Modelling GHG emissions of cacao production at plot level in the Republic of Côte d'Ivoire

MSc Thesis at Environmental System Analysis and Plant Production Systems

Name:	Wieke Vervuurt
Student number:	931210885020
Supervisors:	dr. ir. LGJ van Bussel (ESA)
	dr. ir. MA Slingerland (PPS)
Commissioner:	dr. ir. AA Pronk (Agrosystems Research)
Examiner:	prof. dr. HBJ Leemans (ESA)
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Contact office.bmw-mes-mue-mcl@wur.nl for access to data, models and scripts used for the analysis

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Content

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Abstract

The current expansion of cacao cultivation in the Republic of Côte d'Ivoire is associated with deforestation, forest degradation, biodiversity loss and high greenhouse gas (GHG) emissions. Global concerns about these emissions that are associated with tropical commodity production, are increasing. Consequently, changing the present cacao-growing practice into a more sustainable cultivation system with lower GHG emissions per unit of product, high carbon storage in its standing biomass, with similar or even higher yields (climate-friendly cacao) is urgently needed. I estimated GHG emissions associated with cacao production by using various tools, including the *Perennial-GHG model*, the *Cool Farm Tool*, allometric equations and guidelines developed by the *Intergovernmental Panel on Climate Change*. These tools are all data intensive, and require literature, survey and fieldwork data. I found that, on average, 3.6 kg CO_2-equivalents were emitted per kilogram of cacao produced. Composting cacao-tree residues and fertiliser application contributed largely to these GHG emissions, while shade- and cacao tree biomass contributed mainly to CO_2 storage. The present study revealed that it is feasible to produce high yields while at the same time storing a high amount of carbon in the standing biomass and causing low GHG emissions. Although some uncertainties exist, I found that the climate-friendliness of cacao production is strongly related to farm management. Therefore, farm management is a key factor in producing climate-friendly cacao. Farm management that significantly contributes to climate-friendliness of cacao includes the presence of shade trees and leaving biomass residues on the soil.

Keywords: greenhouse gas emissions, climate friendly, cacao production, carbon storage, biomass

1. Introduction

1.1. Background

Cacao (*Theobroma cacao*), which is a perennial crop, is mainly cultivated in Africa, Asia and South America (Asase, Ofori-Frimpong, Hadly & Norris, 2008). 70% of all the world cacao supply is grown in West Africa, with the Republic of Côte d'Ivoire being the main producer (Wessel & Quist-Wessel, 2015). The Republic of Côte d'Ivoire managed to increase the cacao production from 900,000 tons in 1995 to 1,500,000 tons of cacao beans in 2011 (Wessel & Quist-Wessel, 2015). Since the yields per hectare remain low, the production increase is mainly due to expansion of the cultivation area (Wessel & Quist-Wessel, 2015). Current cacao cultivation is expected to further expand in the Republic of Côte d'Ivoire over the next decades, because of the growing consumption in developing countries and an increase in average prices and support measures by the government (Wessel & Quist-Wessel, 2015; Recanati, Marveggio & Dotelli, 2018). The expansion of cacao cultivation is associated with deforestation, forest degradation, biodiversity loss and high greenhouse gas (GHG) emissions (Wessel & Quist-Wessel, 2015; Gockowski & Sonwa, 2011).

Global concerns about anthropogenic GHG emissions are rising and concerns about environmental issues associated with tropical commodity production are also increasing (Neslon & Phillips, 2018). Consequently, there is an urgent need to change the present cacao growing practice into a more sustainable cultivation system with lower greenhouse gas emissions per unit of product with similar or even a higher yields (Schroth, Laderach, Martinez-Valle, Bunn & Jassogne, 2014). Many cacao traders, manufacturers and non-governmental organisations launched sustainability initiatives in West Africa (Neslon & Phillips, 2018). Among all the initiatives, Mondelēz – manufacturing large quantities of cacao - funded *Cocoa Life* with the aim to protect the environment and ecosystems, by providing training in sustainable practices (Mondelēz, 2019). Barry Callebaut - one of the largest cacao manufacturers in the world – even launched a goal to produce climate positive cacao by 2025 (Barry Callebaut, 2017). Their strategy includes 'investing in climate-smart agriculture to increase productivity on existing suitable land' and 'the promotion of responsible farming practices that safeguard the environment' (Barry Callebaut, 2017). Additionally, the UTZ organisation developed guidelines for better farming methods to care for nature and future generations. Still, these 'sustainable practices' and 'responsible farming practices' are not specified and seem to focus solely on productivity increase and planting non-cacao trees.

Since the GHG emissions associated with cacao farming are highly depend on management practices (MPs), changing farm management is a key factor in achieving a more sustainable cultivation system (Recanati et al., 2018; Ledo, Heathcote, Hastings, Smith & Hiller, 2018; Schneidewind et al., 2018). Cacao plantations can be managed in very different manners, ranging from traditional low input agroforestry systems to intensive monocultures (Recanati et al., 2018). In the Republic of Côte d'Ivoire, cacao trees are traditionally grown under a thin shade layer, using the forest soil fertility (Wessel & Quist-Wessel, 2015). However, since the full-light tolerant Amazon hybrids became available, the share of monocultures has increased (Wessel & Quist-Wessel, 2015; Schroth et al., 2014). MPs include shade management, pruning, residue management and the use of fertiliser. The latter being responsible for two thirds of the input-related GHG emissions (Schroth et al., 2016). A number of organic and inorganic fertilisers are used in cacao, including urea, manure, organic residues and chemical fertiliser. These can be applied in the planting hole, in a circle around the stem or by foliar application and differ in dosages (Recanti et al., 2018). These different fertiliser input and application methods are all associated with different direct field emissions (Recanti et al., 2018; Van Rixoort, Schroth, Läderach & Rodríguez-Sánchez; Materechera, 2010). Although not well understood, the effect of applying fertilisers on biomass growth is mediated by the shading intensity, depending on pruning practices and shade trees (Van Vliet, Slingerland & Giller, 2015). Shade trees commonly include timber trees such as *C. alliodora*, leguminous trees such as *E. poeppigiana* and fruit trees such as orange, avocado and mango. Overall, shade trees account for a large part of the total aboveground biomass of the plantation and therefore for a large part of the carbon accumulation (Beer et al., 1990; Dawoe, Asante, Acheampong & Bosu, 2016). Pruning waste, as well as cacao husks and other residues in the fields are commonly burnt or composted (Van Vliet, Slingerland & Giller, 2015). Consequently, the GHG emissions vary across plantations depending on the farm management (Recanti et al., 2018).

It is highly debated whether the production of cacao is associated with net GHG emissions or net storage (Ortiz-Rodriguez, Villamizar, Naranjo & Carcia-Caceres, 2016; Defra, 2009; Schroth et al., 2016; Montagnini & Nair, 2004). On the one hand, forest conversion, burning organic material and applying fertiliser is associated with GHG emissions (Ledo et al., 2018). While on the other hand, perennials such as cacao, also have the potential to restore carbon stocks in their standing biomass (Dawoe et al., 2016; Schroth et al., 2014) and to add carbon inputs to the soil (Ledo et al., 2018). Therefore, quantifying current net GHG emissions associated with cacao production systems is needed. To enable recommendations for management to mitigate GHG emissions, sources of GHG emissions and carbon stocks first need to be identified and quantified (Ledo et al., 2018). As farm management is a potential tool for GHG emission mitigation, understanding the relation between MPs and the associated net GHG emissions is a prerequisite for developing actions related to the mitigation of GHG emissions.

Several studies tried to assess the environmental impact of cocoa production. For example, Ntiamoah and Afrane (2008) and Recanati et al., (2018) conducted a life cycle analysis on the chocolate supply chain. Somarriba et al. (2013), Silatsa, Yemefack, Ewane-Nonga, Kemga and Hanna (2017), Asase et al. (2008), Gama-Rodrigues, Gama-Rodrigues and Nair (2011), Schroth et al. (2014), and Magne, Nonga, Yemefack and Robiglio (2014) conducted detailed research to specify the carbon cycle in the cacao production. Although the body of cacao research is very large, comprehensive knowledge on GHG emissions of cacao production in relation to various MPs is lacking. As acknowledged by Recanati et al. (2018) and Silatsa et al. (2017) deeper research is needed on the environmental impact of various cacao cultivation systems, including the emission of GHGs. Therefore, my study aimed to: (1) quantify the current GHG emissions from cacao production in the Republic of Cote d'Ivoire; (2) identify the most important MPs determining the GHG emissions from cacao production; (3) investigate whether high yields, high carbon stocks and low GHG emissions are compatible in the cacao production, and (4) formulate recommendations to reduce GHG emissions associated with cacao production. In order to calculate the GHG emissions associated with cacao production, four existing assessment tools are improved and used (see Section 2.2.) and field data on cacao biomass has been collected (see Section 2.7.).

1.2. Purpose of the study

My study aims to acquire insights in GHG emissions associated with cacao production. The outcomes include CO_2-equivalents GHG emissions of the current cacao production practices in the Republic of Côte d'Ivoire and understanding how various MPs affect GHG emissions. The results of the present study serve as a basis to explore interventions to reduce GHG emissions of cacao production.

The primary focus of my study is on cacao farms in the Republic of Côte d'Ivoire. When data from other countries become available, their GHG emissions can be calculated using the assessment tools that will be presented and improved by my study (see Section 2.2.).

The purpose is elaborated in the following research questions (RQs):

- RQ1: How can GHG emissions associated with cacao production be assessed?
  - RQ1a: How does the IBM model need to be parameterised to calculate the GHG emissions associated with cacao production?
  - RQ1b: Which additional tools are needed to assess the GHG emissions associated with cacao production?
  - RQ1c: Which parameters of the assessment tools most impede accurate assessment on greenhouse gas emissions related to cacao production?
- RQ2: How much on field GHG emissions are associated with the cacao production in surveyed plots in the Republic of Côte d'Ivoire?
  - RQ2a: Which management practices are most commonly being used by cacao farmers in the Republic of Côte d'Ivoire?
  - RQ2b: Which management practices are the largest contributors to the GHG emissions associated with cacao production in the Republic of Côte d'Ivoire?
  - RQ2c: Which management practices contribute to low GHG emissions, high carbon stocks and high yields at the same time?

Developing methods to assess GHG emissions associated with cacao producting (RQ1) is mainly a methodological question and is therefore elaborated in Section 2.2.. Data from literature, a survey and fieldwork is used to parameterise the various tools (RQ1bc). These different datasources form the structure of the resultsection. The results from literature, a survey (RQ2a) and fieldwork are followed by results from modelling, answering RQ2. In Section 6.2., elaborating on the results of modelling, RQ2b is answered. The conclusion reveals the MPs contributing to the production of climate-friendly cacao, answering RQ2c. Eventually, on the basis of RQ2c, recommendations for the cacao growing industry were formulated.

2. Methodology

2.1. System boundaries

The evaluation of the GHG emissions of cacao production in the present study is based on the methodology developed by Ledo et al. (2018). The farm boundary is used as a starting point, assessing GHG currently emitted on farm. A schematic overview of the sources and sinks of the GHG emissions taken into account are presented in Figure 1. The GHG emissions include the annual carbon sequestration in the vegetation (i.e. negative emissions), but excludes the cumulative carbon stored in the cacao biomass (Van Rikxoort et al., 2014). The cumulative carbon stored in tree biomass is referred to as carbon stocks and is assessed separately. Also deforestation and fertiliser application is assessed separately.

The assessment focuses on farm level activities within the year 2017, including the effects of deforestation, the application of fertilisers, management of biomass residues and the presence of shade trees. In- and output flows of the system are assessed, referring to the materials entering and leaving the farm. The inputs include farm electricity, fuel for machinery and fertiliser and the outputs include cacao bean yield, tree-, pruning- and cacao husk residues. The impact of materials is only calculated between entering and leaving the farm gate. For example, the emissions of applying fertiliser in the field within that specific year are included, while the emissions during the manufacturing of fertilisers are not taken into account. Even so, if respondents state to handle materials as a farm output, such as biomass residues, these are considered as climate neutral (Ledo et al., 2018). Because the present study focuses only on the production phase of the cacao beans in 2017, the effect of managing trees that died in that same year are included in the calculations, while the effect of the management of the plantation at the end of its lifecycle is not included.

The functional unit refers to a 'quantified performance of a product system for use as a reference unit' (International Organization for Standardization, 1997). The functional unit is a kilogram of cacao. So, the GHG emissions are expressed in CO_2-equivalents per kg of cacao yield.

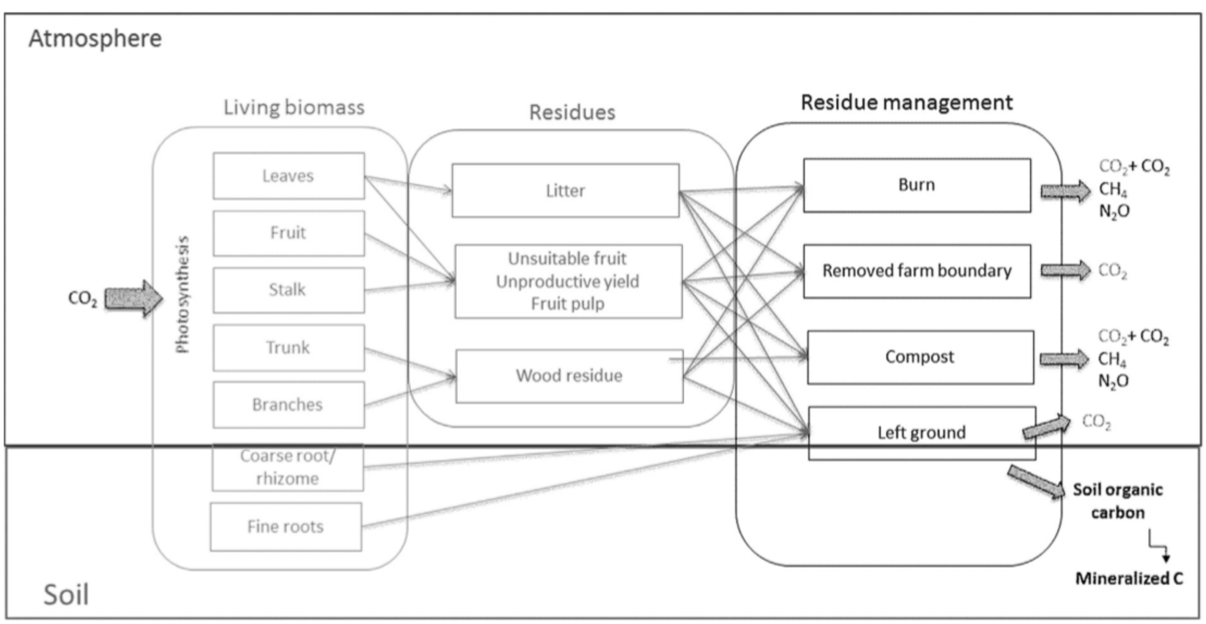

Figure 1 Considered sources and sinks of GHG emissions. GHG in grey are neutral emissions, whereas the black ones are negative emissions. Adapted from: Ledo et al. (2018).

2.2. Modelling GHG emissions

To understand the behaviour of processes in ecological systems, modelling is an important tool (Glover & Beer, 1986). Modelling GHG emissions as a result of biomass growth and MPs forms the base of the present study. Additonally, the *Cool Farm Tool*, an allometric function and Guidelines from the Intergovernmental Panel on Climate Change (IPCC) are used. All tools are able to deal with different MPs (see Appendix I) and are combined to cover the most important MPs. The outcomes of the tools are integrated to calculate the CO_2-equivalents per hectare per year and per kilogram of product, considering carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). The global warming potentials for N_2O, CH_4 and C are 298, 34 and 6.7 respectively (Myhre et al., 2013).

The IBM model is a new generic allometric model to estimate biomass accumulation and GHG emissions from perennial food plants production (Ledo et al., 2018). The model uses two different scripts: one simulating biomass accumulation and one simulating GHG emissions on the basis of MPs indicated by a respondent, in this case a cacao farmer. The biomass script was not yet parametrised for cacao, which has been done as part of my study (see Section 2.3.1.). Next to that, shade trees, fertiliser application, climatic conditions and soil properties are not integrated in this model. The CFT is used to calculate the GHG emissions from fertiliser application taking into account climatic conditions and soil properties. The CFT expresses the GHG emissions into CO_2-equivalents per hectare per year and per kilogram of product (Schroth et al., 2014). Also the CFT is not parameterised for cacao and coffee is selected instead. Coffee parameters will not cause inaccuracies in this case because CFT is used for the effect of fertiliser application on GHG emissions solely. Furthermore, the annual carbon stored in shade trees is estimated by the use of an allometric function (see Section 2.5.). And finally, the methodology described by Eggleston et al. (2006) is used to calculate the annual effect of deforestation on GHG emissions (see Section 2.6.). An overview of all the models and data requirements is provided in Appendix I.

