x		x
farm 3	x	x	x	x	x		x	x
farm 4	x		x	x	x		x	x
farm 5	x		x	x		x	x	x
farm 6	x	x	x	x		x	x	x
farm 7	x	x	x	x		x	x	x
farm 8	x	x	x	x	x		x	x
farm 9	x	x	x	x	x		x	x
farm 10	x	x	x	x	x		x	x

All triplets of cocoa trees had similar size (height, DHB and crown area). To compare the cabruca system with another cocoa producing system becoming common in Brazil, we added one full-sun irrigated highly intensified farm as a reference. For logistic reason, we selected the nearest full-sun irrigated farm with mature cocoa trees located in the municipality of Uruçuca, Bahia (45 km distance from Barro Preto). On this farm we also selected 3 individual cocoa trees in each of 3 plots without shade (3 x 3 = 9 cocoa trees). The plots on this farm are referred as 'full-sun irrigated' plots.

Measurements were made to define each of the shade tree plots including: cocoa tree variety (common Amelonado, hybrids or identified clones (i.e CCN51, TSH1188, PS1319), diameter at breast height (DBH), height, crown area, number of stems and pod number; shade tree DBH, height and crown area. Cocoa pod counts per tree were made monthly for one year from March 2016 to February 2017. Light was assessed by measuring Global Site Factor

(GSF): for each shade plot hemispherical photos were taken by positioning an EOS 5D Nikon camera with a hemispherical lens above the cocoa tree canopy using a telescopic mass with a gimbal early on mornings on cloudy days in February-March 2016. All pictures were analysed using Canopy analyser HEMIv9 (HemiView, Delta-T, Cambridge, UK) to produce gap fractions which were converted into Global Site Factor (GSF) which is the proportion of global solar radiation (direct and diffuse) at a given location relative to that in the open and integrated over time.

Additionally, to assess the shade tree species effect on cocoa tree nutrition, we analysed nutrient concentrations in cocoa leaves. Eight to ten live cocoa leaves were collected on the cocoa trees under each of the shade trees species in each plot of the 10 cabruca farms. Leaves were dried and ground to form one composite leaf sample per shade tree per farm. All samples were sent to a Brazilian laboratory for analysis. Cocoa leaves were analysed for N, P, K concentration: Kjeldahl method for N and nitro-perchloric decomposition for P and K.

3.2.3. Fertiliser addition experiment on mature trees

To assess possible effect of nutrient deficiency and the effectiveness of fertiliser addition on yield in the cabrucas, we added fertiliser to mature cocoa trees in the 10 cabruca farms. In 800 m^2 permanent plots representative of each of the 10 cabrucas farms, we chose two pairs of productive trees of similar DBH, crown area and height. We compared pod production on 20 mature healthy and productive cocoa trees with fertilisation and with pod production on 20 mature healthy and productive cocoa trees without fertilisation. Treatments (control or fertiliser addition) were randomly assigned to the 20 pairs of trees. Fertilisation rates per hectare were 120 kg N, 80 or 120 kg P and 90 or 150 kg K with P and K depending on results of cocoa leaves analysis (see Table 1a) and b) and Appendix A 3.1: Soil and leaf analysis from the transect to estimate fertiliser addition) and 2 l/ha of commercial foliar micronutrient mix Uraneo®. Doses of P and K were calculated with the reference values recommended by the Brazilian Executive Commission of the Cacao Farming Plan (CEPLAC) for cocoa production based on the results leaf analysis of live cocoa leaves collected in the 800 m^2 transects of the 10 farms: 80 or 120 kg/ha P for leaves analyses ranging between 10 and 20 g/kg and < 10 g/kg of P respectively and 90 or 150 kg/ha K for leaves analyses ranging between 1 and 2.5 g/kg and < 1 g/kg of K respectively. Doses of fertiliser were applied in two fractions: one in July 2016 after the main rain events which followed a long drought caused by El Niño and one 5 months later. Pods on these pairs of trees were counted every three months (from July 2016 to February 2017).

Table 3-2: Fertiliser doses for mature trees

a) Recommendations of fertiliser doses for mature cocoa plantation of average yield 1500 kg/ha

	N	P			K		
Leaf nutrient concentrations	n/a	<10 g/kg	10-20 g/kg	>20 g/kg	<1 g/kg	1-2.5 g/kg	>2.5 g/kg
Fertiliser doses per year	120 kg/ha	120 kg/ha	80 kg/ha	0	150 kg/ha	90 kg/ha	0

b) Doses applied in Barro Preto farms based on the results of soil and leaves analyses (see Appendix 3.1), half of these amounts were added in July 2016 and November 2016.

farm	N kg/ha	P kg/ha	K kg/ha
1	120	80	90
2	120	80	90
3	120	120	90
4	120	120	90
5	120	120	90
6	120	120	0
7	120	120	90
8	120	120	90
9	120	120	90
10	120	0	150

3.2.4. Bioassay: soil sampling and analysis

1) Shade tree species effect on seedlings

Between 7th and 22nd March 2016, for each triplet of cocoa trees we collected 3 soil samples one under each cocoa tree in each shaded and non-shaded plot for the 10 cabruca farms (3 x 7 x 7 + 3 x 6 x 3 =201 samples). Three soil samples were also collected in each of the 3 plots of the full-sun irrigated farm (3 x 3 = 9 samples). The three samples per shade tree species plot were kept separate. (see Appendix 3.2 for the detail of the soils sampled and used in the bioassay). In the statistical analysis, each sample of the plot (3 samples per plot) were treated as nested within the shade type and the farm. We used 5 replicates of 2 controls: C1 most fertile soil found at Mars Centre for Cocoa Sciences (MCCS) and C2 routine potting soil used at MCCS.

2) Fertiliser effect on seedlings

To assess the effect of fertiliser addition on seedlings and assess possible nutrient deficiency in the soils of the cabruca farms, 5 extra soil samples under 5 shade tree species from two farms (9-F and 4-F) were fertilised. It was not possible to do replicates of each shade tree species fertilised within each farm. We also added fertiliser to 5 replicates of the most fertile soil sampled at MCCS: C3. Fertiliser doses for each seedling are detailed in Table 3.3.

Table 3-3 Fertiliser doses for the cocoa seedlings in the bioassay

Fertiliser doses based on CEPLAC reference for potting soil (farms 9-F and 4-F and C3)		Routine potting soil used at MCCS (C2)	
one pot (2 litres)		one pot (2 litres)	
1.2	kg soil	1.6	kg soil
0.3	kg manure	0.4	kg manure
7.5	g single superphosphate (18% P_2O_5)	8	g single superphosphate (18% P_2O_5)
0.3	g FTE BR 12*	0.6	g FTE BR 12*
0.75	g KCl	1	g KCl
1.5	g $CaCO_3$	4	g $CaCO_3$
30	ml 0.5% urea every 15 days	30	ml 0.5% urea every 15 days

*FTE BR 12 is a Brazilian commercial mix of micronutrients: 3.9% S, 1.8% B, 0.85% Cu, 2% Mn, 9% Zn
CEPLAC = Brazilian Executive Commission of the Cacao Farming Plan. MCCS = Mars Center for Cocoa Sciences.

3) Bioassay protocol

The first 30 cm of topsoils were collected, and after removal of roots and stones, put in two-litre polyethylene nursery bags for cocoa seedlings, placed in one plastic saucer to avoid nutrient contamination (via drainage water). Cocoa seeds came from 11 ripe pods resulting from open-pollinated progenies of variety VB1151 (a self-compatible clone) harvested on the same tree on 30th March 2016. Seed sizes were homogenized by discarding the largest and smallest individuals. Seeds were pre-germinated for 3 days in humid sawdust and planted on 1st April 2016. The bags were given a number and positioned randomly in a nursery under mesh providing 30% shade. Bag positions were re-organised randomly every 2 months. After one month, nine un-germinated seedlings were re-planted with new VB1151 homogeneous pre-germinated seeds from the same tree. Seedlings were watered 45 minutes daily. Height and number of leaves of the seedlings were recorded monthly. After 5 months, all seedlings were harvested and separated into i) leaves, ii) roots and iii) stems. All organs were weighed before and after drying at 70°C until they reach a constant weight. (Seedlings replanted one month later were harvested one month later and treated the same way). Leaves of the 5-months seedlings were analysed for N, P and K (Kjeldahl method for N and nitro-perchloric decomposition for P and K). After harvest, outliers were cocoa seedlings that had abnormally low (< 2 g) dry mass resulting from an abnormal growth in the nursery were removed from the statistical analyses.

3.2.5. Litterfall and analyses

Litterfall was collected monthly for one year from March 2016 to February 2017, using 3 one-metre square littertraps, one installed under each of the three cocoa trees under each shade tree and non-shaded plot (3 x 7 traps in each of the 10 cabrucas farms and 3 x 3 traps in the full-sun farm). Litterfall was separated into cocoa leaves, shade tree leaves of the plot and 'the rest' (other leaves, fruits, flowers, twigs, small branches < 5 cm diameter and debris), dried and weighed. Total litterfall dry mass was calculated, per cocoa tree, per shade tree plot and per farm (3 traps per shade tree species and per farm) in g/m^2/year. Litterfall composition of N, P, K was measured by a private local laboratory for each combined sample, one per year per species-plot (Kjeldahl method for N and nitro-perchloric decomposition for P and K). International standards were analysed to check accuracy of analyses (cf Appendix 3.3). Nutrient contents were calculated in g/m^2/year and converted in kg/ha/year for comparison with published studies.

3.2.6. Statistical analyses

Shade tree effect on mature cocoa trees: To assess the effect of shade tree species on pod per we used mixed effect Poisson regression for count data with plots and farms as random variables and species as fixed variable. To assess the effect of shade tree species on Global Site Factor, we used nested Anova with plots and shade species nested within farms. We used Tukey's HSD test to identify pairs of means that were significantly different. The 3 plots of the full-sun irrigated farm were not included in the analysis but are added on the figures as references. To assess the effect of shade tree species on nutrient concentrations of live cocoa leaf of mature cocoa trees, we used nested Anova with cabruca farms as random blocks.

Fertiliser effect on mature cocoa trees: We used Wilcoxon signed rank test for non-parametric data to assess the potential effect of fertiliser on total cocoa pod production per tree 15 months after fertiliser addition.

Bioassay: The effect of shade tree species on bioassay seedlings mass variables (total dry mass, leaf mass, stem mass, roots mass, height and number of leaves at 5 months) were assessed using nested anovas with species and plot (3 soil sample per shade tree plot) nested within farm. The effects of fertiliser additions and the interaction effects of species-fertiliser on seedlings were also assessed using nested anova with the use of fertiliser or not as an additional fixed effect. When there was a significant difference, we used Tukey's HSD test to identify pairs of means that were significantly different. Additionally, the effect of shade tree species and fertiliser on the leaf composition (N, P, K concentrations) of the seedlings were also assessed using nested anova with shade tree species and plot nested within farm and with the use of fertiliser or not as an additional fixed effect.

Litterfall: Litterfall mass and element concentrations and amounts were analysed by nested anova to assess the effect of species, followed by Tukey's HSD test to identify pairs of means that were significantly different. We used Pearson's correlation to quantify relationships between concentrations of different nutrients in litterfall.

We used a Generalised linear models to identify relationships between measured variables (total seedling dry mass, root mass ratio, final height and number of leaves in the bioassay; total yearly litterfall and percentage of cocoa litterfall within the total of litterfall; light variable (GSF); cocoa tree DBH, height, crown, number of stems and percentage of rotten pods, and pod production) per shade tree species and cabruca farms and to find the best predictors of yield for the 204 single cocoa trees. Cocoa trees from the full-sun irrigated farm were not included in the analysis.

3.3. Results

3.3.1. Effect of shade tree species, light and fertiliser on yield in cabruca farms

Cocoa pod production differed under different shade tree species (Fig. 3.2). Cocoa trees produced the maximum number of pods under *Erythrina* (46 pods per cocoa tree per year) and the minimum under *Plathymenia* (7 pods per cocoa tree per year).

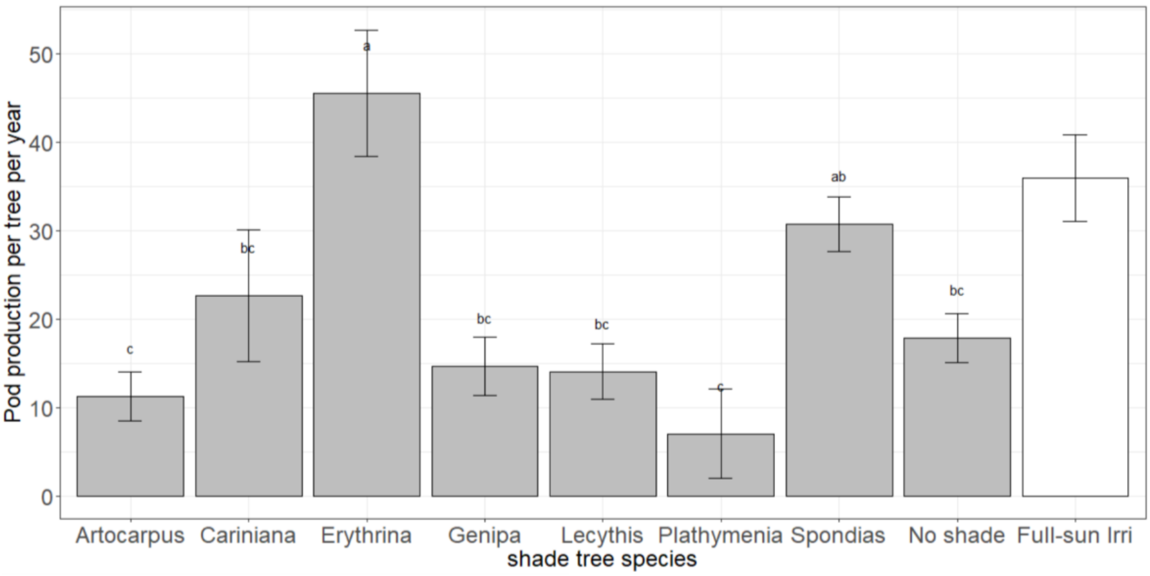


Figure 3-2. Total number of cocoa pods per tree produced in one year (March 2016-February 2017) for 7 shade tree species and no shade in 10 cabruca farms and one full-sun in irrigated farm (Full-sun Irri). Error bars represent standard error of the mean. Different letters above the bars show significant differences between the shade tree species (Tukey–HSD, P < 0.05)

The number of pods per cocoa tree was affected by the levels of light (1 unit increase of GSF increased pod production by 1 pod per year, P << 0.05, see Appendix 3.4 Effect of light on yield). Though the full-sun, irrigated and fertilised farm had 64% more production (36 ± 5 pods per tree per year, 5% shade cover) compared to the average cabruca tree (22 ± 5 pods per tree per year, with 68% shade cover (Fig. 3.3.).

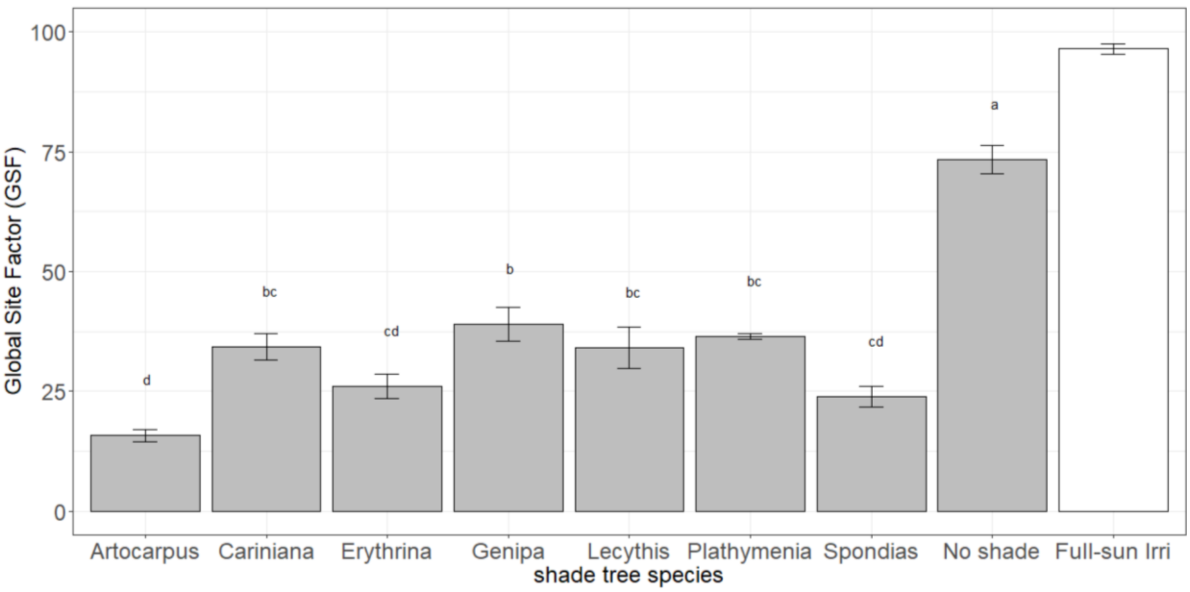


Figure 3.3. Global Site Factor for 7 shade tree species and no shade in 10 cabruca farms and one full-sun irrigated farm (Full-sun Irri). Error bars represent standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, P<0.05)

Fertilised cocoa trees did not produce significantly more cocoa pods per tree (9.2 ± 5.8 pods) than controls (16.2 ± 4.6) over 15 months following fertilisation (Wilcoxon signed rank test, W = 46, *P* = 0.07) (Fig. 3.4 and Appendix 3.5 Effect of fertilisation on mature trees).

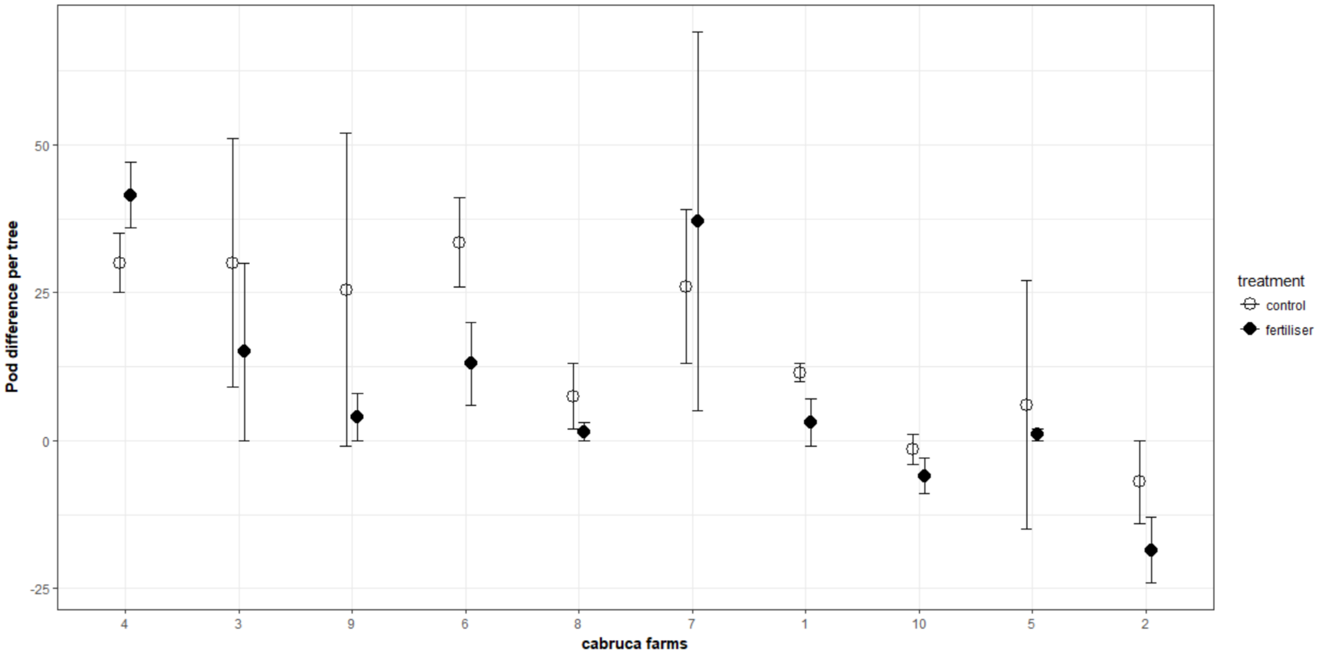


Figure 3.4. Cumulative cocoa pod production (mean and standard error) over 15 months after fertilisation in 10 cabruca farms. Error bars represent standard error of the mean, n = 2 trees per cabruca farm and treatment.

3.3.2. Effect of shade tree species on nutrient concentration in cocoa leaves on mature trees

Cocoa leaf N, P and K concentrations did not differ between cocoa under different shade tree species (Fig. 3.5 a,b and c).

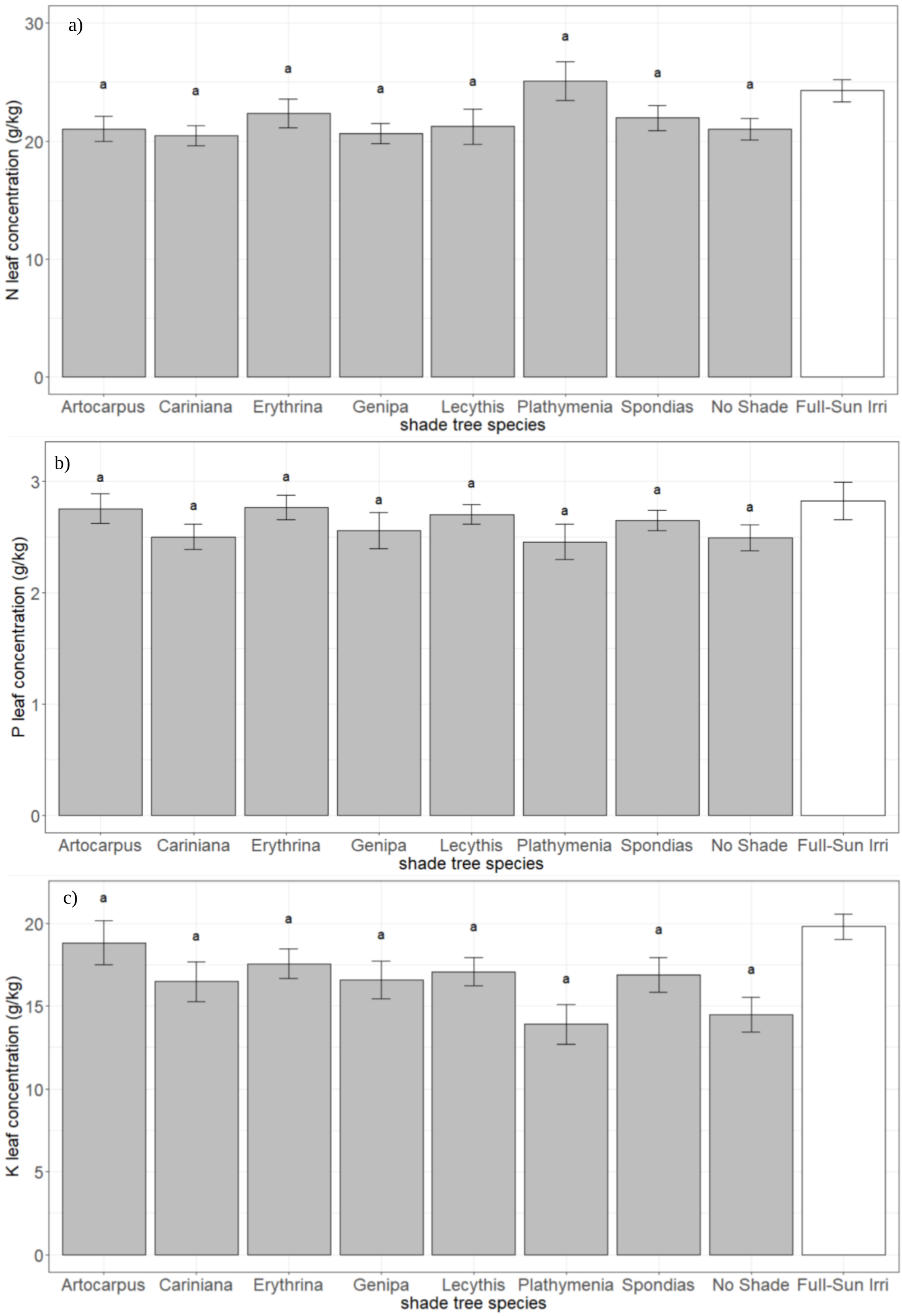


Figure 3.5. Nutrient concentrations in live cocoa leaf under 7 shade tree species and no shade in 10 cabruca farms, and in one full-sun irrigated farm (Full-Sun Irri/FS): a) foliar Nitrogen, b) foliar Phosphorus and c) foliar Potassium. Error bars represent standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, $P<0.05$).

3.3.3. Effect of shade trees species and fertiliser in seedling bioassay mass

In the bioassay, seedling masses did not differ between soils sampled under different shade tree species (nested Anova, F = 0.98, df = 7, *P* = 0.45) (Fig. 3.6 a). Fertilisation increased seedling masses by, on average, 196% (Fig. 3.6 b, F = 61.5, df = 1, *P* = 0.004).

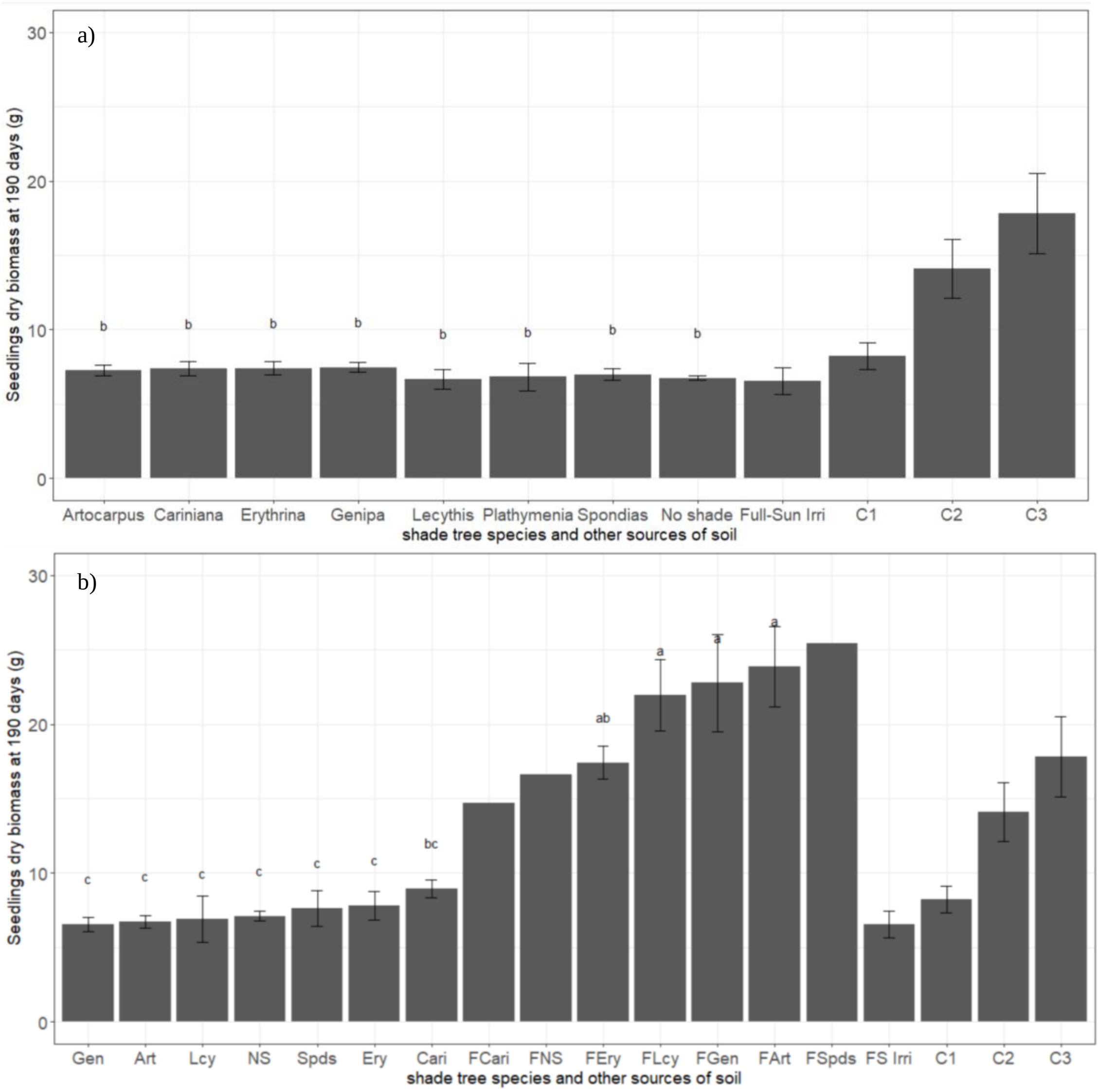


Figure 3.6. Bioassay biomass of seedlings grown in pots of soil collected from different cabruca farms, plus various control soils. Error bars represent the standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, P < 0.05). Labels: Art: *Artocarpus*, Cari: *Cariniana*, Ery: *Erythrina*, Gen: Genipa, Lcy: *Lecythis*, Plty: *Plathymenia*, Spds: *Spondias*, FS: No Shade. C1: MCCS most fertile soil standard MCCS, C2: potting mix for nursery, C3: MCCS most fertile soil + fertiliser. FArt: *Artocarpus* + fertiliser, FCari: *Cariniana* + fertiliser, FEry: *Erythrina* + fertiliser, FGen: *Genipa* + fertiliser, FLcy: *Lecythis* + fertiliser, FSpds: *Spondias* + fertiliser, FNS: No Shade + fertiliser. FCari, FSpds and FNS had no replication.

