Shade trees, disease and cocoa production in Western Ghana – a case study

MSc Thesis Plant Production Systems

Miguel Correia Castillo Leitão
March 2020

WAGENINGEN UNIVERSITY & RESEARCH

Shade trees, disease and cocoa production in Western Ghana – a case study

MSc Thesis Plant Production Systems

Name Student:	*Miguel Correia Castillo Leitão*
Registration Number:	*971227-162-100*
Study:	*MSc Plant Biotechnology –Specialization Molecular Plant Breeding and Pathology*
Chair group:	*Plant Production Systems*
Code Number:	*PPS-80436*
Date:	*March 2020*
Supervisors:	*dr. Marieke Sassen*
	dr. Danaë M.A. Rozendaal
Examiner:	*dr.ir. Maja Slingerland*

Disclaimer: this thesis report is part of an education program and hence might contain (minor) inaccuracies and errors.

Correct citation: Leitão, M.C.C., 2019, Shade, disease and cocoa production in Western Ghana – a case study, MSc Thesis Wageningen University, 57 p.

Contact: miguel.correiacastilloleitao@wur.nl, office.pp@wur.nl for access to data, models and scripts used for the analyses.

WAGENINGEN UNIVERSITY & RESEARCH

Table of Contents

Acknowledgements

I would like to start by thanking my supervisors, Marieke and Danae, who allowed me to develop this project with as much freedom as I could possibly ask for. I am very grateful for the things I have learned in this thesis thanks to both Marieke and Danae, who not only guided me through a particularly unfamiliar topic (to me) but also through the process of data analysis and writing. Their insight was crucial for the development of this project. A special thanks to Marieke for welcoming me to the PPS group and for introducing me to the project.

Secondly, I would like to thank everyone involved in the Cocoa Soils program, with special regards to Ken Giller, head of the PPS group, and to Richard Asare, who not only allowed me to participate in this project but also welcomed me at IITA in Ghana and guided me through the complex arrangements required to perform my field work.

Then, I am extremely grateful to everyone in IITA in Ghana who welcomed me and made sure I felt at home during my stay in Ghana. I cannot thank them enough for everything they have done. I am especially grateful to Mustapha A. Dalaa, Rich K. Kofituo and Abigail Tettay for their helpful insight on the methodology. I am also extremely grateful to Rich for his intensive aid in developing the ODK survey and to Mustapha for all the contacts and arrangements he made for me, for the extra help in the methodology and in general for all the time he spent making sure I was guided and enjoyed my work. And once again, a big thank you to Richard for making all of this happen.

I am also very grateful for the time I spent at CRIG, which was only possible with the help and active participation of Amos Quaye. He made sure I had the opportunity to see and learn what I wanted to learn from the visit and for that I am immensely grateful. Of course, I am also thankful for everyone who took the time to teach me about disease and pests and guide me through the research plots. This was not only very interesting but also crucial for my work in the field. Special thanks to Godfred Awudzi for the additional help in perfecting the methodology for my project.

Then special thanks to Bismark for driving me to the research location and for helping me with the setup of the data collection. Without him it would have been impossible to collect any data. Also thankful to Jackson, my translator and special thanks to all the farmers in the Bepokokoo community who welcomed me and allowed me to study their farms over 4 weeks.

Finally, a general thank you to everyone at PPS, with special regards to Ekatherina for guiding me through the ODK collection system and to Maja for taking the time to examine my thesis.

Last but not least, I am very thankful to my parents for allowing me to travel to Ghana and be part of this project.

Summary

This research addresses the impact of shade trees on smallholder cocoa agroforestry systems from Western Ghana. Improving agroforestry systems in cocoa production has the potential to address the increasing pressure for sustainable cocoa while improving farmers' food security and income diversification. Many different approaches to this problem can be taken. In this study, the effect of shade tree canopy cover was tested on productivity of individual cocoa trees (represented by harvested pod counts) and on disease and pest damage (represented by the presence of mirid damage and black pod). A potential interaction between disease/pests and productivity was also measured as the percentage of pods lost to disease and pests. Finally, the preferences of farmers regarding shade tree species were also addressed to reveal additional benefits of shade trees to cocoa farmers.

18 plots were assessed in this study with varying shade levels (0-90%). Shade tree cover did not have a significant effect on the number of harvested cocoa pods or the number of viable pods, while the number of mature pods before harvest was negatively affected by shade. The percentage of harvested pods that were viable was also not significantly affected by shade and the percentage of harvested pods lost was around 15%.

Shade only significantly increased the percentage of mature pods with black pod per tree while mirid damage was not affected by shade. Young pods (cherelles) had a smaller percentage of damage by mirids and black pod than mature pods.

Farmers participating in the survey (n=6) made use of shade tree products and acknowledged their economic benefits. They also had preferences for shade tree species and were aware of benefits and disadvantages associated with them. Some answers were not described in literature, such as increased pest/disease incidence caused by *M. excelsa*, use of *N. laevis* in yam plantation and two local tree names mentioned as undesirable.

It is concluded that shade tree cover did not significantly affect productivity of cocoa trees or the losses associated with disease and pests in the late development stages of cocoa pods. Additionally, the small sample of farmers noted benefits of shade trees in income diversification, food security and improved cocoa production. Therefore, no significant reason is presented against the potential benefits of shaded systems. Contrastingly, increased shade led to an increased spread of black pod within infected trees, although shade did not increase the incidence of black pod per plot, suggesting that high shade does not increase the spread of black pod to neighbor trees. Therefore, effective pruning and removal of diseased pods should decrease the differences between shade levels. In general, disease and pest counts should focus on immature pods and the causes leading to cherelle wilt, in order to draw better relationships between shade, disease/pests and productivity.

1. Introduction

Cocoa is an important commodity in developing countries, with some of these countries' economies depending largely on the cocoa market. The cocoa tree (*Theobroma cacao*) is only grown as a crop between 10° N and 10°S of the Equator. This factor narrows the production of cocoa to developing countries: up to 90% of the world's cocoa is produced by 5 to 6 million small-holder farmers (Fairtrade Foundation, 2016).

Around 60% of the world's cocoa is produced in Côte d'Ivoire and Ghana alone (International Cocoa Organization, 2015). Despite being the leading producers in volume, the yields per hectare obtained in the West African farms are quite poor compared to those obtained in other continents (Street & Legon, 2014). A typical farm in West Africa produces around 400 Kg (Laven & Boomsmsa, 2012) per hectare per year of cocoa beans, which translated into revenue is hardly enough to sustain the livelihood of a common household of six people.

Cocoa in West Africa

Farmers in West Africa are caught in a vicious cycle of low income and poor yields. On one hand, farms are usually small, with around 2-4 hectares of land (Fairtrade Foundation, 2016), which coupled with relatively low farm gate prices (Fountain & Huetz-Adams, 2018) results in farmers earning very low incomes and many cocoa farmers living in poverty. On the other hand, the input costs are excessively high for an average farmer and most governments are not subsidizing these inputs. The result is a low use of input in these crops (Wessel & Quist-Wessel, 2015). As a consequence, nutrient supply and maintenance of the crops is severely neglected while disease and pests' incidence increase (Wessel & Quist-Wessel, 2015). As a consequence, farmers are met with low yields, aggravating their situation.

In Ghana, cocoa production has increased from 300,000 tons in 1995 to 900,000 in 2014 (Wessel & Quist-Wessel, 2015). This enormous growth has been mostly driven by the Ghana Cocoa Board (COCOBOD). In the beginning of the century this organization managed to reintroduce subsidized agrochemicals and to provide free pest and disease control programmes for cocoa farms (Kolavalli & Vigneri, 2018). Along with other measures, such as distributing hybrid cocoa varieties to farmers, the COCOBOD was able to increase not only the production volume of cocoa in Ghana but also the productivity of individual farms (in yield/ha) (Kolavalli & Vigneri, 2018).

Despite the actions taken by Ghana to improve their cocoa production, most farms are still met with low productivity (around 400 Kg/ha/year) (Kolavalli & Vigneri, 2018). It is then clear that the increased production of Ghana's cocoa is still mostly due to land use expansion.

Climatic suitability for cocoa productions in West Africa is predicted to change until 2050, thereby shifting the current cocoa growing regions and increasing the risk of deforestation for agricultural expansion (Schroth et al., 2016; Läderach et al., 2013). Thus, future strategies need to focus on increasing farm productivity and tolerance to climate change as opposed to an increase in farm size.

Reasons leading to low productivity

There are a few main causes for the low productivity found in Ghana. On one hand, up to 65% of farmers are classified as low production class, as the average yield found in their farms is 400kg/ha. This group is characterized by poor management and input use, such as irregular spacing and density of cocoa trees, inadequate weeding and pruning and poor shade management, no disease and pest control and irregular harvesting

(Laven & Boomsmsa, 2012). Despite the introduction of potentially high-yielding varieties, productivity barely increased in most farms due to poor management and insufficient input. In well managed farms, these improved varieties can indeed increase yields (Wessel & Quist-Wessel, 2015) but can lead to a dependency on subsidies to accommodate the required inputs. Now, with Ghana's government intending to cut subsidies on agriculture, the future of cocoa production in Ghana is at risk.

On the other hand, the advanced age of the trees has also contributed to the low yields in cocoa farms (Wessel & Quist-Wessel, 2015; Dormon et a., 2015; Kolavalli & Vigneri, 2018). Old trees have a higher risk of contracting diseases and are overall less productive than younger trees (Wessel & Quist-Wessel, 2015, Obiri et al., 2007). In Ghana many cocoa trees were reaching 50 years of age before 2012, which severely compromises the farms' productivity (Laven & Boomsma, 2012). In 2012, COCOBOD created a programme to supply 20 million hybrid seeds with the intent of replacing 20% of the cocoa trees per farm (Kolavalli & Vigneri, 2018). Most farmers are not in favour of complete replanting due to the short-term losses in production and the investment costs and so they prefer to plant cocoa trees in new land (Wessel & Quist-Wessel, 2015). However, partial replanting of the existing older trees increases the risk of spreading of diseases, such as Cocoa Swollen Shoot Virus Disease (CSSVD) to the new trees.

1.1. Cocoa agroforestry systems

Agroforestry systems are a form of multiple cropping in which two or more plants interact biologically, where at least one of them is a woody perennial and there is at least one forage, annual or perennial crop (Somarriba, 1992). Including woody shade trees in agroforestry systems may provide several ecosystem services (Table 1). Recent studies have been solidifying the potential of agroforestry for biodiversity conservation (Jose, 2009; De Beenhouwer et al., 2013), carbon sequestration and climate change mitigation (Jose, 2009; Nair et al., 2009; Harvey et al., 2014), air and water quality improvement (Jose, 2009) and profitability, when the trees serve as an extra income source for farmers (Jose, 2009; Obiri et al., 2007).

Table 1 - Ecosystem services of agroforestry, as described by Jose (2009).

Ecosystem Services	Spatial Scale		
	Farm/Local	Landscape/Regional	Global
Net Primary Production	■		
Pest Control	■		
Pollination/Seed Dispersal	■		
Soil Enrichment	■		
Soil Stabilization/Erosion Control	■		
Clean Water	■	■	
Flood Mitigation	■	■	
Clean Air	■	■	
Carbon Sequestration	■	■	■
Biodiversity	■	■	■
Aesthetics/Cultural	■	■	■

As mentioned above, most West African farmers cannot rely on high input systems (Laven & Boomsma, 2012). Agroforestry systems can support production in low input systems especially when the crop seeds are of poor quality (Nair, 2007; Obiri et al., 2007). Although agroforestry systems are still common in Ghana, the introduction of new hybrid varieties has been shifting the landscape of cocoa farms towards intensive unshaded systems (Anglaaere et al., 2011). Ultimately, the reasons for supporting or opposing agroforestry will depend on the stakeholders and their priorities (Krauss, 2017).

Improving agroforestry systems' management might be a strategy to not only offset some of the ecosystem services lost by deforestation but also to improve the overall productivity of the farms with diversified products, therefore supporting increased incomes and food security in Ghana (Jose, 2009). On the other hand, some trade-offs may occur. For example, high shade levels required to increase biodiversity can decrease cocoa yields (Blaser et al., 2018) and the pressure of premiums offered to reduce carbon footprints may limit shade tree biodiversity by forcing farmers to grow only certain shade tree species (Krauss, 2017). Abdulai et al. (2018) also suggest caution when considering agroforestry systems under extreme climate conditions.

In a global perspective, increasing pressure from buyers and producers to improve sustainability of cocoa as well as uncertainty in financial support for cocoa farmers creates an opportunity to improve traditional agroforestry systems, in order to address the concerns of a wide range of stakeholders.

For farmers and suppliers, the main concern is arguably the productivity of the cocoa trees. Many researchers suggest the potential of good shade management in improving productivity of trees (Smith et al., 2012; Zuidema et al., 2005; Blaser et al. 2018; Amadu et al., 2020). A good shade management will depend on spacing, density, shade cover and the species of shade trees. All these factors will influence the potential of agroforestry on yield improvement.