2.3. Input parameters IBM

The IBM model requires data regarding cacao tree biomass (see Section 2.3.1.) and data regarding farm management (see Section 2.3.2.) to be functional and applicable to cacao trees (Ledo et al., 2018).

2.3.1. Biomass parameters

The IBM model uses a non-linear function to determine the biomass growth over time (y):

$$y = a \bullet age^{b} \qquad \text{Equation 1}$$

where y is aboveground biomass and age is the number of years after planting the seedling in the field. The model generates the coefficients a and b for each plant organ specifically for cacao on the basis of empirical data (Ledo et al., 2018). The data needed for parameterisation are dry biomass quantities of different plant parts at different ages for cacao trees. A literature review is conducted to obtain plant biomass quantities. The most accurate method to obtain plant biomass values from literature, is the use of studies that executed destructive sampling to determine plant biomass (Ledo et al., 2018). Since not many of these studies are available, studies that used local allometric equations to estimate biomass as a function of age, height or stem diameter are used as well (Ledo et al., 2018). Several key studies that investigated biomass production of cacao trees can be found in Appendix II. Additionally, the IBM model requires data on the carbon and nitrogen content of the cacao wood, leaves, fruit and roots to calculate the GHG emissions correctly. For the nitrogen and carbon content of the organs, 23 studies were consulted (see Appendix III). Furthermore, the IBM model calculates the GHG emissions of composting on the basis of fresh biomass weight and therefore needs the dry matter (DM) content of the wood, leaves and fruit. The DM percentages for the wood and leaves are sourced from literature. The DM percentage of the fruits is collected during fieldwork and will be elaborated in Section 4.1.1..

2.3.2. Farm management

The IBM model is able to deal with several MPs, see Appendix I. A dataset collected by Ingram et al. (2013) meets the required data regarding the MPs. Ingram et al. (2013) aimed at gathering cacao farmers' knowledge on social and environmental issues, and the implementation of good agricultural practices. The study covers 730 farmers, situated across the three main agro-ecological zones across the Republic of Côte d'Ivoire. According to Ingram et al. (2013), the farmers participating in the survey are representative for the average farmer in the Ivorian cacao sector in terms of age and farm size. The study was conducted on behalf of UTZ, therefore, half of the respondents are UTZ certified and the other half served as a control group. The data collection described by Ingram et al. (2013) was repeated in 2017 and the latter was used for the present study and further referred to as UTZ survey.

Data from respondents who did not state the age of the plot was excluded, because plot age is a prerequisite to estimate biomass growth and thus to run the IBM model. Additionally, plots aged over 70 years have been removed as well, because the accuracy of the IBM model decreases with plots older than 70 years and it is questionable whether plots of an age above 70 years are still productive. Another 57 plots were removed due to missing information about the cacao yield, which is essential for expressing GHG emissions per kilogram of product. After removal, 451 plots were left for analysis, covering 1,559 hectare of cacao plots. An overview of the farm characteristics can be found in Table 1. The distribution of all the plots can be found in Figure 2.

Even though the survey is extensive, data gaps exist and are filled with information found in literature. Data is missing about the number of cacao trees per hectare, the number of cacao trees that die annually and the management of these dead trees, the management of litter and whether the respondents use an open or enclosed composting technology. Although the surveys provide information about which inputs are being used and at which dosages, the content of the inputs is usually not described and remains unclear. According to Magne et al. (2014), there is little consistency in the use of inputs and high variability in the content. Therefore, the content of the inputs being used has been estimated on the basis of literature (see Section 3.7.).

Furthermore, the outcomes of the survey are not in the same format as the options in the model. Therefore, the outcomes of the survey needed to be transformed for usage to be applicable to the IBM model. A transformation with more explanation can be found in Appendix IV.

Table 1 Summary statistics of the farm characteristics and yields

	Plot area (ha)	Plot age (year)	Yield (kg ha^{-1})
Average	3.5	22.0	445
Standard deviation	0.1	0.2	13
Median	3.0	20.0	425
Minimum	0.3	1.0	0
Maximum	18.0	56.0	1750

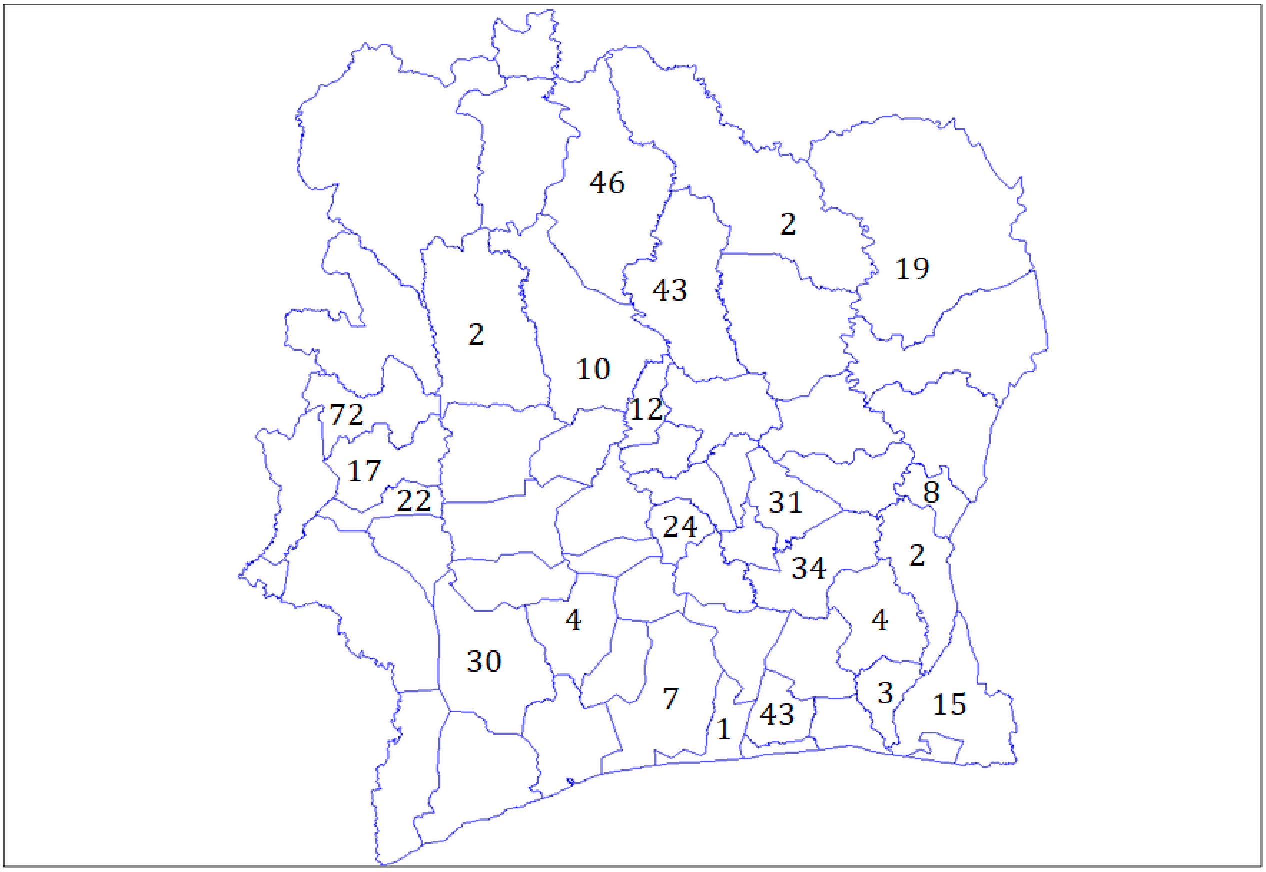

Figure 2 Map of the Republic of Cote d'Ivoire, indicating the distribution of the surveyed plots, adapted from: Rarelibra, 2007[i].

<u>2.3.3. Other input parameters</u>

Apart from tree biomass parameters and data on management practices, the IBM model requires the percentage of infected fruits and decomposition parameters of cacao tree organs. An estimated average percentage of infected fruits is derived from literature. Furthermore, the IBM model requires decomposition rates (k) for cacao litter, fruits, roots, wood and cacao husk. These decomposition rates are gathered by a literature review as well.

2.4. Input parameters CFT

The CFT is able to calculate the GHG emissions from fertiliser application. To calculate these emissions, the CFT requires data on the application of nitrogen and on soil and temperature conditions.

During the UTZ survey (introduced in Section 2.3.2.), respondents were asked whether they used fertiliser. Farmers could choose between commonly used fertiliser types (including Asaase Wura, Cocofeed, Sidalco, Nitrabor, Supercao and Hypersaco), or specify another type of fertiliser. Despite the type of fertiliser being applied is generally well reported, the amount of fertiliser used by the respondents is not. Therefore, it is assumed that all respondents applied fertiliser on a recommended dose. These recommended doses have been gathered from literature and the websites of the fertiliser producers. Apart from the most common used fertiliser types, some respondents stated they used ‘other’ types of fertiliser and compost without specifying. For these cases, as well as for the unknown fertiliser types, a general recommended application is assumed. This standard application of fertiliser is sourced from literature.

In order to calculate the GHG emissions from applying fertiliser and the soil itself, the CFT requires data on various environmental factors. These factors include the average temperature, soil texture, soil organic matter, soil moisture, soil drainage and soil pH. It is assumed that moist soils have slightly higher N_2O emissions than dry ones and soils with poor drainage have significantly higher N_20 emissions than those with good drainage (Cool Farm Alliance, 2016). Soil characteristics are retrieved from the ISRIC database (ISRIC, 2019) on the basis of GPS-coordinates of the respondents. Since GPS-coordinates were not individually recorded, GPS-coordinates on the basis of the department of the respondents were used.

2.5. Shade trees

In the Republic of Cote d’Ivoire, 70% of the cacao systems are shaded (Gockowski & Sonwa, 2011), and therefore it is important to include the carbon stored in shade tree biomass in the present study. The CFT is able to estimate the annual carbon stored in shade tree biomass. The CFT requires information regarding the number of shade trees and their circumference of current and last year. Unfortunately, shade tree species and stem circumference are not collected during the UTZ survey (Ingram et al., 2017). Despite many studies collected the stem diameter of shade trees to calculate carbon storage in cacao systems, not many of them reported the stem diameters in their papers and often the age of the shade trees is not known (Beer et al., 1990; Obeng & Aguuilar, 2015; Magne et al., 2014; Kolavalli & Vigneri, 2017; N’Guessa N’Gbala, Martinez Guéi & Ebagnerin Tondoh, 2017; Jagoret, Kwesseu, Messie, Michel-Dounias & Maléqieux, E, 2012; Schroth et al., 2016; Saj et al., 2017; Dawoe et al., 2016; Silatsa et al., 2007). For these reasons, required input data for the CFT regarding shade trees in cacao plantations is limited. Therefore, the shade tree biomass is calculated apart from the CFT (see Section 2.5.1.).

2.5.1. Shade tree biomass

Because cacao fields are generally established by slash and burn practices instead of planting cacao trees under a thin forest shade (Gockowski & Sonwa, 2011), it is assumed that the cacao and shade trees are planted simultaneously. Therefore, an allometric function to estimate shade tree biomass on the basis of age has been used. Only one allometric function of shade trees on the basis of age was available (Henry et al., 2011). The species described by Onyekwelu (2007), the *Nauclea diderrichii,* occurs on cacao plantations in the Republic of Cote d’Ivoire and is grown for timber production (Smith Dumont, Gnahoua, Ohouo, Sinclair & Vaast, 2014). The volume of the shade tree *Nauclea diderrichii* (*Y in* m^3 ha^{-1}) is calculated by:

$$Y = 63.98 + 21.02x - 0.55x^2 + 0.016x^3 \qquad \text{Equation 2}$$

where *x* is age in years (Onyekwelu, 2007). The volume is recalculated to carbon per hectare by using a wood density of 790 kg m^3 (Opuni-Frimpong & Opuni-Frimpong, 2012) and a carbon content of 47.5% (Silatsa et al., 2017). The equation is based on 540 trees per hectare (Onyekwelu, 2007) and is thus recalculated to the trees per hectare stated by the respondent.

2.5.2. Number of shade trees

UTZ prescribes 12 shade trees per hectare in their Good Agricultural Practices (UTZ, 2017). Therefore, in the UTZ survey it is asked whether the respondent has more or fewer than 12 shade trees per hectare in their plot, and what the spacing of the shade trees is. Respondents could choose between 2x2m (2,500 trees ha^{-1}), 4x4m (625 trees ha^{-1}), 10x10m (100 trees ha^{-1}) and more than 10x10m (density specified by respondent). In case a respondent reported 'more than 12 shade trees', but no spacing was specified, a standard of 37.5 shade trees per hectare (Magne et al., 2014) was assumed. When a respondent stated 'less than 12 shade trees', it was assumed that they had no shade trees.

2.6. Deforestation

To estimate the annual GHG emissions from deforestation, a methodology described by Eggleston et al. (2006) is used. Eggleston et al. (2006) prescribe in 'The IPCC Guidelines for National Greenhouse Gas Inventories' a methodology to estimate GHG emissions from converting tropical forest into perennial cropland. Their methodology includes the carbon stored in and released from above- and belowground biomass, dead organic matter (dead wood and litter), and soil organic matter. The carbon lost and GHG emitted during the removal of biomass by slash and burn practices is attributed to the year of conversion, and is therefore not included in the present study. For dead organic matter, only litter is taken into account, because data regarding dead wood is limited (Lasco et al., 2006). The annual change in carbon stocks in dead organic litter due to land conversion (ΔC_{Litter}) is calculated by the following formula:

$$\Delta C_{Litter} = \frac{(C_n - C_o)}{T_{on}} \qquad \text{Equation 3}$$

where C_n is litter stock under the new land-use category (kg C ha^{-1}), C_o is litter stock under the old land-use category (kg C ha^{-1}) and T_{on} is the time period of the transition from old to new land-use category (in years) (Aalde et al., 2006). Values for C_n, C_o and T_{on} have been gathered from literature. The annual change in soil organic carbon stocks in mineral soils ($\Delta C_{Mineral}$) is calculated by the following formula:

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D} \qquad \text{Equation 4}$$

where SOC_0 is soil organic carbon stock in the last year of an inventory time period (kg C), $SOC_{(0-T)}$ is soil organic carbon stock at the beginning of the inventory time period (kg C) and D is the time to reach an equilibrium SOC value (Aalde et al., 2006). The SOC values for tropical rainforest and cacao systems were gathered from literature. Whether a plot is converted from tropical rainforest to a cacao system is sourced from the UTZ survey.

2.7. Fieldwork

2.7.1. Purpose of fieldwork

Fieldwork was executed to improve the accurateness of sensitive parameters and to fill data gaps. Preliminary research and a simple sensitivity analysis (see Appendix V) show that information is limited concerning the fruits, pruning and soil amendments (Calvo Romero, 2018; Materechera, 2010; Alpízar, Fassbender, Heuveldop, Fölster & Enríquez, 1986; Urquhart, 1955; Schneidewind et al., 2018). For cacao fruits, usually only the semi-dry bean weight is available. Furthermore, data about the fruit is conflicting (see Appendix VI), highly variable across geographical regions (Campos-Vega, Karen, Nietro-Fugueroa & Oomah, 2018), and husk could refer to the husk of the bean as well as the husk of the fruit (Campos-Vega et al., 2018). Accurate information about the cacao fruit in kilograms, ratio beans/fruit and the dry weight considerably enhances the outcome of the model. Because hardly any data is available about the fruit weight in West-Africa and the model is relatively sensitive to the fruit weight and its management, measuring fruits was the focus of the fieldwork. Also pruning data is limited, especially the volume of pruning residues as a percentage of the crown and in kilograms biomass. Therefore, recording pruning residues was part of the fieldwork as well.

2.7.2. Site description

Fieldwork was conducted during November and December 2018, at the Centre National de Recherche Agricole (CNRA) research station, located near Divo, Republic of Côte d'Ivoire (5°46'21.6"N 5°13'45.4"W). The station is about 3,500 hectares and is mainly used for research on cacao, coffee, oil palm and kola (Calvo Romero, 2018). The Republic of Republic of Côte d'Ivoire has a tropical savanna climate (Köppen, 1918), with a mean temperature of 26°C and an average annual rainfall of 1500mm (Calvo Romero, 2018).