Fertilisation significantly increased the mass of bioassay seedlings on soils from under all shade tree species especially under *Spondias, Artocarpus* (+16.4 g on average). There were no significant differences between the masses of bioassay seedlings grown with fertiliser in soils from under different shade tree species (interaction fertiliser-shade tree species): nested Anova, F = 1.7, df = 6, $P = 0.14$ (Fig. 3.6 b)

3.3.4. Effect of shade tree species and fertiliser on nutrient concentrations in live cocoa leaves in bioassay seedlings

Shade tree species did not affect nutrient (NPK) concentrations in cocoa seedlings leaf (Fig. 3.7 a, b and c).

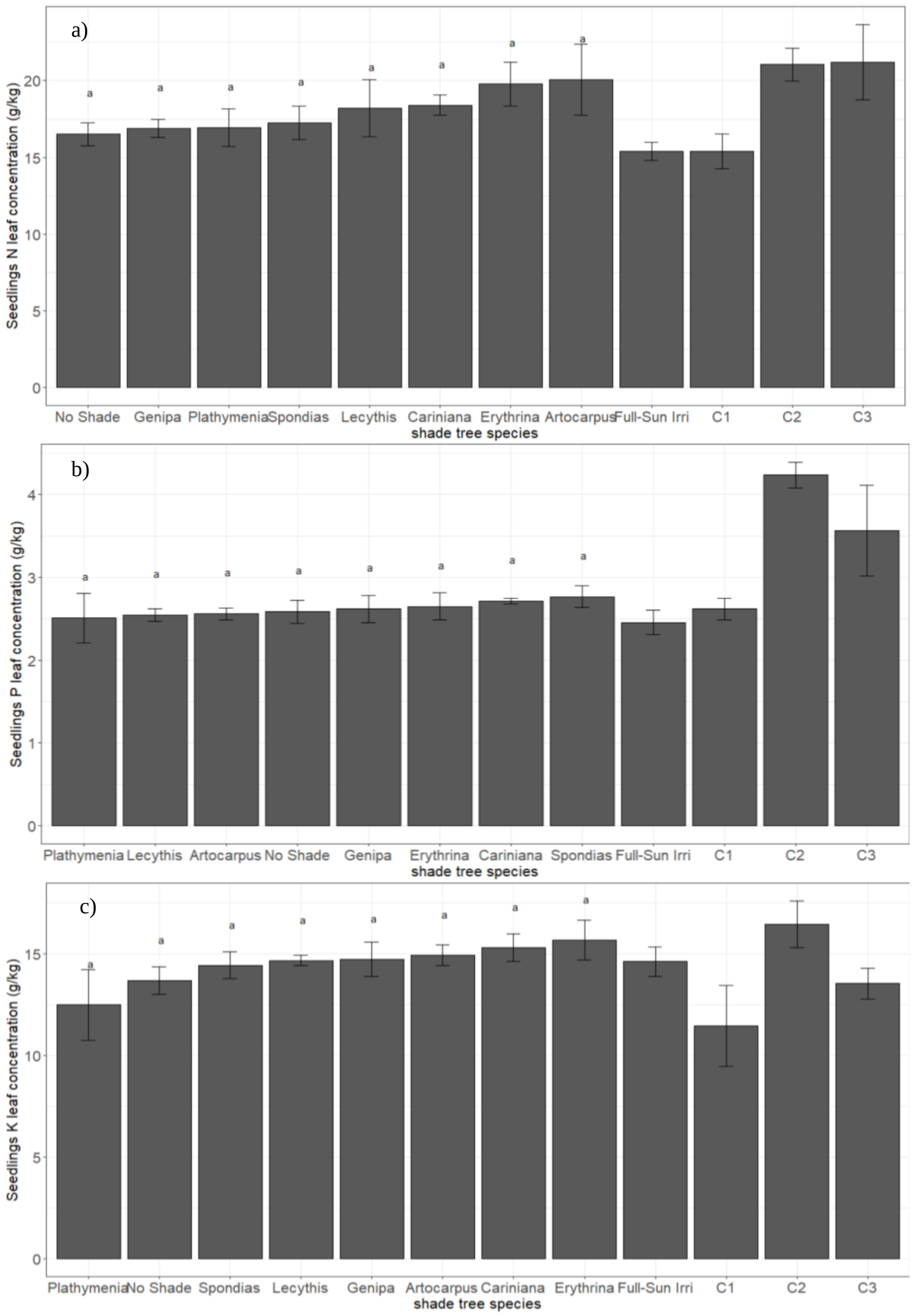


Figure 3.7 Nutrient concentration in leaf of seedlings grown for 150 days in pots of soil collected from 10 different cabruca farms, plus various control soils. a) nitrogen; b) phosphorus and d) potassium. Error bars represent the standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, $P < 0.05$). Labels: C1: MCCS most fertile soil standard MCCS, C2: potting mix for nursery, C3: MCCS most fertile soil + fertiliser.

Overall fertiliser addition increased N, P and K concentration in the cocoa seedlings leaves, but no individual species showed a significant effect of fertiliser addition (Fig. 3.8 a, b and c) (nested anova; nitrogen: $F = 5.60$, $df = 1$, $P = 0.09$; phosphorus: $F = 10.06$, $df = 1$, $P = 0.07$; potassium: $F = 2.49$, $df = 1$, $P = 0.14$).

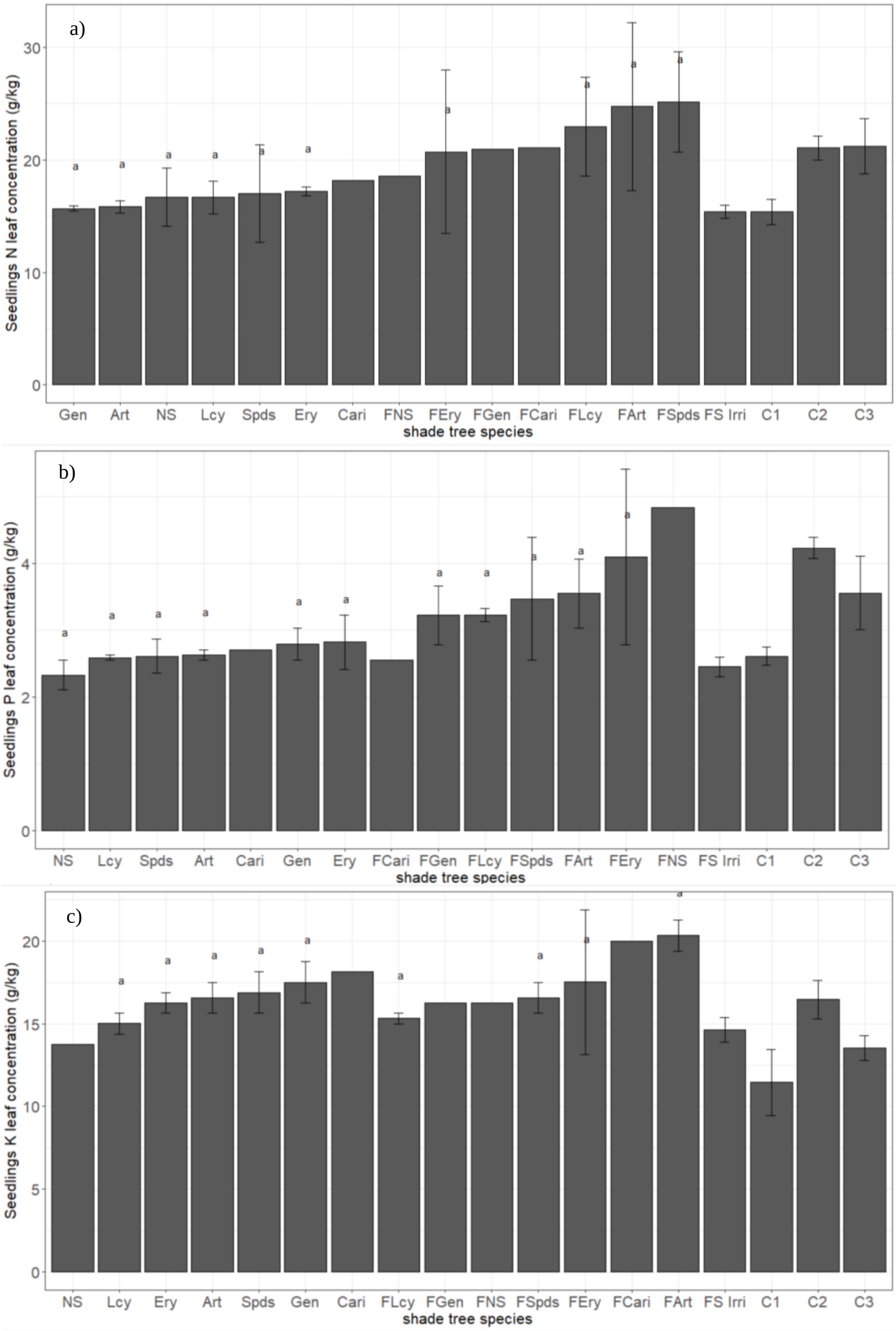


Figure 3.8. Nutrient concentration in leaf of seedlings grown for 150 days in pots of soil collected from two different cabruca farms, plus various control soils. a) nitrogen; b) phosphorus and d) potassium. Error bars represent the standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, $P < 0.05$). Labels: Art: *Artocarpus*, Cari: *Cariniana*, Ery: *Erythrina*, Gen: Genipa, Lcy: *Lecythis*, Plty: *Plathymenia*, Spds: *Spondias*, FS: No Shade. C1: MCCS most fertile soil standard MCCS, C2: potting mix for nursery, C3: MCCS most fertile soil + fertiliser. FArt: *Artocarpus* + fertiliser, FCari: *Cariniana* + fertiliser, FEry: *Erythrina* + fertiliser, FGen: *Genipa* + fertiliser, FLcy: *Lecythis* + fertiliser, FSpds: *Spondias* + fertiliser, FNS: No Shade + fertiliser. FCari, FSpds and FNS had no replication.

3.3.5. Effect of shade tree species on nutrients cycling through litterfall

3.3.5.1. On total litterfall quantity

Total litterfall quantities differed between different shade tree species, from a maximum of about 1055 g/m^2/year on average under *Cariniana, Erythrina* and *Lecythis* to a low of 644 g/m^2/year under *Plathymenia* and 508 g/m^2/year in 'no shade' plots (without shade trees directly overhead, Fig. 3.9). The number of pods per cocoa tree was affected by the quantity of litterfall (the effect of increasing the total litterfall by 1 g/m^2 was to multiply the pod production by $e^{2.3\ ^\wedge 10\text{-}4} \approx 1.0$, P << 0.05, see Appendix 3.6 Effect of litterfall on yield). We observed a total litterfall of 500 g/m^2 corresponding to 18 pods/year under no shade, by increasing the total litterfall to 1000 g/m^2 the pod production corresponded to 36 pods/year. The pattern of litterfall production varied through the year with a peak production of cocoa leaves in January (see Appendix 3.7 Litterfall production per species through one year). Total litterfall in the no shade plot was lower than in any other plot (Fig. 3.9).

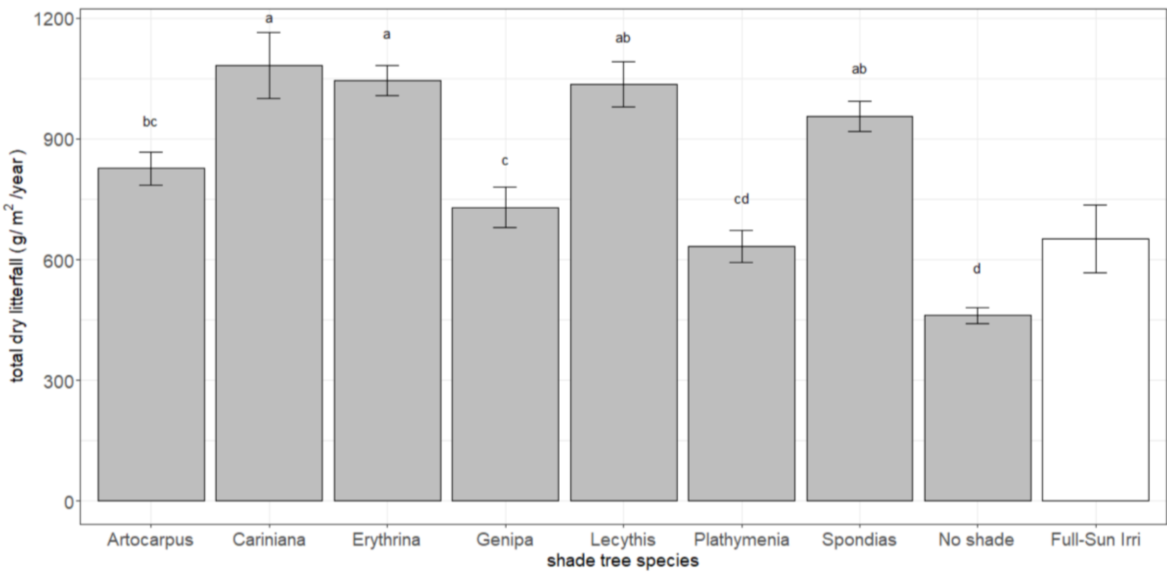


Figure 3.9. Total litterfall (cocoa leaves, shade tree leaves and 'rest') in g/m^2 produced in one year (March 2016-February 2017) for 7 shade tree species, no shade and full-sun irrigated (N = 8). Error bars represent standard error of the mean. Different letters above the bars show significant differences (Tukey–HSD, P < 0.05)

Cocoa litterfall was on average 101% higher in non-shaded plots (245 g/m^2) than shaded plots (122 g/m^2) in the cabruca farms, and 284% higher in full-sun farm (518 g/m^2) than in cabruca farms (135 g/m^2) (see Appendix 3.8 Litterfall production per litter type). Litterfall production was negatively related to light (R^2=0.19, P < 0.05): low GSF was associated to high litterfall production (Fig. 3.10).

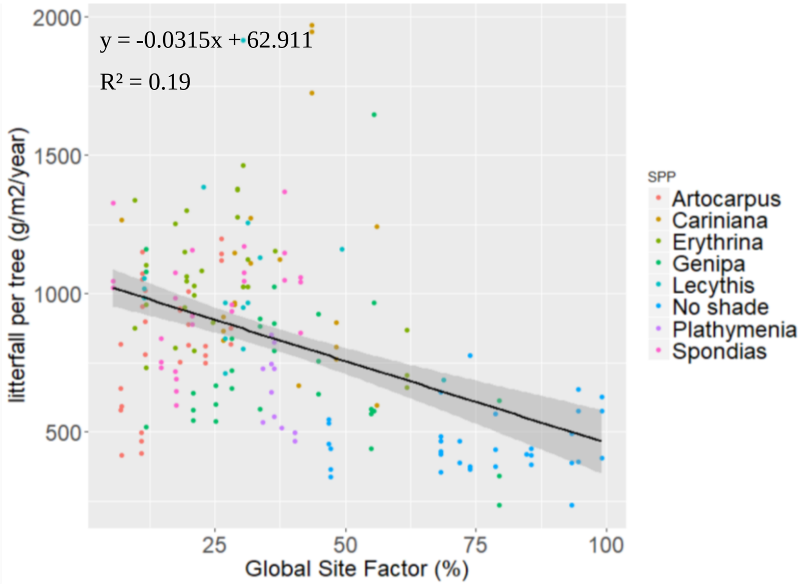


Figure 3.10 Litterfall production per Global Site Factor (GSF) per shade tree species in 10 cabruca farms.

3.3.5.2. On nutrient concentrations in litterfall

Nutrient concentrations in the leaves of the shade tree litterfall were not significantly different between shade tree species (legume trees *Erythrina* and *Plathymenia* had maximum N concentrations 16.5 and 18.2 g/kg respectively). N concentration in the cocoa leaves or ‘the rest’ did not differ between shade tree species (Fig. 3.11).

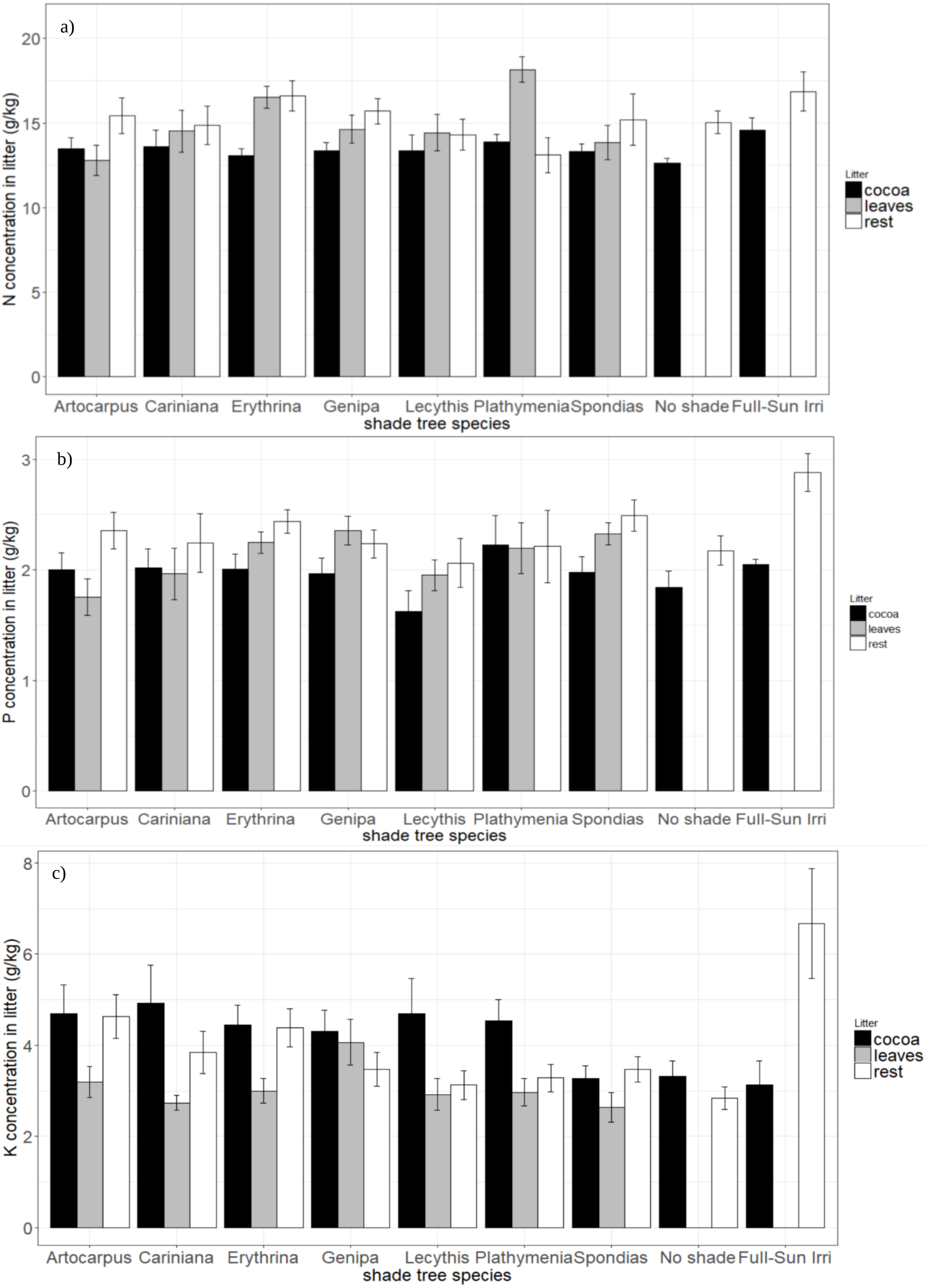


Figure 3-11. Nutrient concentrations (g/kg) for each litterfall type: cocoa leaves, shade tree leaves and 'the rest' in litterfall produced in one year (March 2016-February 2017) for: 7 shade tree species and no shade in 10 cabruca farms and one full-sun irrigated farm (Full-Sun Irri). a) nitrogen concentration per shade tree species, b) phosphorus concentration per shade tree species, c) potassium concentration per shade tree species. Error bars represent standard error of the mean.

N concentrations in all litterfall types ranged from 14.2–18.2 g/kg (Fig. 3.10 a), *Erythrina* and *Plathymenia* leaf litter had significantly higher N concentrations than other shade tree species, cocoa leaf litter had significantly lower N concentrations than the shade tree leaf litter and 'the rest' of the litterfall. P concentrations ranged from 1.1 to 3.3 g/kg. *Genipa*, *Erythrina* and *Spondias* leaf litter had significantly higher P concentrations than *Artocarpus*, 'the rest' of litterfall had significantly higher P concentrations than the cocoa and the shade tree leaf litters (Fig. 3.11 b). K concentrations in litterfall ranged from 1.9 to 10 g/kg, no species or type of litterfall had significantly higher or lower K concentration (Fig. 3.11 c). N, P and K concentrations did not significantly differ between litterfall from different cabruca farms and litterfall from the full-sun irrigated farm. The concentrations of nutrients of shade trees were correlated; species with high concentrations of N also had high concentrations of P and K (see Appendix 3.9 Correlations between N, P and K concentration).

3.3.5.3.On total nutrients recycled in litterfall per year

The variations in total quantities of litterfall and in nutrient concentrations resulted in variability in total nutrient input in litterfall between shade tree species. Total nutrient inputs were highest under *Cariniana* and *Erythrina*; plots with no shade had the lowest input. (Fig. 3.12). The cocoa leaf litter provided on average only 13% of N, 13% P, 18% K in litterfall in shaded plots in cabruca farms, shade tree leaf litter provided 31% N, 31% P, 25% K, the 'rest' component provided most of the nutrients in cabruca farms (55% of N, 55% P, 56% K). In the full-sun irrigated farm cocoa leaf litter provided most of the nutrients with on average 80% of the N, 80% of the P and 87% of the K.

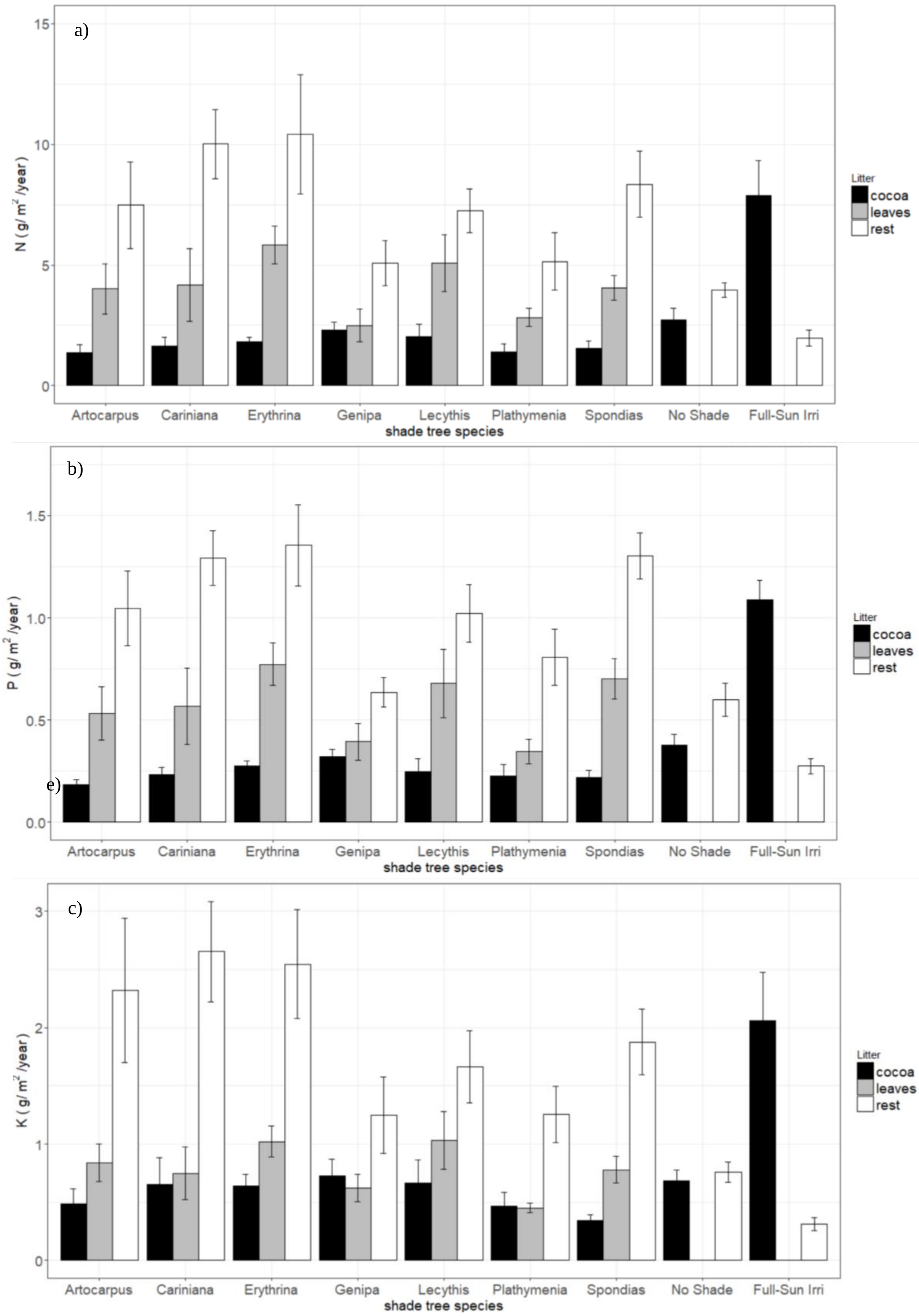


Figure 3.12. Total nutrients provided by litterfall (g/m^2/year) for each litterfall type: cocoa leaf litter, shade tree leaf litter and ‘rest’ in litterfall produced in one year (March 2016-February 2017) for: 7 shade tree species, no shade in 10 cabruca farms and in one irrigated full-sun (Full-Sun Irri). a) nitrogen content per shade tree species, b) phosphorus content per shade tree species, c) potassium content per shade tree species. Error bars represent standard error of the mean.

3.3.6. Relationships between yield, litter, light and other environmental factors

We used mixed effect Poisson regression to establish which variables affected cocoa pod production (AIC = 1975). Farms and plots were random effects. Fixed effects are summarised in Table 3.4.

Table 3.4 Fixed effects on cocoa yield

	Estimate	SE	z value	P	significance
(Intercept)	-6.4	1.1	-5.6	$1.7\ 10^{-8}$	***
SPPCariniana	$3.4\ 10^{-1}$	$5.2\ 10^{-1}$	0.6	0.52	
SPPErythrina	$-1.1\ 10^{-1}$	3.2	-3.4	$6.2\ 10^{-4}$	***
SPPGenipa	$-4.1\ 10^{-1}$	$4.6\ 10^{-1}$	-0.9	0.38	
SPPLecythis	$-4.7\ 10^{-1}$	$5.1\ 10^{-1}$	-0.9	0.36	
SPPNo shade	$-4.1\ 10^{-2}$	$6.6\ 10^{-1}$	-0.1	0.95	
SPPPlathymenia	1.7	$9.2\ 10^{-1}$	1.9	0.06	.
SPPSpondias	-5.5	1.8	-3.0	0.002	**
varietyClone	1.5	$5.3\ 10^{-1}$	2.8	0.006	**
varietyCommon	1.1	$6.3\ 10^{-1}$	1.8	0.07	.
varietyHybrid	1.8	$5.4\ 10^{-1}$	3.3	$8.7\ 10^{-4}$	***
DBH	$5.9\ 10^{-2}$	$1.4\ 10^{-2}$	4.2	$2.7\ 10^{-5}$	***
Stem	$1.1\ 10^{-1}$	$2.8\ 10^{-2}$	4.0	$5.4\ 10^{-5}$	***
Crown	$2.9\ 10^{-2}$	$2.3\ 10^{-3}$	13	$< 2\ 10^{-16}$	***
Height	$2.8\ 10^{-2}$	$2.2\ 10^{-2}$	1.3	0.21	
totalLitterfall	$5.4\ 10^{-4}$	$2.5\ 10^{-4}$	2.1	0.03	*
PerCocoaLitter	$6.7\ 10^{-3}$	$3.2\ 10^{-3}$	2.1	0.04	*
PerPodRotten	$4.6\ 10^{-3}$	$1.5\ 10^{-3}$	3.1	0.002	**
HeightBioassay	$2.3\ 10^{-2}$	$6.7\ 10^{-3}$	3.5	$4.9\ 10^{-4}$	***
LeaveNumberBioassay	$-6.1\ 10^{-3}$	$9.6\ 10^{-3}$	-0.6	0.52	
TotalDryBioassay	$-7.5\ 10^{-3}$	$1.4\ 10^{-2}$	-0.5	0.60	
RootRatioBioassay	2.9	$4.9\ 10^{-1}$	5.8	$5.4\ 10^{-9}$	***
GSF	$1.6\ 10^{-3}$	$5.7\ 10^{-3}$	0.3	0.78	

Significance codes for P values: ***: P<0.001; ** P<0.01; * P<0.05; . : P< 0.1

Variables which positively affected pod production included the varieties ‘clone’ and ‘hybrid’, cocoa trees with larger DBH, crown and number of stems; total litterfall mass and percentage of cocoa litter; percentage of rotten cocoa pods; bioassay height and root mass ratio.