The control of disease and pest incidence through shade management is another particular aspect of agroforestry that sparks interest among researchers (Schroth et al., 2000; Blaser et al., 2018; Ameyaw et al., 2014; Wessel & Quist-Wessel, 2015). Shade trees have been shown to reduce the transmission of windborne fungal diseases (Rice & Greenberg, 2000), to reduce the activity of mirids (Padi & Owusu, 1998) and even to reduce the incidence of two important South American cocoa diseases (Witches Broom and Frosty Pod Rot) (Evans, 1998). Daghela et al. (2013) suggested that a higher diversity in shade tree species may increase the spread of natural enemies of cocoa pests and showed that the density of monophagous herbivores decreases with increased shade level. None the less, Schroth et al. (2000) highlighted the importance of spacing and the species of shade tree in the potential of agroforestry as a control for disease and pests.

This study will assess the effect of shade tree cover on cocoa production. The goal is to evaluate different shade levels in terms of disease and pest control and cocoa tree productivity. Additionally, the study aims to describe the potential additional value of some particular shade tree species to the farmers.

Productivity in shaded systems

It is difficult to describe the relationship between agroforestry and cocoa productivity (i.e. cocoa bean yield). Blaser et al. (2018) suggested that shade tree density will favour productivity (measured in yield) of cocoa farms if it is kept at around 30% shade cover while Zuidema et al. (2005) suggest that productivity is not significantly affected by shade under less than 60% shade cover, above which, productivity decreases. However, cocoa tree productivity will depend on other factors aside from shade.

Cocoa pods can be found in a cocoa tree at various development stages at the same time (Fig. 1). A large fraction of immature pods will not reach maturity, in a process called cherelle wilt. It can happen due to the physiological state of the tree, which can be influenced by nutrient availability, light, the age of the tree and the overall hormone balance. (Bailey & Meinhardt, 2016). Additionally, several diseases and pests may have different impact on pod losses depending on the development stage of the pods (Babin et al., 2012; Mahob et al., 2018; Soh et al., 2013).

In the period between pod maturity and ripeness, it is still possible to suffer losses that will affect final yields. At this stage the losses will be mostly caused by disease and pest damage. If an infection spreads across the whole pod before it is ripe, the cocoa beans can be severely damaged, leading to yield losses.

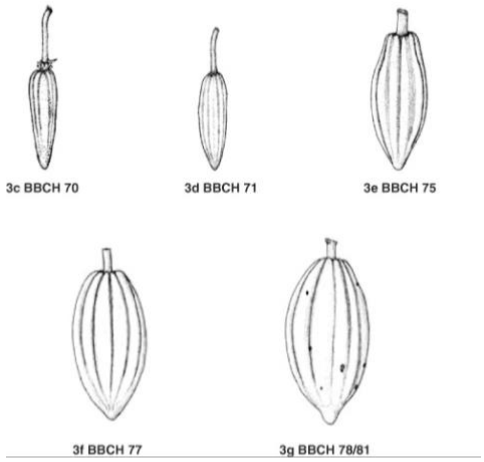


Figure 1 *– Representation of development stages of a cocoa pod as described by Niemenak et al. (2010). Stages BBCH 70 to BBCH 75 represent immature pods. Stages BBCH 70 through BBCH 75 were categorized as cherelles in this report. BBCH 77 represents a mature pod. BBCH 78/81 represents the ripening of the fruit and seed, marked by a change in external color.*

As previously described the age of the cocoa trees will also have an effect on the productivity of those trees (Wessel & Quist-Wessel, 2015, Obiri et al., 2007). Within the same farm it is still possible that not all cocoa trees were planted at the same time.

Other factors can weigh on the performance of an individual tree at the farm level. The input use and management practices taken by the farmers, such as fertilizer and pesticide use, or sanitation habits will also have a direct or indirect influence on the final yields obtained in their farms.

One management practice, pruning, can also influence the amount of shade the cocoa trees are exposed to. Canopy size may be correlated with the fruit bearing of cocoa trees. It is expected that a bigger canopy can produce more assimilates, consequently allocating more assimilates to the reproductive organs. While tree size can be correlated to canopy size (within the same tree species), pruning practices should also affect the size of the canopy. Therefore, it is possible to find tall trees with narrow canopies (and vice-versa).

It is important to understand these causal relationships between potential determining factors in order to better understand the variance found in individual tree productivity (Fig. 2).

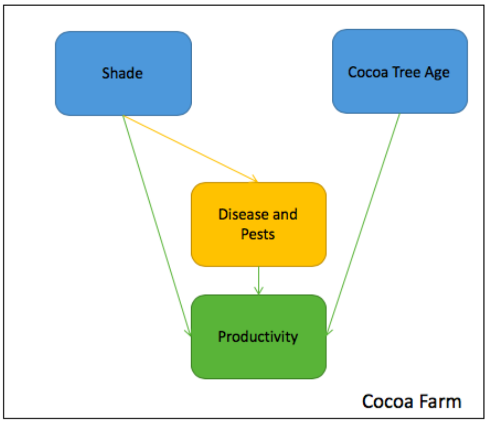


Figure 2 *- Conceptual diagram of causal relationships. The direction of the arrows represents a causal relationship between the different variables represented by the boxes. "Shade" represents the shade to which the cocoa trees are exposed. "Cocoa tree age" refers to the age of the cocoa trees. "Disease and pests" represent the impact of a disease or pest in a cocoa tree. "Productivity" includes the responses in productivity of a cocoa tree. Management practices are assumed to be equal throughout the same farm.*

Pests and diseases

Pests and diseases are the cause of around 25% of total yield losses in Ghana and 30-40% in Côte d'Ivoire (Wessel & Quist-Wessel, 2015).

Phytophthora Pod Rot (PPR) commonly known as black pod disease is a major cause of yield loss in West African cocoa. As an oomycete *Phytophthora spp.* spreads more efficiently in humid conditions (Xiang & Judelson, 2014), so controlling the microclimate caused by shade trees by pruning cocoa trees, removing infected pods from cocoa trees and from the soil should help reducing its spread. Nevertheless, the most effective control so far is the regular spraying of fungicides, which may not be sustainable for small farmers (Acebo-Guerrero et al., 2012).

Miridae (mirids) are some of the most destructive pests affecting cocoa. They have been shown to increase mortality in very early stages of cocoa pod development (Babin et al., 2012; Mahob et al., 2018). They spread particularly well in unshaded conditions (Babin et al., 2010). Although a better shade management can be effective in reducing outbreaks, insecticides are still the main form of control (Wessel & Quist-Wessel, 2015).

Shade tree species selection

There are a few main properties to consider when selecting shade trees. The canopy size and light transmissivity of shade trees are important variables in agroforestry systems. Some trees may have wide canopies but allow a great amount of light to be transmitted (or vice-versa). The root depth is also important when considering below ground interactions between cocoa and the shade trees. It is favourable to have trees that do not compete too much with cocoa for water and nutrients. The resistance and or susceptibility to pests and diseases is also important to take into account. Some institutes in Ghana, such as the Cocoa Research Institute of Ghana (CRIG) have suggested some shade tree species as being more suitable for cocoa farms than others (Asare, 2015; Graefe et. al. 2017).

Some trees may attract pests or diseases that affect cocoa, as is the case of *Ricinodendron heudelotii* and *Cola nitida* (Dumont et al., 2014). Others, such as *Citrus* and Oil palm (*Elaeis guineensis*) may serve as disease barriers (Wessel & Quist-Wessel, 2015). Some trees may reduce soil moisture (*Piptadeniastrum africanum*) while others may increase it (*Milicia excelsa*) (Asare, 2015).

Ultimately the farmers will make the decision of which shade tree species to add/keep in their farms. This decision might be influenced by the above-mentioned properties but also based on the economic value and cultural value of a certain species. Farmers might prefer trees whose products provide an extra source of income. *Terminalia superba*, *Terminalia ivorensis* and *Milicia excelsa* are just some examples of trees that have been described as preferred trees by farmers (Graefe et. al. 2017). It is possible, however, that some shade tree species that are preferred by the farmers are not the most compatible with cocoa trees.

1.2. Research objectives and questions

This study will assess the influence of shade tree cover on the productivity of individual cocoa trees. It will also test the effect of shade in the spread of black pod and mirids. Finally, it will illustrate some of the decisions behind farmers' preference for a shade tree species.

To accomplish these goals, this report will address the following research questions:

RQ1. *What is the relationship between productivity of cocoa trees and shade?*

RQ2. *What is the relationship between disease incidence and pest damage and shade?*

RQ3. *What other benefits can some preferred shade tree species have for farmers, based on those trees' characteristics?*

Hypotheses

Shade tree density is expected to improve productivity until about 30% canopy cover (Blaser et al., 2018), but above that productivity is expected to decrease. Regarding the productivity of individual trees, the number of harvested pods is expected to follow a similar pattern.

The relationship between shade and pest/disease control will vary with the species of pest/pathogen. If management practices are conserved under different shade covers, it is expected that black pod will thrive under high shade cover (Xiang & Judelson, 2014) and that mirid damage will be more common under low shade cover (Babin et al., 2010).

Regarding shade tree preferences, it is expected that farmers will favour trees that provide them the most services rather than those which only favour cocoa production.

2. Methodology

2.1. Study site

The research was conducted in the Western region of Ghana, in the Wassa Amenfi West district. The Western region alone accounts for 50% of the national cocoa production (Abenyega & Gockowski, 2001). The region has both rainforests and deciduous forests.

As a reference, the nearest climate data available comes from the Sefwi Bekwai weather station in the Western region. Here the temperatures round 28 ºC maximum and 24 ºC minimum but 2019 witnessed a rise in the average temperature (Fig. 3). The warmest weather is found between January and March, while the coolest month is August. Despite being a humid region throughout the whole year, there are two dry seasons, a short one in August and a longer one between December and February. Rainfall goes down to around 20 mm (in January) and peaks at close to 200 mm (in October). However, 2019 has witnessed an abnormal peak in rainfall with close to 600 mm (Fig. 3) (World Weather Online, 2020).

The data collection took place between November 18 and December 20, 2019. This period coincides with the beginning of the dry season and warmer temperatures.

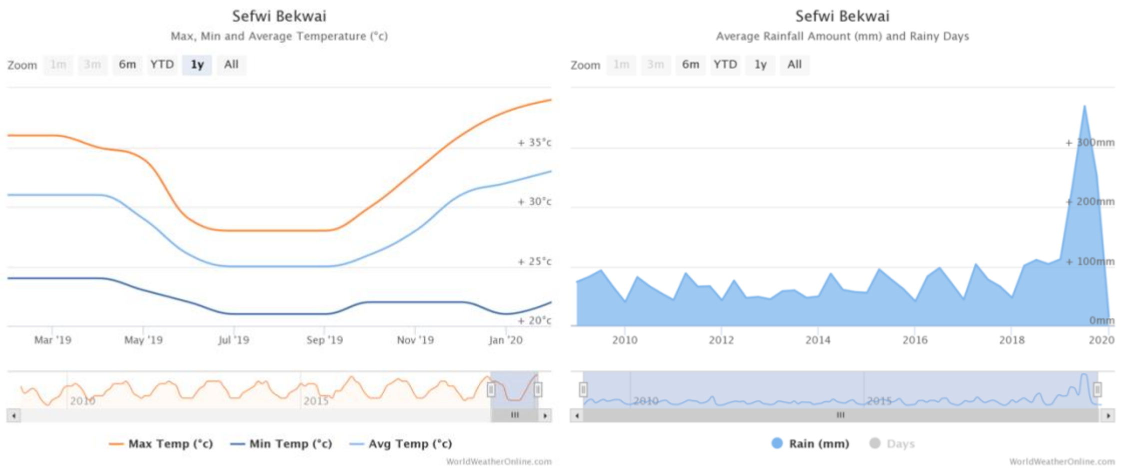


Figure 3 *– (Left): Temperature variation in Sefwi Bekwai in 2019. (Right): Historical rainfall amount in Sefwi Bekwai, from January 2009 to January 2020 (World Weather Online, 2020).*

2.2. Farm sampling

The farms sampled in this study were chosen using baseline data granted by CocoaSoils, a program aimed at providing soil fertility management recommendations to cocoa farmers in West Africa. The farms were chosen within the same community with the intent of reducing variability of confounding factors as much as possible. In addition, on included farms a sufficient number of cocoa pods was present in the cocoa trees so that the trees could be harvested at least once within the period of time available to this project. Farms were at least 1 hectare in size and included three different shade levels (high, moderate and no shade).

The high rainfall intensity this year led to an early harvest of the cocoa trees. As such, many farms were already depleted of cocoa pods in their trees. Therefore, only six farms that were suitable for this study were selected.

Field work was done on the same six farms during 4 weeks in November 2019.

2.3. Plot measurements

Plot delimiting

On each of the six farms sampled, three plots were chosen based on the level of shade available to the cocoa trees. The plots were circular with 25 m in diameter (Fig. 4). Two of the plots in each farm were under some level of shade tree cover and the remaining plot did not include any shade tree canopies. The two shaded plots per farm should demonstrate two approximately different shade tree covers. The goal was to represent three different shade conditions in each farm. For this matter, circular plots were found to be more effective and simpler to draw than square plots, as the plot could be drawn around a central shade tree (in shaded plots).