2.7.3. Selection of the trees

The field at which the fieldwork has been conducted is a former fertiliser experiment site which is currently used for research on pruning. The trees are 10 years old and spaced at 2.5 by 3 meter, resulting in 1,333 trees per hectare (Calvo Romero, 2018). The field experiment is a monoculture consisting of 4 by 6 blocks (see Appendix VII). In each block, 5 x 6 cacao trees are planted. All 48 trees in the inner part of the fertilised blocks were selected for measurements, to avoid the effect of fertilisation and the boundary effect.

2.7.4. Determining fruit biomass

Yield obtained during the survey is not comparable with how yield was originally defined in the IBM model. Since the IBM model is developed for apples, the IBM model assumes fresh fruit biomass as yield. Because cacao yield only includes commercial beans (8% moisture content), yield and fruit biomass are not the same. Therefore, the IBM model has been adjusted to estimate the dry cacao fruit biomass as follows:

$$dry\ cacao\ fruit = yield \bullet 0.92/percentage\ beans \qquad \text{Equation 5}$$

where *yield* refers to the semi-dry cacao bean yield reported by the respondent. Comprehensive information about the cacao fruits is important, in order to calculate the fruit residues and hence the GHG emissions as a result of their management.

Therefore, the aim of this part of the fieldwork was to obtain the following data:

- Percentage of the husk, including the placenta;
- Percentage of beans in the fruit, including the bean shells;
- DM percentage of the husk;
- DM percentage of the beans; and
- DM percentage of the fruit.

Within my study, fruit refers to the whole cacao fruit, including the husk, pulp, beans and bean shells (see Figure 3). The husk consists of the epicarp, mesocarp and endocarp and includes the placenta. The husk is considered as fruit waste. The beans include the bean shells and are the commercial product (also called yield). Both the beans and the pulp are farm output.

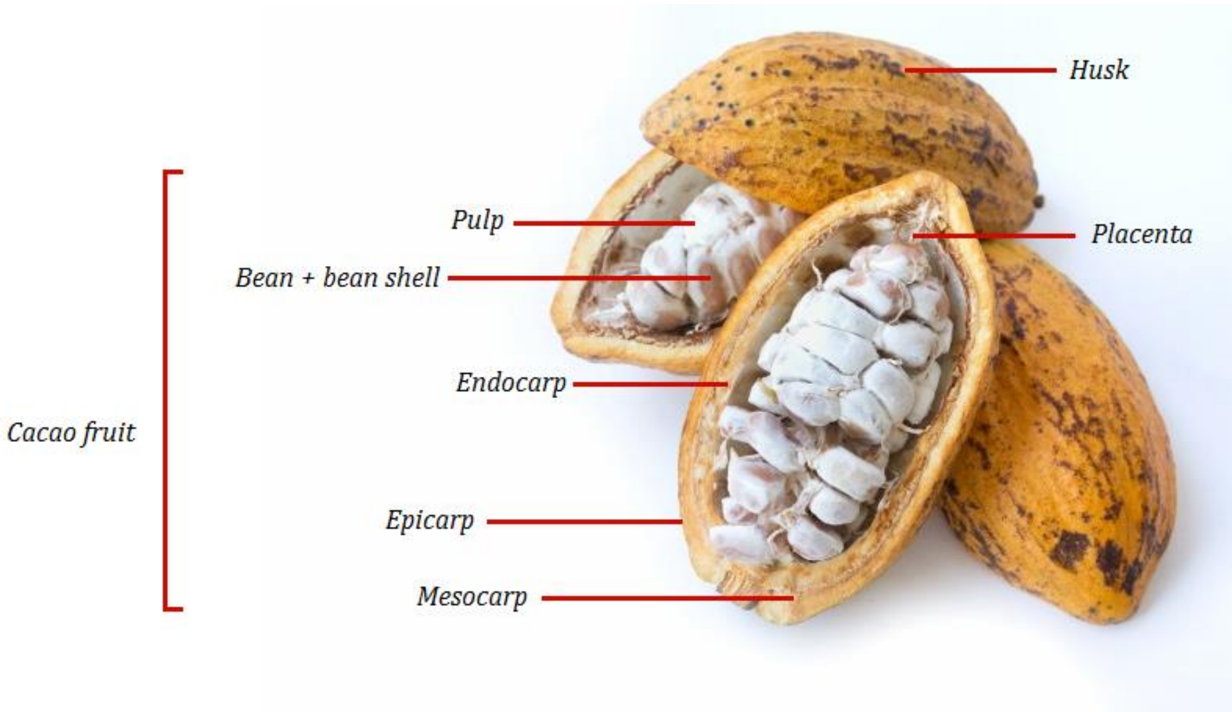

Figure 3 Cacao fruit, adapted from: Luamduan, n.d.[ii]

At the experiment, every three weeks all mature fruits were collected and counted. All mature fruits from one harvest flush during the yield peak in November have been collected, marked and counted, following the methodology described by Saj et al. (2017). Of all the fruits, the tree number, length, diameter and fresh weight (FW) were noted, based on the methodologies described by Fassbender, Alpízar, Heuveldop, Fölster and Enríquez (1988), Deheuvels, Avelino, Somarriba and Malezieux (2012), and Daymond and Hadley (2008). All samples were classified by fresh weight in the following categories: <300, 300-500 and >500 gram, based on the weight distribution described by Abenvega and Gockowski (2003), Vriesmann, de Mello Castanho Amboni and Oliveira Petkowicz (2011), Rucker (2009) and Apshara (2017). From each tree, one fruit has been selected for DM determination, selecting two fruits per fresh weight category per subplot, adding up to 48 fruits. Because some trees did not have fruits, a fruit of a tree within the same block and with the same management was chosen. When a fruit in a certain category was not available, the fruit closest to the category was chosen. The husk, pulp and beans were separated and their fresh weights noted (Fassbender et al., 1988; Daymond & Hadley, 2008). Subsamples of the samples were taken, weighed and dried in a dry oven for 96 hours at a temperature of 70 °C (Calvo Romero, 2018; Daymond & Hadley, 2008). Sub samples were weighted again, to calculate the wet to dry weight conversion ratio (Lockwood & Pang Thau Yin, 1996). Furthermore, the length and the diameter of the fruits is a good indicator for calculating the volume of the fruit (*V*). The volume can be calculated by using the shape of a prolate spheroid (ellipsoid), in the formula:

$$V = \frac{4}{3}\pi abc \qquad \text{Equation 6}$$

where a is the length in cm and b = c = the diameter in cm. The fruit density (p) can be calculated accordingly:

$$\rho = \frac{M}{V} \quad \text{Equation 7}$$

where M is mass in grams and V is the volume in g in cm^3.

2.7.5. Determining pruning biomass

Trees are pruned in various manners, usually adapted to local climatic conditions as well as to the growth phase of the cacao trees (Schneidewind et al., 2018; Urquhart, 1955). On some farms, mature trees are pruned once or twice every year while others are pruned with an interval of two years and even various non-pruned agroforestry systems exist (Schneidewind et al., 2018; Borden, Anglaaere, Adu-Bedu & Isaac, 2017). Other strategies include a light pruning annually and a heavy pruning once or twice during their lifetime (Borden et al., 2017). The IBM model is able to work with differentiated pruning strategies over time. The pruning interval is indicated per plot individually, sourced from the UTZ data. However, this data does not include the amount of biomass pruned, which is obtained during fieldwork.

The IBM model requires the percentage of biomass being removed (Ledo et al., 2018). This was calculated by dividing the fresh woody pruning residues by the total fresh woody biomass weight before the pruning intervention. The fresh pruning weight was obtained during fieldwork by separating the wood and leaves from the fresh pruning residues and weighing the woody biomass. The total fresh woody biomass weight before pruning can be estimated by an allometric function, based on data of the same field experiment (Calvo Romero, 2018). The allometric function for estimating the fresh woody biomass weight in kg per tree is as follow:

$$fresh\ AGBwoody = 2.8913e^{0.0145x} \quad \text{Equation 8}$$

where x is the stem circumference at 20 cm, R^2=0.94 (Calvo Romero, 2018).

2.8. Data analysis

Ideally, cacao production systems generate negative net GHG emissions, maximize carbon stocks, while optimising yields. It is highly debated whether trade-offs occur between carbon sequestration and yield in cacao systems (Somarriba et al., 2013; Magne et al., 2014). These two interrelated dimensions – carbon storage and yield – both need to be optimised in order to produce more climate-friendly cacao (Van Rikxoort et al., 2014), as the necessity to grow more cacao on less land is generally recognised (Wessel & Quist-Wessel, 2015). My study adds a third dimension, namely the GHG emissions resulting from MPs. So, climate-friendly cacao covers three aspects: GHG emissions, carbon stock in standing biomass and cacao yields. Three analyses were executed to assess these aspects, based on the methodology described by Van Rikxoort et al. (2014).

2.8.1. Balancing GHG emissions and yield

The 451 cacao plots from the UTZ survey are divided in four groups: those with GHG emissions above median and yield below median (Quadrant A) – the least desirable combination; those with GHG emissions below median and yield above median (Quadrant D) – the most desirable combination; and the two groups with intermediate combinations of GHG emissions and yield (Quadrants B and C). The MPs of Quadrant D will be compared with the others to identify which MPs are important to produce climate-friendly cacao. A two-sample T-test with assuming unequal variances was conducted to test whether the MPs of plots in Quadrant D were significantly different than the MPs in the other plots.

2.8.2. Balancing high carbon stocks and low GHG emissions

The 451 cacao plots from the UTZ survey are divided in four groups: those with a C stock above median and emissions below median (Quadrant A) – the most desirable combination; those with a C stock below median and GHG emissions above median (Quadrant D) – the least desirable combination; and the two groups with intermediate combinations of C stock and emissions (Quadrants B and C). The MPs of Quadrant A have been compared with the others to identify which MPs are important to produce climate-friendly cacao. A two-sample T-test with assuming unequal variances was conducted to test whether MPs of plots in Quadrant A were significantly different than MPs in the other plots. The carbon stored in annual growth of cacao and shade tree biomass are excluded from the GHG emissions (X-axis), as these are part of the carbon stocks (Y-axis).

2.8.3. Balancing high carbon stocks and high yields

According to Somarriba et al. (2013), it is a key question whether it is possible to design cacao plantations with large stocks of carbon both in the cacao and shade trees that also produce high yields. This part of the analysis attempts to give insight into this issue. Accordingly, the 451 cacao plots from the UTZ survey are divided in four groups: those with a C stock above average and a yield above average (Quadrant B) – the most desirable combination; those with a C stock below average and yields below average (Quadrant C) – the least desirable combination; and the two groups with intermediate combinations of C stock and yields (Quadrants A and D). MPs of Quadrant B have been compared with the others to identify which MPs are important to produce climate-friendly cacao. A two-sample T-test assuming unequal variances was conducted to test whether MPs of plots in Quadrant B were significantly different than the MPs in the other plots.

2.8.4. Assessing uncertainties

A sensitivity analysis determines how independent variables affect dependent variables. A parameter is sensitive when a minor change in a parameter has a strong effect on the GHG emissions. In this case, a simple sensitivity analysis was carried out to quantify the uncertainties mentioned in the discussion section. In order to do so, values of parameters or variables were adjusted with 10%.

3. Results from literature review

3.1. Biomass of cacao trees

As described in Section 2.3.1., 32 scientific papers have been consulted for the parameterisation of cacao biomass (see Appendix II). These papers reported biomass data of cacao production systems covering Bolivia, Brazil, Cameroon, Costa Rica, the Republic of Côte d'Ivoire, Ecuador, Ghana, India, Indonesia, Malaysia, Nigeria and Venezuela. The plantations described vary from 0.5 to 33 years old and the tree density varies between 625 and 2,500 cacao trees per hectare. Only 3 studies were complete, in the sense that they covered the total aboveground biomass, belowground biomass, the woody biomass (stem and branches), the leaf biomass, the age of the plantation and the tree density (Beer et al., 1990; Calvo Romero, 2018; Fisher, 2018). The data for biomass is very diverse. The total biomass ranged from 0.00358 kg for a young seedling in Brazil (Baligar & Fageria, 2017) to 113 kg for a 19 year old tree in the Republic of Côte d'Ivoire (Calvo Romero, 2018). An overview of all data can be found in Appendix II. The data reveal differences per continent (see Figure 4). However, the biomass growth is dependent on many factors, such as spacing, pruning and the use of shade trees (Subler, 1994) and not enough data is available per continent to draw conclusions. Data for all contients was used, since the sample size for West-Africa alone is too small (n=15).

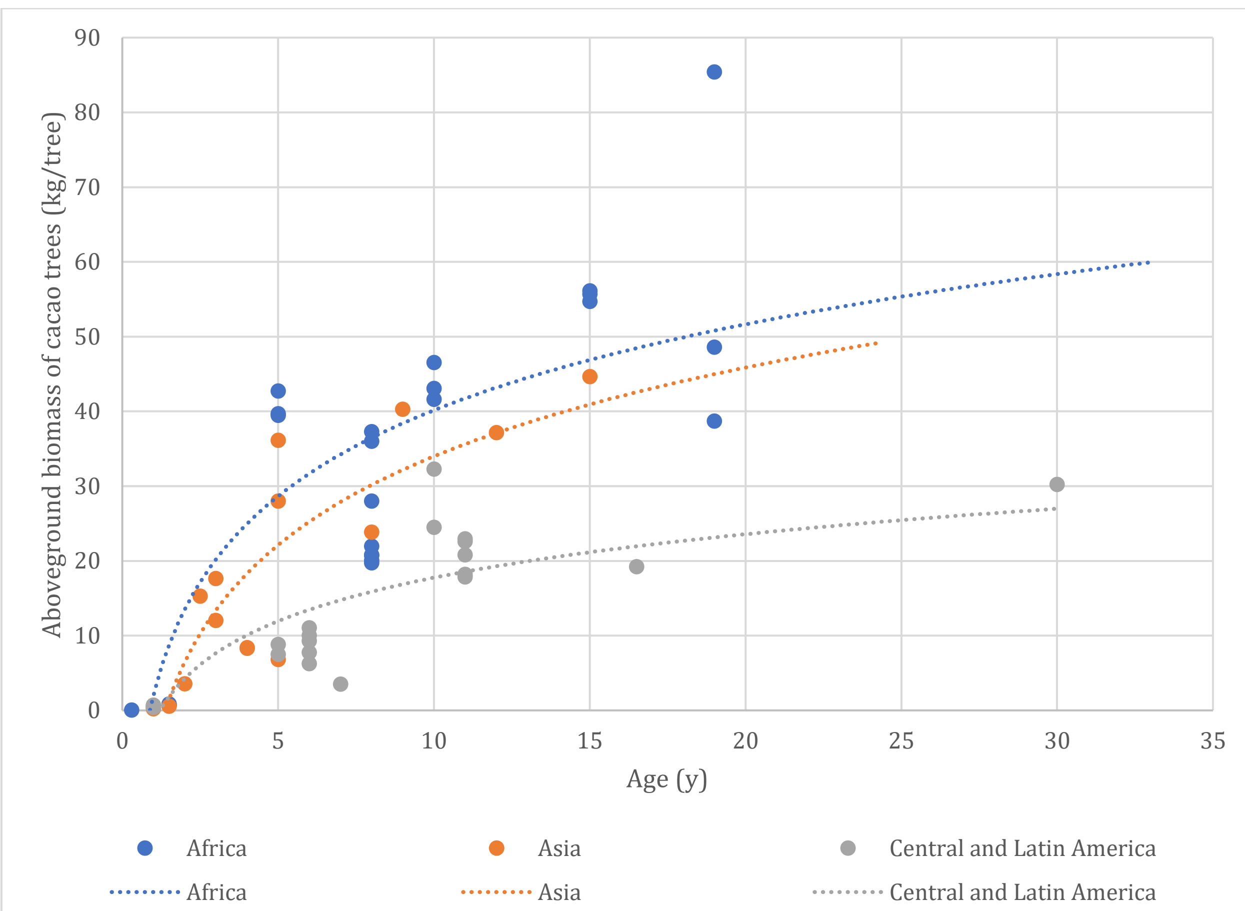

Figure 4 Aboveground cacao biomass per continent for Africa (R^2=0.61), Asia (R^2=0.73) and Central and Latin America (R^2=0.71)

3.1.1. Dry matter percentages of cacao tree organs

Although many studies calculate and use a DM percentage to calculate the dry biomass per hectare, not many of them report the DM percentage of crop organs itself (Alpízar et al., 1986; Baligar & Fageria, 2017; Beer et al., 1990; Borden et al., 2017; Isaac, Timmer & Quashie-Sam, 2007; Jaimez et al., 2017; Oladele, 2015; Da Silva Branco, Furtade de Almeida, Dalmolin, Ahnert & Baligar, 2017; Subler, 1994). Fortunately, Calvo Romero (2018) reported the DM percentage for all cacao tree organs. Calvo Romero (2018) reports a DM percentage of 41% for stem and branches and 38% for leaves.