3.4. Discussion

3.4.1. Shade tree species affected yield

We found higher cocoa yield under shade trees species that produced the most litterfall, the highest production was under *Erythrina*. Concentrations of N were 16.6 g/kg in *Erythrina* litterfall the second highest of the seven shade tree species; where concentrations ranged from

12.9 – 18.0 N g/kg. Phosphorus and K concentrations were also high in *Erythrina* litterfall. Nutrient concentrations were correlated, species with high N had high P and K. The amounts (per area per time), as well as the concentrations, of N, P and K in litterfall was also high under *Erythrina* because the mass of litterfall per area per year was high. Most, 51%, of the litterfall under *Erythrina* was not from *Erythrina* or cocoa, it was 'the rest' – leaf litterfall of other species, and flowers, fruits, twigs of all species. In a study in Bahia, in cabruca farms shaded by different shade tree species, Santana and Cabala-Rosand (1982) concluded that *Erythrina* increased N content in soil. Thus in our experiment under *Erythrina* shade there was higher cocoa pod production, which was associated with higher rates of nutrient cycling of many ecosystem components. In a study comparing cocoa yield and tree productivity under two shade tree species (*Erythrina poeppigiana* and *Cordia alliodora*) in Costa Rica, Fassbender et al., (1988) found difference in total litterfall and productivity (higher for *E. poeppigiana* than *C. alliodora*) but no difference in cocoa yield between the shade tree, however all plots were fertilised.

3.4.2. Shade and cocoa production

Light had a positive effect on cocoa yield. An increase in values of Global Site factor increased pod production. However, the positive effect of species, particularly *Erythrina* (GSF: 26%), was stronger than the effect of light. Many studies show that the amount of shade affects cocoa production, and that shade and nutrient supplies interact. A well-known study (Murray 1952) showed an interaction between fertiliser and light levels – where highest light levels only increased pod production if trees were fertilised, unfertilised trees had lower pod production at high light levels. Two, more recent, studies on sites with low soil fertility are consistent with this in that yield was not higher in less shade (Ahenkorah et al., 1987, 1974; Wessel and Quist-Wessel, 2015). A further confounding factor is tree age – in 3 studies reduced shade was associated with high pod production at early tree age (in association with fertiliser addition) but as trees aged the increased production due to reduced shade disappeared (van Vliet and Giller, 2017).

3.4.3. Fertiliser did not affect yield

Fertilisation did not result in higher cocoa pod production in our cabrucas, despite higher cocoa production being associated with higher rates of nutrient cycling under *Erythrina*. Because our fertiliser experiment was not designed to investigate interactions between shade tree species and fertilisation the results cannot be analysed to see if fertilisation effects were found under shade tree species associated with low rates of pod production – a new experiment specifically designed to investigate this would be valuable. There are several possible explanations for our lack of effect of fertilisers. Firstly, our experiment was necessarily carried out after cocoa tree productivity was greatly reduced by a very strong drought. It is possible that the lack of response to fertilisers was at least in part due to the strong reduction in cocoa production due to the drought (Gateau-Rey et al., 2018). A second explanation is that the duration of the experiment, 15 months, might have not been long enough to detect a response of this perennial crop; much longer experiments (>10 years) were deemed necessary to obtain consistent cocoa yield responses to fertiliser additions in Brazil and Ghana (Cabala-Rosand et al., 1976; Ahenkorah et al., 1974). However, cocoa farmers probably expect, or need, rapid responses if they apply fertilisers and cannot wait for several years, hence the time scale of our experiment was relevant to the farmers the study was designed to help. Thirdly, only small amounts of nutrients are removed in the harvested pods due to the low productivity of the cocoa trees (a harvest of 240 kg/ha/year of cocoa beans corresponds to 5 kg N, 1 kg P and 4 kg K /ha/year being removed) and the fact that the shade trees were not growing much, because they were large trees decades old, which means that their nutrient requirements were low and could be met by atmospheric inputs.

Surprisingly, we observed a negative, but non-significant, effect of the fertiliser addition on the yield. This suggest that the cocoa trees, affected by the drought, could have mobilised these nutrient resources for growth (flushing) instead of fruiting.

Alternatively, but less likely, the lack of yield response to fertiliser could have been caused by the absence of nutrient deficiency, particularly phosphorus. While interviews with farmers showed that the majority had not used any fertiliser in the past four years the cabrucas farms may have been fertilised in the past – P fertilisation many years ago is likely to have had a persistent effect on soil P status and would explain the relatively high concentration of P in litterfall. However, N and K do not persist in tropical soils which suggest that the lack of response to fertiliser addition did not necessarily mean the absence of deficiencies.

3.4.4. Shade tree species did not affect nutrient concentration in cocoa tree leaves (mature trees and seedlings)

The live cocoa leaves collected under different shade tree species did not show differences in nutrient concentrations. Similarly, live seedling leaves of cocoa grown in soils collected under different shade tree species did not show differences in nutrient concentrations. This suggests that under shade tree species with high litterfall production, and probably higher nutrient availability, cocoa trees did not take up and store in their leaves higher quantities of nutrients than under other shade tree species with lower litterfall production. These results contrast with the findings of Burridge et al. (1964) who showed that the levels of N, P and K in cocoa leaves varied depending on the nutrients available in soil: in a two year fertiliser experiment in Ghana, N and P concentration in leaf were higher and but K concentration in leaves was lower in plots fertilised with N, P and K compared to controls. In the cabruca farms, the small difference in the total nutrient composition of litterfall between shade tree species was probably not sufficient to affect the nutrient concentration (N, P and K) of cocoa tree leaf (as opposed to large quantities of fertiliser addition). However, despite the lack of differences in leaf nutrient concentrations cocoa yields differed under different shade tree species.

3.4.5. The fertiliser experiment versus the bioassay - conflicting results

Our results showed a disconnect between the results of the on-farm study and the results of the bioassay. On-farm we found no fertiliser effect, but shade tree species did affect yield, whereas in the bioassay we found that fertilisers increased seedling growth but that there was no effect of shade tree species on seedling growth. The bioassay showed that cocoa seedlings were sensitive to fertiliser addition and that nutrients were probably limited in the soils collected in the cabruca farms. Pot experiments such as bioassays obviously do not reproduce the mature cocoa tree conditions in cabrucas, none-the-less they can be useful to study soil fertility while reducing other environmental limitations usually found in field conditions (Dalling et al., 2013). Most soils cultivated with traditional cocoa agroforests in Bahia have low to medium soil quality index and low nutrient availability (Araujo et al., 2018). Our bioassay did show that a locally grown cocoa variety responded to fertiliser additions in locally collected soil.

3.4.6. Relationship between yield and environmental factors

3.4.6.1. Fertilisers and shade

Previous studies of fertilisation in cocoa usually showed an effect on yield independent of the presence or absence of shade trees (Ahenkorah et al., 1987; Cunningham and Burridge, 1960; van Vliet et al., 2015; Asare, 2016), and fertilisation of cocoa trees is usually recommended in most parts of the world. In section 4 of the review by van Vliet and Giller (2017), 5 of 7 papers reported negative effects (reduced yields) of sole N fertiliser additions on adult cocoa trees but positive effects of N in combination with P or K. Four papers report a positive response to sole

P addition, but only two report a positive response to sole K addition. It is likely that the literature is biased towards reports of positive effects of fertilisers because it is probably more difficult to publish studies showing no effects of fertilisers, none-the-less it is clear that fertilisers often increase cocoa yields.

3.4.6.2. Yield, species effect and nutrients in litterfall and other explaining variables

The results of our study showed interactions between yield, shade trees species litterfall quantity and light. Highest yields were found under *Erythrina spp*, a potentially N-fixing shade tree species which produced one of the largest quantities of litterfall (10 t/ha/year) among all studied species commonly found in Bahia. High litterfall quantity was associated with low GSF (low light) due to the presence of large shade trees. In contrast, lower yields (cf. *Erythrina*) were found under no shade, which corresponded to the lower quantity of litterfall. No shade plots had the highest GSF but the lowest quantity of litterfall recycled (4.6 t/ha/year). This suggests that the presence of shade trees such as *Erythrina* benefited cocoa yield more than the full-light provided by the absence of shade trees.

Additionally to shade tree species, light and litterfall, cocoa yield was also affected by individual characteristic of cocoa trees such as size (DBH, crown area, number of stems), varieties and percentage of pods affected by fugal disease. This suggest that improving cocoa material at individual tree scale will increase cocoa yield.

Finally, the lack of yield response to short-term fertilisation addition contrasted with the positive yield response to long-term nutrient cycling by shade trees such as *Erythrina spp*.

3.5. Conclusion

Shade trees probably play a major role in maintaining long term but low productivity in cabruca farms with limited inputs. Our results suggest that the choice of shade tree species could affect cocoa yield: shade trees species producing large quantities of litterfall, some of which are legume species, were associated with higher cocoa production. Our findings also indicated that adding fertilisers in these shaded cabruca farms did not increase yield, though it is possible that the trees did not respond to fertiliser because the experiment was carried out immediately after a severe drought. Our results also suggest that in order to increase yield in these cabruca farms it would be worth experimenting with propagating individuals with high yields – in all cabruca farms there were always a few very productive trees, which suggests that the climate, soils and husbandry were adequate in all farms, it’s just that a small proportion of trees produce most of the crop – a phenomenon called the 75/25 rule (25% of trees produce 75% of the crop (Somarriba and Beer, 2011)).

Finally, this study showed that cabruca systems allow low but reliable yields, with few or no inputs in terms of labour (for pruning, weeding and harvesting), fertilisers, pesticides, fungicides and irrigation. In Cameroon, similar agroforestry systems with high shade tree density (140 trees/ha, no light measurement provided) that increased soil organic matter, were found to remain productive over at least 40 years without fertiliser input which suggests that shaded cocoa agroforestry systems have reached a stable nutrient balance but also a stable competition equilibrium (Jagoret et al., 2011; Saj et al., 2017b). Yield in cabruca farms in Barro Preto were probably limited by nutrient deficiencies and shade; and yields were low probably as a result of a combination of other environmental factors not considered in this study, such as drought, disease, or unproductive genetic material. The co-limitations (Sadras, 2004) have reached an equilibrium allowing low yields with a minimum of farmer management but over a very long term (50 years). Any farmer intervention would possibly require interfering simultaneously with several potentially limiting factors at once to get any yield response. In the current economical context of low cocoa price and high labour price in Brazil, farmers cannot invest in intensive management. Cabruca systems are adapted to this extensive low labour strategy, they do not depend on continuous investment from the farmers and they can remain temporary neglected without threatening the survival of the crop which probably make them resilient to cocoa price shocks.

Chapter 4 | How climate change could threaten cocoa plantations: effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil

Abstract

Climate models predict an increase frequency of strong climate events such as El Niño-Southern Oscillation (ENSO), which in parts of the tropics are the cause of exceptional droughts, these threaten global food production. Agroforestry systems are often suggested as promising diversification options to increase farmers' resilience to extreme climatic events. In the Northeastern state of Bahia, where most Brazilian cocoa is grown in wildlife-friendly agroforests, ENSOs cause severe droughts which negatively affect forest and agriculture. Cocoa (*Theobroma cacao*) is described as being sensitive to drought but there are no field-studies of the effect of ENSO-related drought on adult cocoa trees in the Americas; there is one study of an experimentally-imposed drought in Indonesia which resulted in 10 to 46% yield loss. In our study, in randomly chosen farms in Bahia, Brazil, we measured the effect of the severe 2015-16 ENSO event, which caused an unprecedented drought in cocoa agroforests. We show that drought caused high cocoa tree mortality (11%) and severely decreased cocoa yield (80% loss); the drought also increased infection rate of the chronic fungal disease witches' broom (*Moniliophthora perniciosa*). Our findings showed that Brazilian cocoa agroforests are at risk and that expected increases in the frequency of strong droughts are likely to cause decreased cocoa yields in the coming decades. Furthermore, because cocoa, like many crops, is grown somewhat beyond the climatic limits of its natural range, it and other crops could be the 'canaries in the coalmine' warning of forthcoming major drought effects on semi-natural and natural vegetation.

4.1 Introduction

Climate change is likely to affect global food production (Parry et al., 2004; Porter et al., 2014; Springmann et al., 2016). Agriculture is threatened by extreme climatic events such as droughts or floods enhanced by climate change (FAO, 2015). Some climate change scenarios predict an increase in extreme events, including an increased frequency of strong El Niño Southern Oscillation (ENSO) events (Cai et al., 2014; Sheffield and Wood, 2008; Timmermann, et al., 1999), which cause drought and flooding in the tropics. Starting in October 2014 and lasting until May 2016 there was a strong ENSO event, it was responsible for severe droughts in North-eastern Brazil (Getirana, 2016) where previous ENSO-related droughts have affected forest cover (Dessay et al., 2004; Oliveira et al., 2010; Rolim et al., 2005) and agricultural yields (Anderson et al., 2017; Araújo et al., 2011).

Brazil is the largest cocoa producer in South America with an average production of 270,000 tonnes of dry cocoa beans in 2014-2015 (ICCO, 2015), 75% of which was produced in Bahia. Cocoa is usually grown under the shade of large trees, which are a mixture of native species from the Atlantic Rainforest and introduced species grown for food, timber or nitrogen fixation. These agroforestry systems, called cabrucas in Bahia (Lobão et al., 2004; Setenta and Lobão, 2012) are a type of crop diversification commonly found in the tropics. Such diversifications are often suggested to increase farmers' resilience to extreme climatic events (Abou Rajab et al., 2016; Jacobi et al., 2015; Lin, 2011). However, there is no field-based study of the effect of ENSO-related drought on cabrucas despite the importance of cocoa as a crop in Bahia and the frequent droughts experienced in the region - on average every 6 years-though with much variation (Rodrigues et al., 2011).

Cocoa is described as being sensitive to drought (Wood and Lass, 1987), but there are few field-studies on the effect of drought on cocoa. Published studies of cocoa bean yields and their decrease due to ENSO-related droughts are based on interviews with farmers and/or official national statistical data. In Sulawesi (Keil et al., 2008) found that ENSO-related drought caused a 62% loss of cocoa production compared to their usual levels - based on data provided by the farmers. In West Africa (Ruf et al., 2015) reported 27% loss compared to a normal year, but this loss was mainly due to a decrease in the planted area due to forest fires, it was not much caused by lower production in drought affected cocoa trees. In Ecuador Vos et al. (1999) found a 19% loss of cocoa planted area as a result of the 1997-98 ENSO. A physiological production model compiling data from 30 sites in 10 cocoa producing countries, concluded that water limitation was responsible for 50% loss in yield (Zuidema et al., 2005). A climate change model for West African cocoa production (Laderach et al., 2011; Schroth et al., 2016b) predicted that the possible decrease in area suitable for growing cocoa by 2050 was mainly due to increased temperature and surprisingly not due to a decrease in rainfall. Overall these reports show that many areas have strong reductions in cocoa production due to drought though none of the studies is based on detailed research of the effects of drought on cocoa trees on farms.

The only large detailed on-farm study of the effects of drought on cocoa is of an experimentally imposed drought on six-year old cocoa grown with six-year old *Gliricidia* shade in Indonesia (Schwendenmann et al. 2010). The c. 78% rainfall exclusion over 13 months (of about 3000 mm rain in that period) caused only a 10% loss in cocoa yield during the rainfall exclusion, though a further 45% reduction was recorded after the end of the drought; no cocoa tree mortality was observed.

Our study measured the effect of a severe ENSO-related drought on cocoa trees in randomly chosen farms in the traditional cocoa producing area in the Northeast of Brazil, where 75% Brazilian cocoa is grown. The region has been affected by severe ENSO-related droughts in the past, however the severity of 2015-16 ENSO-related drought was unprecedented. Our major concern is that ENSO-related droughts are threatening cocoa production in traditional agroforests in the area in the long-term. We used permanent transects to measure the effect of a very strong drought on cocoa trees in 32 randomly-chosen farms with traditional cocoa agroforestry systems. To our knowledge, this is the first on-farm study of the effect of a severe natural drought on adult cocoa trees where cocoa was compared before and after an ENSO event. We expected to find reductions in cocoa yield and thus that predicted increases in drought are likely to cause major reductions in cocoa yield in the coming decades as the climate changes and strong droughts increase. Forest drought has recently emerged as a research priority (Clark et al., 2016); drought effects on cocoa agroforestry could be a ‘canary in the coal mine’ warning of problems to come both in agriculture and in semi-natural and natural vegetation due to increased intensity and frequency of droughts in a changing world climate.

4.2 Materials and Methods

4.2.1 Study site

The study area was in the municipality of Barro Preto in the south of Bahia State, Brazil (14.05° S, 39.040°W) at 150 m a.s.l. The climate is Af in the Köppen classification (Alvares et al., 2013). Annual rainfall average is 1608 mm per year with May and September being the driest months, with respectively 110 mm and 67 mm (2001 to 2014 average data from Mars Center for Cocoa Sciences (MCCS) weather station). In Barro Preto, rainfall quantities and distribution pattern are almost at the limits for cocoa production. Mean annual temperature is 26°C. Cocoa flowering follows the seasonal rainfall pattern with peaks immediately after rain events. Bahian cocoa production normally has two harvests per year: the main harvest is from April to August., there is a secondary harvest is from November to February. The soils in Barro

Preto are classified as Latosols or Argisol Red-Yellow soils, they have a clayey-loam composition (Araujo et al., 2013).

We selected Barro Preto municipality because of its location in the centre of the historical cocoa producing region and because of its proximity to the MCCS. The municipality has a forest cover of approximately 80% (DeFries et al., 2000; Hansen et al., 2013). Cocoa farms cover 9,100 ha, more than half of the total area of the municipality (16,000 ha). Traditional cocoa agroforests, called cabrucas, have tree species both native from the Atlantic Forest ecosystem and introduced of economic interest (i.e. fruits, timber and rubber) with cocoa as the main cash crop.

Management practices are usually limited to harvesting and occasionally pruning and manual weeding. Fertiliser and pesticides use are unusual. Most farms use herbicides (Glyphosate) to delay and reduce regrowth after manual weeding. During the study, manure fertilisation was applied in only 2 of the 32 farms. Cocoa trees were pruned annually after the main harvest in most farms.

4.2.2 Experimental design

From the 333 traditional cocoa farms listed in CEPLAC (Executive Commission of the Cocoa Farming Plan, the government organisation part of the ministry of agriculture in charge of research and technical support for Brazilian cocoa production) rural census for Barro Preto, we chose 32 at random, amounting approximately 1760 ha of the area planted with cocoa. In March 2015, we established permanent transects of 8 m x 100 m in areas defined as representative of each farm by the farm administrator. All cocoa trees and woody shade trees > 5 cm of DBH were measured and identified with tags. Cocoa tree and shade tree densities were on average 622 (± 33 SE) and 126 (± 12 SE) per hectare respectively.

4.2.3 Rain, PET data, and drought index

Rainfall and temperature data were recorded at MCCS weather station from January 2001 to February 2017. All farms were located within 15 km of MCCS. The PET was calculated from temperature using FAO ET0 calculator Version 3.2, September 2012 (Raes and Munoz, 2009). This calculator, based on the Penman-Monteith equation, uses average, minimum and maximum day temperature as minimum data inputs. We calculated the sum of average rainfall for the 30 preceding days to compare it with the sum of PET for the 30 preceding days. When the sum of the 30 preceding days of rain was less than the sum of the 30 preceding days of PET, we considered that the cocoa trees where facing a drought event. We compared water balance (rain, PET and soil water holding capacity) for a two-year period during ENSO (March 2015 to February 2017), which was the worst two-year drought since 2001 including the ENSO of 2008 (May 2007 to April 2009). The severity of the 2015-16 drought was also assessed using the widely used Standardized Precipitation-Evapotranspiration Index (SPEI), calculated from the SPEI package in R (Vicente-Serrano et al., 2010), and 15 years of MCCS rainfall as input data. We used the database from National Oceanographic and Atmospheric Administration (NOAA) to identify the duration of El Niño-Southern Oscillation (ENSO) events and to classify their strength using the Oceanographic El Niño Index (ONI), based on anomalies in Sea Surface Temperature (SST): weak (0.5 to 0.9 °C SST anomaly), moderate (1 to 1.4 °C SST anomaly), strong (1.5 to 1.9°C SST anomaly) and very strong (>1.9°C SST anomaly).

4.2.4 Soil water holding capacity

We measured soil water holding capacity in the middle of each transect in 10 of the 32 farms in April 2017. Because of limited resources and time, we could not make measurement in all 32 farms. In situ soil had its roots cut (in the top 5 cm of soil) was saturated with water one day and samples were collected the next day from the top 60 cm (0-20, 20-40, 40-60 cm). Samples were fresh weighed and then dried for 3 days at 90°C and reweighed. The difference in weight allowed us to calculate the water content, ($m_{water}=m_{wet}-m_{dry}$, with m_{water} : mass of water, m_{wet}: mass of wet soil and m_{dry}: mass of dry soil). This mass of water was converted into water depth (mm), at field capacity using the formula $h= V/(\pi \times r^2)$ with h: water height in the soil core in mm, V= volume of water in mm^3 and r = radius of soil core (15 mm) . One of the ten farms was excluded because the soil was extremely rocky.

4.2.5 Tree mortality

The number of dead cocoa trees was recorded in the middle of the second drought in April 2016 and compared to the number of live cocoa trees recorded in April 2015. Dead trees were recorded again in November 2017 and additional mortality was marginal (1.7%). The mortality rate of the cocoa trees (m) is given by $m = 1-[(N_0-N_m)/N_0]^{1/t}$ where N_0 is the number of trees at the beginning of the interval, N_m the number of trees that died after one year (time t = 1 year) (Sheil and May, 1996). Cocoa trees were classified into 3 groups by MCCS technicians based on field characteristics: 1) ‘common’ - Amelonado including Marañon and Pará the varieties most commonly found in Bahia; 2) ‘clones’, grafted or rooted cuttings of identified clones such as CCN51, TSH1188, PH16 or PS1319 selected by research institutes; and 3) hybrids, seed material produced in the 1960's by CEPLAC mainly from hybridization of the 'clones' and other varieties.

4.2.6 Cocoa yield and pod loss due to disease

The number of cocoa pods (length > 10 cm to exclude numerous small fruits that fall before reaching 10 cm) was counted on each tree before the harvest by the farmers in April 2015, April 2016, November 2016, April 2017 and November 2017. Yield was estimated using a conversion factor of 40 g of dry cocoa beans per healthy cocoa pod (a relationship established for cocoa in the area). The fungal infection rate (mainly caused by *Moniliophthora perniciosa* but also infrequently by *Phytophthora palmivora*) was assessed by recording the number of rotten pods on each tree. *M. perniciosa* primarily affects the leaves and vegetative development, but also impacts directly cocoa pods. The November 2015 harvest was not recorded for logistic reasons. Potential losses due to drought and disease were calculated by comparing the number of pods counted during harvests during and after the drought with the number of pods counted during harvest before the drought.

4.2.7 Data analyses

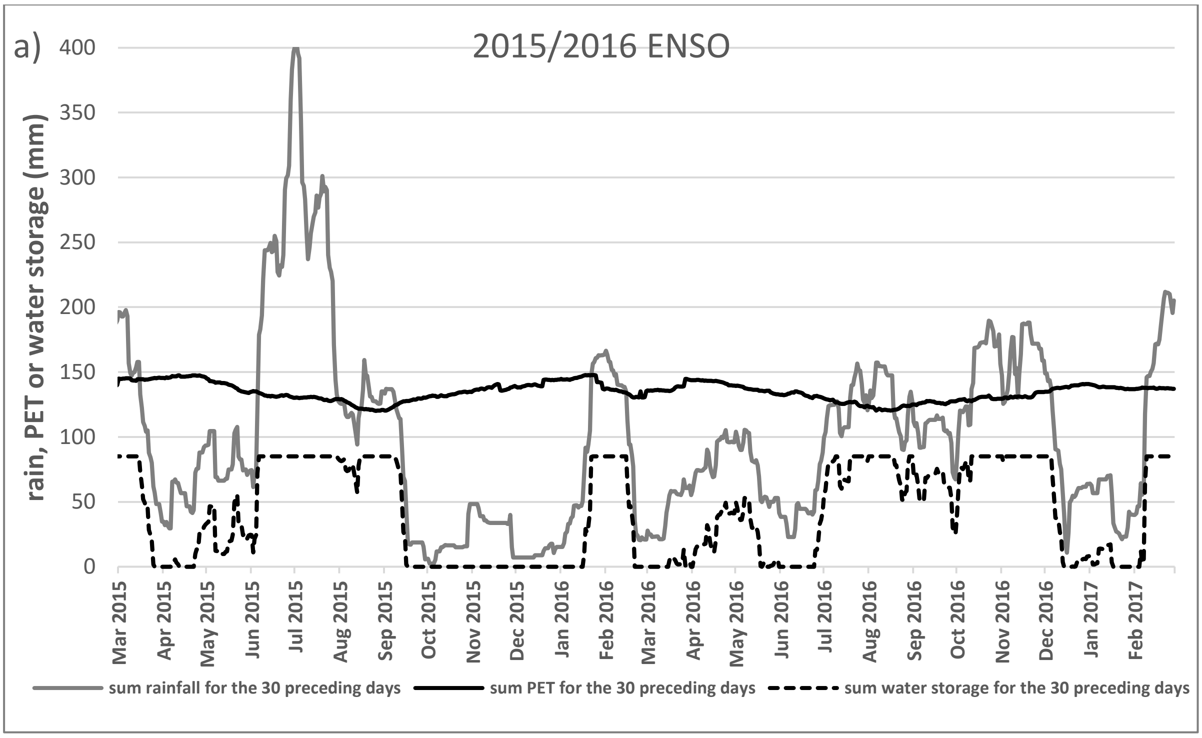
Mean pod numbers for each transect were calculated for each date. Generalized mixed effect models were used to explore relationships between tree mortality and individual tree and farm variables (farm characteristic: longitude and soil water holding capacity; shade: Ground cover and sum of shade trees DBH per transect). Data on tree mortality and pod loss were log-transformed. We hypothesised that the effect of the drought on cocoa tree mortality and yield could be emphasised by environmental variables: 1) high shade tree density and basal area increase cocoa mortality and decrease yield, 2) high levels of light (GSF) increase tree mortality and increase yield, 3) low soil water holding capacity increases mortality and decreases yield. All statistical analyses were computed using R Stat version 3.4.1.

4.3 Results

4.3.1 ENSO, rainfall, PET and drought index

When the study began in March 2015, NOAA reported an Oceanic el Niño Index (ONI) anomaly of > + 0.5°C in Sea Surface Temperature (SST). ONI reached a maximum of +2.3°C in December 2015 and was > + 0.5°C for 16 consecutive months until May 2016. The ENSO 2015-16 caused an abnormally strong drought in the cocoa region of Bahia in Brazil. Rainfall between August 2015 and August 2016 was 770 mm (and 786 mm between August 2016 and

May 2017); this is 53% lower than the 1621 (± 71) mm yearly average for 14 years from August 2001. The months with the minimum rainfall were September and November 2015 with 6 and 7 mm per month respectively (Fig. 4.1).



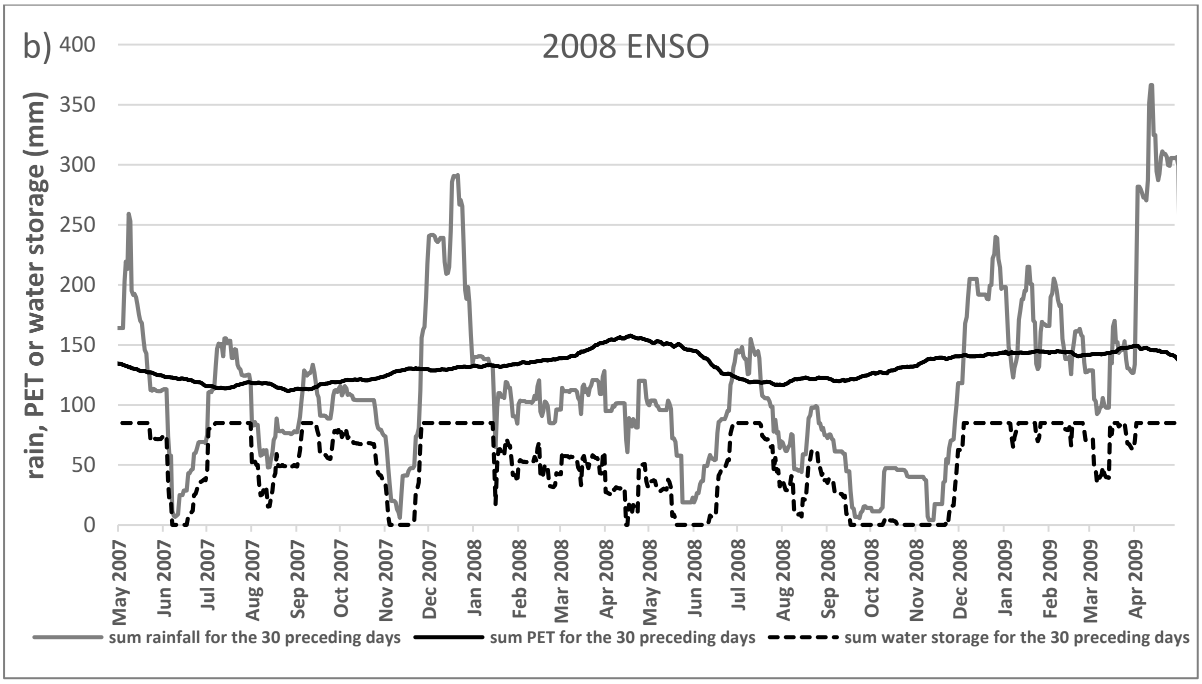


Figure 4-1. Sum of 30 preceding days for rainfall, PET and average soil water content in mm during ENSO 2015-16 event (a) and during ENSO 2008 (worse scenario since 2001) (b). Black line represents PET based on temperature, dark grey line represents rainfall and dotted line represents soil water storage.