For each plot, 20 cocoa trees were randomly selected in order to sample a significant representation of the plot. The cocoa trees were tagged and their DBH was measured at 130 cm.

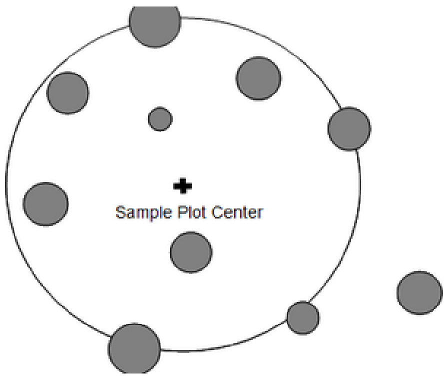


Figure 4 *- Representation of a circular fixed area plot. Grey circles represent shade trees (Klein, 2007)*

Assessment of the level of shade

The crown area of each individual tree was estimated using the average crown diameter. The average crown diameter was obtained by averaging the crown length and crown width (Fig. 5). The total canopy cover within the plot was expressed as a percentage of land coverage.

In the shaded plots the distance between each shade tree and the center of the plot was calculated. Along with the crown area estimation it was possible to create a rough shade tree map of each plot (Fig. 5). The rough map of all plots can be found in the Appendix I.

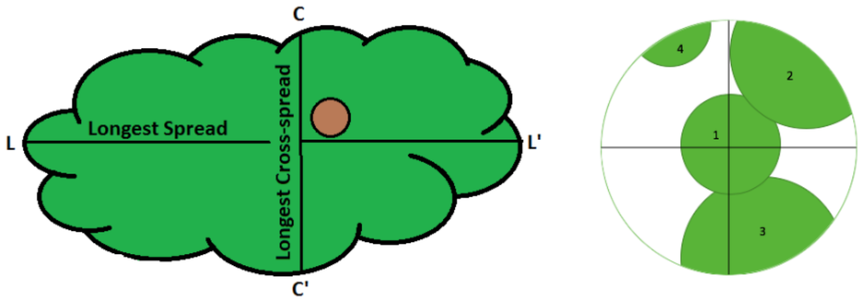


Figure 5 *– (Left): Representation of crown spread measurements (Wikiwand, n.d.). (Right): Example of a plot map representation where each green circle represents a tree crown and the numbers reflect the relative distance to the center.*

ImageJ was used to measure the percentage of shade cover in each plot based on the visual cues exemplified in figure 5. However, since the visual cues are only rough estimates, the calculated percentages were rounded to the closest multiple of 10. The resulting 18 plots ranged from 0% to 90% coverage, including plots with no shade.

The local names of all shade trees found in the plots were registered and can be found in the Appendix II.

Pod count

Pod counts were done for 4 weeks. Each plot was visited once per week and measured once per day. Overall, this resulted in a total of 4 measurements per plot.

Pods were categorized into two labels, "mature" or "cherelle" (Fig. 1). The number of wilted cherelles was also counted every week.

All the measurements involving cocoa pods were done by default under 250 cm from the base of the tree. This was done to increase reliability on the counts since tall and dense canopies can hide pods leading to higher variability.

Disease and pests

The disease and pest selected for this study were chosen from a list of cocoa pathogens based on their occurrence in Ghana (Dormon et. al. 2004). These were black pod, and mirids.

Along with the total pod count, each week the number of pods with black pod and mirid damage was counted for each individual tree. Also, pods with symptoms were differentiated as mature pods or cherelles.

Both incidence and level of infection (per tree) of each disease/pest were measured in each cocoa tree, on every plot. The assessments only include symptoms that were identifiable with the naked eye, on the surface of the pods.

The incidence of a disease or pest is represented as the percentage of trees that show any symptom of that particular disease/pest. So, the incidence is shown as:

$$Incidence = \frac{No.of\ trees\ with\ symptoms}{No.of\ trees} * 100\ \ (Per\ plot) \qquad \textbf{eqn.1}$$

The level of infection for a particular disease/pest in this scenario was estimated as the percentage of pods with symptoms, per tree. So, for each tree, the level of infection is calculated as:

$$Level\ of\ infection = \frac{No.of\ pods\ with\ symptoms}{Total\ no.of\ pods} * 100\ \ (Per\ tree) \qquad \textbf{eqn.2}$$

While incidence will reflect the presence of a disease/pest in a plot, the level of infection will represent the extent of damage or infection caused by that pest/disease in a tree. It might be that, in a plot, not many trees show signs of damage, but the affected trees have a great number of pods damaged by a disease/pest (for example). Thus, the combination of both analyses can be used to determine the best control strategies.

Black pod (aka *Phytophthora* pod rot) is easily identifiable through the appearance of dark brownish spots in cocoa pods, which can expand until the whole pod is infected and turns completely black (Fig. 6).

Finally, mirid damage can be observed directly in pods. The feeding habits of these insects causes small dark spots (Fig. 7) that can lead to infections by other pathogens, particularly fungi. The insect can sometimes be spotted in the trees (Fig. 7).

Figure 6 - *Symptoms of black pod disease in cocoa pods*

Figure 7 - *Mirid damage in cocoa pods (Left). Adult mirid (Right).*

Harvest

In either week 2 or 3 (depending on the farm) the farms were harvested, meaning all the ripe pods were removed from the trees (including dried mature pods). The total number of harvested pods was counted in each tree as was the number of viable pods. Here, viable pods are harvested pods whose seeds have not been damaged and can still be used in later stages of cocoa production (Fig. 8). In two of the farms, both shaded plots were harvested outside the research schedule, so harvested and viable pod counts are missing for four plots.

This study infers on productivity of individual trees based on pod counts alone. Yield measurements per plot would require two extra steps: fermenting and drying cocoa beans from the cocoa pods harvested in each plot. Both steps would take on average two weeks to finish in a setup that allowed the yields of each plot to be measured separately. For this reason, it was not possible to calculate yield within the timeframe of this study.

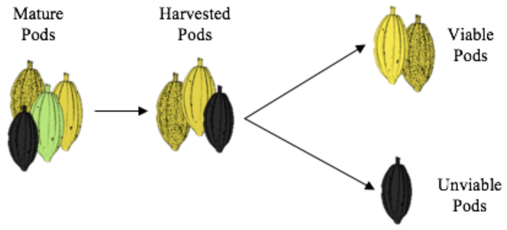


Figure 8 *- Representation of the harvest process in cocoa pods. Only ripe pods are harvested and counted, whereas unripe mature pods (in green) are left in the tree. All ripe pods including those with extensive disease and damage are harvested and the number of viable pods (in yellow) is counted. Pods whose seeds have been compromised (in black) are disregarded.*

2.4. Farmer interviews and additional data

For each farm sampled, only one farmer was queried about land use and management practices, such as input use, land use history and yields obtained in their farm. These farmers were also asked to describe their preferences for shade tree species and why. The survey was divided into 5 sections:

Section 1: Land use
Section 2: Management practices
Section 3: Disease and pest management
Section 4: Shade trees
Section 5: Income and cocoa yield

The questions were conducted together with a local translator. Only the most relevant answers were shown in the results. The detailed questions for the survey can be found in Appendix III.

2.5. Data analysis

The data collected in the field trials was analysed using linear mixed-effects models for each response variable. To reflect productivity, the number of harvested, viable and mature pods and the relative percentages were used as responses. To reflect disease/pest damage, responses included the percentage of pods with symptoms and the number of trees with at least one infected pod. The percentage of shade was included as a fixed effect in all models along with a random intercept per farm, and compared with a model that only included one intercept as fixed effect. Models with and without shade as a fixed effect were compared using AIC (Akaike's Information Criterion). If AIC differed more than 2 units between models, the model with the lowest AIC was considered a better fit to explain the data. Significance in the results refers to the AIC comparison. The respective AIC for each model can be found in Appendix V.

All responses that were measured more than once (pod counts and disease/pest damage counts) were tested using all four weeks of data. The same responses were tested using only one data point per tree, the one taken right before harvest. The results of both methods revealed similar conclusions. Therefore, the results shown in the following chapter only use one data point instead of four, in order to simplify the models.

Results of all mixed models mentioned in the following chapter included shade as a fixed factor and farm as a random effect.

All statistical analyses were performed in R statistical software (R Core Team, 2019); for mixed-effects models the “lme4” package was used (Bates et al., 2015).

In order to test differences between cherelles and mature pods (in number of pods and percentage of disease/pest damage), pairwise comparisons between pod counts in the same tree (e.g. no. of mature pods and no. of cherelles) were done across all trees using the Wilcoxon ranked sum test (Hollander & Wolfe, 1973). A p-value of less than 0,05 was accepted as proof of significant differences between the groups.

The marginal and conditional R_2 were calculated for the full models using the MuMIn package (Bartoń, 2019). The marginal and conditional R_2 are pseudo-R_2 values for mixed-effects models where the marginal R_2 represents the variance explained by the fixed effects and the conditional R_2 represents the variance explained by the full model.

The script used for the statistical analysis in R can be found in Appendix IV.

3. Results

3.1. Farm characterization

One farmer responsible for each of the cocoa farms evaluated in this study participated in the survey described above. The results revealed that the first trees in all farms were planted 10 to 15 years before the interviews took place. The main differences are compiled in the tables below.

Most of the farms were secondary forests before the first cocoa trees were planted. The sizes of the farms were comparable. The main differences were found in the amount of pesticides used. Farmer number 4 reportedly sprayed much more insecticide in his farm than farmer number 5 while farmer number 2 reported the highest amount of fungicide use, in the previous season (Table 2).

Table 2 *- Most relevant properties and management practices of each cocoa farm assessed in this project. Numbers 1 - 6 refer to each of those farms in no particular order.*

Farm	*1*	*2*	*3*	*4*	*5*	*6*
Size (ha)	1,6	1,6	1,6	2,2	2,4	2,8
Previous land use	Secondary Forest	Open field	Secondary Forest	Secondary Forest	Secondary Forest	Secondary Forest
Use of Chemical Fertilizer	yes	no	yes	yes	yes	no
Insecticide use (l/year)	12	18	12	32	9	24
Fungicide use (Kg/year)	2	9	2,5	2	1,4	3

Farms 3, 4 and 6 have increased their yields over time while farm 5 shows a decrease in yield. Overall farms 1, 2 and 3 seem to have much higher yields per hectare than the other 3 farms. Still, this does not constitute proof of the actual number of harvested bags, since these numbers were only reported by the farmers (Table 3).

Table 3 *- Farm yields of cocoa (in Kg/hectare/year) for each farm from the beginning of the 2015 harvest season to the end of the 2018 harvest season. Yields were calculated using the number of bags of cocoa beans harvested and sold in each year and the capacity of each bag (64 Kg). This information was obtained in the interviews and all bags were assumed to be filled to maximum capacity.*

Farm	1	2	3	4	5	6
2015/16	1600	1600	1200	291	800	687
2016/17	2000	1400	1588	349	667	823
2017/18	2000	1400	2000	465	587	914

Farm 5 has the lowest percentage of cocoa trees affected by black pod and/or mirid damage, despite reporting the lowest amount of insecticide and fungicide use (Table 2).

On average, more than 50% of the sampled cocoa trees in all farms had either black pod or mirid damage (or both) in at least one of their cocoa pods (Fig. 9).

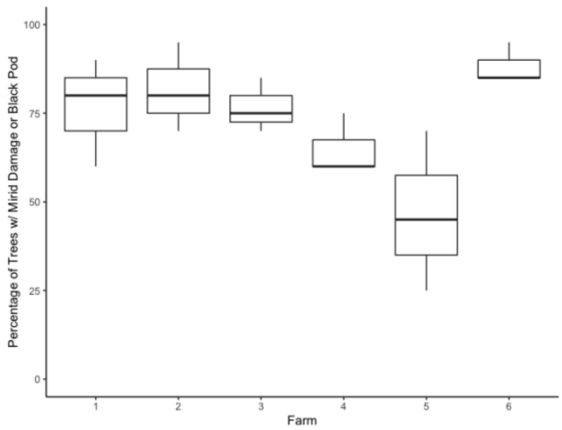


Figure 9 *– Percentage of cocoa trees with at least one pod showing symptoms of black pod or mirid damage, per farm. The numbers in the x-axis refer to the 6 farms assessed in this project, in the same order given in the tables above.*

3.2. Effects of shade

All responses were tested as both linear and quadratic models (see data analysis). However, none of the quadratic models provided a better fit to the data so all the graphs show a linear fitted line.

Effect of shade on cocoa tree productivity

To test productivity responses to shade, the analyses focused on the number of harvested and viable pods and the total number of mature pods in the trees. The effect of shade on the number of cherelles in the trees was also assessed, but it was not significantly affected by shade.