3.1.2. Carbon and nitrogen content of cacao tree organs

The carbon content ranges from 47% in the leaves (Calvo Romero, 2018) to 50% in woody biomass (N'Guessa N'Gbala et al., 2017). The nitrogen content ranges from 0.21% in the woody biomass (Calvo Romero, 2018) to 2.8% in the fruits (Hartemink, 2005). For carbon, average values of 48%, 46%, 50% and 47% were found for wood, leaves, fruits and roots respectively (see Appendix III). For nitrogen, average values of 1.17%, 1.81%, 2.5% and 0.63% were found for wood, leaves, fruits and roots respectively (see Appendix III).

3.2. Number of cacao trees

The number of cacao trees is a substantial determining factor for the carbon stored in standing biomass as well as the yield. Unfortunately, the number of cacao trees per hectare was not well recorded during the UTZ survey. Therefore, the number of cacao trees per hectare is assumed to be uniform and based on literature. The cacao tree density varies across the world, ranging from 625 to 2,500 trees per hectare (Jacobi et al., 2013; Niether et al., 2018; Schneider et al., 2016; Isaac, Ulzen-Appiah, Timmer & Quashie-Sam, 2007). In West-Africa, cacao trees are generally spaced at 3x3 meter, resulting in 1,111 cacao trees per hectare (Asare, 2016; Hardy, 1960; Borden et al., 2016; Dawoe, Isaac & Quashie-Sam, 2010; Magne et al., 2014).

3.3. Infected fruits

The percentage of infected fruits described in literature is diverse. Vanhove, Vanhoudt and van Damme (2015) conducted a field experiment in Malaysia and found a range between 0.16 and 14.12% infected fruits. Ten Hoopen, Deberdt, Mbenoun and Cilas (2012) conducted a field experiment in Cameroon and found that 47% of the fruits were infected or eaten. It is, however, generally accepted that 20-40% of the cacao yield is lost due to pest and diseases in West-Africa (Wessel & Quist-Wessel, 2015; Ten Hoopen, Deberdt, Mbenoun and Cilas, 2012). Therefore, it is assumed that 30% of the cacao fruits are infected.

3.4. Management of cacao litter

The management of litter fall is not reported in the UTZ survey executed by Ingram et al. (2017). Therefore, a uniform practice is assumed for all respondents. Muoghula and Odiwe (2011) assume that cacao tree litter returns to the soil, where it is decomposed by organisms. Also Hartemink (2005) assumes in his study that cacao tree litter does not leave the farm boundary. Hence, litter is assumed to be left on the soil in all plots, where it is decomposed.

3.5. Cacao trees that die annually

According to Wessel and Quist-Wessel (2015), cacao farmers in the Republic of Cote d'Ivoire are dealing with high tree mortality due to inappropriate cultivation practices. Even so, Ten Hoopen et al. (2012) report that up to 10% of the cacao trees die because of the disease *Phytophthora palmivora*. Unfortunately, an exact percentage of cacao trees that die annually could not be found in literature. Even so, the management of dead trees remains unclear. Due to this lack of data, it is assumed that none of the cacao trees die annually. This assumption would not cause great inaccuracies because farmers generally replant dead trees (Wessel & Quist-Wessel, 2015). So the number of trees remains more or less the same over time, while the age of the cacao trees within a plot might vary.

3.6. Decomposition rates of cacao organs

For cacao litter, the annual decomposition rates (k-value) found in literature are diverse. Dawoe et al. (2010) found an average k-value of 0.23, whereas Fontes et al. (2014) found k-values in the range between 0.46 and 0.92. Materechera (2010) specified the k-values for cacao organs separately and reported a k-value of 0.63 for cacao leaves, 1.27 for cacao wood and 1.64 for the reproductive parts. For cacao roots, both Muñoz and Beer (2001) and Van Vliet and Giller (2017) reported a k-value of 1. So, k-values of 0.63, 1.27, 1.64 and 1 were assumed for leaves, wood, cacao fruit and roots respectively.

3.7. Fertiliser application

The recommended application rates for commonly used fertilisers can be found in Appendix XI. For other fertiliser types, a standard application is assumed. According to Loué (1961), a fertiliser application of 60 gram nitrogen per tree is a general recommendation for cacao systems. An application of 60 gram nitrogen results in 67 kg nitrogen per hectare, assuming a cacao tree density of 1,111. For compost, a uniform amount of 6 kg per tree is generally applied (Koko et al., 2013; Vanhove et al., 2015). Although the nitrogen content of compost is highly variable (Adejobi et al., 2014; Munongo, Nkeng & Njukeng, 2017; Quaye, Konlan, Arthur, Pobee & Dogbatse, 2017; Kayode et al., 2018), it is assumed that compost consists of 2.75% nitrogen (Koko et al., 2013).

3.8. Soil and weather conditions

Of all the 451 cacao plots from the UTZ survey, 84% are located on medium and 16% on coarse soils. The average soil organic matter is 3.9% and the soil pH is 5.5 for all plots. All soils are moist, 62% of the plots are well drained while 38% has poor soil drainage. The average temperature over the years 1987-2016 is 26.5°C.

3.9. GHG emissions from deforestation

3.9.1. Dead organic matter

The Tier 1 assumption made by Aalde et al. (2006), is that litter pools in non-forest land categories after the conversion contain no carbon and that all carbon in litter is lost in the year of land-use conversion. However, soils in cacao systems are generally mulched with leaf litter (see Section 3.4.). Therefore, data reported by Dawoe et al. (2016) is used to calculate the annual change in carbon stocks in dead litter due to land conversion. Dawoe et al. (2016) found that litterfall for 3 and 15 year old cacao systems is lower than for a secondary forest, while in a 30 year old cacao system more litter is accumulated than in a forest (see Table 2). Therefore, a distinction is made between the age categories for determining C_n. The carbon in litter is calculated by using a carbon fraction of 50% (Lasco et al., 2006), so C_0 is 4,400 kg C ha^{-1}. The annual change in carbon stocks in litter due to land conversion for three cacao systems can be found in Table 3.

Table 2 Total litterfall (leaves, twigs, small branches and reproductive parts) under forest and cacao systems at three age categories found by Dawoe et al. (2016)

Land use	Total litter (kg DM ha^{-1})
Forest	8,800
Cacao 3 years	5,000
Cacao 15 years	8,000
Cacao 30 years	10,000

Table 3 Annual change in carbon stocks in litter due to land conversion ($\triangle C_{Litter}$) for three cacao systems on the basis of litter stocks (C_n)

Cacao system	C_n (kg DM ha^{-1})	$\triangle C_{Litter}$ (kg C ha^{-1} year^{-1})
Cacao systems 0-3 years	2,500	-633
Cacao system 4-15 years	4,000	-27
Cacao systems >16 years	5,000	20

3.9.2. Soil organic matter

Soil organic carbon can change with management or disturbance if the net balance between carbon inputs and losses from the soil is altered (Aalde et al., 2006). The change is computed based on the carbon stock after the land use change relative to the carbon stock before the land use change. Dawoe et al. (2016) reported the percentage of carbon in the first 20 cm of the soil under a secondary forest and cacao systems of three different ages (see Table 4). The carbon stock can be calculated by the bulk density. The calculated $SOC_{(0-T)}$ is 44,000 kg C ha^{-1}. The annual change in carbon stored in organic matter can be found in Table 5.

Table 4 Bulk density and organic carbon under forest and cacao systems at three age categories found by Dawoe et al. (2016)

Land use	Bulk density (gm cm^{-3})	Organic C (%)
Forest	1.1	2
Cacao 3 years	1.3	1.4
Cacao 15 years	1.2	1.7
Cacao 30 years	1.2	1.7

Table 5 Annual change in carbon stored in soil organic matter ($\triangle C_{Mineral}$) for three cacao systems on the basis of soil organic carbon (SOC_0)

Cacao system	SOC_0 (kg C ha^{-1})	$\triangle C_{Mineral}$ (kg C ha^{-1} year^{-1})
Cacao systems 0-3 years	36,400	-2,533
Cacao systems 4-15 years	40,800	-213
Cacao systems >16 years	40,800	-107

4. Results from fieldwork
4.1. Fruit biomass

Following the methodology described in Section 2.7.4., 253 fruits were measured and weighted, and 42 fruits were analysed in more detail. Figure 5 presents an overview of all the fruits measured and the fruits selected for DM determination.

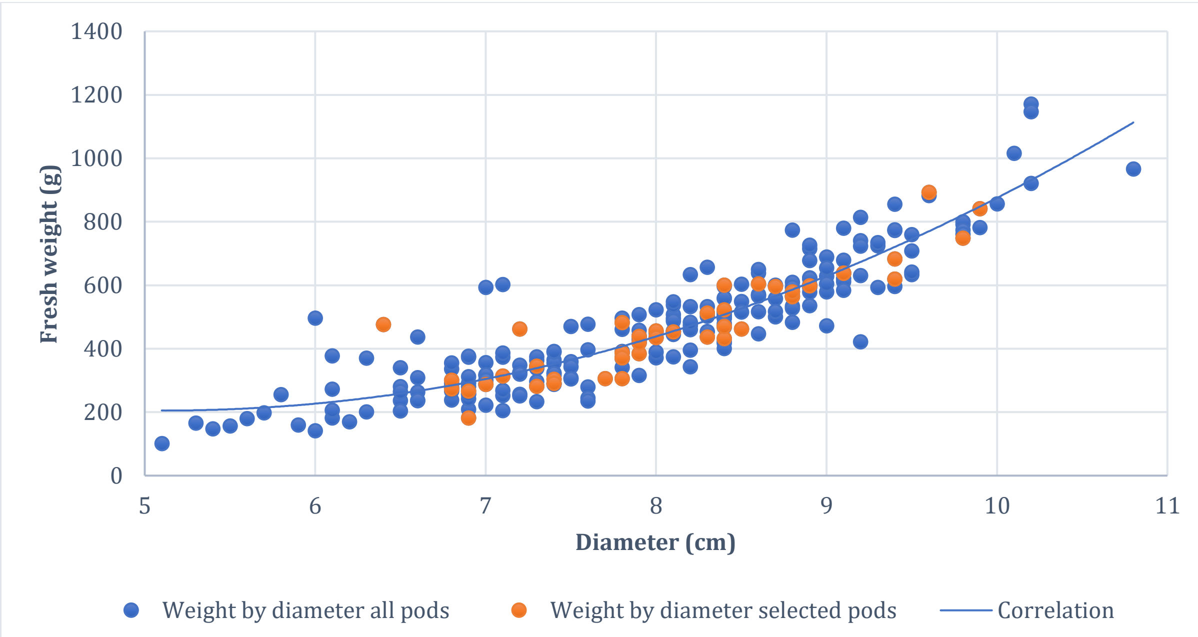

Figure 5 Weight and diameter of all fruits and selected fruits for further research. Fresh fruit weight (g): $y=28x^2-288x+942$, $R^2=0.84$

The length, diameter and hence the volume of the fruits is highly diverse. The length of all mature fruits varies between 9 and 24.5 cm, and the diameter between 5.1 and 10.8 cm. The volume of the fruit varies between 919 and 10,010 cm^3, while the density is rather constant around 0.11 g per cm^3. The fresh weight of the fruits varies between 100 and 1,170 g, with a mean weight of 429 g. The number of beans per fruit vary between 14 and 59 with a mean value of 33.

Although not required for this research, the following finding might be useful for future research. The results indicate that the fresh weight of the fruits can best be determined by the diameter instead of the length (see Appendix XII). The fresh weight of the fruit can be approached with

$$Y = 24.95e^{0.3566x} \qquad \text{Equation 9}$$

where Y is the fresh weight in g, and x is the diameter of the fruit ($R^2=0.81$).

<u>4.1.1. Determination of dry matter and percentage of beans</u>

The data for fresh and dry weight for both the husk and the beans show a large range. The fresh weight of the husk varies between 177 and 756 g. The DM percentage of the husk varies between 7 and 23% with a mean value of 15%. The fresh weight of the pulp and beans varies between 32 and 191 g. The sample contains four bad fruits (either infected or harvested while immature). When these four samples are neglected, the fresh weight of the pulp and beans varies between 45 and 191 g with a mean weight of 101 g. The DM percentage of the pulp and beans is 33%. All in all, this data results in 61% husk and 39% pulp and beans on the basis of DM (see Table 12). A weighted DM percentage for the fruit on the basis of the husk, pulp and beans would be 20%.

5. Results from UTZ survey

5.1. Shade trees

In most of the cacao plots (70%) shade trees are present, while shade trees are absent in only 9% of the plots. Of the other fields, respondents did not know how many shade trees were present. The shade tree density is, on average, 152 trees per hectare. In most of the plots (n=217) 100 or more shade trees are present per hectare.

5.2. Pruning management

Cacao trees are pruned in almost all of the plots (93%). In most of the plots, cacao trees are pruned every year. In 38% of the plots, cacao trees are pruned every two year or less than every two year. In 90% of the plots, the pruning residues are left on the ground, while in the remaining 10% of the plots the pruning residue is handled as a farm output. So in none of the plots, pruning residue is composted or burned.

5.3. Management of cacao husks

In most of the plots (73%), the cacao husks are left in the field. In 24% of the fields, cacao husks are composted. Because the survey does not contain information about the composting technology, it is assumed that an open compost technology is used in this case (Doungous, Minyaka, Morel Longue & Nkengafac, 2018; Fidelis & Rajashekhar Rao, 2017; Vos, Ritchie & Flood, 2003). In 4% of the plots the cacao husks are handled as farm output, and in none of the plots cacao husks are burnt.

5.4. Management of infected fruits

Almost all of the respondents (88%) report that they have infected fruits. In most of the fields (74%), infected fruits are left in the field, sprayed or not. In some plots (30%), infected fruits are removed from the plots. In 8% of the fields, infected fruits are composted and in 6% of the plots unsuitable fruits are burnt. The percentages do not sum up to 100%, because respondents could choose more than one option.

5.5. Fertiliser application

In 26% of the cacao plots, compost is applied. Other types of fertiliser are applied in 60% of the cacao plots. In most of these fields (57%), *supercao* or *NPK 023* is applied (see Table 6). Both of these fertiliser types do not contribute to field emissions, as these do not contain nitrogen. In 18% of the plots, a fertiliser type was used without being specified by the respondent.

Table 6 Fertiliser application. Fertiliser types used; number of plots in which a fertiliser type is used; and a percentage of the plots in which a fertiliser type is used, expressed as a percentage of plots in which fertiliser is used (n=270).

Fertiliser type	Number of plots	Percentage of plots
NPK 023	91	34
Supercao	62	23
Yara	14	5
Chicken manure	10	4
Cocofeed	5	2
Nitrabor	5	2
Sidalco	4	1
Biodepost	4	1
LDC 023	3	1
Urea	3	1
Supergro	3	1
Organic	2	1
Biopower	2	1
Tao-tao	1	0
Base vital	1	0
Other	48	18

6. Results from modelling

6.1. Cacao biomass growth

<u>6.1.1. Modelled parameters to estimate cacao biomass growth over time</u>

When loading biomass data into the IBM model, the model derives the required coefficients *a* and *b* for Equation 1, to predict biomass growth over time (the IBM biomass script can be found in Appendix XIII). With the collected data on cacao, the IBM model derives the coefficients shown in Table 7, with corresponding functions shown in Figure 6.