Comparing the 30-day rainfall totals with the Potential Evapotranspiration (PET) (Fig. 4.1) showed two very long episodes, separated by 25 days, when PET > rain: September 2015 to

January 2016 (136 days) and February 2016 to end of June 2016 (131 days). From July 2016 rainfall returned to approximately equal PET – the average situation except for December 2016 until February 2017, when PET exceeded rainfall (Fig. 4.1). Expressing the same rainfall data in a different way as the ‘standardized precipitation-evapotranspiration index’ (SPEI) showed two episodes of negatives values during ENSO 2015-16 including 4 months with SPEI< -2 and with an extreme deviation of -3.2 in November 2015 (Fig. 4.2). These are exceptional values, SPEI was < -2 during only 4 months in the past 168 months (14 years). More recently the lowest values for SPEI have been decreasing, indicating stronger droughts since 2001 based on MCCS data (Fig. 4-2).

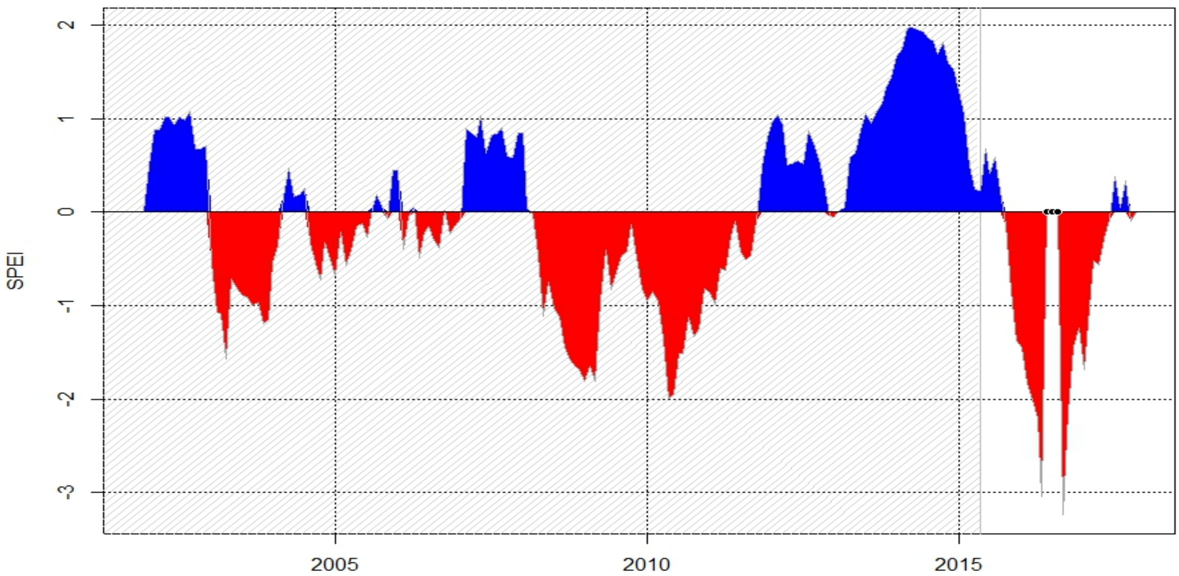


Figure 4-2. Standardized Precipitation-Evapotranspiration index on 12-months base. SPEI is expressed in units of standard deviation from the long-term mean of the standardized distribution. Negative values in red represent drought events. The reference period is the dashed area before ENSO.

4.3.2 Soil water holding capacity

Soil water holding capacity was about 86 (±13 SE) mm in the top 1000 mm of soil (Fig. 4.1), it was higher in the West than the East ($R^2 = 0.63$, $P < 0.01$). During the ENSO-related drought, calculated soil water content was at about zero for 4 months from mid-September 2015 to mid-January 2016 (Fig. 4.1).

4.3.3 Tree mortality

Cocoa tree mortality was 11% (± 2.3 SE) during the ENSO event as compared to < 1% normally (Bastide et al. 2008). In a further 5% (± 1.2 SE) of the trees the large productive stems died but suckers remained alive. Cocoa mortality differed between groups 28% in hybrids, 22% in ‘common’ cocoa and 15% in ‘clones’ (χ^2=53.2, 2 d.f., P<<0.001). There was no relationship between cocoa mortality and shade trees (either numbers of species or total basal area), soil water holding capacity or light (GSF) (Table 4.1). Shade tree mortality during the drought was 7% of the 317 woody shade trees on the transects; no species of shade trees was particularly affected. There were also 337 banana trees before the drought in March 2015 but these normally have a short lifespan (6 to 14 months), so it is not possible to say how many died of drought.

Table 4-1. Relationship between cocoa tree mortality (log of mortality per transect) and five environmental factors: shade trees (number of species: ShadeTrees and sum of basal area: ShadeTreesBA per transect, Global Site Factor : GSF) and farms characteristic (longitude and soil water holding capacity: SWC). (multiple linear regression, df: 7; adj.R^2:0.56; Significance: $P < 0.05$)

	Estimate	SE	t	*P*
Intercept	$-4.5\ 10^{3}$	$4.1\ 10^{3}$	-1.10	0.47
ShadeTreesBA	$-9.7\ 10^{-3}$	$6.1\ 10^{-3}$	-1.57	0.36
ShadeTrees	$-4.3\ 10^{-1}$	$2.5\ 10^{-1}$	-1.75	0.33
longitude	$-1.1\ 10^{2}$	$1.1\ 10^{2}$	-1.09	0.47
SWC	$3.9\ 10^{3}$	$2.8\ 10^{3}$	1.39	0.40
GSF	9.2	3.6	2.58	0.24

4.3.4 Pod loss

The average potential yield per area (based on pod number) on the 32 farms, for the main harvest (of two per year) in April 2015 before the drought, was 242 (± 25) kg/ha. During the drought, in April 2016, the average potential yield was 45 (± 22) kg/ha - an 80% reduction (Fig. 4.3). Nine months after the drought ended in July 2016, the potential yield in April 2017 was still 83% lower than in April 2015. The drought dramatically decreased the number of pods per tree. The 11% mortality of productive cocoa trees caused 11% of the 80% loss.

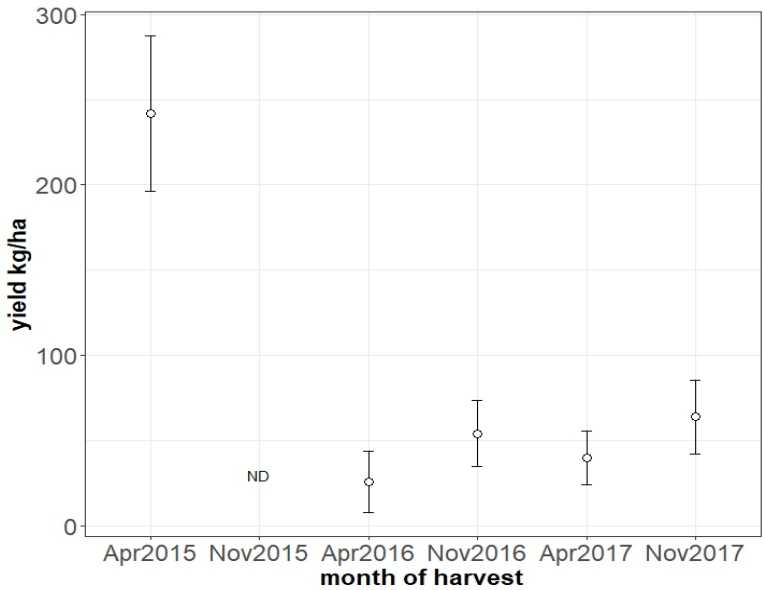


Figure 4-3. Yield per farm based on the number of pods per main harvest: drought decreases pod production on a long term. There was no data (ND) for the peak harvest in November 2015. Means and standard errors are for N = 11 farms.

There was no significant relationship between the pod loss and shade trees (either numbers of species or total basal area), soil water holding capacity or light (GSF) (Table 4.2).

Table 4-2. Relationship between cocoa pod loss (log of percentage of pod loss compared to 2015 harvest per transect) and five environmental factors: shade trees (number of species: ShadeTrees and sum of basal area: ShadeTreesBA per transect, Global Site Factor : GSF) and farms characteristic (longitude and soil water holding capacity: SWC). (multiple linear regression; df: 7; adj.R^2: 0.39; Significance: $P < 0.05$)

	Estimate	SE	t	*P*
Intercept	$-1.2\ 10^{2}$	$3.6\ 10^{2}$	-0.40	0.72
ShadeTreesBA	$2.2\ 10^{-3}$	$1.3\ 10^{-3}$	1.67	0.19
ShadeTrees	$4.5\ 10^{-2}$	$3.7\ 10^{-2}$	0.93	0.42
longitude	-3.2	7.9	-0.40	0.72
SWC	$-7.0\ 10^{-1}$	2.6	-0.27	0.80
GSF	-1.6	2.0	-0.79	0.49

4.3.5. Disease and infection rate

Witches' broom was first recorded in Bahia in 1989 and has resulted in a big reduction of cocoa production since. At the beginning of the study (April 2015), the fungal infection caused about a 15% pod loss. However, during the drought the loss was much higher: 36% in April 2016 and 35% in April 2017 after the drought.

4.3.6. ENSO-related drought and yield loss at local and country scales.

Strong ENSO-related droughts decreased production in Bahia and Brazil as a whole (Fig. 4.4), though weak ENSO events did not.

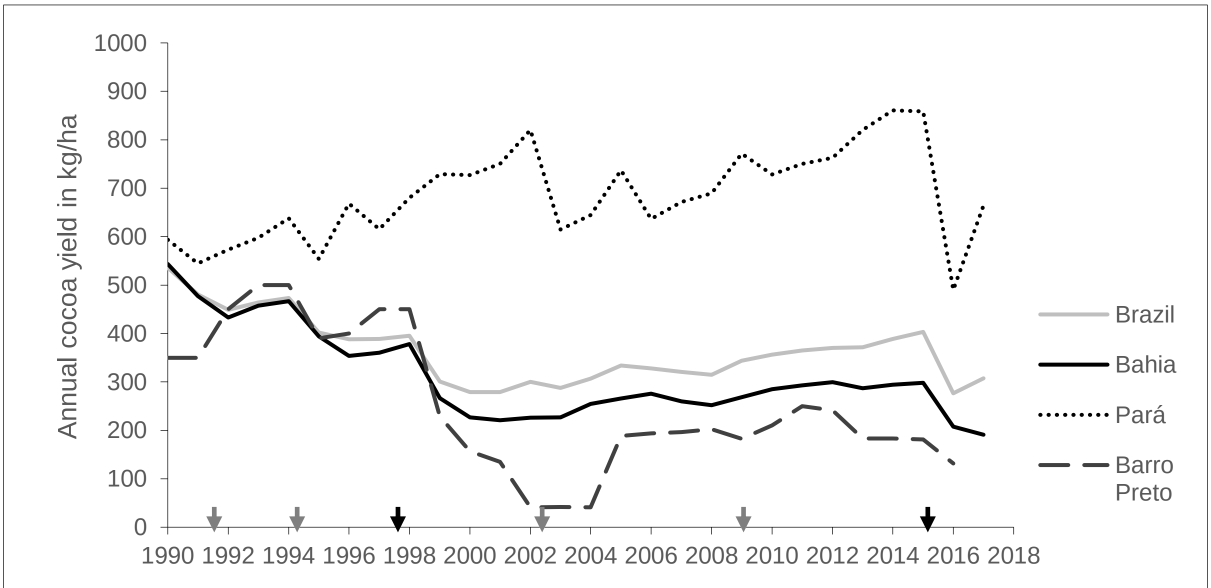


Figure 4-4. Cocoa production in all Brazil, and the states of: Bahia and Pará and the municipality of Barro Preto since 1990 (IBGE, 2017). Black arrows represent strong ENSO events (1997-1998, 2015-2016), grey arrows represent moderate ENSO events (1991-1992, 1994-1995, 2002-2003, 2009-2010). The *Moniliophthora perniciosa* outbreak started in Bahia in 1989.

Cocoa production in 2015-16 during the ENSO-related drought (277 kg/ha) was the lowest recorded since 1990. At a country scale yield decreased from 400 kg/ha before the drought to 277 kg/ha after; in Pará state yield decreased from 860 kg/ha to 490 kg/ha, in Bahia state yield decreased from 300 kg/ha to 200 kg/ha. Production for Barro Preto was not available for 2016-2017.

4.4 Discussion

4.4.1 First field data with quantification of drought sensitivity of cocoa agroforests

To our knowledge, our study on the effect of drought on cocoa agroforests, is the first, in South America, based on natural drought and field assessments on farms. Despite cocoa being known as a drought-sensitive crop (Wood and Lass, 1987) published, reliable, field-data on the effect of natural drought on mature plantations is scarce (Carr and Lockwood, 2011). There seems to be only one other on-farm study of the effect of 2015/16 ENSO drought on cocoa trees, done in Ghana (Abdulai et al., 2018).The authors concluded that full-sun plantations were more resilient to drought than agroforests by comparing mortality, transpiration rates and soil water content in cocoa trees under three specific shading regimes (full-sun cocoa, cocoa-*Albizia ferruginea* and cocoa-*Antiaris toxicaria*) in only one farm. The generality of this conclusion has been questioned by (Norgrove, 2017; Wanger et al., 2017) who pointed out that 1) these two cocoa-shade tree associations were not representative of an agroforest and 2) the sub-optimal climate of the region (based on a single site) was not representative of climate conditions where cocoa is usually grown (low rainfall). Thus, our study is the first recording the effect of a natural severe drought on shaded cocoa in complex agroforestry systems based on data from several cocoa farms. Studies of the effect of previous ENSO events on cocoa plantations at regional scales in Asia, Africa and America were based on indirect data resulting from interviews and/or national statistical compilations of yield and planted area (Keil et al., 2009; Ruf et al., 2015; Salafsky, 1994; Vos et al., 1999). Our on-farm results confirm that cocoa is sensitive to very strong droughts, but the Brazilian yield data suggest that cocoa is not sensitive to mild droughts caused by weak, moderate or strong ENSO events; only 'very strong' ENSOs reduce yield but they do so very markedly. However, the sensitivity of cocoa yield to drought depend on the rainfall regime for particular areas. As a consequence, in sites with lower rainfall even mild drought may have an effect and decrease cocoa yield.

4.4.2 2015-16 ENSO was the strongest event recorded over the past decades

Despite large uncertainty (Christensen et al., 2013), severe ENSO events are expected to increase in frequency following climate change (Cai et al., 2015, 2014; Timmermann et al., 1999). Droughts are not unusual in Bahia and the probability of extreme droughts in Northern Brazil is one year in nine (Awange et al., 2016). We showed that recent ENSO was associated with the highest ONI values since the 1997-98 ENSO. It caused the strongest drought episode recorded for the last 15 years in Barro Preto, Bahia. At the global scale the ENSO 2015-16 is considered as the strongest event in the last 23 years with an SST anomaly of 0.3°C more than the highest anomaly recorded during strong 1997-98 ENSO (Kogan and Guo, 2017). Based on satellite data, northern Brazil and the Amazon were dramatically affected by the severe drought related to 2015-16 ENSO (Getirana, 2016; Shimizu et al., 2017). Northern Brazil had the maximum negative correlation between Vegetation health indices (VHI) and SST (−0.70) showing that vegetation was experiencing very high stress at large scale (Kogan and Guo, 2017). Thus, both natural vegetation and a major tree crop, cocoa, were affected by the same exceptional ENSO-related drought.

4.4.3 Drought effect on yield

Potential yield losses in 2016 and 2017 were about 80% compared to the harvest in April 2015 before the drought. The decreases are much higher than the decrease in annual cocoa yield reported for the state of Bahia from 2015-2016 (about 30%: 298 to 207 kg/ha). The difference could be due to one of several, non-mutually exclusive, reasons. Firstly, our farms may have been unusually affected by the drought as compared to the rest of the state of Bahia; we cannot test this but point out that our farms were a random sample from 333 farms in the Barro Preto region (160 km^2) however this is only 0.5% of the cocoa region of the State of Bahia (32,000 km^2) and although the area sampled was large (16 km West to East and 10 km North to South) it is small compared to the ‘cocoa area’ of Bahia. Secondly, it could be that in wetter parts of the cocoa region of Bahia (i.e. in the North: Salvador) the ENSO-related drought had little effect or even increased growth because in wetter areas, the potential reduction in yield due to some drought may be overwhelmed by the increased production resulting from increased solar radiation. Thirdly, drought may cause abnormally high leaf loss in shade trees, which has two effects it potentially somewhat reduces water use by the shade trees and it also lets more light through to the cocoa trees below, thus increasing yield (a situation found in liana seedlings in semi-evergreen rain forest in Panama where a stronger dry season resulted increased seedling growth (Aide and Zimmerman, 1990)). Finally our experiment did not show the average variability in yield for normal (non-ENSO) years.

There seems to be only one other on-farm study of the effect of drought on cocoa yield - an experimental drought, simulating an ENSO event, in Indonesia, where rooves reduced rainfall by about 78% over 13 months, when the actual rainfall was 2937mm. In this experiment, there were no extended periods without rain and the ‘relative extractable water’ from the soil only reached close to zero for one month near the end of the experimental drought. Cocoa yield was only reduced by 10%, though interestingly yield was reduced by 45% *after* the rooves were removed; there was no cocoa tree mortality (Schwendenmann et al., 2010). By contrast, in our study of natural drought we had an 80% lower yield and a 11% cocoa tree mortality; the large differences between the studies were probably due to the fact that our natural drought was much stronger (136 and 131 days with PET > rain versus 32 and 60 days under the shelters in the Indonesian experiment).

In addition to the direct effect of drought reducing cocoa tree growth and pod production drought was associated with an increase in disease infection rate (15% of all pods before the drought to 30% during the drought). Rotten pods resulting from disease contributed significantly (35% of the total April 2017 harvest) to the reduction in the number of pods counted after the drought. This increase in infection rate was also observed in the artificial drought experiment in Indonesia (Schwendenmann et al., 2010). Pathogen cycles have been observed for fungal diseases for cocoa (black pod, *P. palmivora*) in Bahia (Cazorla et al., 1995) and in Nigeria (Papaioannou, 2016). Fungal disease is the major cause of cocoa yield loss worldwide being responsible for a 30% loss of production. Climate events including droughts increase these fungal infections rate and increase yield losses (Crowder and Harwood, 2014), thus putting cocoa production at risk.

4.4.4 Cocoa tree mortality

Cocoa tree mortality, 11%, was exceptionally high for reasonably healthy old cocoa plantations, where normal annual tree mortality is usually < 1% (Allen 1989; Bastide et al. 2008). High tree losses during droughts are often caused by fire, but fire did not affect any cocoa plantations in Barro Preto during the study. However, 2,000 ha of cabrucas and forest burnt in the neighbouring municipalities as a result of the drought (reported in Intituto Arapyau: http://www.arapyau.org.br blog/2016/01, online access: 25-07-2017). Exceptionally high infection rates of pests and diseases can also be responsible for high tree mortality, for example a change from heavily shaded agroforests to non-shaded systems resulted in insect attack in Sao Tome and Fernando Po in the 1920's (Johns, 1999) and Vascular Streak Dieback disease *(Oncobasidium theobromae*) in Malaysia in the 1990's (Chok, 1998). No lethal pests or diseases were observed in our experiment (*Moniliophthora perniciosa* does not kill trees). The high mortality of mature cocoa trees caused by drought is important because it will reduce yields for a minimum of 3-5 years until replacement trees become productive.

Modern clones selected for their drought-tolerance characteristic were not found in our plots. However, we showed that clones not necessarily selected for the drought were more resistant than hybrids or traditional common amelonado. These clones include e.g CCN51, CCN10, PS1319 and TSH1188, accessions often selected for their high yield and disease resistance in high input and low-shade conditions, which could partially explain their drought tolerance. Numerous drought-tolerant cocoa accessions have been identified (Carr and Lockwood, 2011; de Almeida et al., 2002; Santos et al., 2014). However most of the candidate clones have only been assessed in greenhouses or at very early stages of growth in plantations. There is an urgent need to assess these drought-tolerant clones in farm conditions and to introduce drought-tolerant clones in the Brazilian market of cocoa varieties. Recent ENSO-related droughts could result in 'mass selection' of the more drought-tolerant Amelonado at farm scale. As compared to most other crops, varietal selection by growers remains marginal in cocoa in Bahia (only 30% of the cocoa trees recorded were grafts or rooted cuttings selected as high-yielding disease-tolerant material); most cocoa found in Bahia is the semi-natural Amazonian Amelonado. A combination of 'mass selection' of local varieties and genetically selected drought-tolerant varieties will be necessary to limit the damage in future strong droughts.

4.4.5 Trends and future of cocoa production

Recent ENSO-related drought has changed the balance of cocoa production between Brazilian states; Bahia used to produce 95% of Brazilian cocoa, but since the 1990's, Bahian production has been declining mainly because of witches' broom whereas production in Pará state has been increasing considerably since it started in the 2000's. In 2017 just after the drought, Pará state became the most productive Brazilian state. The 2015-16 ENSO- drought reduced cocoa production in Bahia, which was already weakened by chronic fungal infection. Such changes in producing areas are common in cocoa and have been described as part of boom and bust cycles (Ruf, 1995). In the case of Brazil, these changes will result in a decrease in extensive traditional environmentally-friendly cocoa agroforestry systems with high species diversity ('cabrucas'), which will be replaced by simplified systems with intensive inputs. These changes reflect a trend in world cocoa production to switch from shaded agroforests to intensively managed monocrops. Diversified agroforestry systems are often presented as the best management strategy to increase small farmers' resilience to severe climate events by relying on different crops (Jacobi et al., 2015; Obeng and Aguilar, 2015; Steffan-Dewenter et al., 2007; Tscharntke et al., 2011). However, our study did not include agricultural products other than cocoa, thence it is not possible to conclude on the economic resilience of cabrucas systems to climate change.

World cocoa production is negatively affected by ENSO years and positively affected by la Niña years (ICCO, 2010). However-attempts to show clear relationships between rainfall and cocoa yield at regional scales remain inconclusive (Ali, 1969; Dunlop, 1925; Lawal and Omonona, 2014; Toxopeus and Wessel, 1970). Only extreme ENSO events cause reduced cocoa yield in Bahia. ENSO events are often associated with yield losses in crops due to drought but also to flooding (Haggar and Schepp, 2011; Rojas et al., 2014). ENSO events are also responsible for losses in vegetation cover (Gonsamo et al., 2016) and are a threat to tropical forests (Allen et al., 2010; Phillips et al., 2010). Forest mortality due to ENSO droughts vary from 1.4 to 80% - the higher ones being due to fire (see Appendix 4.1 Literature review on the effect of ENSO droughts on forests). In natural forests, the effects may be limited because dead trees are rapidly replaced by regrowth and many forest systems are resilient to drought, unless they burn when it takes much longer for them to recover. In the case of crops including cocoa, tree mortality means at least three years without a cocoa crop – a serious loss of income for farmers. Crops often have low resilience to extreme climate events because they are often grown in sub-optimal regions where, for example, water could be limiting. This is the case for Barro Preto, where rainfall quantities and distribution pattern are almost at the limits for cocoa production.

Thus, we have shown, for the first time on-farm, that a severe El Niño drought reduced cocoa production by 80% for the main (April) harvests in 2016 and 2017, and killed 11% of cocoa trees. Strong droughts are not uncommon in Bahia Brazil, but an eleven-month event with two successive droughts of 136 and 131 days (separated by 25 days) was unique. It is likely that such droughts will become longer and more frequent in the tropics and thus cocoa yields in such areas will be strongly reduced. Cocoa is an example of many crops grown somewhat beyond their normal climatic range; which are sensitive to drought and whose yields might be greatly reduced in future due to changed climates with stronger and more frequent droughts. Such crops could be the ‘canaries in the coal mine’ warning of problems to come due to increased intensity and frequency of droughts (Allen et al., 2010; Rojas et al., 2014) both for crops and semi-natural and natural vegetation.

Chapter 5 | General Discussion and Conclusion

This thesis aimed to contribute to understanding how to increase sustainability in cabrucas in a climate change context. I have demonstrated that yield was limited by several variables including unproductive trees and diseases; shade trees density and light were limiting factors but not species richness (chapter 2). I have shown that nutrients were not limiting factors. The shade trees contribute to a long-term higher nutrient availability resulting in high long-term cocoa yield with almost no labour (chapter 3). These results strictly apply to conditions during and immediately after a severe drought; an unavoidable and unexpected drought due to El Niño event happened between November 2015 and May 2016 while our experiment was already established. However, this also allowed us to collect a unique set of on-farm data on the effect of drought on cocoa and to show that increase in frequency of climate events such as El Niño-related droughts are a threat to cabrucas (chapter 3).

The four key questions this thesis aimed to investigate were:

1. How can farmers increase income without decreasing the biodiversity?

2. What were the factors limiting cocoa yield in cabrucas?

3. What are the effects of shade trees on nutrient dynamic and yield in agroforests?

4. How will climate change and particularly increased frequency of severe climatic events affect cocoa production.

In this final chapter, I return to these research questions and assess how this thesis addresses them. I discuss limitations and provide suggestions for future research. Finally, I conclude with the implications of my results for the cocoa industry and possible scenarios for decision-makers to reach a more sustainable cocoa production.

5.1 Increase cocoa farmers' income without damaging the biodiversity

5.1.1 Increase cocoa yield: close the yield gaps

Closing yield gap by intensification is the strategy promoted by the chocolate companies and research institutes to increase cocoa yield. ("more cocoa on less land")

Annual global production is approximately five million metric tonnes of dried beans for 9,9 million hectares planted area (FAOSTAT, 2017). The world's population is projected to reach 9.8 billion by 2050 (FAO, 2011). Change in diet will increase chocolate demand by 5% by 2020. Worrying about a possible cocoa shortage, the chocolate industry wants to increase the cocoa production. Their strategy, supported by international research organisations, is to intensify the cocoa production using technology. Cocoa is a tropical crop grown in extensive production systems (agroforestry systems) resulting in low cocoa yield (300 kg/ha on average). However, intensified plantations using large amount of inputs, labour and technology can reach 4000 kg/ha. This difference between potential attainable high yield and average observed low yield is known as the yield gap (Lobell et al., 2009). Closing the yield gap is the current strategy supported by the chocolate companies and promoted by rural development agencies. In cocoa research, priority is given 1) to fight diseases responsible for 30 - 40% world yield loss, 2) to select and to propagate high yielding disease-tolerant varieties and 3) to support farmers with technical knowledge ('farmer field schools') and to promote technology package (fungicides, pesticides, herbicides, fertiliser, reduced shade) to increase yield (MARS, 2017).

Known limiting factors: unproductive trees, disease, shade, labour, water, nutrition

The factors causing yield gaps can vary considerably. In the only published study from Ghana, the cocoa yield gap between attainable yield in experimental trials and yields in farms was over 1500 kg/ha. The main factors which explained yield gaps were technical: farm size, choice of clones, frequency of fertiliser, fungicide and herbicide use (Aneani and Ofori-Frimpong 2013). However, in Bahia we found that environmental and management factors explained 72% of the yield gap between on-farm attainable yield and observed yield. These main factors were: the high percentage of unproductive cocoa trees, the low density of cocoa trees, the high shade tree cover, the high cocoa tree mortality due to the drought and the low soil fertility.

Low productivity of trees could be due to a combination of factors such as chronic fungal disease infection, poor genetic material (e.g with self-incompatible flowers for pollination or seedlings resulting from seeds harvested on clones/hybrid trees unfit for high yields), nutrient deficiency and heavy shade conditions. Cocoa trees must be managed at cocoa tree scale, grafting or replacing trees identified by the farmers as unproductive by high-yielding disease tolerant trees.

Low density is common in agroforests where cocoa trees are planted with a mixture of shade trees. In Bahia, cocoa plantations were old (30-50 years) and cocoa trees were not replaced when they died; Cabrucas need to be densified by replanting missing trees.

High shade cover limits yield because of light competition between shade trees and understorey cocoa trees. In cabrucas shade cover was 35%. Shade cover could be reduced by removing or pruning shade trees. However, pruning shade trees require high investments, because of their great height – often 30-40 m, and we did not implement any experiment to study the effect of reducing shade. In previous experiments, it was found that removing shade trees increased yield during a short period of time before declining due to high pressure of pests and diseases (Chok, 1998; Johns, 1999).

Water stress causing high cocoa tree mortality has been observed after the 2015/16 El Niño drought. Cocoa could be grown in irrigated plantations to reach exceptionally high yields. However, high investments are needed, and cocoa farmers usually cannot afford to irrigate their farms.

Soil nutrient deficiency is common in old plantations and contributes to low yield. Most shaded cocoa plantations do not receive any fertiliser. Agricultural extension programs usually focus on encouraging fertiliser use, however nutrient recommendation for cocoa are often not adapted to the farm conditions. In our experiment in cabrucas, we found no yield response to fertiliser addition after 15 months.

Cocoa yield, light and nutrition

An insufficient supply of nutrients possibly contributes to low yield. Soils in old agroforests (30-50 years old) often have deficiency in nutrients because the nutrients removed by harvests are not replaced by sufficient fertiliser inputs. In our experiment adding fertiliser on mature trees in 10 cabrucas farms did not increase the pod number per trees which suggest that cabruca soils did not show a deficiency in nutrients. However, despite this lack of response to fertiliser, soil analyses and cocoa leaf analyses suggested that seven farms were short of one or more of N, P and K.