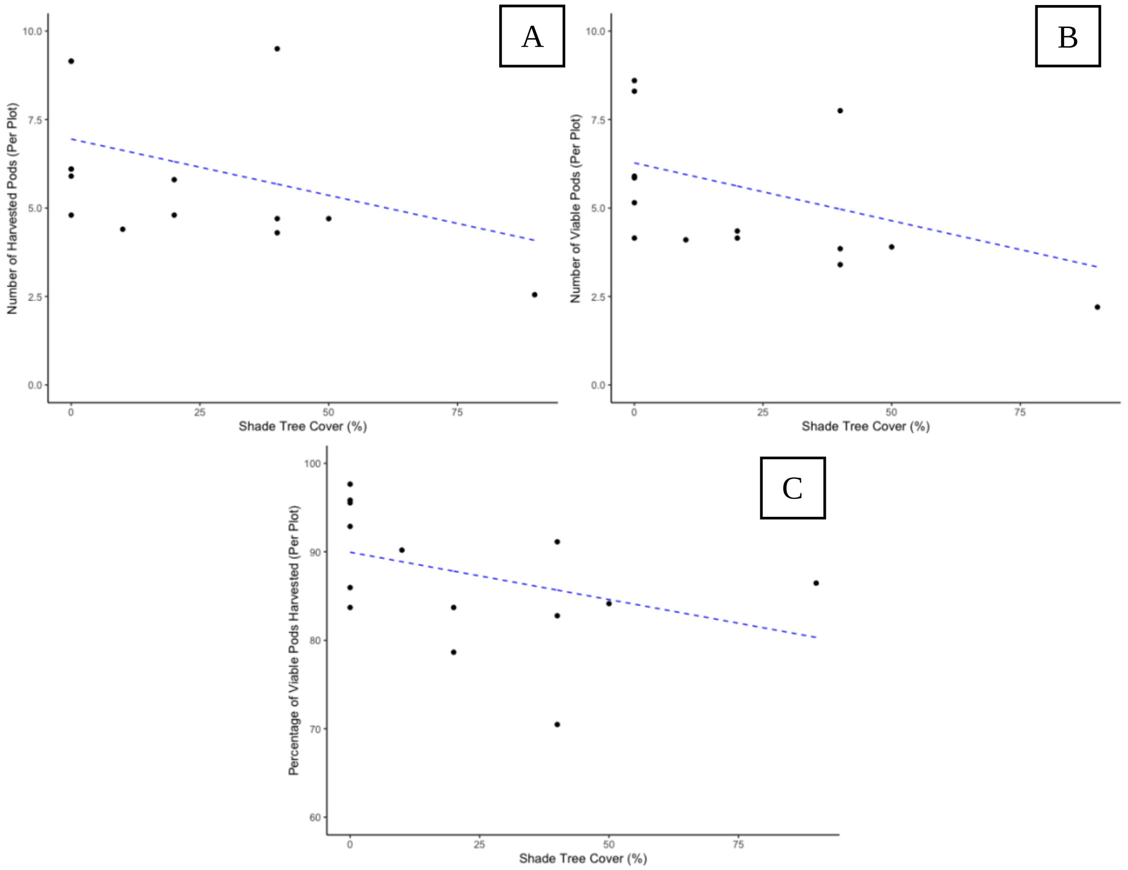


Figure 10 *– Plotted effect of percentage of shade tree cover over the number of harvested pods (A), viable pods (B) and the percentage of harvested pods that were viable (C), per tree, in 6 Western Ghanaian farms. Here, harvested (and viable) cocoa pod counts were collected from the entire tree. The black dots represent the average response of 20 trees for plots under varying shade tree cover. Although each farm had 3 plots, only 14 were used in these analyses due to missing values of harvest counts. The blue lines represent a fitted linear model plotting the predictions of the responses against shade cover. Predictions were obtained from mixed-effects models of each response, with shade as a fixed effect and farm as a random effect. Dashed lines reflect a non-significant effect of shade.*

Despite the apparent negative trend, the mixed model analyses did not reveal a significant effect of shade in the number of harvested pods or viable pods (Fig. 10-A/B). The percentage of harvested pods that were viable was also not significantly affected by shade (Fig. 10-C). The average percentage of viable pods is around 80-90% across all shade levels, which means that only about 10-20% of harvested pods were lost in the last phase of cocoa pod development, due to extensive disease and pest damage.

Not all mature pods were harvested at the same time. The number of mature pods in the trees right before harvest is also a reflection of the performance of a tree. To account for the differences between mature pods and ripe pods, the percentage of mature pods that were ripe at the moment of harvest was also tested and plotted against shade (Fig. 11).

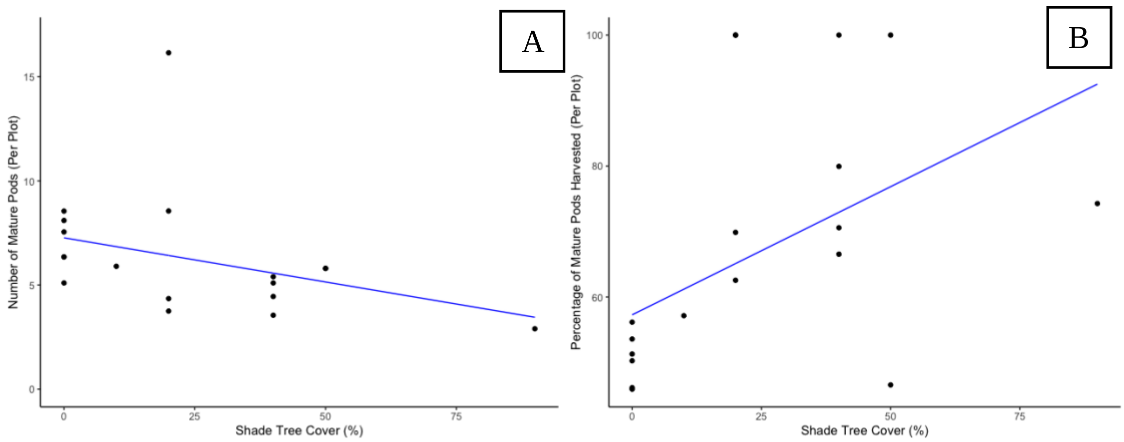


Figure 11 *– Plotted effect of percentage of shade tree cover over the number of mature pods before harvest (A) and the percentage of mature pods harvested (B), per tree, in 6 Western Ghanaian farms. Mature cocoa pods were only counted up to 250 cm on each tree. To calculate the percentage of mature pods harvested the number of pods harvested under 250 cm was used instead of the number of harvested pods on the entire tree. The black dots represent the average response of 20 trees for plots under varying shade tree cover. Although each farm had 3 plots, only 14 were used in the analysis of the percentage of mature pods harvested due to missing values of harvest counts. On the other hand, the analysis on the number of mature pods includes data from all 18 plots. The blue lines represent a fitted linear model plotting the predictions of the responses against shade cover. Predictions were obtained from mixed-effects models of each response, with shade as a fixed effect and farm as a random effect. Solid lines reflect significant effect of shade.*

There is a significant effect of shade on both the number of mature pods and the percentage of mature pods harvested at different shade levels. The number of mature pods tended to decrease with higher shade level (Fig. 11-A). The percentage of harvested pods, in contrast to the number of harvested pods, significantly increased with shade (Fig. 11-B), meaning that a bigger proportion of the mature pods was harvested in plots under higher shade levels.

Effect of shade on disease and pest damage

Level of infection

Black pod

In each tree, the number of pods with black pod infections was divided by the total number of pods to calculate the level of infection per tree. This was done separately for cherelles and mature pods. These percentages were tested and plotted against shade (Fig. 12).

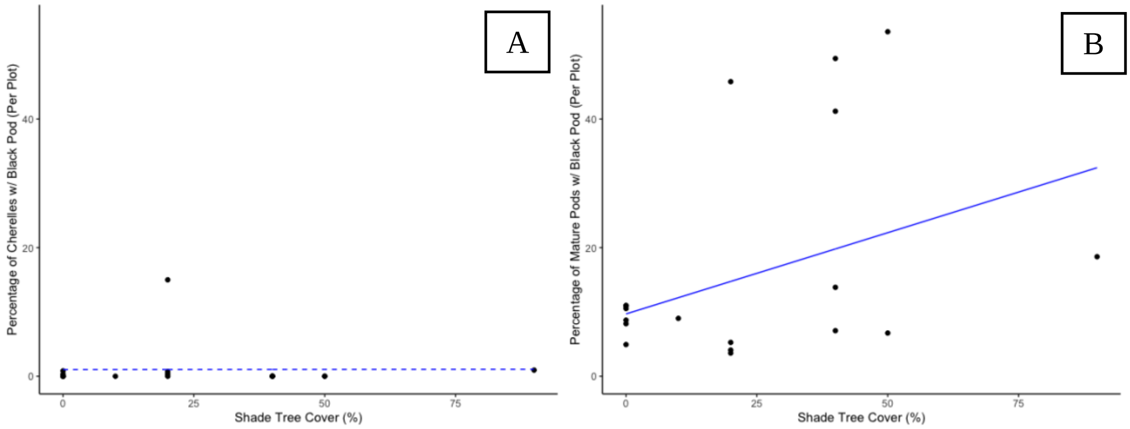


Figure 12 *- Plotted effect of percentage of shade tree cover over the percentage of cherelles (A) and mature pods (B) with black pod infections, per tree, in 6 Western Ghanaian farms. The number of pods with black pod was only counted under 250 cm on each tree. The black dots represent the average response of 20 trees for 18 plots under varying shade tree cover. The blue lines represent a fitted linear model plotting the predictions of the responses against shade cover. Predictions were obtained from mixed-effects models of each response, with shade as a fixed effect and farm as a random effect. Solid lines reflect significant effect of shade while dashed lines reflect non-significance.*

While shade has no significant effect on the percentage of cherelles with black pod per tree, there is a significant increase in the percentage of mature pods with black pod under higher shade cover (Fig.12). There is also a significant difference between the percentage of cherelles and mature pods with black pod (*p-value* << 0.05). The pairwise comparisons across all cocoa trees reveal a higher percentage of black pod in mature pods than in cherelles.

Mirids

In each tree, the number of pods with mirid damage was divided by the total number of pods to calculate the level of damage by mirids per tree. This was done separately for cherelles and mature pods. These fractions where tested and plotted against shade (Fig. 13).

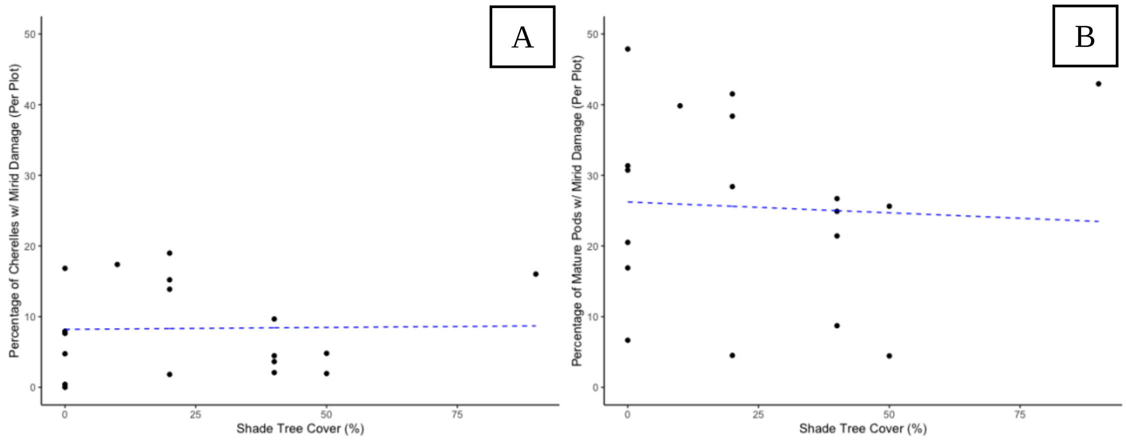


Figure 13 - Plotted effect of percentage of shade tree cover over the percentage of cherelles (A) and mature pods (B) with mirid damage, per tree, in 6 Western Ghanaian farms. The number of pods with black pod was only counted under 250 cm on each tree. The black dots represent the average response of 20 trees for 18 plots under varying shade tree cover. The blue lines represent a fitted linear model plotting the predictions of the responses against shade cover. Predictions were obtained from mixed-effects models of each response, with shade as a fixed effect and farm as a random effect. Dashed lines reflect a non-significant shade effect.

Shade did not significantly affect the percentage of pods with mirid damage in mature pods nor in cherelles. Also, as observed with black pod, the percentage of mirid damage is higher in mature pods than in cherelles (*p-value* << 0.05), across all cocoa trees.

Incidence

While the number of infected pods in a tree reflects the level of infection, the number of infected trees in a plot reflects the incidence of a pest/disease in that plot. The average percentage of trees with black pod infections in at least one cocoa pod were plotted against shade (Fig.14-A). The same was done for the percentage of trees with mirid damage (Fig.14-B).