Table 7 Biomass parameters. AGB_y is aboveground biomass by year, AGW_y is woody aboveground biomass by year, LEAF_AGW is the leaf biomass by the woody aboveground biomass and BGB_y is the belowground biomass by year.

	a AGB_y	b AGB_y	a AGW_y	b AGW_y	a LEAF_AGW	b LEAF_AGW	a BGB_y	b BGB_y
Cacao	5.8283	0.6988	7.4461	0.4010	0.6759	0.5941	2.7646	0.5111

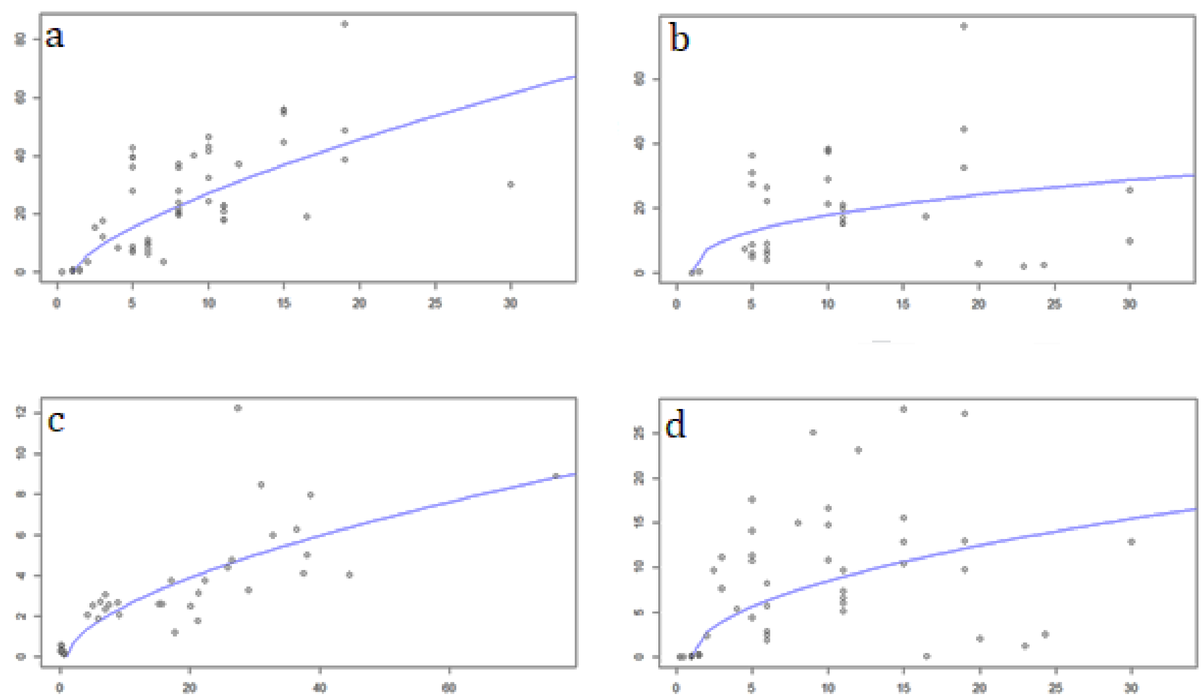

Figure 6 Biomass growth over time. a: aboveground biomass (kg) by age (year). b: woody AGB (kg) by age (year). c: aboveground woody biomass (kg) by age (year). d: belowground biomass (kg) by age (year).

<u>6.1.2. Modelled biomass of pruning residues</u>

It turned out that the pruning percentage caused problems in the IBM model. The pruning percentage obtained during fieldwork was 16% (see Appendix IX). This percentage is higher than the percentage of woody biomass that is grown annually. In case cacao trees are pruned annually, 16% of the woody biomass would be removed annually. This pruning regime results in an annual decrease of woody biomass. This is not realistic and therefore another pruning regime was assumed, based on the maximal natural regrowth of the woody biomass. The pruning percentages are therefore based on the age of the cacao trees and can be found in Table 8.

Table 8 Pruning percentages based on cacao plot age. Cacao trees are not pruned in the first six years.

Age (y)	% Pruning	Age (y)	% Pruning	Age (y)	% Pruning	Age (y)	% Pruning
1	-	11	4	21	2	31	1
2	-	12	3	22	2	32	1
3	-	13	3	23	2	33	1
4	-	14	3	24	2	34	1
5	-	15	3	25	2	35	1
6	-	16	3	26	2	36	1
7	6	17	2	27	2	37	1
8	5	18	2	28	1	38	1
9	5	19	2	29	1	39	1
10	4	20	2	30	1	40-70	1

6.1.3. Modelled cacao biomass of the surveyed plots in the Republic of Côte d'Ivoire

On the basis of the parameters mentioned in Section 6.1.1., the IBM model calculates the amount of cacao biomass grown in 2017 and cumulative over the life time for the cacao trees for each plot separately (see Appendix X for the final IBM script). As can be seen in Table 9, wood is the largest part of the cacao biomass, followed by the roots, fruit and leaves. However, it needs to be mentioned that the wood biomass values given in Table 9 are before pruning. To know how much net wood biomass is 'added' in the plots, the pruning biomass needs to be subtracted.

6.1.4. Modelled carbon stored in biomass in the surveyed plots in the Republic of Côte d'Ivoire

As can be seen in Table 9, a considerable amount of biomass is annually accumulated in cacao fruits. Even so, cacao fruits accumulate most of the carbon in the cacao tree biomass annually, followed by wood, roots and leaves. Altogether, an average cacao plot turns 3,817 kg atmospheric CO_2 into biomass per hectare annually. Apart from annual biomass and carbon accumulation, the biomass and carbon accumulated in cacao standing biomass can be found in Table 10. Most biomass and carbon is accumulated in the wood, followed by the fruits, roots and leaves. On average, a plot stores 30,671 kg carbon in its cacao standing biomass per hectare (see Table 10). Apart from carbon stored in cacao biomass, most of the carbon is stored in shade tree biomass. Of all the carbon stored in standing biomass in all the 1,559 hectares, 69% is stored in shade trees. Shade trees store on average 92 ton carbon per hectare, of which more than 9 ton carbon is accumulated in biomass grown in 2017.

Table 9 Cacao biomass and carbon stored in cacao biomass, accumulated in 2017

Cacao biomass (kg DM ha^{-1} $year^{-1}$)		
Plant part	Mean	Standard deviation
Wood*	703	30
Leaves	122	11
Fruit	888	25
Root	429	12
Total trees	2,142	-
Carbon stored in cacao biomass (kg ha^{-1} $year^{-1}$)		
Plant part	Mean	Standard deviation
Wood*	340	15
Leaves	56	5
Fruit	443	13
Roots	202	6
Total trees	1,041	-

* Before pruning

Table 10 Total cacao standing biomass and carbon stored in cacao standing biomass, accumulated during the complete time-span of a cacao plot

Cacao biomass (kg ha^{-1})		
Plant part	Mean	Standard deviation
Wood	22,924	272
Leaves	6,644	48
Fruit	19,789	737
Roots	14,169	199
Total trees	63,526	-
Carbon stored in cacao biomass (kg ha^{-1})		
Plant part	Mean	Standard deviation
Wood	11,077	131
Leaves	3,047	22
Fruit	9,879	368
Roots	6,668	94
Total trees	30,671	-

6.2. Modelled GHG emissions of cacao production of the surveyed plots in the Republic of Côte d'Ivoire

Perennials such as cacao may have net zero or even negative emissions (Ledo et al., 2018). The present study reveals that for the production of 693 ton cacao beans, 2,472 ton CO_2-equivalents are emitted (including the plots that emit GHG but are not productive yet) (see Table 11). So on average, 3.6 kg CO_2-equivalents are emitted per kilogram of cacao produced. Nevertheless, high variation occurs among plots, ranging from 212 kg CO_2-equivalents stored to 116 kg CO_2-equivalents emitted per kilogram of cacao. On average of all plots, composting residues is responsible for 84% of the GHG emissions, while the GHG emissions from the soil and fertiliser application were responsible for 7%, burning residues for 8% and deforestation for only 2% (percentages do not add up to 100% because of rounding numbers). 78% of the GHG storage of cacao production was due to shade tree biomass, 20% due to cacao tree biomass and 2% due to leaving biomass residues on the soil. Shade trees and composting practices explain the largest part of the GHG emissions stored and emitted, see Figure 7. These results confirm the important role of shade trees in terms of carbon storage (Magne et al., 2014). Because the plantation age determines the amount of accumulated carbon in biomass in shade- and cacao trees and hence the GHG emissions from residue management, it was tested whether the plantation age is a strong determinant of the GHG emissions per kilogram of cacao. Furthermore, yield as a determining factor was tested. Both factors (plantation age and cacao yield) were not strongly correlated with the GHG emissions per kilogram of cacao produced (see Appendix XIII). This result indicates that the residue management and shade tree density are more important in explaining the GHG emissions than the accumulation rate of biomass itself.

Table 11 Absolute greenhouse gas emissions (in kg CO_2-equivalents) for all surveyed plots

Average GHG emissions per plot	5,494
Standard deviation	3,717
Minimum	-588,764
Maximum	539,964
Sum of all plots	2,472,307

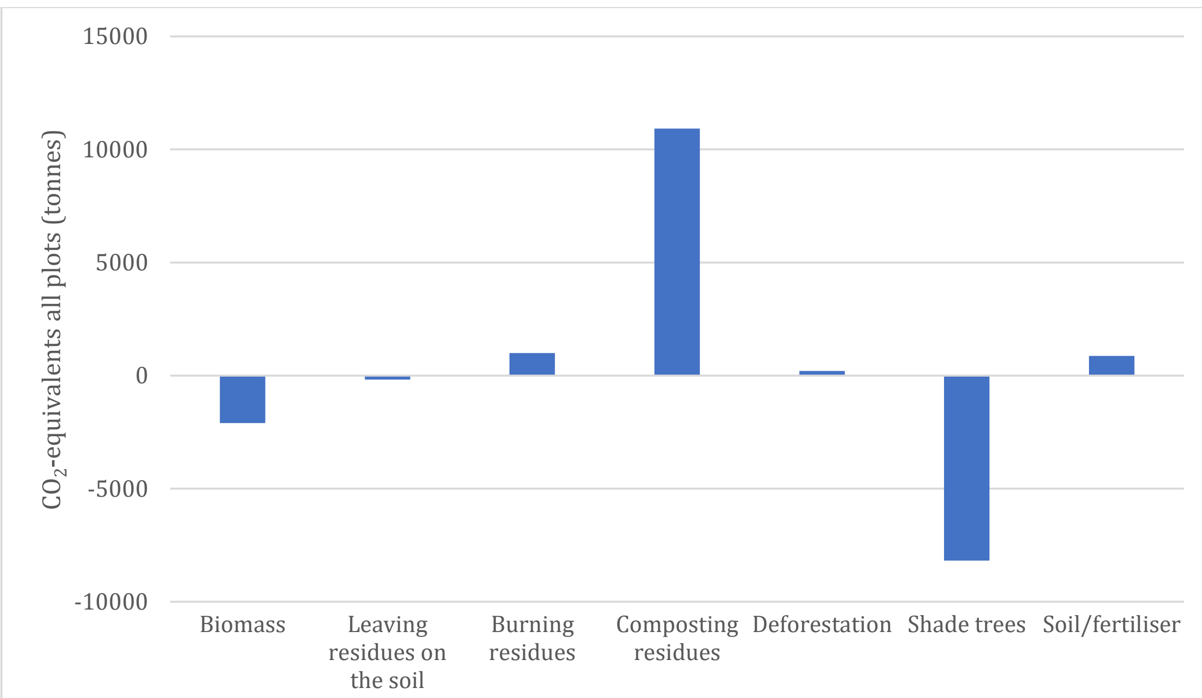

Figure 7 CO_2-equivalents annually emitted or stored per management practice, where positive values mean emissions while negative values mean storage.

<u>6.2.1. Balancing GHG emissions, yield and carbon stocks</u>

6.2.1.1. Balancing GHG emissions and yields

From the data in Figure 8, it is apparent that relatively few plots belong to Quadrant D. However, these plots are the most interesting, because these show that both storage of GHGs and high yields is attainable. It is therefore that MPs of the plots of Quadrant D are compared with MPs of Quadrant A, B and C. On average, the plots of Quadrant D are similar in age and area compared with plots of the other quadrants. Because of the selection criteria, only plots with above median yields belong to Quadrant D. It is therefore not surprising that yields of plots of Quadrant D (615 kg ha^{-1}) are significantly higher than yields of plots of the other quadrants (412 kg ha^{-1}). Despite the higher yields in plots of Quadrant D, less fertiliser and compost is applied in these fields. However, it must be noted that the difference in the application of fertiliser and compost between plots in Quadrant D and plots in other quadrants is not significant. Furthermore, a significant higher percentage of cacao biomass residues is treated as a farm output in plots of Quadrant D, compared to the other plots. Also, a significant lower percentage of cacao husks are composted in plots of Quadrant D. Because composting is associated with considerable GHG emissions, the above mentioned observation might be the reason why plots in Quadrant D score so well on the emissions part. The most striking result to emerge from the data, is that plots of Quadrant D have a significant higher number of shade trees (317 trees ha^{-1}) than the others (108 trees ha^{-1}).

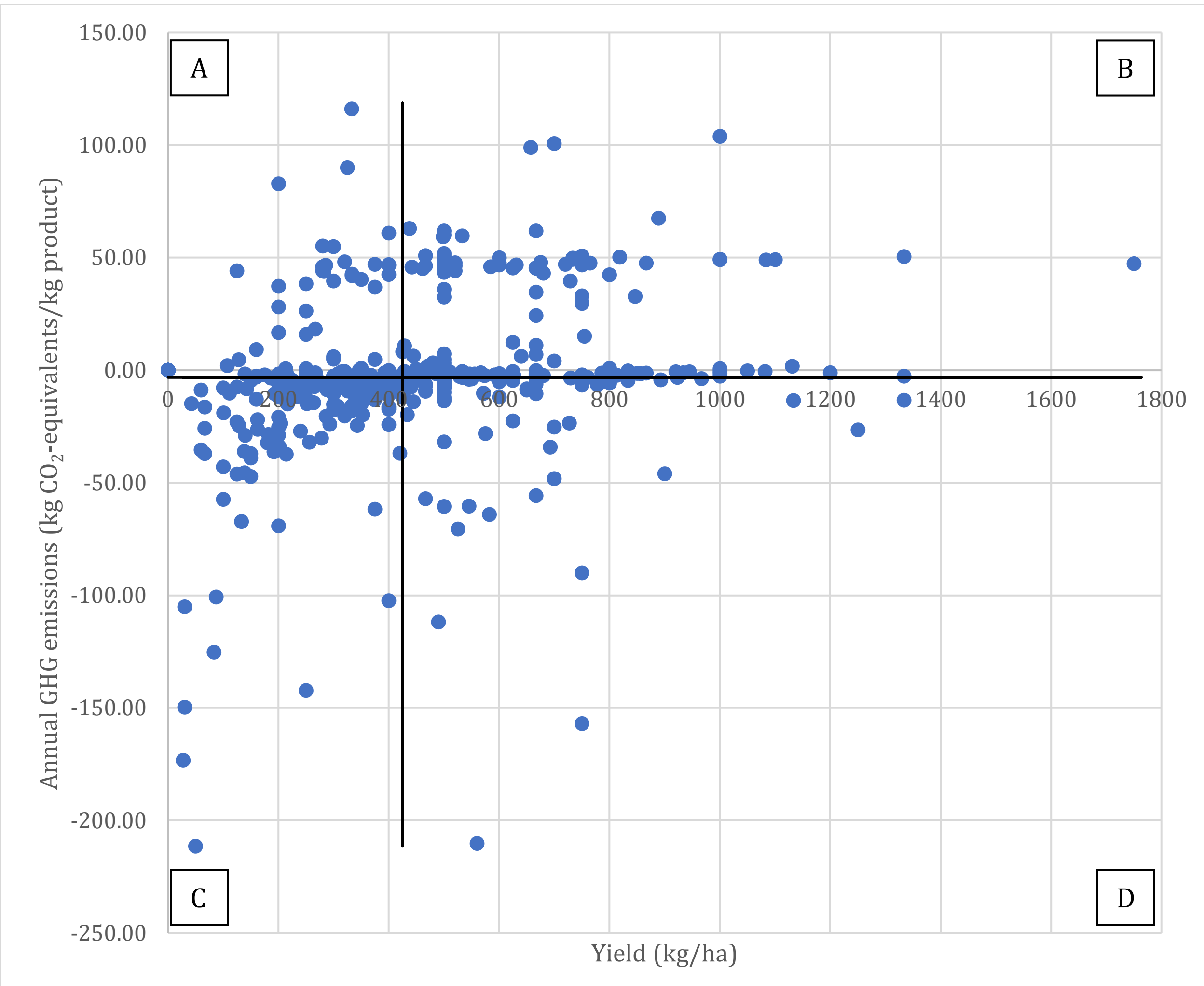

Figure 8 Relation between annual GHG emissions (including cacao and shade tree biomass, application of fertiliser and burning, composting and leaving on the ground biomass residues) and plot yield.