Cocoa trees are usually responsive to fertiliser addition: the results of our bioassay showed a significant increase in cocoa seedlings size after fertiliser addition. Cocoa yield response to fertiliser is affected by shade. However, reviews of literature on cocoa fertilisation report a significant increase in cocoa yield after fertiliser addition with or without the presence of shade trees (Snoeck et al., 2016; van Vliet et al., 2015). The addition of N-P-K fertiliser in the absence of shade trees increased yield to a maximum, however the addition of fertiliser in the presence of shade trees also significantly increased yield but to a lower extent (Fig. 5.1 a and b). We expected that cabrucas would response to NPK addition, despite being heavily shaded.

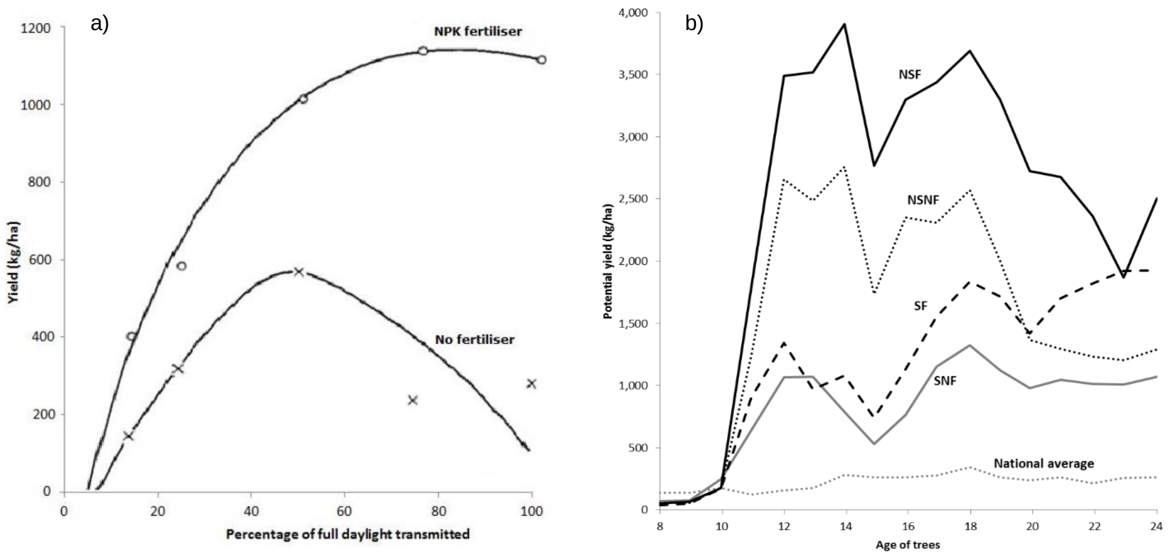


Figure 5-1. Light and fertiliser effect on cocoa yield: a) Relashionship between cocoa yield and light intensity for control and NPK fertilised cocoa (after Murray 1952), b) Changes in yield in mature cocoa trees along time depending on fertiliser and light treatment NSF: No shade + fertiliser, NSNF: No shade + no fertiliser, SF: Shade + fertiliser, SNF: Shade + no fertiliser (after Ahenkorah et al., 1974).

It is also possible that the soils were deficient in nutrients, but the trees did not respond to fertiliser addition. There are three possible explanations for this: i) the time of the experiment, 15 months, may have been too short to observe a response in yield; ii) the fertiliser experiment was carried out immediately after a severe drought which could have impacted the cocoa trees' physiology causing limited yield response to any fertiliser addition and/or; iii) old cocoa trees were 'checked', which is when mature trees fail to respond to fertilisation, when young individuals of the same species in the same site do respond to fertilisation, a phenomenon commonly observed in timber production (Taylor, 1991), and could not respond to nutrient addition.

We found contradictory results in our study. Two of our experiments and observations suggested that nutrients could limit yield. 1) In a bioassay using soil from the 10 same cabruca farms, seedlings grew larger with fertiliser addition than without fertiliser. 2) Soil and fresh mature cocoa tree leave were analysed and compared to reference values, the results suggest deficiencies in P K (and cations). The results of these experiments suggest that cocoa yield could be limited by nutrients in cabrucas. However, soil bioassays are not representative of on-farm conditions. Adding fertiliser and getting a positive response in seedling growth in pots was easy to detect whereas adding fertiliser and getting a response in yield on mature trees was not. Furthermore, the laboratory controls to assess the accuracy of the soil and fresh leaf analyses showed a lack of repeatability for all cations. This suggest that we cannot conclude that there was nutrient deficiency based only on bioassay and nutrients analyses.

Another surprising result was the low P concentration in live cocoa leaves (c. 2.8 g/kg) and the relatively high P concentration in litter (1.9 g/kg; compared to other studies in cocoa agroforests and tropical forests). P deficiency is often found in cocoa plantations and could limit yield (Wessel, 1971). Adding P fertiliser usually offset P deficiency and significantly increased cocoa yield (Morais, 1998). However, P fertiliser addition did not increase yield in cabrucas. This confirms that P was not limiting in cabrucas. Low P in live cocoa leaves could possibly be due to inaccuracies in the laboratory analyses. These also suggest that the high quantity of P in litter was accessible and available to cocoa trees (there was no P fixation in cabruca soils). High P concentration in litter could be due to persistence of P in soil due to past fertilisation of cabrucas (more than five years ago).

Finally, in the 10 cabrucas farms, we showed that cocoa trees receiving more nutrients in litter were associated with higher cocoa production. It is possible that when more nutrients are circulating it is easier for cocoa trees to access some of those nutrients. In heavily shaded cabrucas with no fertiliser, low cocoa yield resulted from the combination of two environmental factors related to the shade trees: low light and high nutrient content in litterfall (cf Fig. 5.2).

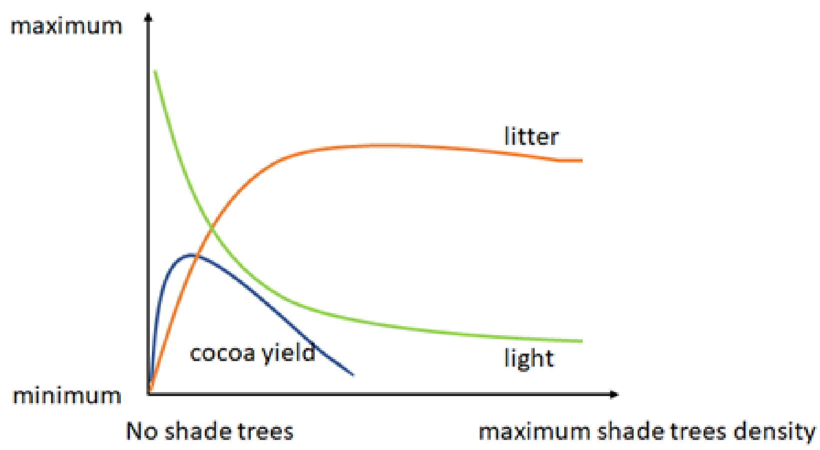


Figure 5-2. Model of cocoa yield limitation resulting from the balance between light and litter provided by the shade trees in cabruca systems (in a system with no fertiliser input).

The overall yield under any shade tree in cabruca remains low (20 pods per tree per year on average). Thus, the quantity of nutrients removed from the system through the beans harvest was small and nutrient were probably not limiting factors in cabrucas.

Fertilisation in cocoa

Recommended doses for fertilisers in cocoa production are incomplete and based on the results of a limited number of experiments often carried out in the 90's or earlier, see recent reviews (Snoeck et al., 2016; van Vliet et al., 2015). In most annual or perennial crops, yield response to fertiliser curves shows clear increases in yield with an increase in fertiliser quantities until the yield reach a plateau. However for cocoa, yield response curves are incomplete (no experiment long enough to reach a plateau and no response curves available to reach very high yield 4 t/ha cf Fig. 5.2). Cocoa yield does not respond to N only addition. P and K addition in large quantities must be coupled with N fertilisation to get a yield response.

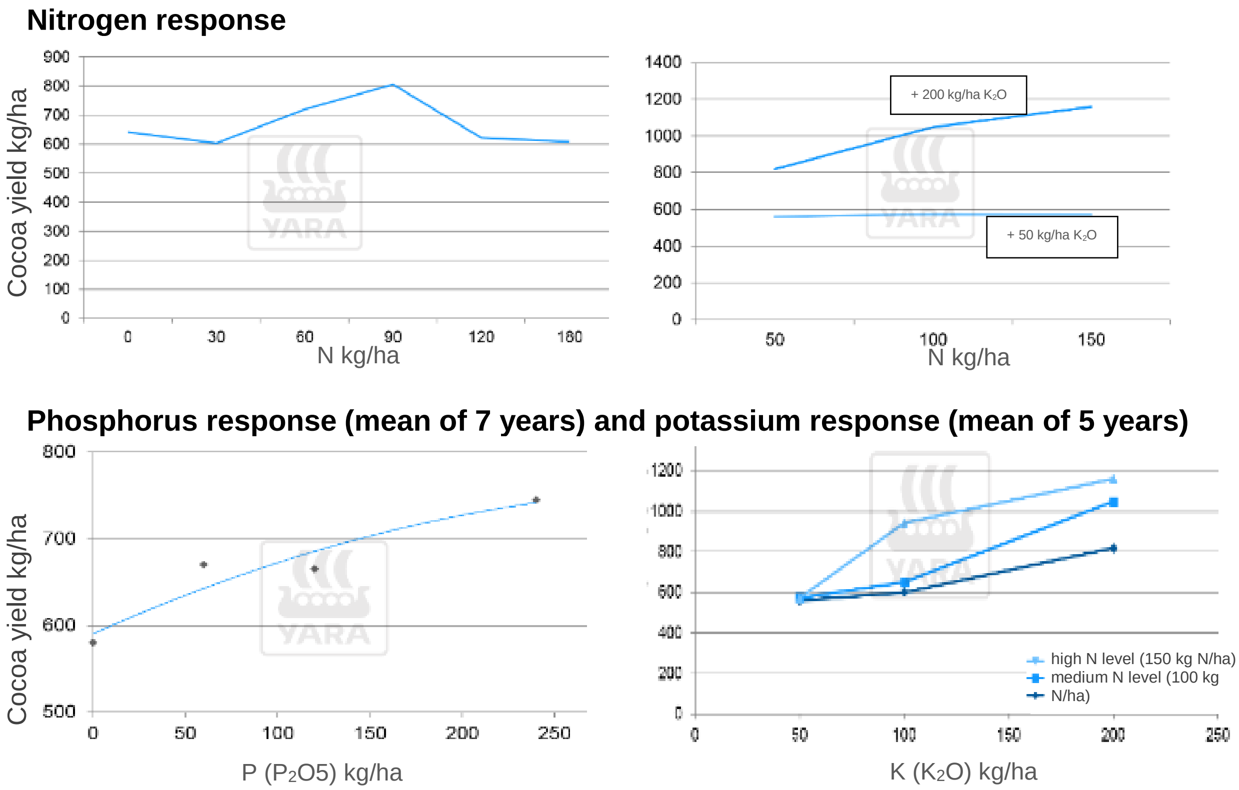


Figure 5-3. Fertiliser recommendations and partial yield response curves (source: http://www.yara.com.gh/crop-nutrition/crops/cocoa/key-facts/agronomic-principles/)

Yield response is often observed only after years of intensive fertiliser application in agroforests. Furthermore, fertiliser addition causes an increase in vegetative material but not in fruit production. An intensive pruning is necessary to maximize the effect of fertiliser addition on fruit production. Very often the farmers do not have access to the information on fertiliser and/or cannot afford to buy large quantities of fertiliser. In Brazil, farmers often know about the existence of fertilisers for cocoa but often rely on technicians and consultants to manage the fertiliser application in their cabrucas. Most cabrucas are not fertilised because the farmers cannot afford to buy large amount of fertiliser and to pay a consultant. In Brazil, fertiliser dose recommendations depend on the results of soil and leaf analyses, following a protocol developed by the Ceplac in the 50's, established by Malavolta (1997) and recently updated by Chepote et al. (2013). However, these recommendations for macro and micronutrients were often established in experimental stations, in lightly shaded cocoa which does not correspond to the heavy shade conditions in cabrucas farms. Recommendations for cocoa fertilisation are unprecise and outdated (van Vliet et al., 2015). The interaction cocoa tree-nutrition is complex and there is a gap of knowledge on cocoa fertilisation.

Our results showed no significant positive yield response to fertiliser addition at farm scale (cf typology of cocoa farms in Chapter 1) or at tree scale (cf fertiliser addition on mature tree in Chapter 2). This suggests that fertiliser use in cabrucas cannot be recommend to farmers to increase yield within one year. More research is needed on yield response to fertiliser in cabrucas.

Cocoa is a labour-intensive crop with no mechanisation (low technology and labour limit)

Cocoa production has not been mechanised as opposed to intensive monoculture crops, common in food production. Cocoa is often planted in areas difficult to access with tractors (steep slopes, no roads). Most cocoa farmers use draft animals (donkeys or mules) to bring the freshly harvested seeds from the plantation to the farm facilities. Cocoa production depends on manual labour for all tasks of the agricultural process to grow cocoa: planting, pruning, weeding, grafting, harvesting or fertilisation. Post-harvest processes also include tasks which are currently not mechanised: removing the cocoa pod husks to extract the fresh seeds, turning over the seeds during the fermentation process or spreading the beans in the sun to dry the fermented seeds.

Cocoa plantations suffer chronic labour deficiency: cocoa farmers often have debts and cannot afford to pay for intensive labour. In Bahia, because of the high price of labour, often all crop management tasks are reduced to harvesting only. Farm workers are reduced to one permanent administrator and few temporary workers contracted for few days to complete specific tasks (harvests or grafting). Bahian farm which used to rely on numerous workers paid with low wages now rely mainly on sharecroppers' labour ('parceiros'). Sharecroppers receive few hectares of old cocoa plantation to take care in exchange of half of the cocoa harvest as a rent for the land. In practice, sharecroppers are very impoverished rural workers and cannot afford to contract workers or buy inputs to rejuvenate or replace the old plantations. They exploit the low productive plantations (in a process very similar to extractivism) until the old trees die or the landlord sells the farm.

Existing examples of mechanisation of the cocoa production are still experimental: in Brazil, Ecuador and Indonesia few monoculture fields have been planted with distance between cocoa tree rows large enough to allow a small tractor to circulate and collect the fruits cut manually by workers. However, as opposed to many tree crops, cocoa harvest cannot be entirely mechanised: cocoa pods grow from flower cushions located on the trunk (cauliflory). These floral cushions could become unproductive if they were damaged by cuts during the harvest.

The previous Lula da Silva socialist government increased workers' rights and protection but also increased labour's price. The high price of Brazilian labour (900R$ (c. £200) per month and approximately 100R$ (c. £22) per day for temporary workers) cannot compete with extremely low salary paid to cocoa growers in Africa: minimum wage in Ivory Coast is 36,607CFA (c.£50) per month, but cocoa growers are usually paid less or not at all (e.g share-croppers and child labour). Brazilian cocoa beans cost on average 50% more than African cocoa, the cost of labour makes Brazilian bulk cocoa non-competitive on the global commodity market. Brazilian cocoa needs to be sold as a differentiated high value product to be profitable.

5.1.2 Increase cocoa price and income: internalise the value of forest

Cocoa price on the commodity markets is under $2000 per tonne for standard low-quality cocoa (bulk cocoa). Organic or rainforest friendly certified cocoa prices are usually 10-20% higher than bulk cocoa. The price of Fine & Flavour cocoa (5% of the world production) is a minimum $6000 per tonne but varies depending on the country of origin. Brazilian bulk cocoa has a higher price ($3600 per tonne) than West African bulk. Brazilian cocoa authorities and farmers are in the process of joining the restricted list of Fine & Flavour cocoa producing countries defined by ICCO. Fine & Flavour cocoa could reach a price of $10,000 per tonne, slightly less than three-fold the value of Brazilian bulk cocoa (CEPLAC http://www.ceplac.gov.br/noticias/200511/not00177.htm). Finally, bar chocolate made using cocoa from Brazilian cocoa farms (single estates chocolate) can reach $10 per 100 g of 70% dark chocolate ($100,000/t), that is 50 time the price of bulk cocoa. The chocolate market is growing with an increasing demand in Brazil (Rezende, 2012). During the last two decades, the number of Brazilian bean-to-bar chocolate companies have been increasing with approximately 30 companies originally from or sourcing cocoa from Bahia. Many of these chocolate companies own their cocoa plantations and have small scale chocolate factories (transforming less than 50 t of beans per year) on the farms: this allows the farmers to increase the price of their product at the farm gate. Small scale local chocolate production directly from the farm by the farmers is very specific to Brazil and Latin America: 80% of the world's chocolate is produce by multinational companies that buy their cocoa beans from smallholders in a country, then transform the beans into chocolate in a different country.

Developing wildlife friendly bean-to-bar chocolate for Brazilian market

There is also a market for cocoa beans and chocolate bars which contribute to forest and wildlife conservation. Brazilian cabrucas are unique because they maintain Atlantic Forest species and create corridors between remnant patches of forests while they produce cocoa. Cabrucas have low productivity because they have this biodiversity and wildlife (low cocoa tree density, low human disturbance, low level of light due to the numerous shade trees). The price of cocoa from cabrucas or wildlife friendly systems does not differ from the price of cocoa produced in monocultures and without shade trees. Increasing the price of cocoa specifically grown in cabrucas will encourage farmers to maintain the forests. This type of subsidy as payment for ecosystem services would allow the cocoa farmers to produce lower quantities of cocoa than in intensified systems but to encourage the conservation of the biodiversity.

Developing certifications including Atlantic Forest conservation-oriented prices

The existing certification scheme for wildlife friendly cocoa production include organic certification, UTZ and Rainforest Alliance. Only two large farms in Bahia are certified Rainforest Alliance. In Barro Preto, only 4 out 333 farms were certified (UTZ or organic), and 10 additional farms were in the process of being UTZ-certified (cf Barro Preto Project). Certified cocoa represents less than 1% in Brazilian production, but demand is growing (Rezende, 2012). Furthermore, there is an on-going process since 2014 lead by NGOs (Associação Cacau Sul da Bahia), local authorities and farmers to establish a Geographically Protected Indication (GPI) for 'South Bahia Cocoa'. In January 2018, the GPI was officially registered by the Instituto Nacional da Propriedade Industria (INPI). Barro Preto was among the 83 municipalities included in the area covered by the GPI (61.460 km²). However, the GPI does not require cocoa to be grown in cabruca systems which could change the dynamic in the cocoa region and threaten these systems.

Include cabruca agroforestry in REDD+ programs, carbon sequestration and PES schemes

The possibility to include cocoa agroforests in REDD+ and Carbon sequestration programmes has been explored in West Africa (Dawoe et al., 2016). There are no existing REDD+ schemes for Atlantic Forest or cabruca cocoa plantations in Brazil. However, a successful REDD+ program has been established in Brazil with the support of the Norwegian government (1$ billion in development aid) to protect the Amazon since the 2008 (Brazil's Amazon Fund). Following this experience, it could be possible to establish REDD+ projects collaborating with cocoa farmers to preserve cabrucas and the Atlantic Forest and to sequestrate Carbon. Shade tree and cocoa tree above ground biomass in cabruca in Barro Preto represented a total average carbon stock of 69.1 ± 2.7 Mg C ha^{-1} (with the shade tree accounting for 65% of the carbon). This value was lower than carbon value found for cocoa agroforests in Ghana (Dawoe et al., 2016) or in Latin America (Somarriba et al., 2013). However, in a recent study on 12 indigenous communities and cocoa smallholders in South Bahia Viana (2015) recommended to include cabrucas as part of REDD+ scheme targeting impoverished rural populations. In another pilot study in a cabruca farm as part of the Barro Preto it was recommended to include the economic value of the timber and the carbon sequestrated by the shade trees in the economical assessment of the farm to facilitate the farmers' access to rural credits (Zugaib et al., 2016). Furthermore, cocoa cabrucas should be part of REDD+ and PES program to preserve Atlantic Forest at landscape scale in South Bahia (Schroth et al., 2015).

Diversify crops within cabrucas: develop markets for high value products compatible with cocoa and shade trees

An advantage of agroforestry systems is the diversity of crops grown on the same land. Cabruca's main product are cocoa beans but numerous other crop species are also grown and provide fruits (Jackfruit, Genipa, Spondias), rubber or traditional medicine. Fruits are often consumed on the farm and not sold. However, by harvesting and transforming the fruits into high value and transportable products (jam, juices, liquors, sorbet, dried fruits) the farmers could obtain additional income from their cabrucas. Some other agricultural crop with high value such as coconut, açai berries, rubber, palm trees for palm heart, spices such as pepper, cinnamon, cardamom or vanilla could be planted to enrich the cabrucas. This could help diversify and increase the farmers' income. However, these diversified products require high levels labour for harvest and post-harvest treatment. Most farmers have limited number of contracted workers that are already insufficient for the cocoa production (and the cattle raising) and could not afford to contract more workers.

5.1.3 Change agro-environmental policy

Develop land sparing strategy: cabrucas to be abandoned to re-wilding

With the debate on land sparing or sharing for conservation and food production, it has been established that land sparing wildlife friendly farming were less efficient than intensive farming in small land areas to spare more pristine land for conservation (Ewers et al., 2009; Balmford et al., 2012; Phalan et al., 2011). Cabrucas are wildlife friendly farming systems with low cocoa yields. However, the area with intensive cocoa monocrops with high yield are increasing. For example, Pará state has recently become the main cocoa producing state by planting intensive full-sun cocoa plantations. Abandoned cabrucas can be reviewed and present favourable condition for the regeneration of Atlantic Forest (Rolim et al., 2017). By designing national farming and environmental policies it would be possible to produce more cocoa on less land and spare more forests. For example, through subsidies and compensation schemes farmers in Pará could be encouraged to intensify their cocoa plantation to reach high yields, and farmers in Bahia could be encouraged to abandon cabruca systems for cocoa production but to re-wild and protect them as area of conservation for Atlantic Forest regeneration. However, the current state/national approach for cocoa production and biodiversity conservation does not consider this land sparing scenario. Furthermore, Bahian cabrucas contribute to maintaining 40,000 farmers and the 'cocoa establishment' represents a strong political power in Bahia.

Legal definition of cabruca but no information on shade tree density and composition, authorised long-term timber exploration.

In Brazil, the Forest Law (Codigo florestal) requires the farmers to spare 20% of their farmland for biodiversity conservation (Area of Permanent Preservation APP and/or Legal Reserve LR). Areas of permanent preservation are areas of strict conservation which include riparian systems, steep slopes (> 45°) and hill tops. These areas of conservation cannot be used for agricultural production, except in Indigenous Reservations, (Sparovek et al., 2010). In practice, large deficits in implementing protected areas are observed on riparian zone and private farmlands (Sparovek et al., 2010). Most cabrucas are located along rivers, on steep slopes and on the tops of hills which legally restrict farmers from exploiting them. Cocoa farmers are required by law to spare 20% of their land for biodiversity conservation. Patches of secondary Atlantic Forests can still be found in large Bahian farms. Prioritization of these remaining forests habitats will allow the maintenance a higher level of biodiversity and higher carbon sequestration than preserving species-depleted cocoa agroforests which have lost most of their biodiversity (Kessler et al., 2012). The majority of the farmers in Barro Preto did not comply with the 20% land sparing requirement or did not distinguish between cabrucas and legal reserves. In June 2014, the Bahia State Decree n°15180 gave a legal definition of cabruca (defined as cocoa plantation shaded by minimum 20 native trees per hectare located in the Atlantic Forest ecosystem). The decree allowed farmers to extract and sell native and exotic timber from plantations with more than 40 shade trees per hectare under strict conditions. Cabrucas with over 40 shade trees/ha can now be declared as part of the legal reserves (the 20% land requirement). We found on average 126 ± 12 shade trees per hectare of cabrucas in Barro Preto. The threshold of 40 trees per hectare (with no explicit requirement on the trees' size) seems very low as a definition of cabrucas. This could undermine the protection of cabrucas with high density of shade trees and high biodiversity value. Furthermore, no requirement is given on the shade species composition in cabrucas, which could threaten the biodiversity richness in the cabrucas. These changes in environmental law could encourage farmers to plant and rejuvenate cabrucas and open access to credit for farmers. They could also increase legal deforestation and biodiversity depletion in cabrucas. The success of these policies depends on a strict enforcement of the Forest Law and large attribution of resources to the organisations which control the protected area (e.g INEMA).

5.2 Limitation to increase yield without decreasing the biodiversity

5.2.1 Limitation to increase yield

Missing possible yield limiting factors not assessed: pollination, future disease outbreaks

The yield gap assessment allowed us to identify the main factors limiting cocoa yield in Barro Preto. This assessment showed that out of the 17 studied variables, many environmental factors caused yield limitation. However, we could not explore additional factors which could possibly reduce yield such as pollination: cocoa trees with self-incompatibility or depleted pollinator populations. Furthermore, we have no information on pest and disease outbreaks, which could happen and dramatically decrease yield in the future. At the end of the 80's, the sudden outbreak of witches' broom *(Moniliophthora perniciosa)* was unexpected and rapidly became the main cause of yield loss. It caused a decrease by 70% of the cocoa production in 10 years in Bahia. Frosty pod rot (*Moniliophthora roreri*), a fungal disease occurring in west African cocoa plantations, is absent in Bahia so far. Frosty pod could be even more damaging than witches' broom if an outbreak was to happen in Bahia.

Difficulty to assess cocoa nutrition analyses or compare cocoa growing regions

All our results on nutrient concentrations in soil, fresh leaves and litterfall resulted from analyses from one accredited lab in Brazil. Strict regulation on export permits does not allow us to fly samples overseas to analyse them in the UK. We concluded that nutrient composition differs between species of shade trees in litterfall; we also found differences in soil fertility between farms. However, we found no significant differences between fresh cocoa leaf concentration in different farms or under different shade trees; no significant difference between dry cocoa leaf content in the different farms or under different shade trees; no significant difference between the composition of the total litterfall in the different farms or under different shade trees. These conclusions rely on the accuracy of the lab analyses. To assess the laboratory, we send two types of controls within the different batches of samples: internal controls (repetitions of the same samples within the batch of samples) and external controls (repetition of a standard sample (loose black leaf tea) were also sent to two laboratories located abroad (Switzerland and New Zealand) and a second independent Brazilian laboratory. The variability between same samples within the same Brazilian laboratory was acceptable for value of N, P and K but were extremely high and unacceptable for Ca, Mg, Zn, Mn, Cu, Fe, B. (cf appendix 3.3). Furthermore, the variability between the same standard sample send to 4 labs was extremely high for most elements.

This is problematic because farmers depend on laboratory results to calculate the doses of fertiliser they will use on their cocoa plantations. Fertiliser recommendations must be tailored with care based on the farm soil, deficiency in plants and technical practices. This high variability in the quality and results of the lab analyses makes it difficult to establish efficient fertiliser recommendations.

Low economic viability of cocoa farms: off-farm incomes, cattle ranching replacing cocoa.

Cocoa production in cabruca farms is just about profitable, while the Brazilian cocoa price remains high. Economic data were collected in each of the 32 cocoa farms in Barro Preto: gross margin for each farm were calculated based on input price, labour and outcome (cocoa and if relevant cattle and cabruca by products). The price considered for cocoa was 10,900 R$/tonne (183 R$/@ which correspond to 2700 £/tonne, source: http://www.ceplacpa.gov.br) using 2014-2015 data (before the drought). The gross margin per year per farm varied between 6,120.00 and 696,530.00 R$ (cf Appendix 5.1). Two farms had negative gross margin value when cocoa was considered as the only product. Cattle production added high value to the farms' income. This suggests that some of these cocoa farms are profitable but any crisis (e.g: price, drought) could put their profitability at risk. Most landowners were upscale professionals (lawyers, politicians, doctors, engineers) who did not live in Barro Preto but in larger cities. These landlords had access to off-farm incomes. Cocoa production is not the main activity of these landlords who often inherited their land and entrusted administrators to maintain the farms with very low resources. Many farmers in Barro Preto were looking for opportunities to sell their farms or to transform the cabrucas into pasture for cattle ranching. This cocoa production system with very little investment but low cocoa yield is probably not resilient to crisis and not sustainable on a long term.

Furthermore, the results of the pilot study 'Barro Preto project' suggest that increasing farmers' income could make cabrucas economically profitable on a long term. However, the initial investment to increase yield required large investments provided through subsidies. The average investment per farm was 35,000 R$/ha over 4 years to reach increase in yield of only 53 kg/ha by the 5th year (from the initial 300 kg/ha) cf Appendix 5.2: Barro Preto project results. This small increase does not make the large investment profitable. Furthermore, the farm will remain unprofitable without an increase in cocoa bean value through UTZ certification (+ 20%) or ideally though Fine & Flavour scheme (+ 300%). Barro Preto project farms were still in the process of conversion toward a UTZ certification schemes. At the end of this study, the cocoa beans were still sold at the price of bulk cocoa and did not receive any premium. The time and investment required to make cabrucas economically viable on a long term, is difficult to justify in a Bahian cocoa economy in crisis.

5.2.2 Limitation to increase value

Limits in Geographically Protected Indication (GPI).

Establishing the first GPI for cocoa is a long-term process. The preliminary study to establish a GPI started in 2014, but the GPI has only just been approved legally in January 2018. In practice, only the area defining the GPI has been defined. There is no legal biding regarding the production system: no mention of cabrucas or biodiversity conservation in the definition of the GPI. The content of the GPI requirements (cocoa varieties, technical practices, agronomical systems) are still under negotiation and will determine if the cocoa production in Bahia will be sustainable or not in the future. There is a risk that decisions could be monopolised by farmers with large proprieties, with intensive farming and with political influence (e.g. M. Libânio 2300ha, Cantagalo 15 farms, Vale do Juliana 4000 ha) looking for short-term profit in intensive plantation instead of long-term sustainable production with biodiversity conservation.