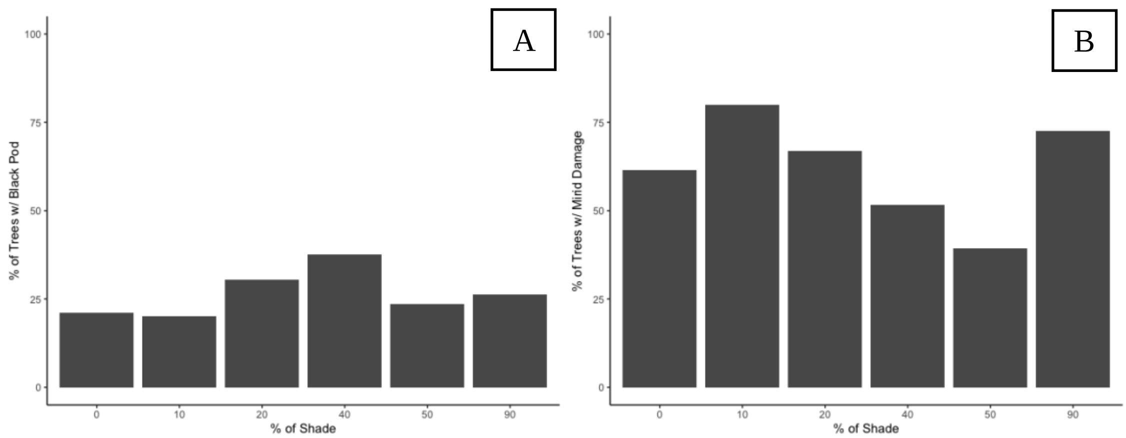


Figure 14 – Bar plots of the effect of percentage of shade tree cover over the incidence of black pod (A) and mirids (B), per plot, in 6 Western Ghanaian farms. Each bar represents the average percentage of infected trees out of all plots with similar shade cover. Results were based on mixed-effects models, with shade as a fixed factor and farm as a random effect.

Despite the apparent fluctuations, there was no significant difference between shade levels regarding the incidence of black pod and mirid damage.

3.3. Explained variation

The models used to test the responses to shade considered differences between farms as random effects. The marginal and conditional R_2 where calculated for each model to illustrate the variance explained by shade alone (marginal R_2) and by the full models (conditional R_2) (Bartoń, 2019), thus including fixed and random effects (Table 4).

Table 4 *– R_2 for mixed models using R_{2GLMM} (Nakagawa & Schielzeth, 2013). All responses were modeled with percentage of shade cover as a fixed effect and farm as a random effect. The responses include: Number of viable pods; Number of harvested pods; Percentage of mature pods and cherelles with black pod; Percentage of mature pods and cherelles with mirid damage, per tree, across 18 cocoa plots with varying shade cover, in Western Ghana. Marginal and conditional R_2 are represented by $R_{2GLMM(m)}$ and $R_{2GLMM(c)}$ respectively. Marginal R_2 represents the variance explained by the fixed effects and the conditional R_2 represents the variance explained by the full model.*

Response	Viable Pods	Harvested Pods	Black Pod		Mirid Damage	
			Mature	Cherelles	Mature	Cherelles
$R_{2GLMM(m)}$	3.2%	2.3 %	5.3%	~ 0%	0.1%	~ 0%
$R_{2GLMM(c)}$	13.1%	9.7 %	12.2%	5.5%	13.5%	5.3%

Results suggest that differences between farms explain more variance than the different shade levels (Table 4). The R_2 values also differed between the percentage of disease/pest damage per tree in cherelles and in mature pods, suggesting that in general the models explain more variance in disease/pest damage in mature pods than in cherelles.

3.4. Shade tree preferences

Out of the six farmers interviewed, four reported that products obtained from shade trees in their farms contribute to some extent to their income (Table 5). Even more so, only one of the farmers reported not using any products from shade trees at all and only because of the young age of his shade trees. In five out of the six farms shade trees proved to be useful in ways other than providing shade.

Table 5 *- Farmer's perception of the importance of shade tree products to the economy of their household in Asankragua, Western Ghana. The scale ranges from 0 – 5 where 0 would mean "No economic value" and 5 would mean "Great economic value". The six farmers interviewed are listed from 1 to 6 in no particular order.*

Farmer	*Economic value of shade tree products*
1	4
2	3
3	1
4	0
5	2
6	0

The main potential products of shade trees reported by the farmers included timber and its by-products, fruits and other organs with medicinal use. Additionally, *Newbouldia laevis* was desired for its support in yam plantation.

Farmers were asked to mention their desired species of shade trees and a few reasons why they appreciate them (Table 6).

Table 6 *- List of desired shade tree species mentioned by the six farmers interviewed in Asankragua, Western Ghana. The table includes the number of farmers who mentioned a tree species and the reasons behind their choice.*

Scientific Name	**Local Name**	**Frequency**	**Reason(s)**
Terminalia ivorensis	Emere	4	Useful Products Shade
Khaya ivorensis	Mahogany	3	Useful Products Improved cocoa productivity Medicinal use
Terminalia superba	Ofram	3	Useful Products Improved cocoa productivity

Newbouldia laevis	Susumasa	2	Medicinal use Yam plantation
Persea americana	Pear	1	Useful Products
Triplochiton scleroxylon	Wawa	1	Useful Products
Cola spp.	Cola Tree	1	Useful Products

Two *Terminalia* species and *K. ivorensis* were commonly referred by farmers due to the usefulness of their products and benefits to cocoa production. The least common species were only mentioned due to the usefulness of their products to the farmer. Farmers did not mention which products were obtained by each species but it was implied that they were either timber or fruit trees.

The same six farmers were asked to list the least desirable shade tree species for their farms and explain why (Table 7).

Table 7 *- List of undesired shade tree species mentioned by the six farmers interviewed in Asankragua, Western Ghana. The table includes the number of farmers who mentioned a tree and the reasons behind their choice.*

Scientific Name	**Local Name**	**Frequency**	**Reason(s)**
Triplochiton scleroxylon	Wawa	3	Soil level competition for water and nutrients Deteriorated cocoa productivity
-	Nyankere	3	Products are not useful Soil level competition for water
-	Oteye	2	Products are not useful Deteriorated cocoa productivity
Cola spp.	Cola Tree	2	Soil level competition for water Increased pest/disease incidence
Rauwolfia vomitoria	Kakapenpen	1	Products are not useful

Milicia excelsa	Odum	1	Increased pest/disease incidence

This time, competition for water with cocoa trees was the most common reason for considering a tree as undesirable. Other reasons leading to the farmers' choices were deteriorated cocoa productivity, higher disease/pest incidence and useless products. Additionally, *Cola spp.* and *T. scleroxylon* were mentioned as desirable and undesirable trees by different farmers.

4. Discussion

This research aimed to evaluate the effect of shade tree cover on disease/pest damage and productivity in cocoa farms in Asankragua, Western Ghana. Additionally, the study described the local farmers' preferences and disfavours regarding shade tree species. The first two research questions related shade with pod counts to assess productivity and disease/pest damage. Results did show a significant negative effect of shade in the number of mature pods in cocoa trees and a positive effect of shade on the percentage of harvested pods per tree. Also, under higher shade a higher percentage of mature pods had black pod. Contrastingly, the number of harvested and viable pods, the percentage of cherelles with black pod and the percentage of pods with mirid damage were not significantly affected by shade. Research question number three aimed to clarify the farmers' motivations for growing shade trees in their farms and their perception of the impact of shading on cocoa trees. The results showed that most farmers had preferences and were aware of some of the benefits and disadvantages of the species listed. The fact that some species were both listed as desirable and undesirable shows that perceptions can vary among farmers.

Relationship between productivity of cocoa trees and shade

The number of pods harvested and viable in each plot was not significantly affected by shade. Nevertheless, the plots (Fig.10) suggest that there is a negative trend in the number of harvested and viable pods caused by shade. Zuidema et al. (2005) suggest that cocoa bean yield is not substantially affected by shade under moderate shade cover, but above 60% shade cover it decreases significantly. The plots in figure 7 suggest a similar trend, since the average number of harvested and viable pods under 90% shade tree cover appear to be lower than in other plots. However, since there is only one plot with more than 60% shade cover this correlation may not be strong enough to be observed in this study.

On the other hand, the number of mature pods just before harvest was lower under higher shade levels while the percentage of mature pods that were ripe during harvest increased. Since the number of harvested pods is unaffected by shade, the results suggest that the number of harvested pods was independent from the number of mature pods, i.e. the same number of ripe pods was found in the trees regardless of the total number of mature pods. A logical explanation would be that pods develop faster under higher shade levels and therefore ripen faster. However, there is no evidence that light affects the development rate of fruits, which is accelerated by higher temperature and hormonal cues (Zuidema et al., 2005). Note, however, that ripening takes between 20-30 days to complete (Niemenak et al., 2010). So, the harvested pods were not all equally ripe by the time they were harvested. It is possible that the variability found in harvest counts is related to the different ripening of the harvested pods. Additionally, harvest data was collected from one single harvest, meaning that these observations represent a snapshot of the productivity of trees at one point in time. Therefore, the results may not be representative of the whole harvest period, where harvest can take place every month, sometimes more than once. One single harvest might show too much variability to reflect an effect of shade.

Regarding the percentage of viable pods, it was found that on average 80-90% of harvested pods were still viable. Conversely, the percentage of lost pods (inverse of the percentage of viable pods) is a reflection of losses to disease and pests at the harvest stage. So, 10-20% of harvested pods were lost to disease or pest damage in the last stage of cocoa development. Blaser et al. (2018) fitted disease incidence under different shade covers with a quadratic function and their results suggest that if shade cover was kept between 30-40%, losses to disease would be minimal. This result was not observed in this study. Nevertheless, the average number of mature pods across all trees is 4.9 while the average number of cherelles, including wilted cherelles was 17.6. Therefore, the main losses happened before maturity, as expected (Niemenak et al., 2010; Soh et al., 2013; Babin et al., 2012, Bos et al., 2007), showing that most of the productivity losses are likely caused by cherelle wilt.

In this report productivity is a measure of individual tree performance in fruit production and not of farm performance. Differences between farms and management practices will determine productivity on the whole farm (Wiredu & Mensah-bonsu, 2011). Within the same farm it was assumed that the same inputs were distributed equally across the farm, therefore the main differences between plots would likely be caused by either tree density and interactions between trees or inherent characteristics of individual cocoa trees, such as age, size and canopy openness (Hui et al., 2012).

Relationship between disease incidence and pest damage and shade

The second research question focused on the distributions of black pod and mirids under different shade levels, which was represented by the percentage of trees/pods with a disease/pest damage. Not to be confused with the impact of disease/pests on productivity, which was represented by the percentage of harvested pods that were viable.

There was a significant effect of shade on the percentage of mature pods with black pod. The percentage increased with higher shade levels. Schroth et al. (2000) highlight the higher incidence of black pod with high humidity and low aeration which can explain the results found in this study as well. Note that while the level of infection increased, the incidence of black pod was not affected by shade. This means that the disease spreads more efficiently in a tree under higher shade level, but the dispersal of the oomycete between trees is not affected by the level of shade. Ndoumbe-Nkeng et al. (2004) suggest that removal of diseased pods can be an effective additional control for black pod. Therefore, by removing pods infected with black pod from infected trees and by pruning cocoa trees under higher shade, it is likely that the level of infection of black pod under higher shade levels can be reduced.

Contrary to expectations, there was no significant effect of shade on mirid damage in cocoa pods. Babin et al. (2010) found that mirids cause more damage under lower shade cover, which was not observed in this study. Note that despite the different shade levels found in the three plots per farm, the whole farm had random patterns of shade tree distribution. It is possible that the influence of shade on mirid damage is not observed in individual plots because the proximity of the plots allows mirids to affect the whole farm in a similar way.

In general, it is also possible that the actual level of infection by black pod and mirids was underestimated due to differential infection levels throughout the cocoa tree, from base to canopy (Adu-Acheampong et al., 2014, Opoku et al., 2007, Tondje et al., 2007).

In cherelles, the observed black pod and mirid damage was lower than in mature pods. Soh et al. (2013) suggest that cherelles are more susceptible to black pod than pods in later developmental stages. The same pattern has been described for mirids (Babin et al., 2012; Mahob et al., 2018). The number of cherelles with black pod and mirid damage were therefore expected to be higher than observed in this study. However, note that immature pods were categorized as cherelles or wilted cherelles, while mature pods where all categorized in one single group. It is likely that the actual number of cherelles with black pod or mirid damage was higher than the number recorded if the damage had already caused cherelles to wilt. Unfortunately, it was not possible to determine the cause of wilt without tracking individual pods from an early development stage. This may have resulted in an underestimation of the effect of disease and pests in cherelles.

Note that despite the differences in the amount of pesticides used in the farms, the time of the last application might also affect the disease/pest patterns. A farmer might spray the farm less often during the year, but he may have sprayed it closest to the date of the pod counts. Also, the amounts and frequency of application of fungicide and pesticide might vary from season to season. The variation can be explained by higher or lower incidence and damage caused by diseases and pests.

Farmer preferences for shade tree species

The result of the semi-structured surveys revealed that most farmers were aware of benefits and problems associated with some shade tree species.