6.2.1.2. Balancing carbon stocks and yields

In Figure 9, the carbon stored in biomass and cacao yields are plotted. On average, the plots of Quadrant B are similar in size and somewhat older (23 compared to 21 years). The latter is not surprising, as trees accumulate carbon in their biomass over the years. Also, less trees in plots of Quadrant B are pruned, resulting in a higher standing biomass. Yields of plots of Quadrant B (654 kg ha^{-1}) are much higher than the yields of the others (379 kg ha^{-1}). However, no difference could be observed in the application of fertiliser and compost between plots of Quadrant B and the other plots. The more interesting difference between plots of Quadrant B and the others in the data is the difference in shade trees. Plots of Quadrant B have on average 298 shade trees per hectare, compared to 86 shade trees per hectare in the other plots. It must be noted that only the latter difference was found to be statistically significant.

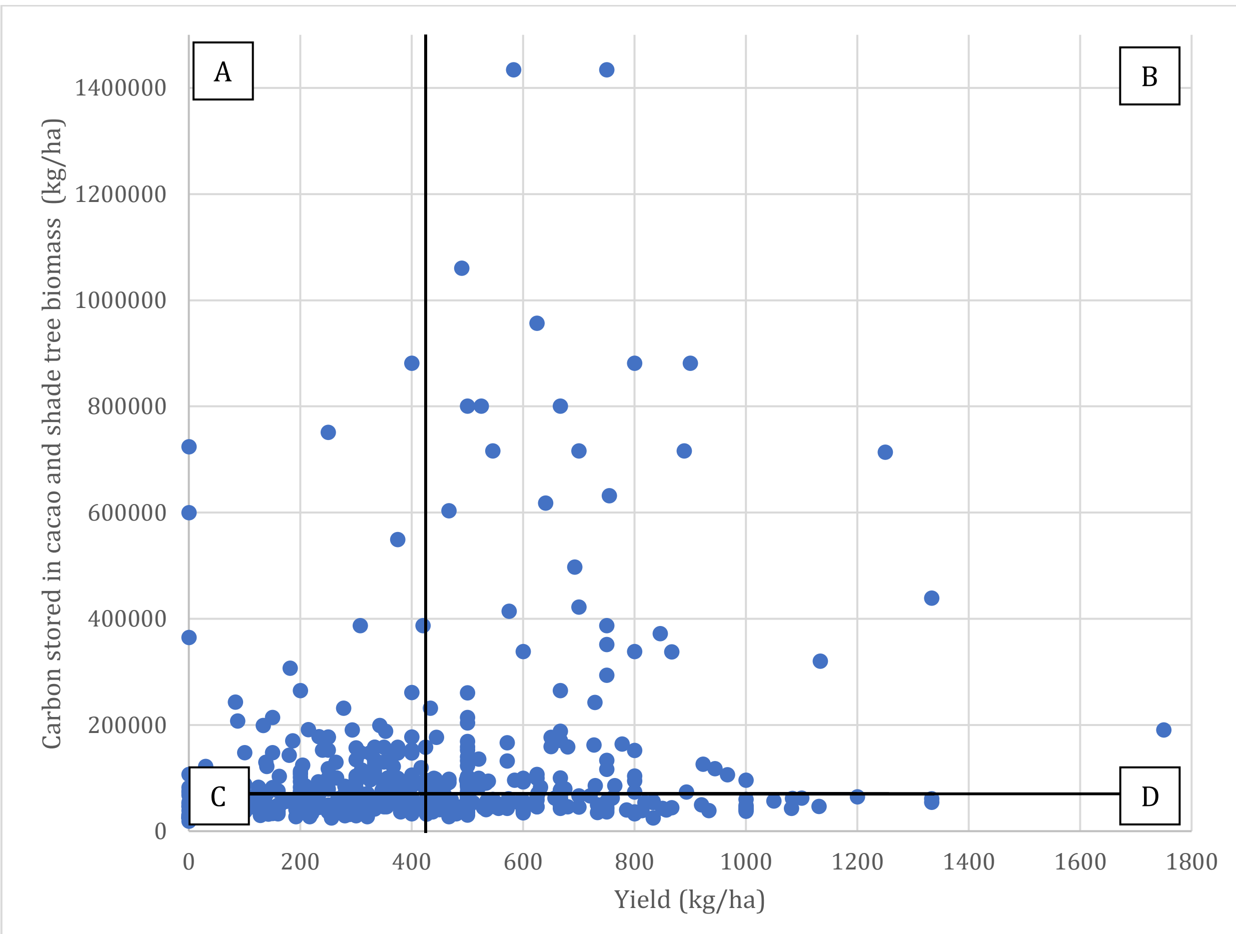

Figure 9 Carbon stored in cacao and shade tree biomass and cacao yield

6.2.1.3. Balancing high carbon stocks and low emissions

In Figure 10, the carbon stocks and GHG emissions per kilogram of cacao are plotted. On average, the plots of Quadrant A are similar in size and produce significant more cacao than the other plots (500 kg ha^{-1} compared to 429 kg ha^{-1}). Furthermore, the plots of Quadrant A (on average 26 years old) are significant older than the others (on average 20 years old). The more interesting difference between the plots is the management of cacao fruit residues. In none of the plots of Quadrant A, cacao husks or unsuitable fruits were composted. Instead, significant more of the cacao residues are left in the field or treated as a farm output in the plots of Quadrant A. Again, a big difference between the plots is due to shade trees. Plots of Quadrant A have on average a shade tree density of 235 trees per hectare, while the shade tree density of other quadrants is only 118 trees per hectare.

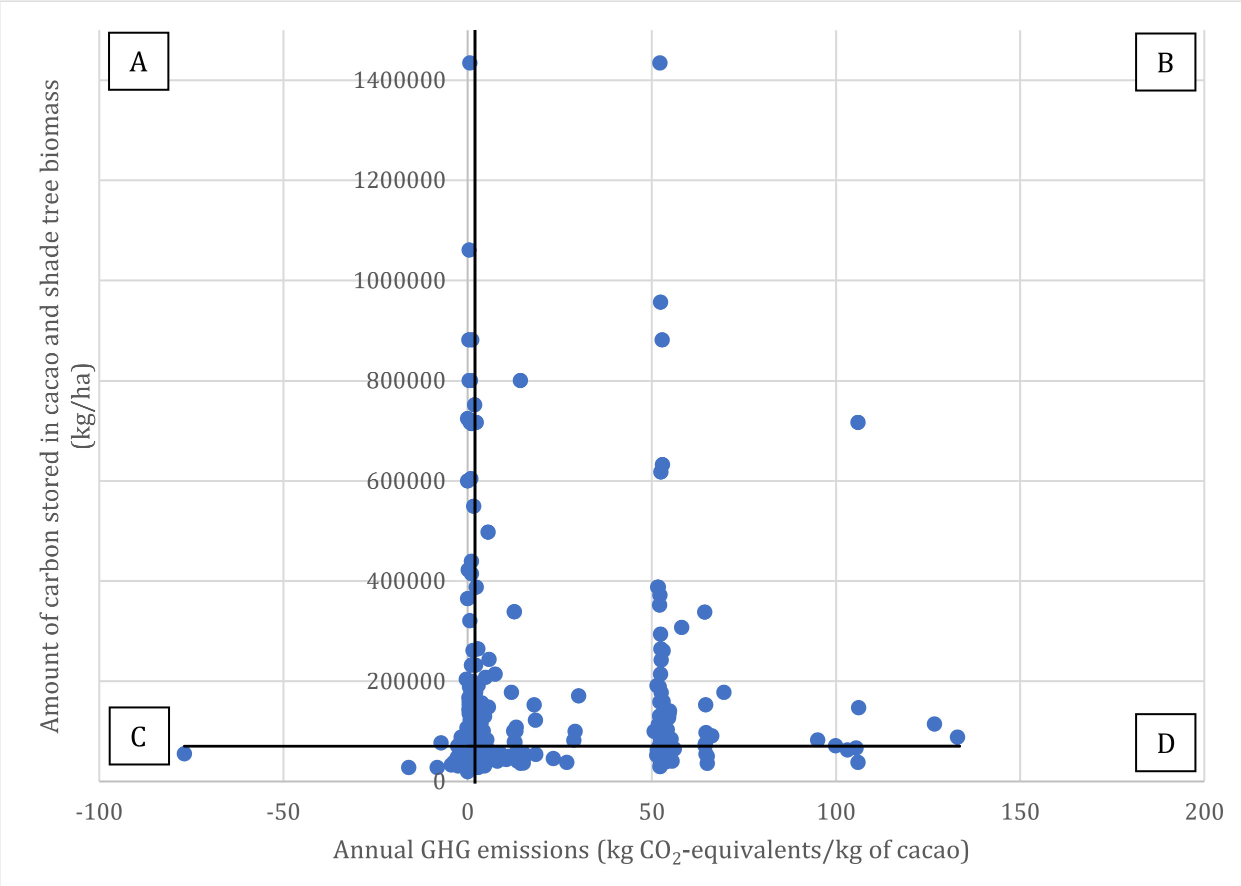

Figure 10 Carbon stored and GHG emissions (including application of fertiliser, and burning, composting and leaving on the ground biomass residues)

7. Discussion

7.1. Discussion of the methodology

7.1.2. Fieldwork

During the drying process of cacao husks, beans and pulp, the samples grew moldy. The mold is included in the dry weight of the cacao husks and beans and pulp, which might have led to an overestimation of the DM percentage for the cacao husks, beans and pulp and the cacao fruit in total. A sensitivity analysis shows that a 10% change in DM percentage of the cacao fruit and husk causes a bigger relative change in total GHG emissions (see Appendix V). This result indicates that the GHG emissions are strongly affected by the DM percentages of the cacao fruits (used to calculate the GHG emissions from composting fruit residues). In other words, the IBM model is sensitive to changes in DM percentages of the cacao fruit. Although the sensitivity analysis suggests a strong uncertainty, moldy samples unlikely caused a 10% change in DM percentages. Therefore, uncertainties resulting from moldy samples are neglectable, probably not strongly influencing the GHG emissions associated with cacao production.

7.1.3. Plot size and cacao yield

During the UTZ survey, 70% of the plot sizes were measured by using a GPS. For the other 30%, plot sizes were based on the estimations given by respondents. According to Jagoret (2017), farmers usually overestimate their plot size, resulting in lower yields per hectare. Likewise, Smiley and Korschel (2010) conclude in their study that farmers have difficulties with correctly estimating their cacao yields. This inaccurate estimate of yield per hectare might affect the calculated GHG emissions, due to emissions resulting from fruit residue management. This statement was tested with a simple sensitivity analysis. The result shows that a 10% change in cacao yield results in a larger relative change in total GHG emissions as well as expressed per kilogram of cacao yield. This again stretches the importance of cacao yield in the IBM model, as the IBM model is sensitive to cacao fruit parameters. The accuracy of cacao yields and fruit biomass is further discussed in Section 7.3.4.2..

7.1.4. Shade trees

On average 10 shade tree species are grown in cacao plantations (Smith Dumont et al., 2014), while in the present study it was assumed that only one species of shade trees was grown, *Nauclea diderrichii*. Moreover, this tree species is only grown in 5% of the cacao plantations in the Republic of Côte d'Ivoire (Smith Dumont et al., 2014), and therefore not representative for the shade tree biomass in the cacao plots of the Republic of Côte d'Ivoire. Besides, this tree species is naturally regenerated (Smith Dumont et al., 2014) and not planted simultaneously with cacao seedlings, contrary to what is assumed in the present study (see Section 2.5.). Because shade trees are regenerated, their age is probably lower than assumed in the present study, leading to an overestimation of carbon stored in shade tree biomass. This uncertainty has been quantified. The result shows that a 10% change in shade tree biomass results in a larger relative change in total GHG emissions (see Appendix XIV). This result indicates that the GHG emissions are strongly affected by shade tree biomass, indicating large uncertainties. To see whether these uncertainties actually caused unrealistic results in terms of GHG emissions associated with cacao production, carbon stored in shade trees is compared with literature in Section 7.3.5.1..

All in all, many assumptions had to be made and standard data had to be used to estimate carbon stored in shade tree biomass. Although much is written about shade trees and many allometric functions to estimate their carbon storage are developed, on the annual accumulation of carbon in their standing biomass related to their age is not yet reported. Studies assessing carbon stored in shade trees generally report mean values and findings, rather than making available the data they collected, such as stem diameters, total biomass and tree ages. This limited the development of an allometric function calculating shade tree biomass on the basis of age as part of my study. Since shade trees have a strong effect on the GHG emissions and carbon stored in standing biomass, it would be relevant for future studies to assess the amount of carbon stored in shade trees related to the age of cacao plantations.

7.2. Discussion of the models

Each model is a simplification of reality and therefore only a limited part of reality is assessed (Müller, Breckling, Jopp & Reuter, 2011). Because of that, each model has its limitations. The CFT and the IBM model are inductive models, which means that the models are based on empirical data. Both models are dynamic explanatory models, as these are based on causal relationships, require high data inputs and involve a time-aspect. Both models quantify cause and effect, but states and rates are only considered in the IBM model. Unfortunately, not all parts of the IBM model interact with eachother. For example, the biomass growth of the cacao trees is independent of the MPs (e.g. no difference in cacao biomass exists between plots were compost is applied or not). Pruning is an exception here, because the woody biomass is a result of the pruning regime. Although the IBM model is able to simulate nutrient limited biomass growth, parametrising this limited growth was beyond the scope of the present study. Future studies can considerably enhance the reliability of the IBM model by filling the nutrient limited growth arameter on the basis of MPs (such as applying fertiliser or leaving biomass residues on the soil). In such a way, trade-offs between MPs and the related GHG emissions could be assessed in a more accurate way.

7.2.1. Pruning cacao trees

The IBM model subtracts pruning waste from the growth of woody biomass. However, the growth of woody biomass is based on data obtained by literature research, which might include trees that are already pruned. For example, cacao tree biomass assessed by Alpízar (1986) is, among other studies, used for modelling the cacao biomass growth curve. Alpízar (1986) reports that these cacao trees are pruned during the experiment. So, in fact, the IBM model subtracts pruning waste from an already pruned tree. Despite this deficiency, this is the best attainable option in this case, as most of the studies do not state whether the cacao trees in their experiment were pruned and even Alpízar (1986) did not record the pruning data. This deficiency might underestimate woody biomass. Additionally, because data on biomass removed during a pruning interval is lacking, pruning percentages of the present study were based on the growth curve of cacao woody biomass (see Section 6.1.2.). The uncertainties around the woody biomass of cacao trees have been quantified and the result shows that a 10% change in woody biomass results in a 10% change in GHG emissions (see Appendix XIV). Despite the proportional change, inaccuracies resulting from pruning cacao tree biomass lower the reliability of the outcomes in terms of GHG emissions associated with cacao production. In order to lower these uncertainties, future studies should examine and report the biomass of pruning residues on cacao farms, reflecting actual practices.

7.2.2. Applied cacao growth curve function

In continuation of the previous discussion point, the form of the cacao growth curve is suboptimal. Calvo Romero (2018) and Fisher (2018) each assessed the biomass growth of cacao trees of one cultivation type at different ages by destructive measurements. Calvo Romero (2018) concluded that the biomass growth of cacao trees levels off at an age of five years. The trees in the plots analysed by Fisher (2018) did not reach a plateau, probably because he assessed an intense cultivation system including heavy pruning. Although Figure 4 shows that cacao trees grow fast in the first few years, the plotted aboveground biomass function does not reach a plateau at a certain age. This is probably due to the origin of the data, as the data is gathered from a wide range of cacao cultivation types. The function itself could be another explanation, as the IBM model fits a curve in the form of a power function. A power function is not able to reach a plateau, even when the data points give rise to such a function. Since trees do not grow endlessly in time, a sigmoid function is likely to describe the growth curve of cacao trees more accurately. Due to the limited data points and their high variability, assessing whether the data set gives raise to a sigmoid curve is difficult (see Section 3.1.). Because these data points do not obiously reach a plateau, the uncertainties associated with the cacao growth curve are considered to be limited.