Furthermore, we advocate the development of rainforest-friendly certification and small-scale chocolate production on farm. However initial investment into certification and machinery to transform beans into chocolate are expensive. Farmers are often in debt and cannot afford to invest in these niche markets. Farmers' cooperatives are not commonly found in Bahia. However, establishing cooperatives of cocoa farmers could be a solution to reduce cost of facilities and material.

Increasing yield using technology packages does not improve farmers' wellbeing but is profitable for private companies with large domains

Finally, recommendations to close the yield gap are often based on implementing a technology package and intensifying the cocoa plantation to increase yield. However, intensification also has environmental impacts like resource depletions and GHG emissions (fertiliser addition), soil and water toxicity and human toxicity (fungicides and pesticides), deforestation (shade reduction), or genetic biodiversity depletion (cocoa clone selection for monoclonal agriculture). We calculated that producing one tonne of cocoa in cabrucas was responsible for the emission of 4.5 tCO_2 (and requires 9 ha of land) whereas producing one tonne of cocoa in an intensive irrigated monoculture was responsible for the emission of 93.2 t CO_2 (and requires 1 ha of land). The production of cocoa in cabrucas system and monoculture correspond to 0.5 tCO_2/ha and 93.2 tCO_2/ha respectively (Gateau-Rey, 2012). Furthermore, most of these technology packages benefit mainly farmers owning large domains and do not benefit smallholders. Smallholder agriculture makes a major contribution to feeding the world sustainably and effort should be made to support them.

5.2.3 Limitation to change policy

Brazil is a leader in environmental policy. However, agriculture and human activity is still responsible for most forest loss. Most Brazilian environmental laws have been carefully designed and based on scientific evidence (Metzger, 2010). However, there are insufficient resources to implement these laws and monitor environmental protection. In a country facing a political and economic crisis since 2014, biodiversity conservation and long-term cocoa production are not priorities on the political agenda.

5.3 Future work on yield, nutrients and biodiversity

5.3.1 On-farm long term trial on reducing yield gap

On farm trials to reduce yield gap and replant native shade trees should be studied experimentally in the long term in Barro Preto. Our initial study plan included experiments to increase yield by adding fertiliser, hand pollination and using treatment against witches' broom. However, we had to abandon hand pollination because it was too time and resource consuming and witches' broom treatment (biocontrol *Trichoderma spp* use) because the only supplier (CEPLAC) discouraged any user to apply the treatment during or immediately after the drought (there is no other existing effective treatment to witches' broom except sanitation). Only the fertiliser experiment was carried out, and fertiliser addition did not increase yield, possibly due to the post-drought conditions. In addition, there was another study which aimed to increase yield and income for cocoa farmers by intensifying cabrucas in Barro Preto: the Barro Preto project, a development project lead by CEPLAC, MARS and Barro Preto municipality. Ten farmers agreed to make available approximately 2 ha of cabruca land for the trial. The farmers were provided with technical support and subsidies (to invest in inputs and in labour). Technical management which required intensive labour included: replanting cocoa trees and native shade trees, grafting unproductive trees with high yielding clones, pruning cocoa trees and removing witches' broom, pruning shade trees to decrease light competition, add liming and fertilisers. The 5-year project ended in 2016. However, there was no scientific monitoring of the outcomes of the trial (no yield measurement, no control plots, different treatments in each farm). Hence, it is not possible to conclude if the investments in labour and inputs affected the cocoa yield. However, the project established a long-term relationship between the project leaders and the 10 farmers. Among the farmers, 8 out of 10 were happy with the outcome of the Barro Preto project and were willing to accept additional experiments on their farms. Furthermore, the study reported in this thesis developed a larger network of 32 farmers open to future experimental studies on their farms. These create an opportunity to implement on-farm experiments with several treatments per farm. The effect of treatment on cocoa yield could be monitored in the long-term to identify the best options to increase farmers' income while maintaining the cabrucas systems.

5.3.2 Promote innovations

Furthermore, innovations to increase farmers' income and maintain the biodiversity have been identified in cabrucas in Barro Preto. Technical innovations included using biochar, organic compost, biological control of witches' broom or new pruning techniques. Cocoa sector innovations also included developing small scale on-farm chocolate factories, developing a high value cabruca-friendly cocoa (certifications, GPI, Fine & Flavour Cocoa). These innovations must be explored using a scientific approach: experimental trials to validate the technical innovations and participative social studies to explore the cocoa sector innovations (e.g developing cocoa cooperatives for fermentation).

5.3.3 Standard for soil and leaf analysis, cocoa fertilisation trials

More research is needed on fertiliser use in cocoa production. First, the priority would be to produce curves of cocoa yield response to fertiliser for mature cocoa trees in cabruca conditions. Long term experiments would probably be required to obtain these response curves for this long-lived perennial crop (20-30 years). Different quantity of fertilisers with different nutrient compositions should be applied to cabruca plots to establish which fertiliser doses are needed to reach high yield (> 700 kg/ha) in cabrucas. Cabrucas are extremely diverse and fertiliser trials should be installed considering the diversity in soils, shade composition and density and cocoa variety composition.

Furthermore, strict laboratory protocols should be established to standardise the quality and repeatability of leaf and soil analyses for nutrient composition. By standardizing the nutrient analyses among laboratories, it should be possible to compare the results of analyses provided by Brazilian reference laboratories with results of analyses provided by laboratories based in different cocoa producing countries (something not currently feasible so far). This will help establish accurate fertiliser recommendations for the farmers by comparing results of analyses with reference values. Finally, internal controls (repetition of standard samples) must always be included in any batch of samples sent for analysis.

5.3.4 Support environmentalists' action to improve cabrucas' management

MARS has played an important role in promoting sustainable cocoa and cabrucas in South Bahia: it co-lead the Barro Preto project, supported the GPI 'South Bahia cocoa' process lead by NGO Instituto Cabruca and promoted the recognition of a legal status for cabrucas in the Forest Law. It should continue to encourage initiatives towards a sustainable cocoa production in Bahia. There are two main urgent issue where MARS could influence the protection of cabrucas: i) encourage the inclusion of the cabruca systems and environmental friendly practices in the list of requirements which defines the GPI cocoa produced in Bahia and ii) encourage an amendment of the definition of 'cabruca' in the Forest Law with clear information on species composition and richness, trees size and to promote the prevention of legal deforestation related to the Decree n°15180-2018.

5.4 Climate change could be a threat to cocoa agroforests

5.4.1 Yield loss and change in Brazilian cocoa production due to ENSO

We showed that El Niño 2015/16 was responsible for high cocoa loss and high tree mortality which affected the cocoa production dynamic in Brazil. In 2014, we established the study without predicting that an El Niño event would happen in November 2015 causing a severe drought in Bahia. On-farm data on climate effects on cocoa are scarce. The data we collected contributed to understand the effect of climate change and drought on cocoa production. Climate models are predicting that the frequency of strong El Niño-related droughts will increase in the future. These changes could threaten the cocoa production in Bahia. In Barro Preto, 11% of the productive cocoa tree died because of the drought. In Bahia, the area planted with cocoa decreased by 9% (47,380 ha) comparing before and after the drought. Dead cocoa trees have not been replanted. Cabrucas are being abandoned and/or transformed into pasture for cattle ranching. Bahia used to be the state producing 95% of the Brazilian cocoa in the 80's. After the 2016 drought, Pará state became the main cocoa producing state: 50% of Brazilian cocoa comes from Pará whereas 44% of Brazilian cocoa came from Bahia in 2017. The drought accelerated the change in the cocoa production area in Brazil. The drought also accelerated a change in the cocoa producing system: decreasing areas of cabrucas production systems in Bahia, which have been replaced by increasing areas of intensive low shade plantations in Pará.

The environmental impact of the plantations in Pará are high: high quantities of inputs are used (fertilisers and irrigation); no native shade trees are maintained in the plantations and new plantations are installed on cleared forest (Melo et al., 2017). This shift from extensive wildlife-friendly cocoa to an intensified cocoa production is not compatible with a sustainable cocoa production. Increased frequency of severe drought events are a risk for sustainable cocoa production. In Brazil, the drought accelerated the current agricultural dynamic towards an intensive cocoa production, which could be harmful to the environment.

5.4.2 Design complex cocoa agroforestry systems to mitigate the effect of climate change

Our survey in Barro Preto showed that the farm administrators were not preoccupied by future droughts and believed no drought would happen again soon (28/30 interviewed). To the question ’what could you do to protect cocoa trees from death when the next drought happen?’, 26/30 farmers answered ‘nothing’ or mentioned God’s will; 3/30 farmers answers ‘plant shade trees’ and 2/30 farmers considered installing irrigation system in part of their farms. There is no clear evidence that shade trees could benefit cocoa trees during drought events. The relationship between shade tree and cocoa trees is complex and studies looking at water competition between cocoa and shade trees found contradictory results: no water competition was found by Isaac et al., (2014) and Köhler et al., (2014) whereas high competition was found by Abdulai et al., (2018). Furthermore, most farmers are indebted and cannot invest in expensive irrigation systems. This suggest that solutions to limit the effect of drought are limited. However, it could be possible to reduce yield loss due to drought by implementing technical innovations: planting/grafting cocoa clones tolerant to drought, planting drought-tolerant shade trees and diversifying crops within the agroforests to diversify incomes.

We propose to design climate resilient agroforestry systems with three different objectives and based on the farmers’ preferences in Fig. 5.3: 1) increase carbon sequestration by planting large shade trees; 2) diversify crops within the cabruca to increase farmers’ income and decrease risks; 3) increase cocoa yield and resilience to climate change by replacing old cocoa material with drought tolerant clones. The best strategy will probably be a balance between these 3 scenarios depending on the farmers’ priorities.

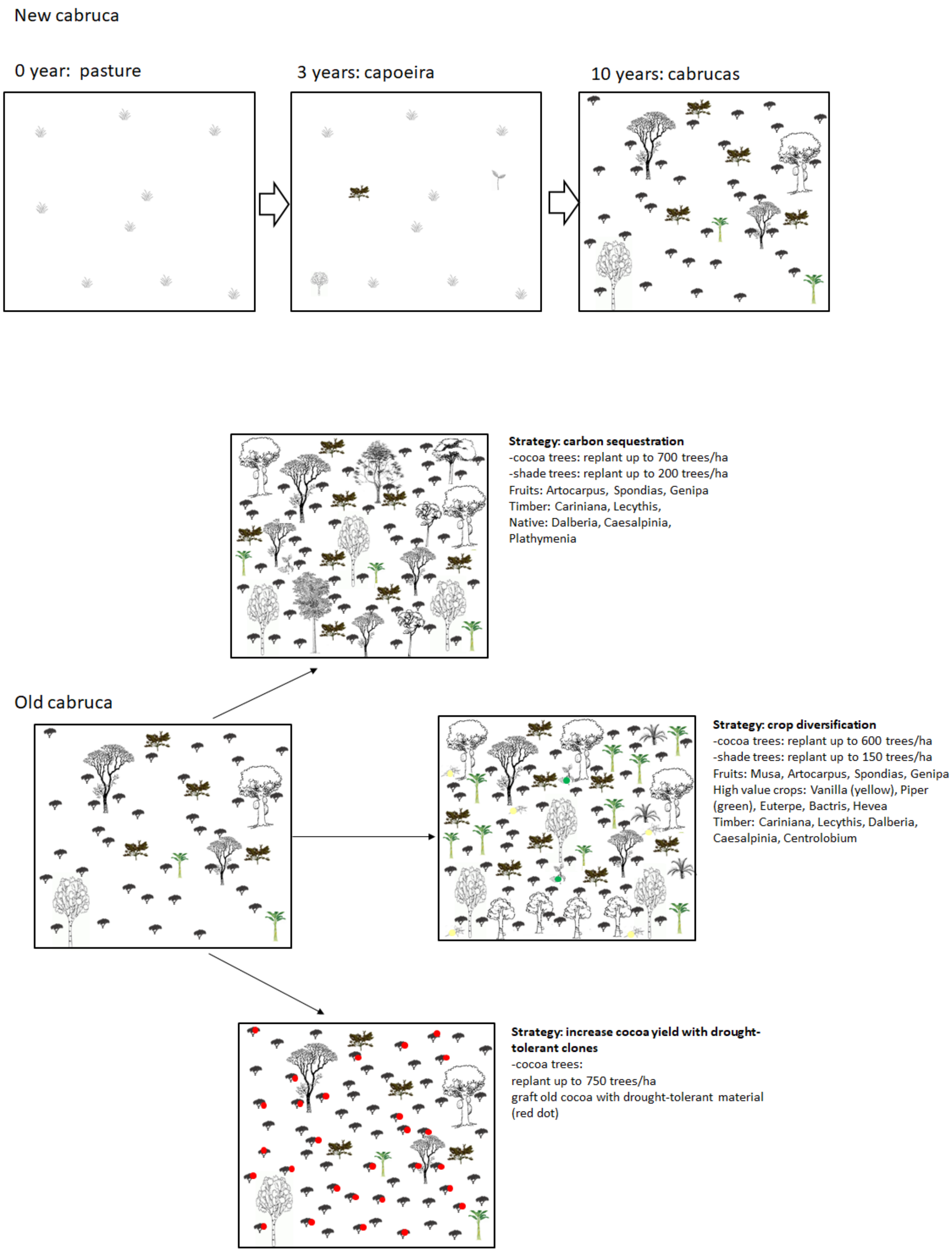


Figure 5-3. can be converted into cabruca by rewilding old pasture 1st) into secondary vegetation (capoeira), and 2nd) selecting native regrowth trees and planting cocoa and shade trees. Old cabruca could be intensified following three strategies: i) Carbon sequestration: replant shade trees and cocoa trees; ii) diversify crops: replant cocoa, fruits, crops, timber and understorey high value plants (vanilla, black pepper); iii) increase yield and replace old trees by drought tolerant clones.

5.4.3 Existing climate models for cocoa

Studies on the effect of climate change on cocoa production are scarce. In a physiological model, a change in precipitation and irradiance was responsible for 70% of the variation in yield (Zuidema, et al., 2005). The main climate prediction model for West Africa (MaxtEnt model), showed that area suitable for growing cocoa could decrease mainly due to temperature warming (but not to change in rainfall pattern) (Läderach et al., 2013; Schroth et al., 2016b). However, this model did not include an increase in CO_2 concentration. The overall the impacts of increased CO_2 concentrations could be positive to cocoa yield (Medina and Laliberte, 2017). Overall studies agree that climate change is a threat to cocoa production.

5.5 Limitation regarding data on climate change

5.5.1 Little data on local precipitation and issue with national precipitation data

The precipitation and potential evaporation information were based on the data recorded by the MCCS weather station (14°0' S and 39°2' W, 101 m). For logistic reason, we did not collect rainfall and temperature data for each cocoa farm in Barro Preto. There was a high variability in tree mortality between cocoa farms. We found differences in water capacity in soils between farms, which could partially explain this variability in mortality. However, the variability in rainfall between the farms locations within the studied area (120 km^2) could have also explained this variability in mortality.

We found 80% cocoa yield loss in 2016 after the drought in Barro Preto. However, IBGE reported 30% yield loss in 2016 at the scale of Bahia state. This difference could be explained by high variability in rain causing variability in yield loss between Bahian municipalities. For examples, Recôncavo area around Salvador, could have received more rain than Barro Preto between November 2015 and May 2016. These differences in rain could have cause a compensation phenomenon with some locations producing more cocoa than others. At global scale, it has been observed that El Niño years result in lower global cocoa production than in La Niña years (ICCO, 2010).

Furthermore, official weather data available on Brazilian government services (INMET) for Bahia were often missing data and sometimes incorrect. We decided to use only the data from MCCS weather station. However, MCCS data were available only from 2001: the strongest recent El Niño happened in 1997/98 and 1982/83 are not included on this dataset.

5.5.2 Missing data on climate change and cocoa

The initial plan was to include a study the contribution of cocoa production to GHG emissions by measuring nitrous oxide emissions from litterfall decomposition in cocoa plantations. However, for logistic reasons, it was not possible to collect and measure NOx emissions in samples in cabrucas and full-sun plantations.

Furthermore, field data on the indirect possible effects of drought/climate change are missing. For example, drier climate could cause a collapse in the population of pollinators. Cocoa fruit development depends on pollination. A decrease in pollinator populations could cause important loss in yield. However, cocoa pollinators are understudied, but recently new a method using camera traps was developed to monitor cocoa pollinators populations (Toledo-Hernández et al., 2017). Another indirect effect of climate change could be an increase in fungal diseases and pest outbreaks in cocoa plantations. A future change in rainfall patterns could increase loss due to pest and disease. We found that the drought was responsible for high cocoa yield loss due to an increase in witches' broom infection rate. However, we did not study the life cycle of witches' broom (or other disease or pest) and the changes in humidity at plot scale. Finally, we did not study the genetic aspect of the cocoa tree resistance to drought. It is possible that 2015-16 drought selected drought tolerant trees which could resist future drought events. Some of these trees could be used as grafting material or for hybridization. However, the duration of our study was not long enough to validate these potential drought tolerant clones.

5.6 Future work on cocoa and climate change

5.6.1 ENSO 2015-16 effect on world cocoa production: comparison of El Niño effect on cocoa in Brazil, Ghana

We found a negative effect of El Niño on cocoa yield in Brazil. However, another research group found a positive effect of El Niño on cocoa yield in Ghana (Y. Malhi, personal communication). We started a collaboration with this research group based in the School of Geography and the Environment, Oxford, and expect to publish a comparative study on El Niño effect on cocoa production in different locations: Brazil, Ghana (and possibly Papua New Guinea). El Niño may have different effects in different cocoa growing countries, especially if they have different rainfall regimes. Establishing a long-term study of El Niño effects on global cocoa production using permanent field plots in the main cocoa growing regions could be necessary to investigate to what extend El Niño phenomenon is a threat to world cocoa supply chain.

5.6.2 Model climatic envelops and scenario for cocoa production in Brazil: identify areas affected by climate changes where cocoa production is at risk

There are no studies using climate envelop models to predict the effect of climate change on the distribution of areas suitable for growing cocoa in Brazil. A model could be design to include the prediction of distribution of cocoa as well as native Atlantic Forest tree species in cabrucas using the approach for plant distribution proposed by Hijmans and Graham (2006). In a climate envelop model for the distribution of golden lion tamarin (*Leontopithecus spp.*), a native of Atlantic Forest, Meyer et al. (2014) showed that future climate would cause large habitat loss. The authors also concluded that the protection of cabrucas in Bahia could have a role in preserving *L. chrysomelas* from going extinct. However, we need explore the area of cabrucas which could be affected by climate changes in the future.

5.6.3. Develop selection and farmers' access to drought tolerant cocoa clones

Research is needed on developing drought-tolerant cocoa plantations: few studies have already identified drought-tolerant clones in greenhouses or experimental stations (Ahnert, 2017; de Almeida and Valle, 2007). It is necessary to assess these clones in farm conditions. The cocoa varieties usually introduced by the farmers (through replanting or grafting) are chosen for their tolerance to disease and potential high yield but not for their drought-resistance characteristics. It is necessary to develop farmers' access to cocoa trees selected for their tolerance to drought.

5.6.4. Install experiments on comparing the effects of drought on agroforestry systems and full-sun cocoa systems; a pilot experiment on irrigated cabruca

It is necessary to study the resistance to drought or climate stress to different type of cocoa growing systems. The intensive low shade systems are expanding, replacing the traditional extensive heavy shade agroforests. In Brazil, cabrucas are gradually being abandoned in Bahia while areas planted with intensive cocoa plantation is increasing in Pará. However, to our knowledge there are no comparative studies on the resilience to climate change of cocoa trees grown in tradition agroforests and in intensive plantations in Brazil. A recent study in Ghana, (Abdulai et al., 2018) concluded that cocoa trees under full-sun conditions were more resilient to drought than cocoa agroforests. However, the generality of this conclusions were contested by (Norgrove, 2017; Wanger et al., 2017). It will be necessary to establish long-term trials comparing the resistance to drought (and heavy rainfall) of cocoa trees grown in intensive full-sun plantations and shaded agroforests.

Finally, research is also needed on irrigation. Studying the effect of irrigation in agroforests has never been done. It would be interesting to measure the effect of irrigation on cocoa trees planted in cabrucas systems. An experiment with 3 ha of irrigated cabruca has just started at MCCS in 2017.

5.7. Scenario for a sustainable cocoa production

5.7.1. Strategy of quantity: decrease of Bahian cocoa production, increase of Pará production

The objective of the Brazilian government in to increase cocoa yield at low cost. The current strategy of the government officials, chocolate industry and farmers associations is to increase Brazilian cocoa production to 300,000 t/year in 5 years and to 400,000 t/year in 10 years (current Brazilian production is 270,000 t/year). Pará state has been identified by CEPLAC as the most suitable state to develop Brazilian cocoa production: available land, smallholders' agriculture, low production costs and high yield (http://www.ceplacpa.gov.br/site). Bahia is still considered by CEPLAC as a leading cocoa production state but with aging plantations, low yield, high production costs and farmers' environmental values, which are not compatible with an intensive cocoa production. Bahian cocoa production is gradually being replaced by Paraense cocoa.

The high price of labour is a main problem for large Bahian plantations (150 ha on average). Historically, this large latifundium used to rely on slave labour: 8,000 hectare of cocoa plantation required 100-120 slaves (Walker, 2007). After the abolition of slavery, the cocoa landlords continued to rely on abundant low paid labour. Nowadays, these large plantations system are not economically viable. Cocoa needs to be produced by smallholders to be profitable (Pará cocoa production comes from smallholders). Furthermore, in the 80's Brazil started an agrarian reform under the pressure of Landless Rural Workers' Movement (MST). Rural workers gain access to private land ('assentamientos') after occupying large unproductive farms. After the approval of the governmental and the landlord, the farm is divided into smallholder plots and given to 'assentados'. The largest cocoa farms with few workers are often the target of MST. Therefore, farms with most remnant forests or more diverse cabruca are most susceptible to be occupied and given to assentados. Assentados are impoverish workers who cannot afford to rejuvenate the old plantations. Cocoa trees are often harvested until they die and very few smallholders replant cocoa trees in their plots. This slow land reform is also affecting the shade trees: valuable timbers are often sold, and no shade trees are replanted. Bahian cabrucas are slowly disappearing.

5.7.2. Strategy of quality: Increase of niche differentiated cocoa

In the 2000's, Bahian landlords discovered an interest in niche markets for high value cocoa such as certified cocoa, Fine & Flavour, bean-to-bar chocolate or geographically protected cocoa.

A new wave of investors composed of grandchildren of the cocoa elite educated in cities or new entrepreneurs not from the traditional cocoa elite started to develop high-value cocoa production in Bahia. They used the eco-friendly image of the cabruca as a marketing argument. With support of chocolate companies, they also develop certified plantations (organic, UTZ and Rainforest Alliance) to produce cocoa for export. Certifications are expensive, and they are more profitable for large cocoa plantations than for smallholders (Tayleur et al., 2018). Bahian large plantations with a centralised management are suitable for certifications scheme.

These new cocoa farmers with the support of researchers, NGOs and Bahian authorities, lobbied to obtain the recognising of Bahian cocoa as 'Fine & Flavour' quality from the International Cocoa Organization. Historically, Brazilian cocoa is considered as inferior standard quality (bulk) on the international cocoa market because Bahian farmers did not systematically ferment the beans and often dried them using wood-oven which gave a smoky taste to the cocoa. Bahia is now recognised as provider of high quality single origin beans for internationally recognised chocolate makers.

Furthermore, these new cocoa investors developed a small to middle scale chocolate production directly from the beans harvested on farm. This 'bean-to-bar' chocolate is aiming at the Brazilian middle and upper class in cities. The chocolate produced directly on cocoa farms represent less than 0.5% of the world chocolate market. The majority of the world's cocoa beans are sold to grinders (i.e Cargill, Barry-Callebaut, Delfi) before being sold to chocolate makers. Bahian bean-to-bar chocolate is a rare example of local food network without middleman, it provides high income for the farmers in the cocoa supply chain.

Finally, these new generation of farmers with the support of Instituto Cabruca, created an association to develop a geographically protected indication for Cocoa South of Bahia.

Bahian cocoa had all the requirement (socio-cultural background, original agricultural system) to be recognised as a differentiated product with high market value. This will be the first GPI for cocoa in the world and it will bring some recognition to the Bahian cocoa industry.

Geographically Protected Indication is probably the most environmental-friendly scenario for cocoa production. However, this strategy is suitable for small quantities of beans for niche markets, not for large amounts of beans for mass production required by 80% of the cocoa companies (MARS, Nestlé, Ferrero, Mondelez, Cargill or Barry-Callebaut).

5.7.3. Intermediary strategy: specialisation per region

The most realistic scenario for cocoa production in Brazil will be the development of high yielding intensive (possibly average bulk quality) in Pará and development of niche high value eco-friendly cocoa in Bahia. In Pará, Brazilian authorities and chocolate industries encourage farmers to develop and increase the area planted with cocoa. In Bahia, the Forest law could be enforced more strictly (sparing 20% of the farmland for biodiversity). This could encourage the Bahian farmers to i) abandon cabrucas for rewilding and raise cattle on the rest of their land; and/or ii) conserve the cabrucas as legal reserve. A restricted number of large cabrucas farmers could remain but farmers would specialize in the production of high-value cocoa.

Cocoa, as most agricultural commodities, follow ‘boom and burst’ cycles (Ruf, 1995). Bahia used to be the world’s largest cocoa producer in the 19th century. The Bahian cocoa boom resulted from intensive slave labour in large plantations planted on new fertile lands. However, the Bahian cocoa economy ‘bust’ in the 1990’s with the witches’ broom outbreak. Pará state seems to be at the beginning of a new cocoa boom: the area newly planted with cocoa on fertile deforested land (the ‘forest rent’ described by Ruf and Zadi (1998)) has started to be productive. However, this boom in production will possibly reach a maximum and start to decrease (e.g full-sun intensive plantations often face pest and disease pressure after 10-20 years). Furthermore, Brazil cannot compete with the low production cost for cocoa production in Ivory Coast, Nigeria or Indonesia. Brazil cannot compete with the constant boom in West Africa or Indonesia if the workers remain underpaid compared to Brazilian workers. In the short-term future, West Africa will remain the main world cocoa supplier.

Finally, several chocolate companies are developing their own intensive cocoa plantations. They often chose to produce cocoa in high inputs full-sun conditions with high yield rather than in extensive agroforests with low yield. However, these intensive production systems are not compatible with the sustainability of the cocoa supply chain on a long term. Currently, five million smallholders grow 80% of the world cocoa production. Replacing cocoa smallholder agriculture by intensive corporate farming could have dramatic social and environmental impacts.

5.8. Limitation for a sustainable cocoa production scenario

5.8.1. Low price of cocoa

In theory environmental and social certification, Fine & Flavour denomination and Geographically Protected cocoa have a high value and provide farmers with high incomes. In practice cocoa farmers did not get a sufficient increase in price to make their cocoa harvest profitable. The expected 20% price premium for organic or UTZ certified cocoa is not sufficient to pay off the investment needed to obtain the certification (cf Appendix 5.2: results of Barro Preto project). Furthermore, the Fine & Flavour denomination and the GPI are still under negotiation and are not operative yet. It is a long process to change a supply chain which used to favour quantity over quality into a quality-oriented market. It is likely that a few more years will be necessary before for the farmers get paid a premium price when selling their differentiated cocoa beans. The Bahian farmers are not benefiting from this approach so far. The price of cocoa remains low despite the Brazilian cocoa price being higher than that of the general commodity market. Indeed, the price of over 80% of the cocoa produced worldwide is defined by commodity markets based in London and New York. This price is independent of the farming system: the beans grown in environmental-friendly agroforests have similar prices to beans grown in intensive low shade systems.

5.8.2. Political limitation: conflict of interest and short-term profits

Brazil is facing political instability and political decisions in the long-term are not possible in this context. Furthermore, the political strategy for Brazilian agriculture is motivated by industry lobbies and often driven by personal benefit. For example the current Minister of Agriculture, Livestock, and Supply is also the world’s largest soybean producer responsible for large deforestation in the Amazon. The same conflicts of interest are observed in the cocoa sector: an ex-governor of the state and the main political figures own the largest cocoa domains in Bahia. The strategy of short term profit could be responsible for the extinction of cabrucas and the raise of the deforestation of the Amazon forest in Pará.

5.9. Future work on sustainable cocoa production

5.9.1. The cocoa and forest initiative

Cocoa agriculture is responsible for deforestation. The fast growing area planted with cocoa in the Transamazonian region is a threat to the Amazon forest. In Ivory Coast and Ghana chocolate companies are taking action against deforestation and started the Cocoa and Forest Initiative (http://www.worldcocoafoundation.org/cocoa-forests-initiative/). This initiative is led by the World Cocoa Foundation, IDH and Prince of Wales's International Sustainability Unit. It is an agreement between most of the largest chocolate companies to end deforestation caused by cocoa cultivation and to “produce more cocoa on less land”. Currently, the initiative focuses only on West Africa, however cocoa is often grown in biodiversity hotspots. A global approach to reduce deforestation due to cocoa should include all cocoa growing regions where cocoa plantations are competing with native ecosystems of high conservation value (e.g Liberia, Indonesia, Brazil). Including Brazil in the Cocoa and Forest initiative could help reduce/avoid deforestation in Pará but also in Bahia.