T. ivorensis and T. superba are a known source of timber and firewood (Dumont et al., 2014). These species are also considered to be favourable shade trees for cocoa plantations due to high quality of shade and soil fertility improvement as well as improvement of soil moisture in the case of *T. superba* (Dumont et al., 2014). *Khaya ivorensis*, commonly known as African mahogany is mostly known for its high-quality wood. However, it has also been shown that its bark has medicinal value and that the tree can be used for enrichment planting, meaning it can enrich the soil for other crops to grow (Agbedahunsi et al., 2004). Both *Terminalia* species and *K. ivorensis* are good sources of timber, which can be used by the farmers and sold for additional revenue. Obiri et al. (2007) suggest that shaded cocoa plantations might still be profitable despite competition with full-sun tolerant varieties, assuming some of the revenue comes from timber trees. Therefore, analyses of profitability of shaded cocoa farms should consider the additional sources of income from shade tree products. In fact, growing cocoa under shaded conditions is expected to provide more stability in spite of cocoa yield and cocoa price variations (Obiri et al., 2007; Duguma et al., 2001).

The bark of *Newbouldia laevis* has been shown to have medicinal properties (Idu & Onyibe, 2007). Additionally, it is used as support for the growth of the shoot system of yam (genus *Dioscorea*). The reason why these trees are particularly useful in yam plantations is not clear. *P. Americana* is an exotic species in Ghana, but it was relatively common to find in the farms in study. The tree provides avocados for consumption and possibly to sell, and there are reports of its medicinal use (Dumont et al., 2014). As with other shade tree species, products that are not sold can still be used by the farmers, further increasing their livelihood's security. That would explain why products obtained from shade trees seem to be a determining factor in farmer's preferences.

Most of farmers interviewed were aware of benefits and problems associated with some shade tree species. However, some of those benefits and problems where not backed up by literature. Farmers reported that *Cola spp. and M. excelsa* can increase the incidence of some pests and diseases. While this has been reported in some *Cola* species (Asare, 2015), evidence was not found to support the claim that *M. excelsa* increases pest/disease incidence. In both *K. ivorensis* and the *Terminalia* species, the exact way in which these species "improve cocoa production" was not explored in this study. Additionally, the local names of two undesirable species were not described in literature, therefore the scientific names were not found. Researchers should then use farmer insight as a baseline for the study of shade tree and cocoa tree compatibility, in order to fill the gaps that exist in literature.

Depending on the farmer, *T. scleroxylon* and *C. nitida* were considered desirable and undesirable species. It shows that farmers may have different perspectives on shade trees. For some farmers, products obtained from *T. scleroxylon* and *C. nitida* may offset any negative impact or they are not aware of negative impacts. Others are aware or may be suffering from negative impacts of either of these trees. Therefore, relevant programmes should evaluate the benefits of a shade tree to the whole farm and not just to cocoa trees, in order to create recommendations of compatible shade trees for cocoa farms.

Considerations for future research

The previous results were drawn out of only 6 farms. It is possible that strong effects of shade were not found due to the small number of farms sampled. Farm differences seem to explain more variance than shade, as suggested in table 4. However, the number of farms sampled was too low to compare farm differences. The original design for the data collection included at least 10 cocoa farms. Due to an early harvest this year it was not possible to find enough farms in the area around Asankragua that met the requirements for this study. So, the first suggestion for future research is to increase the number of sampled farms.

With interviews, the subjective interpretation of the questions may have led to contradicting answers. This, along with the small number of farmers interviewed compromised the potential comparisons between farms. Note however that this report did not aim to compare the different farms in the first place. However, in social studies it is more effective to have more open questions in order to make sure the questions are understood by farmers and that the answers are correctly interpreted.

Cocoa production will likely vary between different agroecological regions due to different disease and pests' distributions, water and light availability, humidity and soil conditions. Across Ghana there are very different agroecological regions, varying in terms of soil characteristics, landform and climatic conditions. These differences will also influence biodiversity and crop performance. In this research, data was retrieved from the same local community, in order to minimise potential differences in climate, land and vegetation type. As such, these factors were not variable enough to safely extrapolate this data to other cocoa growing regions. To describe the whole cocoa growing region of Ghana, other distinct agroecological regions should be evaluated and recommendations should be site specific.

In this study, shade cover calculations were done by hand, based on manual estimations of canopy cover. Using hemispherical canopy photography or similar technology would help to get more accurate estimates of shade tree cover in a plot. Also, in this study shade cover was used as a proxy for light availability. Yet, in reality, it is likely that different levels of canopy openness and overlap between shade trees will also affect the light availability in a plot (Montgomery & Chazdon, 2001). For practical reasons, this was not done during the field trials. It is possible that strong effects of shade have been masked by the method used to estimate shade in this study, since all plots were rounded to the nearest multiple of 10.

Regarding pod counts, cherelles were all classified under the same category, disregarding the intermediate development stages. Niemenak et al. (2010) differentiated two more phases in the early stages of cocoa development. Soh et al (2013) suggested that cherelles are the most affected by black pod, but in their work they included two more development stages above cherelles (young and adult). Therefore, a better description of the development stages should be taken into account in future research.

Farmers noted a higher occurrence of black pod this year due to higher rainfall than previous years before the dry season (Fig. 3). There is not enough evidence to support the farmers' claim that black pod occurred more frequently in cocoa pods this year compared to previous years. However, Codjoe et al. (2013) suggested that climate change could alter rates of development of cocoa pests and diseases and influence host-pest/disease interaction. Therefore, the effect of climate change on disease/pest patterns should be considered in future research.

5. Conclusions

It was hypothesized that a shade cover around 30% would increase productivity, which was not observed in this study. Shade tree cover was not found to have an effect on the number of harvested pods, despite the decreased number of mature pods found in trees under higher shade covers. Pests and disease caused on average close to 15% losses on harvested pods, but the percentage of lost pods was also not affected by shade. It is then concluded that disease and pests will likely lead to more losses in earlier stages of fruit development, associated with cherelle wilt. These results support the stakeholders invested in promoting agroforestry systems, since increased shade cover did not compromise the number of harvested pods nor did it increase the losses to pest and disease at the harvest stage. However, the results used only one single harvest and the number of harvested pods does not reflect the yield (in Kg/ha) of cocoa beans obtained.

Another hypothesis suggested that higher shade could decrease mirid damage and increase black pod infections. Shade significantly increased the percentage of mature pods with black pod infections, but the incidence of black pod was unaffected by shade, suggesting that correct pruning under high shade and infected pod removal can decrease the effects of high shade. On the other hand, there was no observed link between mirid damage and shade. In cherelles, no relationship was found between shade and disease/pests. The incidence of either black pod or mirid damage in plots was also not affected by shade. To draw conclusions on agroforestry for disease/pest control, further disease and pest assessments should focus on young pods and defining the stages of fruit development more thoroughly. Additionally, further research on disease and pest impact on cocoa production should take into account climate change scenarios in order to predict potential behaviour modifications of pathogens and pests.

Finally, it was hypothesized that farmers will favour trees that provide them the most services rather than only favouring cocoa production. While the number of farmers surveyed was too small to draw significant conclusions, farmers did have preferences for shade trees and stressed the importance of some of these trees' services on cocoa trees and in their own lives. This supports stakeholders promoting agroforestry, since farmers were increasing their net profits and food security by using shade tree products. It is suggested that recommendations on shade tree species should include a thorough analysis of the economical relevance of these species to farmers in order to determine the best strategies to improve agroforestry systems in cocoa farms in Ghana.

Overall the results of this research do not provide any strong evidence against the potential of shaded systems, since there was no effect of shade on productivity and farmers were making use of shade tree services. Future research in this topic should focus on explaining and reducing losses in early stages of cocoa pod development.

6. References

Abdulai, I., Vaast, P., Hoffmann, M. P., Asare, R., Jassogne, L., Van Asten, P., … Graefe, S. (2018). Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Global Change Biology*, *24*(1), 273–286. https://doi.org/10.1111/gcb.13885

Abenyega, O., & Gockowski, J. (2001). *Labor practices in the cocoa sector of Ghana with a special focus on the role of children: Findings from a 2001 survey of cocoa producing households*. 1–42.

Acebo-Guerrero, Y., Hernández-Rodriguez, A., Heydrich-Pérez, M., El Jaziri, M., & Hernandez-Lauzardo, A. N. (2012). Management of black pod rot in cacao (Theobroma cacao L.): A review. *Fruits*, *67*(1), 41–48. https://doi.org/10.1051/fruits/2011065

Adu-Acheampong, R., Jiggins, J., Van Huis, A., Cudjoe, A. R., Johnson, V., Sakyi-Dawson, O., … Quarshie, E. T. N. (2014). The cocoa mirid (Hemiptera: Miridae) problem: Evidence to support new recommendations on the timing of insecticide application on cocoa in Ghana. *International Journal of Tropical Insect Science*, *34*(1), 58–71. https://doi.org/10.1017/S1742758413000441

Agbedahunsi, J. M., Fakoya, F. A., & Adesanya, S. A. (2004). Studies on the anti-inflammatory and toxic effects of the stem bark of Khaya ivorensis (Meliaceae) on rats. *Phytomedicine*, *11*(6), 504–508. https://doi.org/10.1016/j.phymed.2003.07.009

Ameyaw, G. A., Dzahini-Obiatey, H. K., & Domfeh, O. (2014). Perspectives on cocoa swollen shoot virus disease (CSSVD) management in Ghana. *Crop Protection*, *65*, 64–70. https://doi.org/10.1016/j.cropro.2014.07.001

Amadu, F. O., Miller, D. C., & McNamara, P. E. (2020). Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics*, *167*(August 2019), 106443. https://doi.org/10.1016/j.ecolecon.2019.106443

Anglaaere, L. C. N., Cobbina, J., Sinclair, F. L., & McDonald, M. A. (2011). The effect of land use systems on tree diversity: Farmer preference and species composition of cocoa-based agroecosystems in Ghana. *Agroforestry Systems*, *81*(3), 249–265. https://doi.org/10.1007/s10457-010-9366-z

Asare, R. (2005). Cocoa agroforests in West Africa: a look at activities on preferred trees in the farming systems. In *Forest & Landscape Working Papers no. 6*. Retrieved from about:blank

Babin, R., Ten Hoopen, G. M., Cilas, C., Enjalric, F., Yede, Gendre, P., & Lumaret, J. P. (2010). Impact of shade on the spatial distribution of Sahlbergella singularis in traditional cocoa agroforests. *Agricultural and Forest Entomology*, *12*(1), 69–79. https://doi.org/10.1111/j.1461-9563.2009.00453.x

Babin, R., Djieto-Lordon, C., Cilas, C., Dibog, L., Mahob, R., & Bilong, C. F. B. (2012). True Bug (Heteroptera) Impact on Cocoa Fruit Mortality and Productivity. *Journal of Economic Entomology*, *105*(4), 1285–1292. https://doi.org/10.1603/ec12022

Bailey, B. A., & Meinhardt, L. W. (2016). Cacao diseases: A history of old enemies and new encounters. *Cacao Diseases: A History of Old Enemies and New Encounters*, 443-499. https://doi.org/10.1007/978-3-319-24789-2

Bartoń, K. (2019). MuMIn: Multi-Model Inference. R package version 1.43.15. https://CRAN.R-project.org/package=MuMIn

Bates, D., Maechler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Blaser, W. J., Oppong, J., Yeboah, E., & Six, J. (2017). Shade trees have limited benefits for soil fertility in cocoa agroforests. *Agriculture, Ecosystems and Environment*, *243*(October 2016), 83–91. https://doi.org/10.1016/j.agee.2017.04.007

Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., & Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nature Sustainability*, *1*(5), 234–239. https://doi.org/10.1038/s41893-018-0062-8

Bos, M. M., Steffan-Dewenter, I., & Tscharntke, T. (2007). Shade tree management affects fruit abortion, insect pests and pathogens of cacao. *Agriculture, Ecosystems and Environment*, *120*(2–4), 201–205. https://doi.org/10.1016/j.agee.2006.09.004

Codjoe, F. N. Y., Ocansey, C. K., Boateng, D. O., & Ofori, J. (2013). Climate Change Awareness and Coping Strategies of Cocoa Farmers in Rural Ghana. *Journal of Biology, Agriculture and Healthcare*, *3*(11), 19–29.