7.2.3. Carbon and nitrogen content parameters for tree organs

The IBM model is able to work with differentiated carbon and nitrogen content and DM percentage for each tree organ. However, the IBM model assumes the same carbon and nitrogen value for the whole fruit, while the carbon and nitrogen values are different between husks and beans (Afrifa, Dogbatse & Arthur, n.d.). Since husks and beans are managed differently, the GHG emissions resulting from husk waste and beans are not accurate. Furthermore, carbon and nitrogen values of leaf litter are different from the values of fresh leaves (Calvo Romero, 2018; Van Vliet, Slingerland & Giller, 2015). Though, the IBM model assumes a uniform value for both. Even so, a uniform decomposition rate is assumed for all cacao systems, while litter in shaded farms decompose more rapidly than litter in un-shaded farms (Ofori-Frimpong, Asase, Madon & Danku, 2007). Additionally, the DM percentage of leaves is highly influenced by the leaf age and shading and it is therefore difficult to determine an accurate DM percentage for individual plots (Van Vliet & Giller, 2017). Although the DM percentage is highly variable between fields, a uniform DM percentage is assumed for all leaves in all plots in the IBM model. Since all litter is left on the field, the inaccurate estimates of carbon and nitrogen content, decomposition rate and DM percentage are not negatively affecting the results of the present study.

7.2.4. Effect of leaving biomass on the soil

Ledo et al. (2018) assumed that if biomass parts are spread on the soil, they either increase the soil organic carbon pool or decompose and emit CO_2. However, in a similar study executed by Ortiz-Rodriguez et al. (2016), cacao residues left on the ground are assumed to have a strong impact on GHG emissions due to the anaerobic decomposition, which represents more than 85% of the GHG emissions. Contrary to the assumption made by Ortiz-Rodriguez et al. (2016), it is not likely that the soils in cacao plots are saturated, making anaerobic decomposition plausible. This instantiates that the assumptions underlying calculations strongly affect the final outcome. As for the rest of the study, the assumptions made by Ledo et al. (2018) are adopted.

7.2.5. Deforestation

During the survey, respondents were asked whether their plot was formerly primary forest, secondary forest or fallow. However, the effect of deforestation is calculated on the basis of data collected from a secondary forest. Using a uniform factor causes inaccuracies in the simulated GHG emissions because a primary forest stores twice as much carbon as a secondary forest (Roozendaal et al., in preparation). Therefore, the GHG emissions from deforestation calculated in Section 6.2. are probably underestimated. This hypothesis was tested. Adjusting the GHG emissions from deforestation with 10%, resulted in a smaller relative change in total GHG emissions. Therefore, the inaccuracies because of a lack of differentiating between primary and secondary forest is limited.

7.3. Discussion of the results

7.3.1. Biomass parameters IBM model

As can be seen in Figure 3, cacao biomass data reveal differences per continent. The data points indicate that the weight of aboveground biomass of cacao trees is higher in Africa than in Asia and Central and Latin America. If only data from Africa would have been used, the accumulation of carbon in cacao trees would have been higher. This suggests that the carbon stored in cacao systems in Africa might have been higher. This hypothesis was tested. Indeed, the GHG emissions would have been much lower when only cacao biomass data points from Africa were used. However, it is difficult to draw conclusions because the number of datapoints is limited (n=15) (see Section 3.1.). Despite the uncertainties, the results in terms of carbon stored in biomass per hectare matches findings from literature (see Section 7.3.5.). Therefore, choosing for all datapoints from all continents together has probably been a proper decision (see Section 3.1.).

7.3.2. Fruit biomass found during fieldwork

The fresh cacao fruit weights found during fieldwork are more diverse than the values found by Abenvega & Gockowski (2003), Vriesmann et al. (2011), Campos-Vega et al. (2018), Apshara (2017) and Carvalho Santos, Luiz Pires & Xavier Correa (2012). The values found during fieldwork are used as parameters to estimate the fruit biomass in the IBM model, on the basis of yield estimations gathered in the survey. Diverse values might influence the GHG emissions resulting from waste management of empty pods and unsuitable fruits, as the model proved to be sensible to data on fruit weight (see Appendix V). Though, the number of beans per fruit found during fieldwork fit in the range described by Campos-Vega et al. (2018).

Little is written about the ratio of husk, beans and pulp of the cacao fruit. Furthermore, it remains unclear for many studies whether the percentage of beans of the fruit are expressed in fresh or dry matter. Even so, for many studies it is unknown whether the bean shell (and even the pulp) are included in the bean weight. Campos-Vega et al. (2018) present in their study a figure containing the husk, pulp, bean and bean shell percentages of the fruit. However, it is not stated whether these percentages are expressed in fresh or dry matter. Comparing these values with the values found in the present study and by Fassbender et al. (1988), it seems likely that the values Campos-Vega et al. (2018) found are based on fresh weight.

The percentage husk, beans and pulp found in the present study were similar to what Fassbender et al. (1988) found, see Table 12 and Table 13. However, Fassbender et al. (1988) did not state whether the bean weight included the bean shell or pulp. Furthermore, Ntiamoah and Afrane (2008) found that the cacao husk is 67% of the fresh fruit weight, which is similar to the value found in the present study (see Table 6).

Table 12 Percentage husk, beans and pulp found in the present study

	Percentage husk	Percentage beans and pulp
On the basis of fresh weight	78%	22%
On the basis of dry weight	61%	39%

Table 13 Percentage pod husk, beans and pulp found by Fassbender et al. (1988)

	Percentage husk	Percentage beans
On the basis of fresh weight	-	21%
On the basis of dry weight	-	41%

<u>7.3.3. Representativeness of the experimental field</u>

In the harvesting period, the 48 cacao trees yielded on average 32 fruits per tree. Despite only nine harvest moments, the number of fruits is already higher than the amount found by Jagoret (2017). Yet, 32 fruits fall in the wide range described by Marticou and Muller (1964) and Tan (1990). Wessel (1971) reported the cacao yield distribution throughout the year (see Figure 11). Using these insights, the six harvest moments cover 79.74% of the yield per year. This gives an estimated annual yield of 40 fruits. To compare the yield of the experimental field with common yields reported by farmers and scientific studies, the number of fruits will be converted to commercial bean yield per hectare per year. Jagoret (2017) formulated the following equation to execute such a conversion:

$$Yield = NbFruits \bullet Wbeans \bullet TC \bullet KkoDens \quad \text{Equation 10}$$

where Yield is in kg ha^{-1} $year^{-1}$, NbFruits is the mean number of fruits per cacao tree, Wbeans is the mean weight of the fresh beans per fruit (kg), TC is the marketable cacao/fresh bean weight transformation coefficient, and KkoDens is the number of cacao trees per hectare. NbFruits is 40, following the logic of the beginning of this section. Wbeans is 0,088 kg when corrected for the percentage of pulp (Campos-Vega et al., 2018). TC is 0.35, as described by Schneider et al. (2016). KkoDens is 1333, calculated on the basis of the 2.5 x 3.0 m spacing. This results in a marketable yield of 1,642 kg per hectare per year. This amount does not fall in the range of 500-600 kg marketable yield per hectare per year in the Republic of Côte d'Ivoire described by Wessel and Quist-Wessel (2015). The yield of the experimental field is almost triple the amount of the highest yield attained by an Ivorian farmer reported during a survey executed by Bymolt, Laven and Tyszler (2018). Though, the yield of the experimental field does fit in the wider rage of 897 to 2,230 kg per hectare per year described by Bisseleua et al. (2009). Also, the yield of the experimental field fits in the range of yield found in the UTZ survey. Even so, yields of around 3,360 kg per hectare have been achieved in on-station trials in Ghana, while the national on-farm average is around 400 kg per hectare (Aneani & Ofori-Frimpong, 2013). Generally, experimental fields have higher yields, because of good managament practices (Aneani & Ofori-Frimpong, 2013). Furthermore, contrary to farmer practices all fruits were counted during the experiment, including infected fruits, small fruits and in odd shaps, which leads to an overestimation of the number of fruits per tree. Even when corrected for a 30% share of affected fruits (Wessel & Quist-Wessel, 2015), the marketable yield of the experimental field is still high (1,149 kg per hectare per year). The difference in yield between the experimental field and the national average yield does probably not negatively affect the outcomes in terms of GHG emissions. Rather than using the marketable yield, only the number of fruits, percentage husk and percentage beans was used as an input parameter for the IBM model.

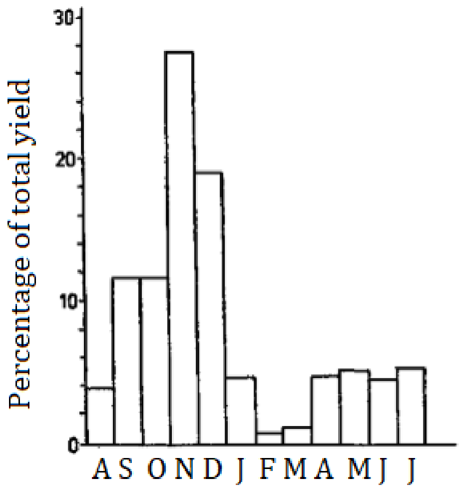

Figure 11 Yield distribution through the year, adapted from: Wessel (1971)

7.3.4. Comparing modelled tree biomass with literature

7.3.4.1. Root:shoot ratio of cacao

Modelling cacao biomass resulted in an average of 14 ton cacao roots per hectare and 49 ton aboveground biomass (see Table 10), resulting in a root:shoot ratio of 0.29. This value is similar to the ratios between 0.22 and 0.28 found by Borden et al. (2017), Moser et al. (2010), Leuschner et al. (2013) and Abou Rajab et al. (2016).

7.3.4.2. Cacao fruits

As can be seen in Table 9, modelling the cacao fruit biomass on the basis of the yield indicated by the respondent resulted in 888 kg cacao fruits per hectare per year. This value is extremely low when compared to the values of Abou Rajab et al. (2016) and Fassbender et al. (1988) (see 14). A likely explanation is that fields assessed in the literature are all in a productive stage, which is not the case for all plots in the survey. When excluding plots which are not yet in a productive stage, remaining plots yield an average of 938 kg cacao fruits per hectare per year, which is still lower than the values found in literature. This difference could possibly be explained by the difference in yields. The cacao yields obtained during the survey are much lower than those found in experimental fields.

Table 14 Cacao fruit production

Fruits in kg DM ha^{-1} $year^{-1}$	Cacao system	Age	Cacao bean yield in ha^{-1} $year^{-1}$	Study
9,700	Monoculture in Indonesia	24.3	2,100	Abou Rajab et al., 2016
10,900	Cacao-*Gliricidia* in Indonesia	20.0	2,100	Abou Rajab et al., 2016
8,300	Agroforestry in Indonesia	23.0	2,000	Abou Rajab et al., 2016

7.3.4.3. Leaf litter

As shown in Table 10, a cacao production system produces on average 160 kg DM leaves per hectare annually. The IBM model calculates that 40 kg leaves per hectare fall as litter annually. This is an extremely low value when compared to values found in literature, see Table 15. The difference can partly be explained by the difference in litter components. Only three studies assessed the annual production of cacao litter fall separately (Dawoe et al., 2010; Pérez-Flores, Pérez, Suárez, Bolaina & Quiroga, 2018; Fontes et al., 2014). Still, the amount of cacao leaf litter they found is extremely high when compared to the amount resulting from the IBM model. Because the IBM model calculates the amount of leaves that are grown annually on the basis of literature, it is not likely that the IBM model underestimates the amount of leaves grown annually.

Table 15 Range of annual litterfall in cacao systems based on literature

Annual leaf litterfall (kg DM ha^{-1} $year^{-1}$)	Cacao system	Study
5,460*	Litter of cacao trees in agroforestry	Ling, 1986
7,630*	Litter of cacao trees in agroforestry	Aranguren et al., 1982
7,071*	Total litter in agroforestry	Heuveldop et al., 1988
8,906*	Total litter in agroforestry	Heuveldop et al., 1988
9,000-14,000**	Total litter in shaded and unshaded plots	De Oliveira Leite and Valle, 1990
5,000*	Total litter without permanent shade	Wessel, 1985
4,600	Leaf litter of cacao trees in agroforestry	Dawoe et al., 2010
8,400	Leaf litter of cacao trees in agroforestry	Dawoe et al., 2010
5,000*	Total litter in agroforestry	Beer, 1988
20,000*	Total litter in agroforestry	Beer, 1988
945	Leaflitter of cacao trees in agroforestry	Pérez-Flores et al., 2018
582	Leaflitter of cacao trees in agroforestry	Pérez-Flores et al., 2018
5,300*	Litter of cacao trees in monoculture	Abou Rajab et al., 2016
2,900*	Litter of cacao trees in agroforestry	Abou Rajab et al., 2016
1,079-5,107	Leaflitter of cacao trees in agroforestry	Fontes et al., 2014
900-2,000*	Shade tree litter in agroforestry	Ofori-Frimpong et al., 2007
3,096-5,112*	Cacao tree litter in agroforestry	Ofori-Frimpong et al., 2007
1,200***	Cacao leaf litter in agroforestry	Norgrove and Hauser, 2013

* Includes branches, twigs, leaves, fruits and flowers
** Total accumulated litter, including branches, twigs, leaves, fruits and flowers
*** Total accumulated litter instead of annual litterfall

7.3.5. Carbon stored in the cacao system

7.3.5.1. Carbon stored in cacao and shade tree biomass

Modelling carbon stored in cacao biomass resulted in an average of 30 tons of carbon stored in cacao biomass per hectare (see Table 10). When including the carbon stored in shade trees, an average plot stores 136 tons carbon per hectare. This amount is somewhat higher than the average amount found in literature, see Table 16. The difference in carbon storage is probably due to the number of shade trees. As discussed in Section 5.1., the shade tree density based on the survey is, on average, 152 trees per hectare. This results in a total of 1,263 trees (cacao and shade) per hectare, which is higher than the densities found in literature (see Table 16). When comparing the carbon storage in standing biomass of the present study with similar systems in West-Africa, similar amounts of carbons storage are found (Norgrove & Hauser, 2013; Silatsa et al., 2017; Mohammed et al., 2016). This again underlines the importance of the presence of shade trees in the storage of carbon. The average density of 152 shade trees per hectare found in the present study is higher than the range between 6 and 56 shade trees per hectare in the Republic of Cote d'Ivoire found by Gockoski and Sonwa (2011). Also Magne et al. (2014), Norgrove and Hauser (2013) and Schroth et al. (2016) reported lower shade tree densities, in Cameroon and Brazil respectively.

Table 16 Carbon stored in biomass in cacao systems based on literature

C stored (ton ha^{-1})	Cacao system	Country	Age (years)	Tree density (trees ha^{-1})*	Study
93	Agroforestry	Niceragua	20.3	855	Somarriba et al, 2013
96	Productive shade	Guatemala	18.1	826	Somarriba et al., 2013
106	Specialized shade	Honduras	20.5	808	Somarriba et al., 2013
122	Mixed shade	Costa Rica	24.9	1071	Somarriba et al., 2013
132	Productive shade	Panama	26.9	1065	Somarriba et al., 2013
155	Mixed shade	Guatemala	30.8	544	Somarriba et al., 2013
231	Agroforestry	Cameroon	35	1477	Norgrove and Hauser, 2013
186	Agroforestry	Cameroon	25	-	Kotto-Same et al., 1997
10	Agroforestry	Ghana	+/- 10	10.8**	Dawoe et al., 2016
18.5	Agroforestry	Ghana	+/- 10	9.33**	Dawoe et al., 2016
13.2	Agroforestry	Ghana	+/- 10	14.2**	Dawoe et al., 2016
15.7	Agroforestry	Ghana	+/- 10	16.3**	Dawoe et al., 2016
15.6	Agroforestry	Ghana	+/- 10	16.2**	Dawoe et al., 2016
15.4	Agroforestry	Ghana	+/- 10	20.6**	Dawoe et al., 2016
12.6	Agroforestry	Ghana	+/- 10	15.1**	Dawoe et al., 2016
23.4	Agroforestry	Ghana	+/- 10	22.8**	Dawoe et al., 2016
17.9	Agroforestry	Ghana	+/- 10	12**	Dawoe et al., 2016
11.5	Agroforestry	Ghana	+/- 10	18.3**	Dawoe et al., 2016
50.3	Young cacao	Cameroon	3-5	-	Silatsa et al., 2017
92.1	Mature cacao	Cameroon	8-10	-	Silatsa et al., 2017
144.5	Old cacao	Cameroon	15-20	-	Silatsa et al., 2017
196.9	Very old cacao	Cameroon	30-50	-	Silatsa et al., 2017
128.4	Agroforestry	Bolivia	13	921	Jacobi et al., 2014
143.7	Agroforestry	Bolivia	14.3	1324	Jacobi et al., 2014
86.3	Monoculture	Bolivia	9.5	649	Jacobi et al., 2014
11	Monoculture	Indonesia	24.3	892	Abou Rajab et al., 2016
57	Multishade	Indonesia	23	1741	Abou Rajab et al., 2016
81.8	Monoculture	Ghana	7-28	-	Mohammed et al., 2016
153.9	Monoculture	Ghana	7-28	-	Mohammed et al., 2016
104	Agroforestry	Cameroon	-	1125	Gockowski and Donwa, 2011
67.7	Full sun cacao	Cameroon	-	1125	Gockowski and Donwa, 2011

* Both cacao and shade trees
** Shade trees only

7.3.5.2. Carbon stored in cacao roots

As can be seen in Table 10, cacao roots store on average 7 tonnes of carbon per hectare. This value is somewhat higher than the range of 5,400-6,400 kg carbon in cacao roots per hectare found by Borden et al. (2017). This is probably due to age of the plantation and the cacao tree density. The plots assessed by Borden et al. (2017) were 15 years old (7 year younger than the trees in the present study) and 1,111 trees per hectare (362 trees per hectare less than in the surveyed plots). Recalculating the carbon stored in roots per hectare to individual trees, results in 6 kg C stored in the root system per tree. Although this value is quite high as well, it fits in the range of 0.2-6.7 kg carbon in cacao roots per tree found by Saj et al. (2013), Jacobi et al. (2014), Leuschner et al. (2013), Somarriba et al. (2013), Abou Rajab et al. (2016) and Nogrove and Hauser (2013).