5.9.2. Implement reforestation programme and rejuvenate cabrucas, REDD+ and wildlife-friendly certification

The new generation of Bahian farmers are open to changes and to technical support to improve their agricultural management. Some of them also understand the environmental value of the biodiversity found in their cabrucas. They are also willing to explore the economic value cabrucas could bring through environmental-friendly certification or Payment for Ecosystem Services (REDD+, access to credit based on Carbon sequestration). Farmers are willing to participate in reforestation programme including establishing nurseries of Atlantic species and replanting shade trees in their farms. They are also willing to rejuvenate their cocoa plantation by replacing their old unproductive trees, planting new trees and grafting. However, the renewal of Bahian cabrucas is not possible without the support of the government. Environmental NGOs and the civil society should maintain the pressure to keep biodiversity conservation in the political agenda.

5.10. Concluding remarks

It is possible to increase cocoa farmers' income without reducing the biodiversity in cabruca by increasing yield (increase cocoa tree density, replace unproductive trees by high yielding disease-resistant clones), increasing farmers' income and changing agro-environmental policies. Cabrucas could be intensified to increase cocoa yield: reduce the pressure of the limiting factors; use fertiliser (despite numerous issues about whether yield responds to fertiliser) and increase input of labour. The farmers' income could be increased by developing niche markets for high value cocoa (certification, Fine & Flavour, GPI, or single estate chocolate produced on-farm); develop REDD+ and PES for cabrucas and; diversify crops and product compatible with growing cocoa in cabrucas (fruits, spices or handcrafted products). Changing the Brazilian policy could include abandoning extensive low-yield cabrucas for rewilding while developing intensive high-yield plantations (a land-sparing strategy); change in the definition of cabruca in the Forest Law to avoid legal deforestation; and give more resources and power to environmental authorities to enforce legislation (e.g protect the 20% farmland or stop illegal deforestation).

Climate change could negatively affect agroforests. We need to enhance climate-resilience for cocoa production systems ('Climate smart agriculture'). The last severe ENSO-related drought caused high yield loss and increases the mortality of the cocoa tree. The drought accelerated a transition for the Brazilian cocoa industry, from environment-friendly cocoa production in Bahia to intensive low shade plantations in Pará. Brazilian authorities, Research institutes and technical extension could support farmers towards a drought-resilient cocoa production. Three management axes could be implemented: develop drought-resistant clones, diversify crops to decrease economic risk for farmers and plant shade trees to sequestrate carbon. Replace pasture by planting new cabrucas could also be implemented. Finally, more research is needed to understand the future effect of climate change on cocoa: establish climate envelops for cabrucas, measure GHG emission caused by cocoa production, study the changes in pollinator populations, study disease and pests outbreaks and their relation to rainfall, assess the sustainability of irrigating cocoa plantation.

There are two possible scenarios for the future of cocoa production in Brazil. 1) intensify systems towards the production of large quantity of low quality cocoa beans or 2) develop the production of environmental-friendly cocoa with small quantities of high quality cocoa beans. However, the future of Brazilian cocoa production is likely to be a compromise between these two production scenarios: mainly intensive plantation and high quantity in Pará and mainly extensive wildlife-friendly and high quality in Bahia. The maintenance of Bahian cabrucas will depend on their profitability in the future.

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Appendix

Appendix 2.1 | Measurement to establish the conversion factor from fresh cocoa pod to dry cocoa beans, Barro Preto, Bahia

Table A: Harvest of ripe pods for conversion factors from fresh cocoa pod to dry cocoa beans weight.

May 2012	number of fruits	total fresh pod (g)	fresh husk + residuals (g)	fresh beans (g)	Total dry beans (g)	dry beans /pod (g)
plot 1	5	2857.1	2001.5	861.5	333.4	66.7
plot 2	5	2599.1	2014	570.8	235.5	47.1
plot 3	5	2596.7	2088.7	523.2	152	30.4
plot 4	5	2540.4	2042.2	492.8	186.4	37.3
plot 5	5	1710.8	1355	365.5	155	31.0
plot 6	5	2288.1	2177.1	431.2	145.8	29.2
average dry fermented bean weight						40.3

Appendix 2.2 | Interaction effects between variables on cocoa yield (multiple quantile regression)

estimates	value	SE	t	*P*	signif.
(Intercept)	$-1.23\ 10^{5}$	$8.80\ 10^{4}$	-1.39	0.175	
Mortality	$1.39\ 10^{4}$	$2.37\ 10^{4}$	$5.87\ 10^{-1}$	0.562	
yieldLoss	$4.02\ 10^{3}$	$9.55\ 10^{2}$	4.21	0.000	***
SOM	$4.75\ 10^{4}$	$3.90\ 10^{4}$	1.22	0.234	
WB	$8.73\ 10^{4}$	$7.34\ 10^{4}$	1.19	0.245	
SumDBH	$1.74\ 10^{2}$	$1.17\ 10^{2}$	1.49	0.147	
DensityCHa	$1.29\ 10^{2}$	$1.74\ 10^{2}$	$7.41\ 10^{-1}$	0.466	
Mortality:yieldLoss	$-3.79\ 10^{2}$	$6.00\ 10^{2}$	$-6.31\ 10^{-1}$	0.534	
Mortality:SOM	$-5.96\ 10^{3}$	$9.42\ 10^{3}$	$-6.32\ 10^{-1}$	0.533	
yieldLoss:SOM	$-1.36\ 10^{3}$	$4.34\ 10^{2}$	-3.13	0.004	**
Mortality:WB	$-1.20\ 10^{4}$	$2.09\ 10^{4}$	$-5.75\ 10^{-1}$	0.570	
yieldLoss:WB	$-2.86\ 10^{3}$	$1.03\ 10^{3}$	-2.78	0.010	*
SOM:WB	$-3.54\ 10^{4}$	$3.29\ 10^{4}$	-1.07	0.292	
Mortality:SumDBH	$-1.93\ 10^{1}$	$2.80\ 10^{1}$	$-6.90\ 10^{-1}$	0.497	
yieldLoss:SumDBH	-5.81	1.57	-3.69	0.001	**
SOM:SumDBH	$-6.71\ 10^{1}$	$5.15\ 10^{1}$	-1.30	0.204	
WB:SumDBH	$-1.30\ 10^{2}$	$1.02\ 10^{2}$	-1.28	0.213	
Mortality:DensityCHa	$-1.80\ 10^{1}$	$3.90\ 10^{1}$	$-4.61\ 10^{-1}$	0.648	
yieldLoss:DensityCHa	-3.84	2.76	-1.39	0.177	
SOM:DensityCHa	$-5.53\ 10^{1}$	$7.66\ 10^{1}$	$-7.22\ 10^{-1}$	0.477	
WB:DensityCHa	$-7.30\ 10^{1}$	$1.51\ 10^{2}$	$-4.83\ 10^{-1}$	0.633	
SumDBH:DensityCHa	$-1.82\ 10^{-1}$	$2.09\ 10^{-1}$	$-8.70\ 10^{-1}$	0.392	
Mortality:yieldLoss:SOM	$1.60\ 10^{2}$	$2.30\ 10^{2}$	$6.98\ 10^{-1}$	0.491	

Mortality:yieldLoss:WB	$3.45\ 10^{2}$	$5.57\ 10^{2}$	$6.19\ 10^{-1}$	0.542	
Mortality:SOM:WB	$5.17\ 10^{3}$	$8.27\ 10^{3}$	$6.25\ 10^{-1}$	0.537	
yieldLoss:SOM:WB	$9.86\ 10^{2}$	$5.16\ 10^{2}$	1.91	0.067	
Mortality:yieldLoss:SumDBH	$5.12\ 10^{-1}$	$7.32\ 10^{-1}$	$6.99\ 10^{-1}$	0.490	
Mortality:SOM:SumDBH	8.12	$1.12\ 10^{1}$	$7.26\ 10^{-1}$	0.474	
yieldLoss:SOM:SumDBH	1.98	$7.74\ 10^{-1}$	2.55	0.017	*
Mortality:WB:SumDBH	$1.70\ 10^{1}$	$2.46\ 10^{1}$	$6.89\ 10^{-1}$	0.497	
yieldLoss:WB:SumDBH	4.34	2.05	2.12	0.043	*
SOM:WB:SumDBH	$5.20\ 10^{1}$	$4.57\ 10^{1}$	1.14	0.265	
Mortality:yieldLoss:DensityCHa	$5.03\ 10^{-1}$	$8.75\ 10^{-1}$	$5.75\ 10^{-1}$	0.570	
Mortality:SOM:DensityCHa	8.05	$1.55\ 10^{1}$	$5.19\ 10^{-1}$	0.608	
yieldLoss:SOM:DensityCHa	1.33	1.02	1.31	0.202	
Mortality:WB:DensityCHa	$1.50\ 10^{1}$	$3.49\ 10^{1}$	$4.31\ 10^{-1}$	0.670	
yieldLoss:WB:DensityCHa	2.15	2.38	$9.04\ 10^{-1}$	0.375	
SOM:WB:DensityCHa	$3.64\ 10^{1}$	$6.59\ 10^{1}$	$5.52\ 10^{-1}$	0.586	
Mortality:SumDBH:DensityCHa	$2.44\ 10^{-2}$	$4.55\ 10^{-2}$	$5.37\ 10^{-1}$	0.596	
yieldLoss:SumDBH:DensityCHa	$5.79\ 10^{-3}$	$2.61\ 10^{-3}$	2.22	0.035	*
SOM:SumDBH:DensityCHa	$7.69\ 10^{-2}$	$9.30\ 10^{-2}$	$8.27\ 10^{-1}$	0.416	
WB:SumDBH:DensityCHa	$1.15\ 10^{-1}$	$1.80\ 10^{-1}$	$6.38\ 10^{-1}$	0.529	
Mortality:yieldLoss:SOM:WB	$-1.47\ 10^{2}$	$2.15\ 10^{2}$	$-6.85\ 10^{-1}$	0.499	
Mortality:yieldLoss:SOM:SumDBH	$-2.11\ 10^{-1}$	$2.81\ 10^{-1}$	$-7.51\ 10^{-1}$	0.459	
Mortality:yieldLoss:WB:SumDBH	$-4.64\ 10^{-1}$	$6.85\ 10^{-1}$	$-6.78\ 10^{-1}$	0.504	
Mortality:SOM:WB:SumDBH	-7.15	9.76	$-7.32\ 10^{-1}$	0.471	
yieldLoss:SOM:WB:SumDBH	-1.50	$9.97\ 10^{-1}$	-1.50	0.145	
Mortality:yieldLoss:SOM:DensityCHa	$-2.27\ 10^{-1}$	$3.31\ 10^{-1}$	$-6.85\ 10^{-1}$	0.499	
Mortality:yieldLoss:WB:DensityCHa	$-4.61\ 10^{-1}$	$8.12\ 10^{-1}$	$-5.67\ 10^{-1}$	0.576	
Mortality:SOM:WB:DensityCHa	-6.84	$1.38\ 10^{1}$	$-4.94\ 10^{-1}$	0.626	
yieldLoss:SOM:WB:DensityCHa	$-8.04\ 10^{-1}$	$8.60\ 10^{-1}$	$-9.35\ 10^{-1}$	0.358	
Mortality:yieldLoss:SumDBH:DensityCHa	$-6.40\ 10^{-4}$	$1.04\ 10^{-3}$	$-6.10\ 10^{-1}$	0.547	
Mortality:SOM:SumDBH:DensityCHa	$-1.07\ 10^{-2}$	$1.81\ 10^{-2}$	$-5.89\ 10^{-1}$	0.561	
yieldLoss:SOM:SumDBH:DensityCHa	$-2.03\ 10^{-3}$	$1.09\ 10^{-3}$	-1.85	0.075	
Mortality:WB:SumDBH:DensityCHa	$-2.09\ 10^{-2}$	$4.04\ 10^{-2}$	$-5.17\ 10^{-1}$	0.610	
yieldLoss:WB:SumDBH:DensityCHa	$-3.69\ 10^{-3}$	$2.32\ 10^{-3}$	-1.59	0.123	
SOM:WB:SumDBH:DensityCHa	$-5.42\ 10^{-2}$	$8.06\ 10^{-2}$	$-6.72\ 10^{-1}$	0.507	
Mortality:yieldLoss:SOM:WB:SumDBH	$1.93\ 10^{-1}$	$2.66\ 10^{-1}$	$7.27\ 10^{-1}$	0.474	
Mortality:yieldLoss:SOM:WB:DensityCHa	$2.11\ 10^{-1}$	$3.09\ 10^{-1}$	$6.81\ 10^{-1}$	0.502	
Mortality:yieldLoss:SOM:SumDBH:DensityCHa	$2.80\ 10^{-4}$	$4.00\ 10^{-4}$	$7.04\ 10^{-1}$	0.488	
Mortality:yieldLoss:WB:SumDBH:DensityCHa	$5.70\ 10^{-4}$	$9.80\ 10^{-4}$	$5.89\ 10^{-1}$	0.561	
Mortality:SOM:WB:SumDBH:DensityCHa	$9.24\ 10^{-3}$	1.60E-02	$5.76\ 10^{-1}$	0.570	
yieldLoss:SOM:WB:SumDBH:DensityCHa	$1.35\ 10^{-3}$	$1.06\ 10^{-3}$	1.27	0.215	
Mortality:yieldLoss:SOM:WB:SumDBH:DensityCHa	$-2.60\ 10^{-4}$	$3.70\ 10^{-4}$	$-6.85\ 10^{-1}$	0.500	

Appendix 2.3 | List of shade tree species found in 32 farms in Barro Preto, Bahia

abundance	specie	interest	IUCN statue	native
331	*Musa spp*	fruit		
42	*Artocarpus heterophilus*	fruit		
19	*Ficus spp*	environmental		
18	*Citrus sinensis*	fruit		
18	*Cordia spp*	timber		
15	*Plathymenia foliosa*	timber, N-fixing	vulnerable	Atlantic forest
12	*Spondias mombin*	fruit		
11	*Coffea spp*	fruit		
11	*Erythrina spp*	N-fixing		
11	*Genipa americana*	fruit		
11	*Lonchocarpus glabrescens*	timber, N-fixing	vulnerable	Atlantic forest
9	*Senna multijuga*	N-fixing		Atlantic forest
9	*Trema micrantha*	timber	vulnerable	Atlantic forest
8	*Cedrela spp*	timber	Vulnerable A1cd+2cd	Atlantic forest
8	*Inga spp*	fruit, timber, N-fixing		
7	*Persea americana*	fruit		
6	*Carica papaya*	fruit		
6	*Caryocar brasiliense*	fruit	nd	Cerrado
6	*Citrus reticulata*	fruit		
6	*Erythrina poeppigiana*	N-fixing	nd	
5	*Clitoria fairchildiana*	N-fixing	nd	
5	*Jacaranda puberula*	timber	Vulnerable B1+2ac	Atlantic forest
4	*Andira anthelmia*	medicinal, N-fixing	Least Concern ver 3.1	Atlantic forest
4	*Bactris gasipaes*	heart palm		
4	*Cecropia lyratiloba*	timber	nd	
4	*Cordia superba*	timber		Atlantic forest
4	*Erythrina glauca*	N-fixing	nd	
4	*Euterpe oleracea*	fruit		
4	*Gallesia integrifolia*	timber, medicinal		Atlantic forest
4	*Tabebuia spp*	timber		Atlantic forest
3	*Annona reticulata*	fruit	nd	
3	*Tapirira guianensis*	timber, medicinal		Atlantic forest
3	*Macrosyphonia velame*	timber		Atlantic forest
3	*Mangifera indica*	fruit		
3	*Pithecolobium polycephalum, Albizia polycephala*	timber, medicinal, N-fixing		Atlantic forest
2	*Aegiphila sellowiana*	timber, medicinal	nd	Atlantic forest
2	*Bauhinia fortificata*	medicinal	Least Concern ver 3.1	Atlantic forest
2	*Campomanesia guazumifolia*	fruit	nd	Atlantic forest
2	*Cariniana legalis*	timber	Vulnerable A1ac	Atlantic forest
2	*Citrus spp*	fruit		
2	*Eriotheca macrophylla/Bombax sclerophyllum*	timber		Atlantic forest
2	*Hevea brasiliensis*	rubber		

2	*Psidium guajava*	fruit		
2	*Senefeldera verticillata*	timber		Atlantic forest
2	*unknown*			
1	*Albizia niopoides*	timber, N-fixing	nd	Atlantic forest
1	*Citharexylum myrianthum*	fruit		Atlantic forest
1	*Citrus Limonium*	fruit		
1	*Cordia elaeagnoides*	timber		
1	*Cordia trichotoma*	timber		
1	*Dalbergia nigra*	timber, N-fixing	Vulnerable A1cd	Atlantic forest
1	*Eugenia florida DC*	fruit	nd	
1	*Eugenia uniflora*	fruit		
1	*Handroanthus impetiginosus*	timber, medicinal		Atlantic forest
1	*Heliconia spp*	flower	nd	
1	*Jacaranda cuspidifolia*	timber		
1	*Matayba eleagnoides*	timber		Atlantic forest
1	*Myrcia citrifolia*			Atlantic forest
1	*Myrcia spp*			Atlantic forest
1	*Pinus spp*	timber		
1	*Psidium myrsinites*	medicinal, fruit		
1	*Pterocarpus rohrii*	timber, N-fixing		Atlantic forest
1	*Schefflera morototoni*	timber		Atlantic forest
1	*Swartzia apetala*	timber, N-fixing	Least Concern ver 3.1	Atlantic forest
1	*Syzygium jambolanum*	medicinal		Atlantic forest
1	*Terminalia kuhlmannii*	timber	Vulnerable D2	Atlantic forest
1	*Theobroma grandiflorum*	fruit		
1	*Xylopia aromatica*	spices		

Appendix 3.1 | Soil and leaf analysis from the transect to estimate fertiliser addition

Soil and live cocoa leaves sampled next to the plots where the soils for the bioassay were analysed. Five fresh cocoa leaves per tree were sampled in zig-zag locations on 6 cocoa trees along a 100 m transect, oven-dried 5 days at 70°, ground and combined to form one composite leaf sample per farm (cf Fig. A 3.1). Six soil samples (depth = 0–20 cm) were collected in each transect using an auger in zig-zag locations along the 100 m midline of the transect and combined to form a composite sample. All samples were sent to a Brazilian laboratory for analysis. Cocoa leaves and soils were analysed for N, P, K concentration. Soil organic matter concentration, measured by oxidation ($Na_2Cr_2O_7$ $2H_2O$ 4 mol/L + H_2SO_4 10 mol/L), was also measured.

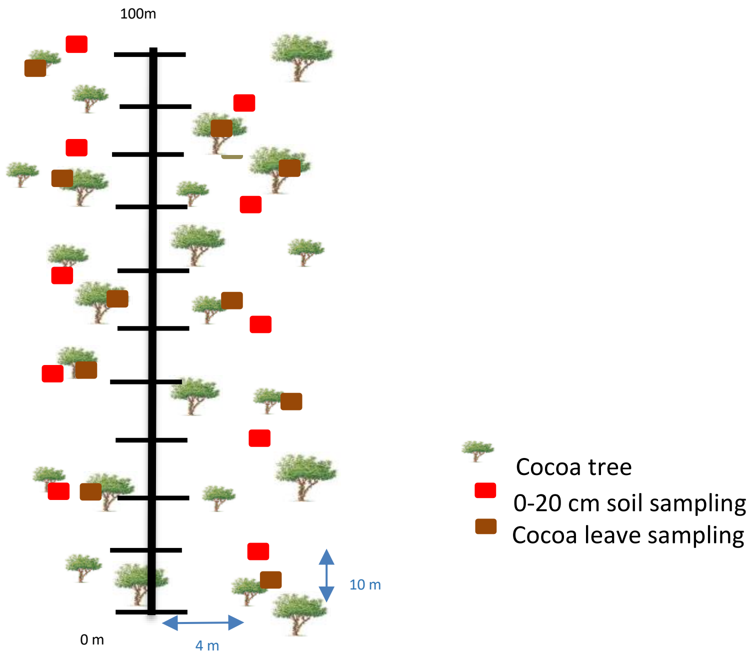


Fig. A 3.1: sampling of cocoa leaf and soils for nutrient analysis to define fertiliser doses.

Table A 3.1 Results of nutrient concentrations in live cocoa leaves and soil in 10 studied cabruca farms used for fertiliser calculation. Reference values are recommendation of adequate ranges given by the CEPLAC.

leaves	N foliar	P foliar	K foliar
Unit	g/kg	g/kg	g/kg
Adequate values range (CEPLAC)	20-35	1.8-2.5	15-23
Farm 1	24	2.0	14
Farm 2	22	1.6	16
Farm 3	20	1.2	16
Farm 4	24	1.5	14
Farm 5	21	1.2	14
Farm 6	22	1.8	15
Farm 7	25	1.2	12
Farm 8	21	1.7	16
Farm 9	22	1.8	18
Farm 10	25	1.8	13

soils	N total (Kjeldahl)	P Mehlich1	K Mehlich1	Soil organic matter
Unit	%	ppm	ppm	% SOM
Adequate values range (CEPLAC)		10-20	60-150	1.6-3
Farm 1	0.20	20	50	2.1
Farm 2	0.26	19	54	2.4
Farm 3	0.27	4	89	2.4
Farm 4	0.17	7	45	2.2
Farm 5	0.31	2	84	3.2
Farm 6	0.25	5	91	2.0
Farm 7	0.29	2	37	2.8
Farm 8	0.30	5	83	2.1
Farm 9	0.30	9	53	2.6
Farm 10	0.34	26	43	2.1

Potassium and P concentrations in leaves and soils suggested nutrient deficiency for K and P in half of the farms before fertiliser addition but no N deficiency, as judged by CEPLAC recommendations. Half of the farms had K values lower than the recommended value and seven out of ten farms had foliar and soil P values lower than the recommended value.

Appendix 3.2 | Soil samples used in the bioassay

	Artocarpus	*Cariniana*	*Erythrina*	*Genipa*	*Lecythis*	*Plathymenia*	*Spondias*	No shade
farm 1	3	3	3	3	3		3	3
farm 2	3	3	3	3		3		3
farm 3	3	3	3	3	3		3	3
farm 4	3		3	3	3		3	3
farm 5	3		3	3		3	3	3
farm 6	3	3	3	3		3	3	3
farm 7	3	3	3	3		3	3	3
farm 8	3	3	3	3	3		3	3
farm 9	3	3	3	3	3		3	3
farm 10	3	3	3	3	3		3	3
farm 4 + fertiliser	1		1	1	1		1	1
farm 9 + fertiliser	1	1	1	1	1		1	1
C1 (fertile soil)								5
C2 (potting compost)								5
C3 (fertile soil + fertiliser)								5

Appendix 3.3 | Laboratory analyses

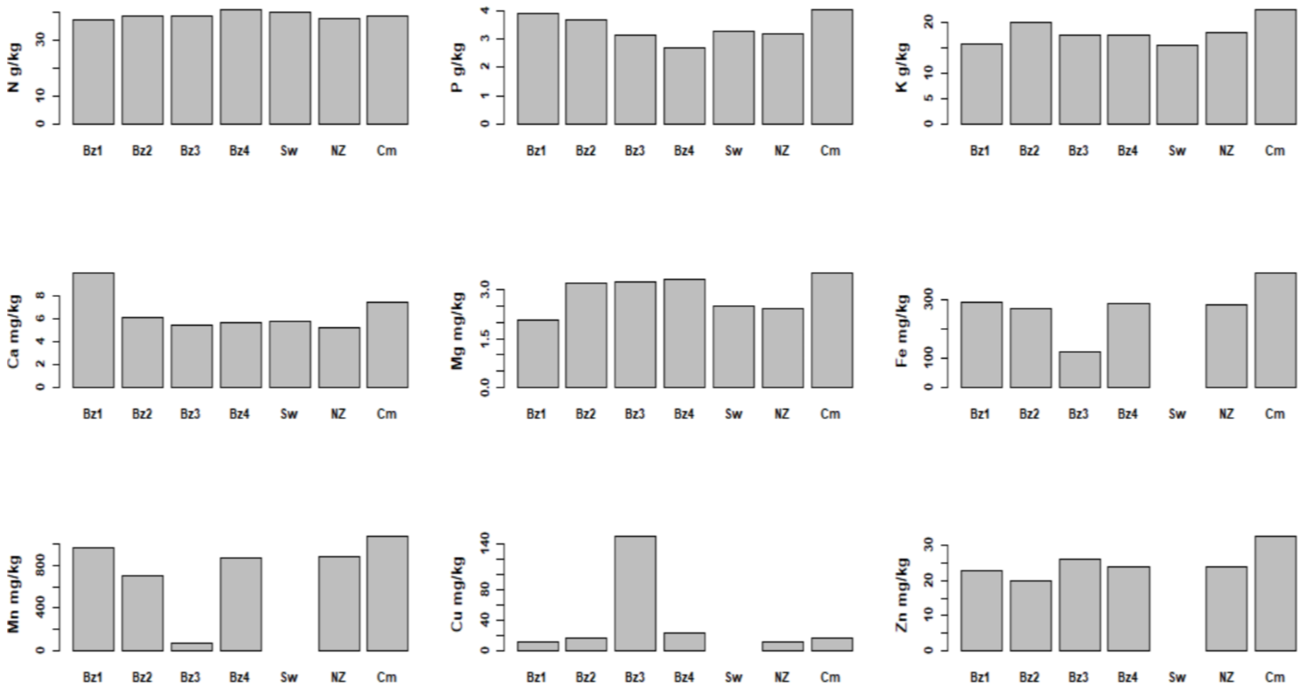
Our analyses of leaf (cocoa and litterfall) and soils to establish the quantity of macronutrients (N, P, K, Ca, S, Mg) and cations were done in the same laboratory in Brazil. Strict regulation on export permits does not allow us to fly samples overseas to analyse them in the UK.

We sent 298 litter samples with 2 types of controls:

-Internal controls: repetitions of samples within the batch of samples, but identified with different numbers.

-External controls: repetition of a standard sample (loose black leaf tea) also sent to other laboratories including one Brazilian laboratory located in a different Brazilian state (Cm) and to two other laboratories located abroad (Switzerland Sw and New Zealand NZ).

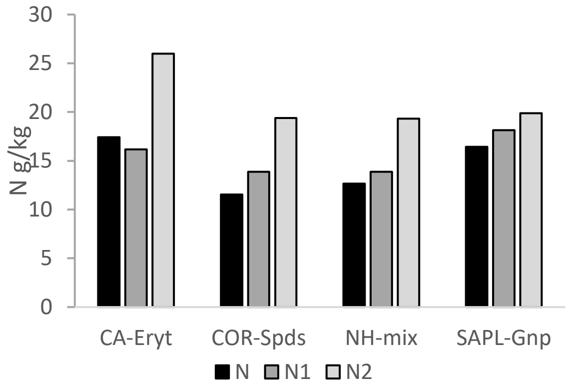
- External variability: Standard black tea leaf (Sainsbury's basic): comparison between 4 labs Sw, NZ, Cm and Bz (Bz1: sample analysed in September 2017 and Bz2, Bz3, Bz4: samples analysed in December 2017)

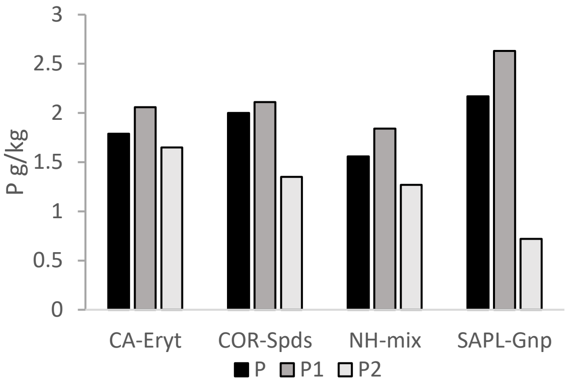


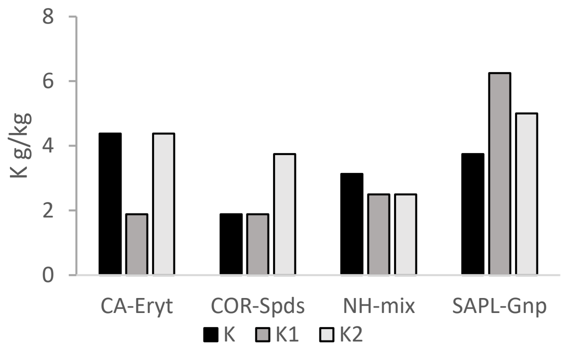
No good repeatability within Bz laboratory was found for analyses of P, K, Zn analysis. Extremely poor repeatability within Bz lab was found for Ca, Mg, Fe, Mn, Cu analyses.

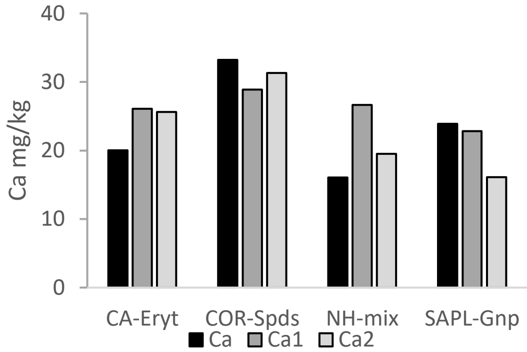
Concentrations were similar for the Sw lab and NZ lab for almost all elements, a little different for K. No good repeatability was found for analyses between Cm Brazilian laboratory and the other laboratories of all elements (excepted N).