Daghela Bisseleua, H. B., Fotio, D., Yede, Missoup, A. D., & Vidal, S. (2013). Shade Tree Diversity, Cocoa Pest Damage, Yield Compensating Inputs and Farmers' Net Returns in West Africa. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0056115

De Beenhouwer, M., Aerts, R., & Honnay, O. (2013). A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agriculture, Ecosystems and Environment*, *175*, 1–7. https://doi.org/10.1016/j.agee.2013.05.003

Dormon, E. N. A., Van Huis, A., Leeuwis, C., Obeng-Ofori, D., & Sakyi-Dawson, O. (2004). Causes of low productivity of cocoa in Ghana: Farmers' perspectives and insights from research and the socio-political establishment. *NJAS - Wageningen Journal of Life Sciences*, *52*(3–4), 237–259. https://doi.org/10.1016/S1573-5214(04)80016-2

Duguma, B., Gockowski, J., & Bakala, J. (2001). Smallholder cacao (Theobroma cacao Linn.) cultivation in agroforestry systems of West and Central africa: Challenges and opportunities. *Agroforestry Systems*, *51*(3), 177–188. https://doi.org/10.1023/A:1010747224249

Dumont, E. S., Gnahoua, G. M., Ohouo, L., Sinclair, F. L., & Vaast, P. (2014). Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. *Agroforestry Systems*, *88*(6), 1047–1066. https://doi.org/10.1007/s10457-014-9679-4

Evans, H.C. 1998. *Disease and Sustainability in the Cocoa Agroecosystem*. Paper presented at the First Sustainable Workshop on Sustainable Cocoa Growing, Panama City, Panama, March 30—April 2, 1998.

Fairtrade Foundation. (2016). Fairtrade and cocoa. *Commodity Briefing: Cocoa*, (April), 28.

Fountain, A., & Huetz-Adams, F. (2018). *Cocoa Barometer*. 1–72.

Graefe, S., Meyer-Sand, L. F., Chauvette, K., Abdulai, I., Jassogne, L., Vaast, P., & Asare, R. (2017). Evaluating Farmers' Knowledge of Shade Trees in Different Cocoa Agro-Ecological Zones in Ghana. *Human Ecology*, *45*(3), 321–332. https://doi.org/10.1007/s10745-017-9899-0

Harvey, C. A., Chacón, M., Donatti, C. I., Garen, E., Hannah, L., Andrade, A., … Wollenberg, E. (2014). Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conservation Letters*, *7*(2), 77–90. https://doi.org/10.1111/conl.12066

Hollander, M. & Wolfe D. A. (1973). *Nonparametric Statistical Methods*. New York: John Wiley & Sons. Pages 27–33 (one-sample), 68–75 (two-sample). Or second edition (1999).

Hui, D., Wang, J., Le, X., Shen, W., & Ren, H. (2012). Influences of biotic and abiotic factors on the relationship between tree productivity and biomass in China. *Forest Ecology and Management*, *264*, 72–80. https://doi.org/10.1016/j.foreco.2011.10.012

Idu, M. & Onyibe, H. I. (2007). Medicinal Plants of Edo State, Nigeria. *Research Journal of Medicinal Plants*, 1: 32-41.

International Cocoa Organization. (2015). *Annual Report International Cocoa Organization (ICCO) 2014/2015*. 76. Retrieved from https://www.icco.org/about-us/icco-annual-report.html

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, *76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Klein, C.H. (2007). Lecture Notes for the Teaching Module Forest Inventory. Institute of Forest Management, Faculty of Forest Sciences and Forest Ecology. Georg August Universität, DE, 164 p.

Krauss, J. (2017). What is cocoa sustainability? Mapping stakeholders' socio-economic, environmental, and commercial constellations of priorities. *Enterprise Development and Microfinance*, *28*(3), 228–249. https://doi.org/10.3362/1755-1986.17-000JK

Kolavalli, S., & Vigneri, M. (2018). *Growth through pricing policy: The case of cocoa in Ghana*. 1–6. Retrieved from http://www.fao.org/3/I8329EN/i8329en.pdf

Läderach, P., Martinez-Valle, A., Schroth, G., & Castro, N. (2013). Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic Change*, *119*(3–4), 841–854. https://doi.org/10.1007/s10584-013-0774-8

Laven, A., & Boomsma, M. (2012). Incentives for sustainable cocoa production in Ghana. *Royal Tropical Institute*, (May), 1–49.

Mahob, R. J., Etam, P. B. N., Dibog, L., Babin, R., Voula, A. V., Begoude, D., … Bilong, C. F. B. (2018). Assessment of the effect of cocoa mosquito mirid true bug, <i>Helopeltis</I. sp. (Hemiptera: Miridae) on the cocoa (*Theobroma cacao* L.) production in Cameroon (Central Africa). *International Journal of Biological and Chemical Sciences*, *12*(4), 1865. https://doi.org/10.4314/ijbcs.v12i4.27

Montgomery, R. A., & Chazdon, R. L. (2001). Forest Structure, Canopy Architecture, and Light Transmittance in Tropical Wet Forests. *Ecology*, *82*(10), 2707. https://doi.org/10.2307/2679955

Nair, P. K. R. (2007) Agroforestry for Sustainability of Lower-Input Land-Use Systems. *Journal of Crop Improvement*, 19:1-2, 25-47.

Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *172*(1), 10–23. https://doi.org/10.1002/jpln.200800030

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

Ndoumbe-Nkeng, M., Cilas, C., Nyemb, E., Nyasse, S., Bieysse, D., Flori, A., & Sache, I. (2004). Impact of removing diseased pods on cocoa black pod caused by Phytophthora megakarya and on cocoa production in Cameroon. *Crop Protection*, *23*(5), 415–424. https://doi.org/10.1016/j.cropro.2003.09.010

Niemenak, N., Cilas, C., Rohsius, C., Bleiholder, H., Meier, U., & Lieberei, R. (2010). Phenological growth stages of cacao plants (Theobroma sp.): Codification and description according to the BBCH scale. *Annals of Applied Biology*, *156*(1), 13–24. https://doi.org/10.1111/j.1744-7348.2009.00356.x

Obiri, B. D., Bright, G. A., McDonald, M. A., Anglaaere, L. C. N., & Cobbina, J. (2007). Financial analysis of shaded cocoa in Ghana. *Agroforestry Systems*, *71*(2), 139–149. https://doi.org/10.1007/s10457-007-9058-5

Opoku, I. Y., Akrofi, A. Y., & Appiah, A. A. (2007). Assessment of sanitation and fungicide application directed at cocoa tree trunks for the control of Phytophthora black pod infections in pods growing in the canopy. *European Journal of Plant Pathology*, *117*(2), 167–175. https://doi.org/10.1007/s10658-006-9082-8

Padi, B., & Owusu, G. K. (1998). Towards an integrated pest management for sustainable cocoa production in Ghana. In *First Sustainable Workshop on Sustainable Cocoa Growing, Panama City, Panama*.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rice, R. A., & Greenberg, R. (2000). Cacao cultivation and the conservation of biological diversity. *Ambio*, *29*(3), 167–173. https://doi.org/10.1579/0044-7447-29.3.167

Schroth, G., Krauss, U., Gasparotto, L., Duarte Aguilar, J. A., & Vohland, K. (2000). Pests and diseases in agroforestry systems of the humid tropics. *Agroforestry Systems*, *50*(3), 199–241. https://doi.org/10.1023/A:1006468103914

Schroth, G., Läderach, P., Martinez-Valle, A. I., Bunn, C., & Jassogne, L. (2016). Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Science of the Total Environment*, *556*, 231–241. https://doi.org/10.1016/j.scitotenv.2016.03.024

Smith, J., Pearce, B. D., & Wolfe, M. S. (2013). Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renewable Agriculture and Food Systems*, *28*(1), 80–92. https://doi.org/10.1017/S1742170511000585

Soh, P. T., Ndoumbè-Nkeng, M., Sache, I., Nguema, E. P. N., Gwet, H., & Chadœuf, J. (2013). Development stage-dependent susceptibility of cocoa fruit to pod rot caused by Phytophthora megakarya. *European Journal of Plant Pathology*, *135*(2), 363–370. https://doi.org/10.1007/s10658-012-0092-4

Somarriba, E. (1992). Revisiting the past: an essay on agroforestry definition. *Agroforestry Systems*, *19*(3), 233–240. https://doi.org/10.1007/BF00118781

Street, B., & Legon, E. (2014). *Cocoa Market Update*. (4), 1–11.

Tondje, P. R., Roberts, D. P., Bon, M. C., Widmer, T., Samuels, G. J., Ismaiel, A., … Hebbar, K. P. (2007). Isolation and identification of mycoparasitic isolates of Trichoderma asperellum with potential for suppression of black pod disease of cacao in Cameroon. *Biological Control*, *43*(2), 202–212. https://doi.org/10.1016/j.biocontrol.2007.08.004

Wessel, M., & Quist-Wessel, P. M. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS - Wageningen Journal of Life Sciences*, *74–75*, 1–7. https://doi.org/10.1016/j.njas.2015.09.001

Wikiwand (n.d.). Tree crown measurement. URL https://www.wikiwand.com/en/Tree_crown_measurement

Wiredu, A. N., & Mensah-bonsu, A. (2011). Hybrid Cocoa and Land Productivity of Cocoa Farmers in Ashanti Region of Hybrid Cocoa and Land Productivity of Cocoa Farmers in Ashanti Region of Ghana. *World Journal of Agricultural Sciences, 7 (2): 172-178*.

World Weather Online (2020). Historical average weather. URL https://www.worldweatheronline.com/lang/pt/sefwi-bekwai-weather-averages/western/gh.aspx

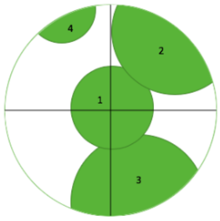
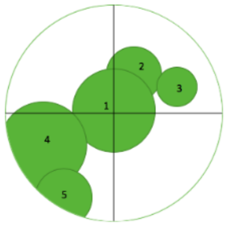
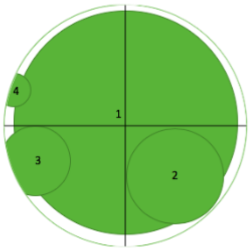
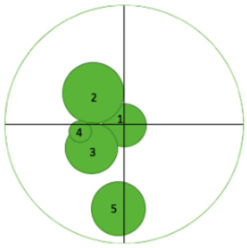
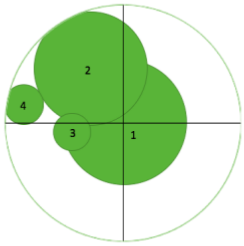
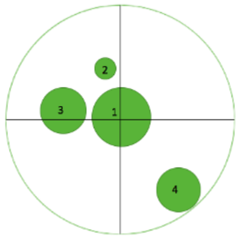
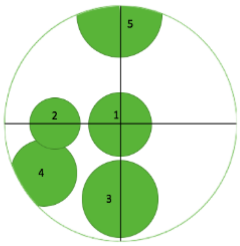
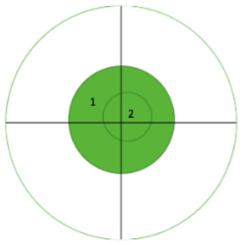
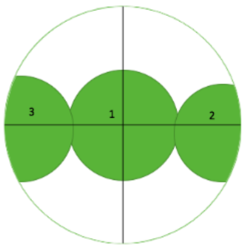
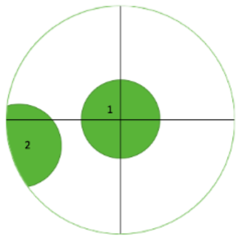
Xiang, Q., & Judelson, H. S. (2014). Myb transcription factors and light regulate sporulation in the oomycete Phytophthora infestans. *PLoS ONE*, *9*(4). https://doi.org/10.1371/journal.pone.0092086

Zuidema, P. A., Leffelaar, P. A., Gerritsma, W., Mommer, L., & Anten, N. P. R. (2005). A physiological production model for cocoa (Theobroma cacao): Model presentation, validation and application. *Agricultural Systems*, *84*(2), 195–225. https://doi.org/10.1016/j.agsy.2004.06.015

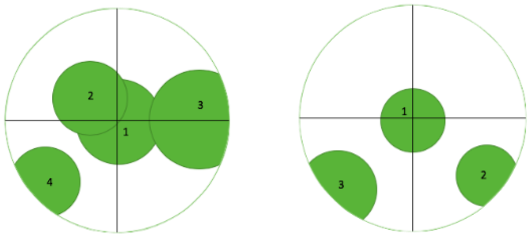
7. Appendix

7.1 Appendix I – Plot map

***Table 8** – Rough map of shade trees per plot, in shaded plots. Green circles represent the average canopy area for each shade tree and the numbers reflect the relative distance to the center of the plot.*

Farm	Plot 1	Plot 2
1		
2		
3		
4		
5		

6



7.2 Appendix II – Local shade tree names

The local names of all shade trees that were found in shaded plots were collected and the frequency of each species is given in table 9.