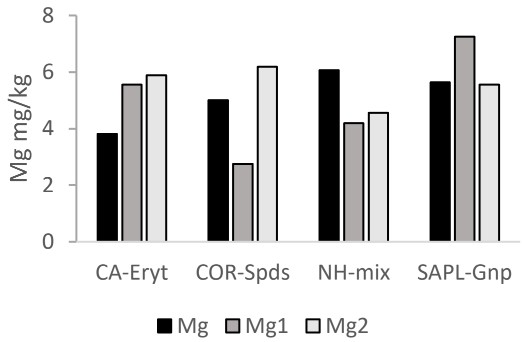
<u>-Internal variability:</u> Litter samples Three repetitions of 4 different litterfall samples: CA-Ery, COR-Spd, NH-mix and SAPL-Geni sent to the same Brazilian lab. Two samples were analysed in September 2017 (N and N1) and one sample was analysed in December 2017 (N2)

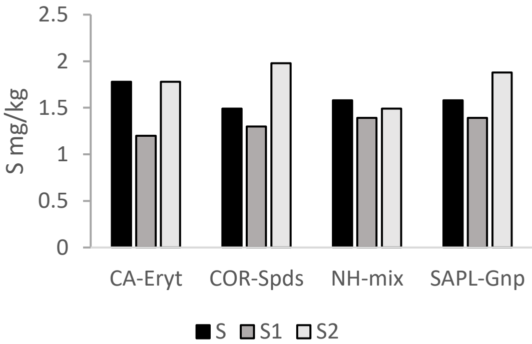

30
25
20
15
10
5
0
N g/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
N
N1
N2

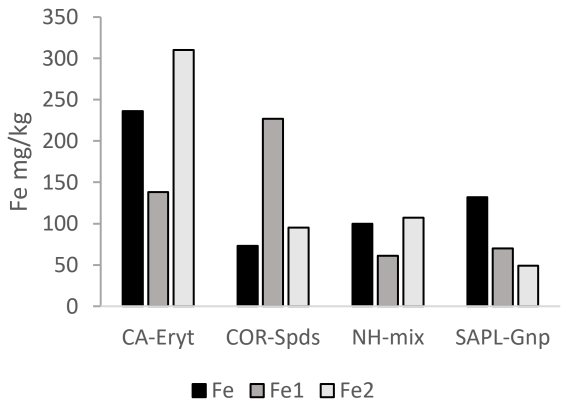

3
2.5
2
1.5
1
0.5
0
P g/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
P
P1
P2

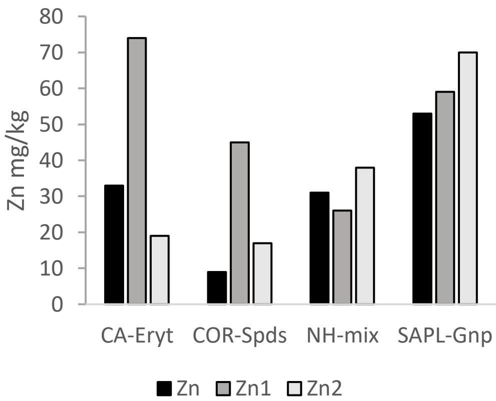

8
6
4
2
0
K g/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
K
K1
K2

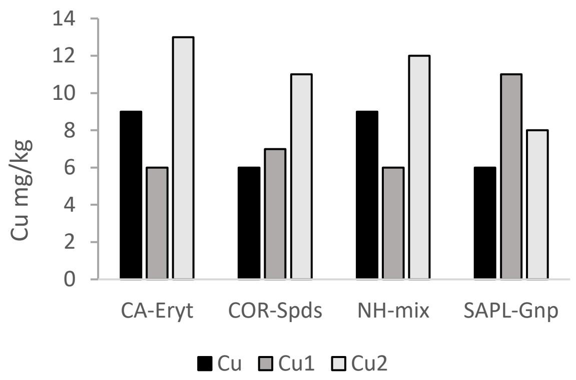

40
30
20
10
0
Ca mg/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
Ca
Ca1
Ca2

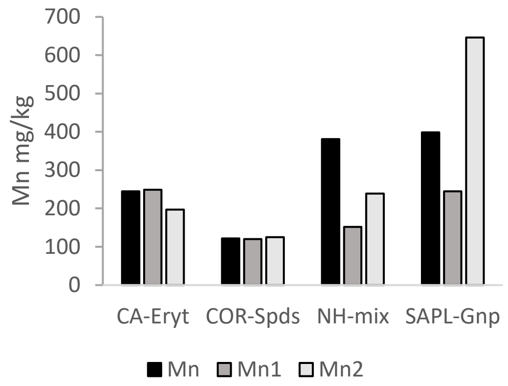

8
6
4
2
0
Mg mg/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
Mg
Mg1
Mg2

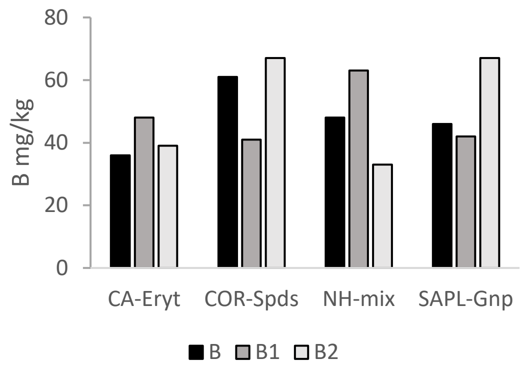

2.5
2
1.5
1
0.5
0
S mg/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
S
S1
S2


350
300
250
200
150
100
50
0
Fe mg/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
Fe
Fe1
Fe2


80
70
60
50
40
30
20
10
0
Zn mg/kg
CA-Eryt
COR-Spds
NH-mix
SAPL-Gnp
Zn
Zn1
Zn2







Very poor repeatability was found within analyses results of the same samples sent to the same laboratory for all elements except for Mn in 'COR-Spds' sample.

Conclusions from the study of the variation within laboratory, between times, and between laboratory for leaf analysis

Comparing replicates within a lab, only values for N and P vary by less than approximately 10%, whereas values for K, Ca, Mg and S differ by 40% to 130%. Results for micronutrient are also inconsistent.

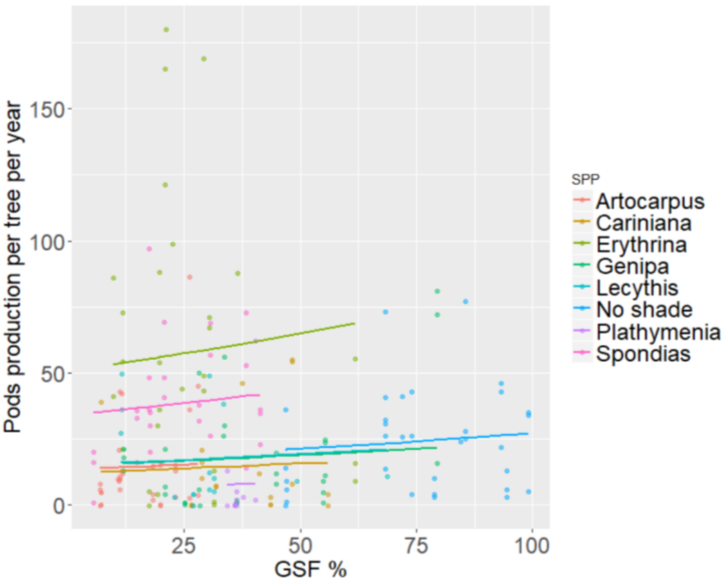
Comparing the replicates between different labs (TEA) values for K are identical; values for N, P are between 10-20% different; but values for other elements varied over 70%.

In a study of interlaboratory variability (Labastide and Van Gore 1975), 21 laboratories across Europe were assessed by sending them 3 pairs of leaf samples for N, P, K, Ca, Mg, Na, Fe, Mn and B analyses. The results showed a large variability between laboratories but also among identical samples analysed by the same laboratory.

This lack of repeatability raises concern on the reliability of any laboratory results when interpreting leaf nutrient compositions.

These results are problematic for my interpretation of differences between farms or between shade species. However, they do allow me to draw conclusions with some confidence about the macronutrients N, P and K.

Appendix 3.4 | Effect of light on yield



Glm(Pods ~ GSF + Spp, family = "poisson")
AIC=4947

	Estimate	Std. Error	z value	P value	Signif.
(Intercept)	2.6	$5.0\ 10^{-2}$	52.1	$< 2\ 10^{-16}$	***
GSFPerc	$4.9\ 10^{-3}$	9.9 10-4	5.0	$5.6\ 10^{-7}$	***
SPPCariniana	$-9.8\ 10^{-2}$	$7.9\ 10^{-2}$	-1.2	0.22	
SPPErythrina	1.3	$5.5\ 10^{-2}$	24.1	$< 2\ 10^{-16}$	***
SPPGenipa	$8.5\ 10^{-2}$	$6.9\ 10^{-2}$	1.3	0.21	
SPPLecythis	0.1	$7.9\ 10^{-2}$	1.4	0.17	
SPPNo shade	0.2	$8.4\ 10^{-2}$	2.4	0.02	*
SPPPlathymenia	-0.7	$1.2\ 10^{-1}$	-6.1	$1.2\ 10^{-9}$	***
SPPSpondias	0.9	$5.8\ 10^{-2}$	16.0	$< 2\ 10^{-16}$	***

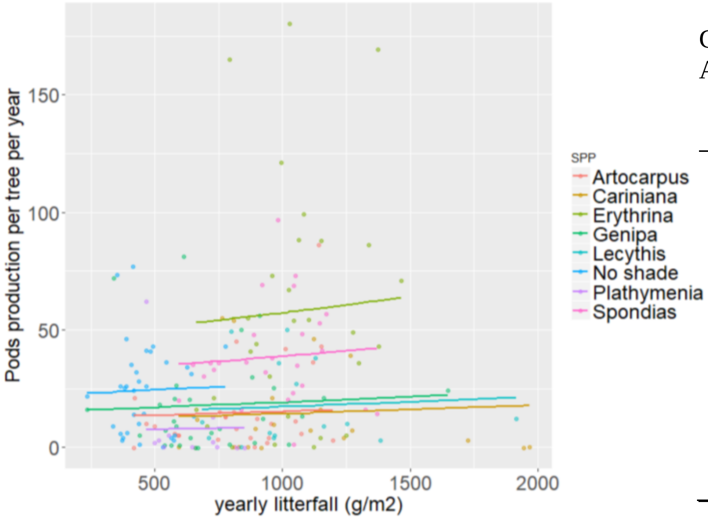
Fig. A 3.4. Effect of light (Global Site Factor) on pod production (total pods and healthy pods only) per cocoa tree in 10 cabruca farms

Appendix 3.5 | Effect of fertilisation on mature cocoa trees

Table A 3.5. Pods per tree before and produced over 15 months following fertiliser addition on mature trees in 10 cabruca farms, means of 2 trees per treatment per farm.

farm	pods per tree before fertilisation (in July 2016)		pods after fertilisation (cumulative for 15 months)		difference before-after	
	control plot	fertilised plot	control plot	fertilised plot	control plot	fertilised plot
1	2	1	14	4	12	3
2	9	29	2	10	-7	-19
3	0	1	30	16	30	15
4	0	0	30	42	30	42
5	20	5	26	6	6	1
6	1	1	34	14	34	13
7	5	1	31	38	26	37
8	0	0	8	2	8	2
9	1	0	27	4	26	4
10	3	9	2	3	-2	-6
average	4.0	4.7	20.2	13.8	16.2	9.2
SE	1.9	2.8	4.0	4.6	4.6	5.8

Appendix 3.6 | Effect of litterfall on yield

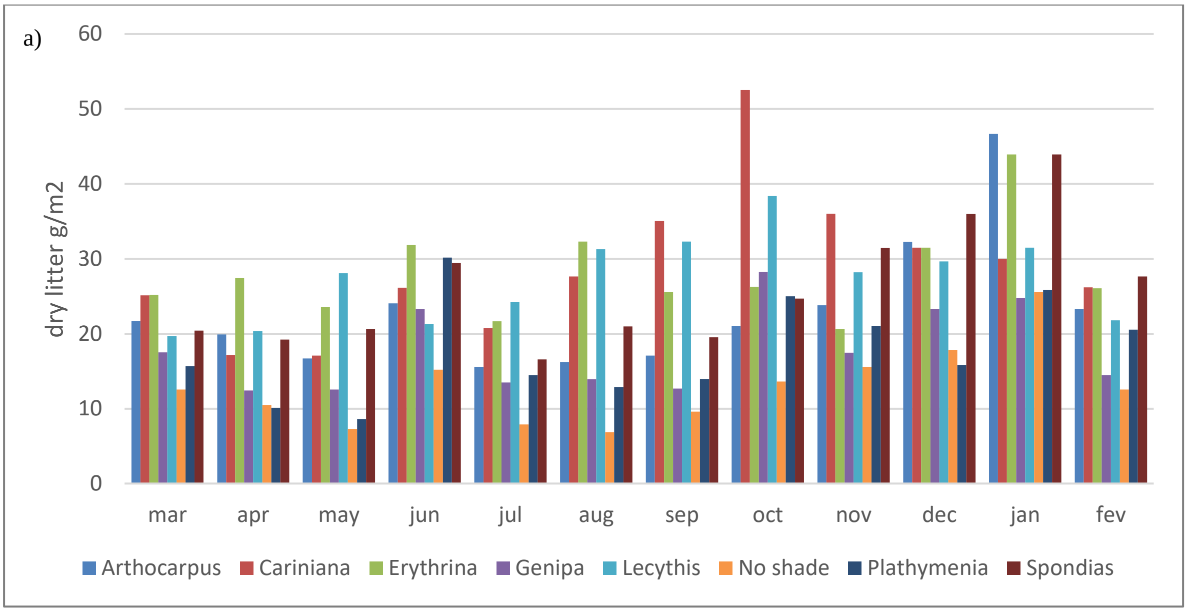


Glm(Pods ~ Litterfall + Spp, family = "poisson")
AIC=4958

	Estimate	Std. Error	z value	P value	signif.
(Intercept)	2.5	7.1 10^{-2}	35.4	< 2 10^{-16}	***
totalLitter	2.3 10^{-4}	6.2 10^{-5}	3.7	2.5 10^{-4}	***
SPPCariniana	-6.0 10^{-2}	7.9 10^{-2}	-0.8	0.45	
SPPErythrina	1.3	5.5 10^{-2}	23.9	< 2 10^{-16}	***
SPPGenipa	2.3 10^{-1}	6.4 10^{-2}	3.5	4.6 10^{-4}	***
SPPLecythis	1.3 10^{-1}	7.9 10^{-2}	1.6	0.12	
SPPNo shade	5.8 10^{-1}	6.4 10^{-2}	9.2	< 2 10^{-16}	***
SPPPlathymenia	-5.8 10^{-1}	1.2 10^{-1}	-4.9	8.8 10^{-7}	***
SPPSpondias	9.3 10^{-1}	5.8 10^{-2}	16.1	< 2 10^{-16}	***

Fig. A 3.6. Effect of litterfall on pod production (total pods and healthy pods only) per cocoa tree in 10 cabruca farms

Appendix 3.7 | Litterfall production through one year



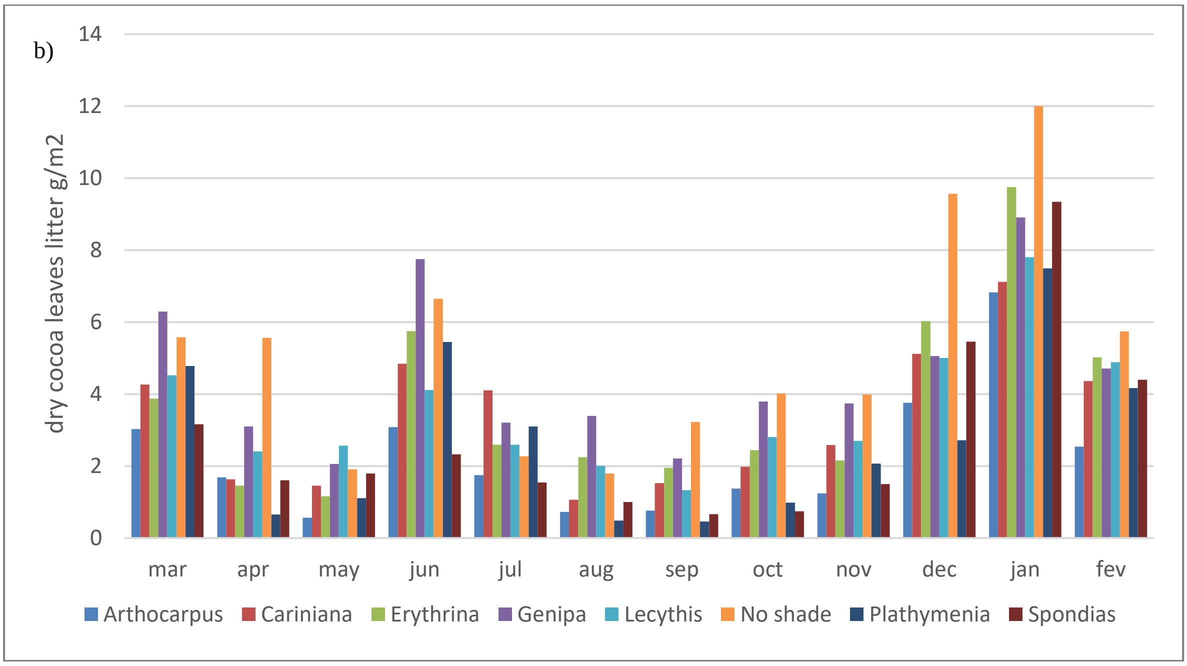


Fig. A 3.7. Litterfall production per shade tree species through the year (arch 2015-February 2016) a) monthly total litterfall production under 7 shade tree species and no shade in 10 cabruca farms in Barro Preto; b) monthly cocoa leaf litterfall production under 7 shade tree species and no shade in 10 cabruca farms in Barro Preto.

Appendix 3.8 | Litterfall production per litter type and per shade tree species

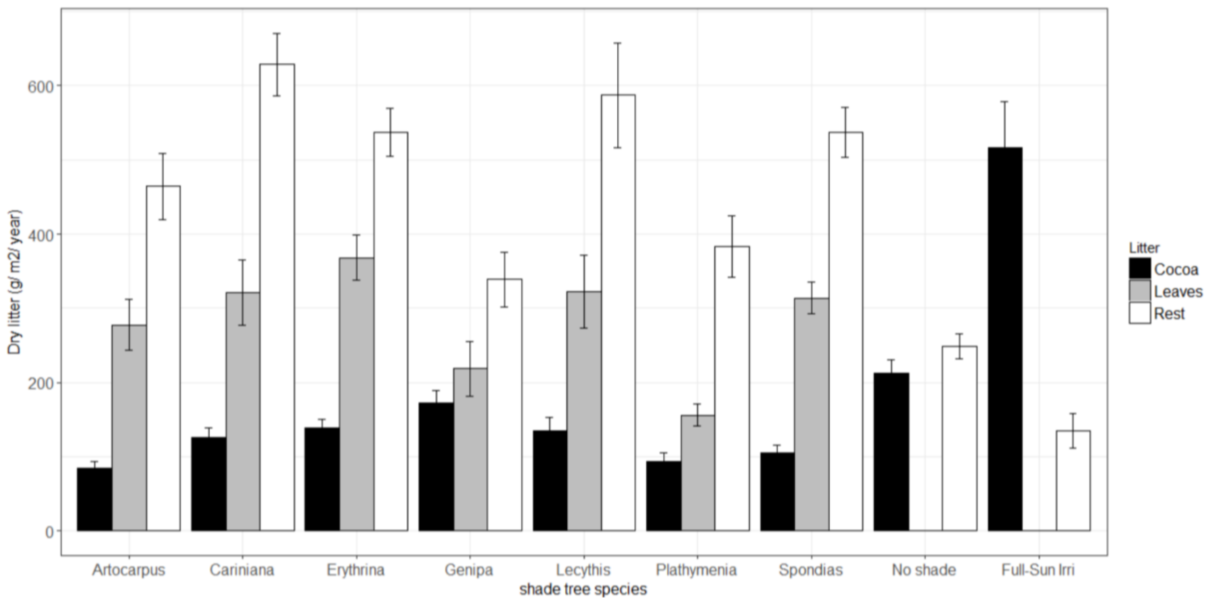


Fig. A 3.8 Cocoa leaf litter, shade tree species leaf litter and the ‘rest’ (other species leaf litter, small branches, twigs, flower, fruits and small fragment) in total litterfall per year for 7 shade tree species, no shade and full sun irrigated farm (Full-Sun Irrigated). Error bars represent standard error of the mean.

Appendix 3.9 | Correlations between N, P and K concentrations in litterfall

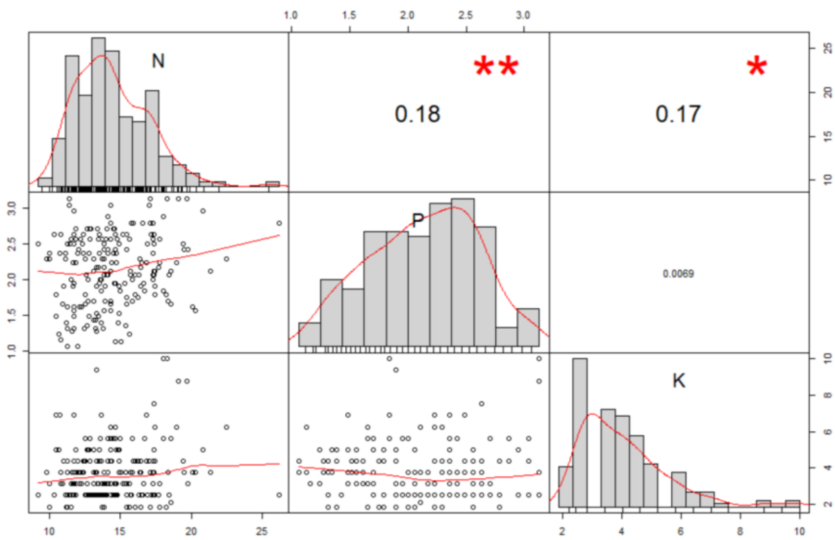


Fig. A 3.7. Correlation between nutrient concentration in litterfall (Correlation coefficient (r) and significance of the relationship: *$P < 0.01$, **$P < 0.05$)

Appendix 4.1 | Review of the studies on the effect of ENSO droughts on tropical forests

Location	Site	Precipitation (monthly range)	Type of forest	Annual tree mortality (normal year)	Years of drought	Comment	References
Indonesia (Sumatra)	Bukit Barisan Selatan National Park	-	Lowland rainforest	24.6% (9.8%)	1997-98	Mainly burnt trees	(Kinnaird and O'Brien 1998)
Indonesian (Borneo)	East Kalimantan	-	Lowland rainforest	25-80% by fires	1997-98	21% burnt area	(Siegert et al. 2001)
Indonesia (Borneo)	East Kalimantan	2100-2500mm	Lowland rainforest	7.9-23.1% 11.2-28.7% 23.9-46.6%	1997-98 1997-98 1997-98	64.2-79% by fire	(van Nieuwstadt 2002) (Slik 2004) (van Nieuwstadt and Sheil 2005)
Malaysia (Borneo)	Lambir Hills National Park, Sarawak	2700 mm/y (167.5-328.4)	Lowland rainforest	4.35-6.37 (0.89%)	1997-98		(Nakagawa et al. 2000)
Costa Rica	La Selva Biological Station	3962 mm/y		1.4-5.6% (0.8-3.7)	1997-98		(Chazdon et al., 2005)
Nicaragua	Autonomous Southern Atlantic Region	4320 mm/y Feb to April: 75–125 mm	Lowland rainforest	~30% (2%)	1997-98	Include fires mortality	(Granzow-de la Cerda et al. 2012)
Panama	Barro Colorado Island (BCI)	2600 mm Dec to April: 215 mm	Semi-deciduous tropical moist forest	2.75-10% (1.98%) 3% (2%)	1982-83 1982-83		(Leigh et al. 1990) (Condit et al. 1995)
Argentina	Nahuel Huapi National Park	1400 mm year^{-1}, 60% falling during May–August.	Mountain forest	11-57%	1998-99		(Suarez and Kitzberger 2008)
Brazil			Amazonian forest	1.91% (1.12%)	1997–98		(Williamson et al. 2000)
	Tapajós National Forest	2000 mm,		3.36% (2.54%)	2000-04	Artificial drought (TFE)	(Nepstad et al. 2007)
	Caxiuanã National Forest Reserve	2000-2500 mm,		2.5% (1.25%)	2001-08	Artificial drought (TFE)	(da Costa et al., 2010)
	All Amazon	Dry June to Nov.		13% of the area	2015-16		(Jiménez-Muñoz et al. 2016)
	Linhares, Espiritu Santo	1200mm	Atlantic forest	4.9% 3.8% (1.4%)	1997–98 1982–83		(Rolim et al. 2005)
	Barro Preto, Bahia		Atlantic forest and agroforest	22%	2015-16		(This study 2017)
10 countries	Mainly Amazon and Borneo		Lowland tropical forests	Increasing water stress increase mortality	1982-83, 1997-98, 2005		(Phillips et al. 2010)
Review	World		All types of forest		From 1904 to 2008	Big trees are more affected, vary depending on species	(Allen et al. 2010)

Appendix 5.1 | Gross margins for studied farms in Barro Preto

	farm name	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Farm 7	Farm 8	Farm 9	Farm 10	Farm 11	Farm 12	Farm 13	Farm 14	Farm 15
Inputs	total fertilise	5000	0	0	0	0	0	0	2500	0	0	0	0	100	0	0
	total manure	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	total liming	5000		10000												
	total pesticic	60				18					182					
	total herbicic	0	0	150	90	75	0	0	165	180	40	120	60	0	0	150
	workers sala	24000	60900	24000	12000	36000	24000	12000	36000	24000	24900	180	0	24000	0	24000
Sub product	total	34060	60900	34150	144446	75213	220428	928664	158198	110774	95973	300	20381	24100	293400	126025
	/ha	2573	1107	385	81	1257	580	2485	869	4633	1164	55	1033	4866.7	489.0	1875.1
output	cacao	65200	146700	94649	189080	26080	206249	206249	65200	277100	53138	3917	11176	3260	342300	407500
	other fruits															
	cattle	19734	0	0	0	0	0	0	538200	502320	53820	0	0	14352	0	0
	dairy cattle	0	0	0	0	79350	0	0	0	0	0	0	0	3450	0	0
	fruits pulpes															
	fish													5000		
	other: cooperative sell															
sub-product	total	84934	146700	94649	189080	105430	206249	206249	603400	779420	106958	3917	11176	26062	342300	407500
	/ha	2850	1834	1352	1891	11223	982	4583	1077487	14938	4462	1119	2032	7260	978	3396
Gross margir	total	50874	85800	60499	44634	30217	-14179	-722414	445202	668646	10985	3617	-9204	1962	48900	281475
	/ha	276	726	967	1810	9966	402	2098	1076617	10306	3298	1064	999	2393.0	489.0	1520.8

	farm name	Farm 16	Farm 17	Farm 18	Farm 19	Farm 20	Farm 21	Farm 22	Farm 23	Farm 24	Farm 25	Farm 26	Farm 27	Farm 28	Farm 29	Farm 30
Inputs	total fertilise	0	0	0	0	0	9800	350	2800	11	0	0	0	6720	0	0
	total manure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	total liming		400	10500	500									1008		
	total pesticides									6	6	15				
	total herbicic	60	60	150	120	30	600	30	90	60	240	90	90	500	0	0
	workers sala	0	12180	49800	24000	0	120000	0	0	0	72000	38700	24900	72000	37350	24000
Sub product	total	42005	55162	60450	57872	30	130400	380	215442	77	72246	333835	24990	80228	37350	46277
	/ha	2100	2615	1937	1228	12	719	119	2736	5	740	1908	417	1526	584	338
output	cacao	100669	97800	98887	83130	14018	104972	24189	265690	2641	142897	118012	102622	193514	59460	83538
	other fruits															
	cattle	8970	3588	0	0	0	73554	0	0	0	32292	23322	16146	0	34086	538200
	dairy cattle	0	0	0	0	0	0	0	0	0	31050	0	3450	0	0	0
	fruits pulpes															
	other: cooperative sells									15000						
sub-product	total	109639	101388	98887	83130	14018	178526	24189	265690	2641	206239	141334	122218	193514	93546	621738
	/ha	22135	6644	3532	1108	5607	2589	2016	5314	880	6025	5283	6317	4032	4706	3248
Gross margir	total	67633	46226	38437	25258	13988	48126	23809	50248	2563	133993	-192501	97228	113286	56196	575461
	/ha	20035	4030	1595	-120	5595	1869	1897	2577	875	5285	3375	5900	2506	4122	2909

Appendix 5.2 | Results of Barro Preto project (document for farmers)

Managements performed to increase cocoa production in Barro Preto project:
-pruning of cocoa trees
-shade reduction (pruning and cut of invasive species)
-field maintenance: manual and chemical weeding
-increase cocoa tree density: planting and grafting
-fertiliser addition (soil acidity correction: limestone addition)
-grafting of high-productive, disease resistant cocoa clones

Managements performed to increase incomes in Barro Preto project:
-crop diversification with tree planting: fruit, timber
-UTZ certification for cocoa
-other hostilities: GPI 'cacau cabruca Sul da Bahia', on-farm chocolate production.

Results of Barro Preto (BP) project after 4 year: average for 11 farm

Inputs:
Labour: 410 days of work for 5 years (82 days/year).
Farm inputs (fertiliser, seedlings, labour): 900R$/ha per year.
UTZ certification: 1500 R$.

Outputs: average of 2 extra fruits per tree in BP project area compared to control area, for a total of 107 fruits per 800 m^2 (4.3 kg of dry cocoa). This corresponds to 1340 fruits/ha (53.5 kg/ha of dry cocoa = 1 bag).
Maximum effect was 7 extra fruits per tree in BP project area compared to control area, for a total of 413 fruits per 800 m^2 (16.5 kg of dry cocoa). This corresponds to 5160 fruits/ha (206 kg/ha of dry cocoa = 4 bags).