Table 9 *– Name and frequency of the shade trees found in the shaded plots across all 6 farms assessed in Asankragua.*

Local name	Scientific name	Frequency
Akomkode	-	1
Adoma	-	1
Dumpuo	-	1
Emere	*Terminalia ivorensis*	1
Kesia	-	15
Mahogany	*Khaya ivorensis*	1
Nyamedua	*Alstonia boonei*	2
Odum	*Milicia Excelsa*	2
Ofram	*Terminalia superba*	2
Okoro	*Albizia zygia*	2
Orange	*Citrus cinensis*	1
Sesemasa	*Newbouldia laevis*	9
Sesia	-	1
Sofo	*Sterculia tragacantha*	1
Panpan	-	1
Pear	*Persea americana*	3
Yaya	*Amphimas pterocarpoides*	2

7.3 Appendix III – Interview questions

SECTION 1: LAND USE

1. What was there in the field before the current cocoa trees were planted?
   (Select one: a. open field; b. forest; c. other crop (specify); d. I don't know)
2. When were the first cocoa trees planted in the field?
   (Select one: a. less than 10 years; b. 10-20 years; c. 20-30 years; d. 30-40 years; e. more than 40 years)
3. Which method of rehabilitation are you engaged in?
   (select one: a. underplanting; b. gradual planting; c. complete replanting; d. no rehabilitation)
4. When did you last replant?
   (select one: less than 5 years; 5-10 years; 10-15 years; 15-20 years; 20-25 years; more than 25 years)
5. Why did you replant?
   (select one: a. cocoa trees overaged; b. cocoa trees diseased; c. others (specify))
6. Overall, how do you appreciate the current status of soil fertility of your cocoa plantation?
   (select one: a. low; b. moderate; c. high)
7. Do you perceive any change in soil fertility status over the last 10 years?
   (select one: a. It has increased; 2. It has decreased; 3. There was no change; 4. I don't know)
8. Overall, do you think your cocoa trees are healthy and strong? (yes/no)
   a. If 8=no: What is causing that (specify)

SECTION 2: MANAGEMENT PRACTICES

1. Do you use chemical fertilizer? (yes/no)
   If 1= yes
   a. When was the last time you applied chemical fertilizer? (specify in months and year)
   b. How frequently did you apply chemical fertilizer in the last two years (number of times per year)? (select one: a. once a year; b. twice a year; c. three times a year; d. other (specify))
2. Do you use organic fertilizer? (yes/no).
3. Do you use herbicide for weed management? (yes/no)
4. Do you remove epiphytes from cocoa trees? (yes/no)
5. What do you do with opened pods?
   (Multiple selection: a. leave in field; b. remove from field; c. other (specify))
6. Do you prune cocoa trees? (yes/no)
   If 8= yes
   a. Why do you prune your cocoa trees?
   (multiple selection: a. sanitation; b. shade management; c. other (specify))
   b. How often do you prune the trees? (specify)

SECTION 3: DISEASE MANAGEMENT

1. Do you use insecticide? (yes/no)
   If 1= yes
   a. Which insecticide(s) do you use? (specify)
   b. Amount of insecticide applied in 17/18 season:
   (specify the number of units)
   c. Unit of measurement for amount.
   (select one: a. Kg; b. g; c. L; d. bags; e. other)
   d. When was the last time you applied insecticide? (specify the month and year)
   e. How frequently did you apply insecticide in the last two years (specify)
   f. Do you use insecticide on shade trees? (yes/no)

2. Do you use fungicide? (yes/no)
   If 1= yes
   a. Which fungicide(s) do you use? (specify the name)
   b. Amount of fungicide applied in 17/18 season:
      (specify the number of units)
   c. Unit of measurement for amount.
      (select one: a. Kg; b. g; c. L; d. bags; e. other)
   d. When was the last time you applied fungicide? (specify the month and year)
   e. How frequently did you apply fungicide in the last two years (specify)
   f. Do you use fungicide on shade trees? (yes/no)
3. Do you remove diseased pods from the cocoa trees? (yes/no)
   If 3= yes
   a. How do you dispose of diseased pods?
   (multiple selection: a. leave in field; remove from field; other (specify))
   b. When was the last time you removed diseased pods? (specify. Hint* in days)
   c. How often do you remove diseased pods? (specify. Hint* every (x) days/weeks/months)
4. Do you "sterilize" your tools used for managing diseased trees before using them on healthy trees?
   (select one: a. always; b. frequently; c. rarely; d. never)
5. Do you practice mulching in your cocoa crops? (yes/no)
   If 4= yes
   a. Which material(s) do you use for mulching? (specify)
6. Do you consider *Phytophthora* pod rot (aka black pod) to be a threat to your cocoa crops? (yes/no)
   a. In a scale of 0-5 how would you classify this disease's effect?
      (select one: a. 0; b. 1; c. 2; d. 3; e. 4; f. 5)
   b. Besides fungicide application, what other strategies do you use against black pod (if any)? (specify)
7. Do you consider mirids to be a threat to your cocoa crops? (yes/no)
   If 7= yes
   a. In a scale of 0-5 how would you classify this pest's effect?
      (select one: a. 0; b. 1; c. 2; d. 3; e. 4; f. 5)
   b. Besides insecticide application, what other strategies do you use against mirids (if any)? (specify)
8. What other pests/diseases do you perceive as important in your cocoa crops? (specify)
9. What other pest/disease management strategies do you apply in your cocoa crops (if any)? (specify)

SECTION 4: SHADE TREES

1. How many shade trees do you have growing in the cocoa farm? (specify)
2. Are the shade trees evenly spread throughout the whole cocoa plantation? (yes/no)
   If 1= no
   a. What proportion of the farm is in full sun? (specify. Hint* Give proportion)
   b. Why is that? (multiple selection: a. the shade trees are naturally regenerated; b. I wanted cocoa trees to be in full sun; c. other (specify))
3. In your view, are the shade trees relevant in disease prevention/control (yes/no)
   If 3= yes
   a. In what way? (specify)
4. Does your household use any products obtained from shade trees? (yes/no)
   If 4=no
   a. Why not? (specify)
   If 4= yes
   b. Which products do you use?

(multiple selection: a. fruits; b. timber; c. leaves; d. other (specify))

5. Do you sell any products obtained from shade trees? (yes/no)
   If 4=no
   a. Why not? (specify)
   If 4= yes
   b. Which products do you sell?
   (multiple selection: a. fruits; b. timber; d. other (specify))
6. Do you have any preferred shade trees? (fill bellow)

Genus/ species name (local)	Do you use products from those trees?	Do you sell products from those trees?	Why do you like these trees?
(specify species 1)	(Yes/no)	(Yes/no)	(see **code 1** below)
(specify species 2)	(Yes/no)	(Yes/no)	(see **code 1** below)
…	…	…	…

Code 1: multiple selection: a. products are useful; b. reduce pest/disease incidence; c. good for shade; d. improve soil quality; e. improve cocoa productivity; f. aesthetics; g. cultural/personal reason; h. no particular reason; i. other (specify)

7. Do you have any shade trees you don't like/ avoid using? (fill bellow)

Genus/ species name (local)	Do you use products from those trees?	Do you sell products from those trees?	Why don't you like these trees?
(specify species 1)	(Yes/no)	(Yes/no)	(see **code 2** below)
(specify species 2)	(Yes/no)	(Yes/no)	(see **code 2** below)
…	…	…	…

Code 2: multiple selection: a. products are not useful; b. increase pest/disease incidence; c. bad for shade; d. competition with cocoa on soil level; e. deteriorate cocoa productivity; g. cultural/personal reason; h. no particular reason; i. other (specify)

SECTION 5: INCOME AND COCOA YIELD

	Total of dry beans harvested in last three seasons (15/16; 16/17; 17/18) **(in bags)**	Weight per bag of dry beans (**in Kg**)	Total of dry beans sold in the last three seasons (**in bags**)
15/16	(specify)		
16/17	(specify)		
17/18	(specify)		

1. Do you think shade tree products are important for the economy of your household? (select one: a. 0; b. 1; c. 2; d. 3; e. 4; f. 5)
2. How has cocoa quantity sold changed over time (5 years)?

(Select one: 1=increased; 2=decreased; 3=no change)

a. What are the 3 most important reasons for the change? (specify)

7.4 Appendix IV – R script (example)

Script used in RStudio to import and create the datasets used in the analyses and an example of the statistical models and graphs made for the total number of mature pods. All responses were tested using the same method.

```
#Import dataset
For_R_ALL <- read_delim("Desktop/Thesis/Data collection/Statistics/For_R_ALL.csv",
                    +     ";", escape_double = FALSE, trim_ws = TRUE)
For_R_ALL_co_pia <- read_delim("Desktop/Thesis/Data collection/Statistics/For_R_ALL - cópia.csv",
                          +     ";", escape_double = FALSE, trim_ws = TRUE)

test<-For_R_ALL_co_pia[For_R_ALL_co_pia$Shade.level=="No",]
data<-For_R_ALL_co_pia
data<-rbind(data,test)
data$Farm<-For_R_ALL$Farm.1
farm<-For_R_ALL_co_pia

#Create tree and plot identifier in each dataset
data$Tree<-paste(data$Tree.number,data$Farm,sep="_")
data$Plot<-paste(data$Farm,data$Shade,sep="_")

#Create shade square in each dataset
data$Shade.sqr<-data$Shade*data$Shade

#Viability column
week_farm.3$viability<-(week_farm.3$Total.viable/week_farm.3$Total.harvested)*100

#Percentage of harvest column
week_farm.3$per.harv<-
(week_farm.3$Harvested.under.250/week_farm.3$Total.no.of.mature.pods)*100

#Convert y and n into 1 and 0
week_farm.3$MD<-ifelse(week_farm.3$Mirid.damage=="y",1,0)
week_farm.3$BP<-ifelse(week_farm.3$Black.pod=="y",1,0)

#Create dataset with only 1 week (before harvest)
Week3<-farm[farm$Week=="3",]
Week3<-Week3[!Week3$Farm=="AL",]
Week3<-Week3[!Week3$Farm=="KS",]
Week2<-farm[farm$Week=="2",]
Week2.2<-farm[farm$Week=="2",]
Week2<-Week2[Week2$Farm=="AL",]
Week2.2<-Week2.2[Week2.2$Farm=="KS",]
Week2<-rbind(Week2,Week2.2)
rm(Week2.2)
week_farm.3<-rbind(Week3,Week2)
rm(Week2,Week3)

#Open lme4 and ggplot2
install.packages("MuMIn")
library(ggplot2)
library(lme4)
library(MuMIn)
```

```
#normality check for residuals
shapiro.test(week_farm.3$Total.no.of.mature.pods)

# test mixed-effects models with linear vs. quadratic for each variable (with all data points)
model<-lmer(Total.no.of.mature.pods~1+(1|Farm/Tree),data = farm)
model1<-lmer(Total.no.of. mature.pods ~Shade+(1| Farm/Tree),data = farm)
model2<-lmer(Total.no.of. mature.pods ~Shade+Shade.sqr+(1| Farm/Tree),data = farm)
AIC(model,model1,model2) #compare models
r.squaredGLMM(model1) # Compare r squared with/wo random effects

#test mixed-effects models with linear vs. quadratic for each variable
model<-lmer(Total.no.of.mature.pods~1+(1|Farm),data = week_farm.3)
model1<-lmer(Total.no.of. mature.pods ~Shade+(1|Farm),data = week_farm.3)
model2<-lmer(Total.no.of. mature.pods ~Shade+Shade.sqr+(1|Farm),data = week_farm.3)
AIC(model,model1,model2) #compare models
r.squaredGLMM(model1) # Compare r squared with/wo random effects

##Final graphs
test<-week_farm.3
model<-lmer(Total.no.of.mature.pods~Shade+(1|Farm),data=week_farm.3)
MeansByShade<-aggregate(Total.no.of.mature.pods~Shade+Farm,data=test,mean) ##
test$pred<-predict(model,test,re.form=~0)
test2<- test[order(test$Shade),]
ggplot(data = test2) +
  geom_point(aes(Shade,Total.no.of.mature.pods),data=MeansByShade)+
  geom_line(aes(x = Shade, y = pred),linetype="solid",colour="blue")+
  xlab("Shade Tree Cover (%)") +
  ylab("Average No. of Mature Pods") +
  theme(panel.grid.major = element_blank(),
                panel.grid.minor = element_blank(),
                panel.background = element_blank(),
                axis.line = element_line(color = "Black"))
```

7.5 Appendix V – Model AIC

Table 10 *– Akaike Information Criterion (AIC) of all models created for the responses described on the left column. Models were constructed with the lme4 package in R. All models included farm as a random effect and were compared to test shade as a fixed effect. If AIC differed more than 2 units between the three models, the model with the lowest AIC was considered a better fit to explain the data. When the AIC differed less than 2 units, the simpler model was accepted as the best fit for the data.*

	Null Intercept	**Shade (Linear)**	**Shade (Quadratic)**
Number of mature pods	2068.499	2065.437	2081.083
Number of cherelles	2604.421	2612.398	2627.069
Number of wilted cherelles	2576.115	2579.135	2589.944
Percentage of mature pods w/ black pod	3061.703	3049.952	3058.732
Percentage of cherelles w/ black pod	2156.569	2164.731	2179.091
Percentage of mature pods w/ mirid damage	2694.051	2700.477	2713.681
Percentage of cherelles w/ mirid damage	3143.974	3149.288	3159.681
Number of harvested pods (whole tree)	1728.367	1731.399	1745.614
Number of viable pods (whole tree)	1652.904	1654.000	1669.785
Percentage of harvested pods that were viable pods (whole tree)	2310.613	2312.776	2318.358
Percentage of mature pods harvested	3229.250	3208.994	3207.369