7.3.5.3. Carbon stocks in relation with cacao yields

It is generally assumed that cacao yield decreases in a non-linear way under increasing shade and carbon level along with it (Magne et al., 2014). Schroth et al. (2016) confirms this general relationship in their study. Also Somarriba et al. (2013) discuss the general relationship between carbon stocks in shade trees and yield. The relationship Somarriba et al. (2013) found did not apply to the data found in the present study (see Figure 12). Also Magne et al. (2014) reported that the data they found in their study was not in line with the general assumptions. Along with the remark of Magne et al. (2014), the diversity of the systems observed made it difficult to assess trade-offs between carbon stocks and yields. Even so, several studies examined the amount of shade on the cacao yields (Zuidema et al., 2005; Isaac et al., 2007-a; Somarriba et al., 2013), a full discussion about shade trees (and carbon stored along with it) and cacao yields is not within the scope of my study. Apart from carbon stored in shade trees, Somarriba et al. (2013) also developed a relationship between carbon yield and carbon stored in cacao biomass. This relationship is similar to a relationship found in the present study, see Figure 13. This result is not surprising because the data points shown in Figure 13 are based on a boundary analysis, only showing the best managed trees.

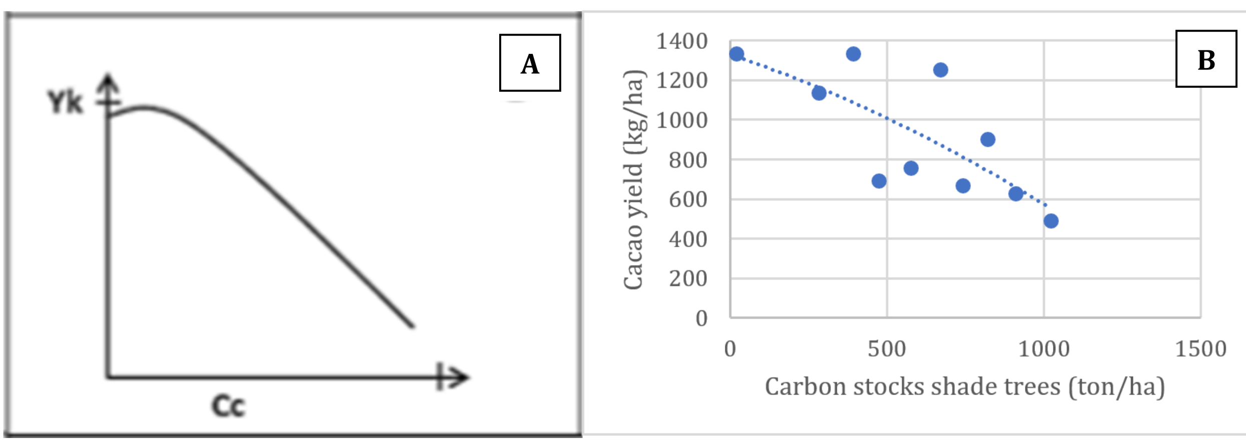

Figure 12a Relation between cacao yield and carbon stocks in shade trees, source: Somarriba et al., 2013. Yk is cacao yield (kg ha^{-1}) and Cc is carbon stored in shade trees (kg ha^{-1}). **Figure 12b** Relation between cacao yield and carbon stocks in shade trees (R^2=0.56), found in the present study. Data points were obtained through a boundary analysis, i.e. presenting only the highest yield data point per carbon stock category (per 100 ton carbon).

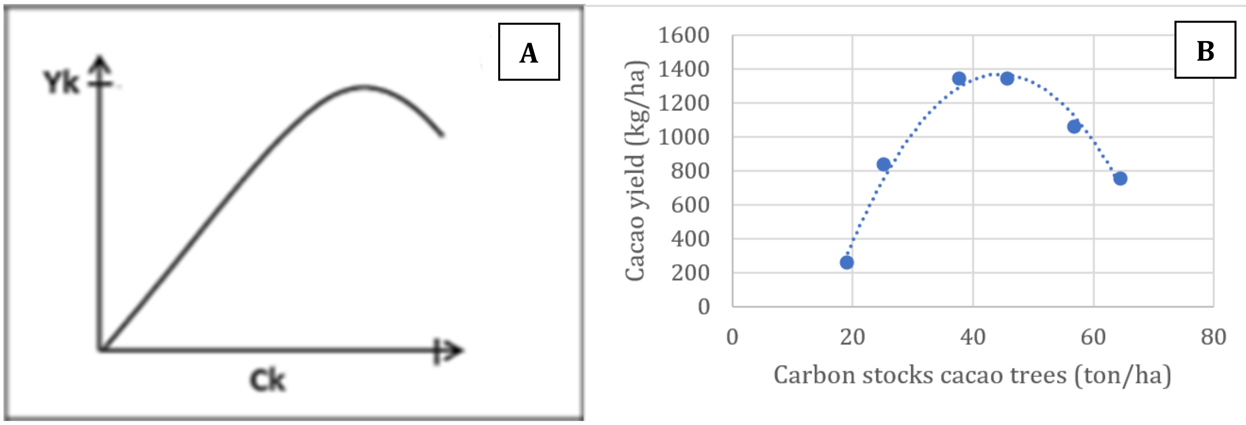

Figure 13a Relation between cacao yield and carbon stocks in cacao trees, source: Somarriba et al., 2013. Yk is cacao yield (kg ha^{-1}) and Ck is carbon stored in cacao trees (kg ha^{-1}). **Figure 13b** Relation between cacao yield and carbon stocks in cacao trees (R^2=0.98), found in the present study. Data points were obtained through a boundary analysis, i.e. presenting only the highest yield data point per carbon stock category (per 10 ton carbon).

7.4. General discussion

7.4.1. Emissions resulting from composting

Ledo et al. (2018) programmed composting in the IBM model as a source of GHG emissions. Ortiz-Rodriguez et al. (2016) found high GHG emissions because of composting practices in the cacao production. Therefore, it could be argued that the use of compost should be avoided. The Sustainable Food Lab (2011) also states that producing compost causes GHG emissions, but also states that the composting process often improves what might have happened otherwise to that raw material. Following that logic, the raw material for compost might cause more emissions elsewhere, so it can even be decided to assume that compost is associated with 'zero emissions' (Sustainable Food Lab, 2011). Though, following the system boundaries set in Section 2.1., the GHG emissions caused by composting are included in the present study. Although compost is associated with GHG emissions, compost could replace artificial fertilisers, which are finite resources and are also associated with GHG emissions. Putting this in perspective, yields in plots in which compost was used were higher than in plots in which no compost was used (see Table 17). Unfortunately, insufficient data was available to compare the GHG emissions from compost (made from cacao residues) with those of nutrient equivalent artificial fertiliser. Though, Ntiamoah and Afrane (2008) tested the effect of exclusive use of compost instead of fertiliser on the environmental impact of cacao production. Ntiamoah and Afrane (2008) found that the use of compost instead of inorganic fertiliser could reduce GHG emissions with a few percentages. Also Ortiz-Rodriguez et al. (2016) state that organic fertilisers are a promising solution for the reduction of environmental associated with the production of cacao. Unfortunately, little is written about the nutrient content of compost made from cacao residues and its ability to replace artificial fertilisers in cacao plantations. A future study could research the effects of using compost made from cacao residues and other types of fertiliser on the cacao yield and GHG emissions, putting the results of the present study in a broader perspective.

Table 17 Cacao yield per fertiliser type

	Yield (kg ha^{-1})	
Fertiliser type	Mean	Standard deviation
Compost (n=34)	537	46
Chemical fertiliser (n=182)	455	18
Compost and chemical fertiliser (n=78)	533	35
No type of fertiliser (n=133)	437	19

7.4.2. Greenhouse gas emissions associated with cacao production

As mentioned in the introduction, very little was found in literature on the GHG emissions from the production of cacao beans. A few studies assessed the GHG emissions associated with the production of cacao beans and chocolate, see Table 18. Even though it is generally acknowledged that perennials may have zero or even net negative emission, all these studies report a net emission of GHGs per kilogram of chocolate or cacao beans produced. It is difficult to compare these values to the one found in the present study, as the way the GHG emissions are expressed differ. Four studies expressed the GHG emissions associated with cacao production per kilogram of cacao beans. The values found in literature vary between 0.36 and 42 kg CO_2-equivalents per kilogram of cacao, in which the emission of 3.6 kg CO_2-equivalents found in the present study fits. The amounts found by Ortiz-Rodriguez et al. (2016) are double the amount found in the present study. A possible explanation for this difference may be the system boundaries. Ortiz-Rodriguez et al. (2016) took into account the establishment and production phase (including required infrastructure and all the equipment for establishment, such as a hoe, plastic bags, wires etc. and even the transport of this equipment). Surprisingly, Ortiz-Rodriguez et al. (2016) found that 86-96% of the emission is a result of the production phase. One of the main source of the emissions are found to be lime, which is not taken into account in the present study and could therefore explain the difference. Another main explaining factor is the different assumption on the decomposition process, discussed in Section 7.2.4.. Defra (2009) included land-use change and export in the assessment and states that 98% of the emissions during the whole process were due to land use change. However, it was not specified how the emissions from land use change were calculated. Harris (2015) assessed only the effect of land-conversion, by attributing the carbon stock change to the production of cacao beans over 20 years. Because Harris (2015) does not assess other sources or sinks for GHGs, it is difficult to compare her findings with the findings of the present study. Furthermore, Schroth et al. (2016) executed a study very similar to the present study, but excluded the emissions of biomass residue management. That might be the reason that Schroth et al. (2016) found a lower value. In addition, Schroth et al. (2016) proposed a threshold of climate friendliness of 0.25 kg CO_2 emissions per kilogram of cacao, which is still compatible with high cacao yields. In the present study, individual plots with emissions low emissions (<0.25 kg CO_2 equivalents) and high yields (>500 kg) were observed too, confirming the findings by Schroth et al. (2016). At the same time, Schroth et al. (2016) propose a threshold between 50 and 65 ton carbon stored in shade trees per hectare, which is still compatible with high cacao yields. Unfortunately, insufficient plots with carbon stocks between 50 and 65 ton per hectare are available in the present study to test this statement.

Table 18 GHG emissions of the cacao production phase, various expressions

GHG emissions of the cacao production phase (kg CO_2-eq)	Expressed as	Study
1.76	Per kilogram of chocolate	Recanti et al., 2018
0.06	Per kilogram of chocolate	Ntiamoah and Afrane, 2008
0.09	Per kilogram of chocolate	Barry Callebaut, 2017
8	Per kilogram of cacao beans*	Ortiz-Rodriguez et al., 2016
8.9	Per kilogram of cacao beans*	Ortiz-Rodriguez et al., 2016
2	Per kilogram of cacao beans*	Ortiz-Rodriguez et al., 2014
4	Per kilogram of cacao beans*	Ortiz-Rodriguez et al., 2014
7	Per kilogram of cacao beans**	Harris, 2015
1.1	Per kilogram of chocolate**	Harris, 2015
8.52	Per kilogram of chocolate**	Harris, 2015
10	Per kilogram of chocolate**	Harris, 2015
2.91	Per kilogram of chocolate***	Konstantas et al., 2018
3.39	Per kilogram of chocolate***	Konstantas et al., 2018
4.15	Per kilogram of chocolate***	Konstantas et al., 2018
42	Per kilogram of cacao beans****	Defra, 2009
0.36	Per kilogram of cacao beans	Schroth et al., 2016

* Including the establishment phase
** Only land conversion
*** Whole chocolate production process
**** Production and export

7.4.3. Permanence of carbon stored in biomass

Following the methodology developed by Ledo et al. (2018), carbon stored in biomass is considered as a negative emission within the present study. Furthermore, perennial agricultural management reduces soil disturbance, adds carbon inputs to the soil and allows soil carbon to be stabilised, hence reducing emissions of CO_2 to the atmosphere via mineralisation in those cases in which the soil is not saturated with carbon yet (Ledo et al., 2018). On the contrary, many similar studies do not include carbon sequestration in above- and belowground biomass, as the sequestration may not be permanent (Van Rikxoort et al., 2016; Brandao et al., 2013). For example, Van Rikxoort et al. (2016) state that: '*In any given tree-crop production system, the biomass in the vegetation may fluctuate cyclically as trees grow, are harvested, pruned back […] or die. Most of the annual biomass increment in the vegetation eventually decomposes or is burnt on a trash heap and releases its carbon back into the atmosphere […].*'. Within the present study, this issue is partly avoided by taking into account the management of biomass waste and partly by setting the system boundaries clearly, estimating the GHG balance only within the year 2017.

6. Conclusion

6.1. Assessing GHG emissions associated with cacao production

GHG emissions associated with cacao production have been estimated using various tools, including the IBM model, CFT, allometric equations and IPCC guidelines. Altogether, these tools are data intensive, requiring data from literature, data from a survey and data obtained through fieldwork. Due to various data gaps, many assumptions had to be made, including the number of cacao trees, shade tree species, management of litter, pruning percentage, fertiliser application rate and the nitrogen content of compost. A high number of assumptions might have caused uncertainties in the output. The output, in terms of GHG emissions per kilogram of cacao, turned out to be sensitive for changes in parameters related to cacao tree biomass, cacao fruits and shade tree biomass. The relative high sensitivities suggest that the calculations behind the GHG emissions are not very robust, possibly causing uncertainties. Although these uncertainties probably exist, the output (GHG emissions per kilogram of cacao) were in the range of values found in literature. All in all, large contributions were made by my study, as a new methodology was developed and many data collected. The main contribution of my study is that many cacao farm systems were assessed, making possible the differentiation between GHG emissions associated with farm management.

6.2. Climate-friendly cacao

My study revealed that producing high yields while at the same time storing a high amount of carbon in standing biomass and causing low GHG emissions, is feasible. For the production of 693 ton cacao beans, 2,472 ton CO_2-equivalents have been emitted (including the plots that emit GHG but are not productive yet). So on average, 3.6 kg CO_2-equivalents were emitted per kilogram of cacao produced. In most of the cacao plots, shade trees are present and fertiliser is applied. In most plots, cacao trees are pruned and pruning residues and other biomass residues are left in the field. Composting cacao tree residues and fertiliser application contributed largely to the GHG emissions, while shade- and cacao tree biomass contributed mainly to negative GHG emissions, i.e. CO_2 storage. On average, a cacao plot stored 136 ton CO_2 per hectare. Compared with other plots, climate-friendly plots are characterised by a similar area and a significant higher age. In these plots, cacao residues are significant more often left on the soil instead of being composted. Furthermore, these plots have a significant higher number of shade trees. Again, the main difference between climate-friendly producing plots and other plots is the significant higher number of shade trees (388 and 123 trees per hectare respectively).

6.2.1. Recommendations for farm management

The climate-friendliness of cacao production is strongly related to farm management. Therefore, farm management is a key factor in producing climate-friendly cacao. Management practices that contribute to the production of more climate-friendly cacao include leaving cacao residues on the soil, avoiding deforestation, applying fertiliser and planting shade trees. The latter two are in line with the recommendation described in a report by the UNDP (2015). The UNDP (2015) promotes reforestation and the use of fertiliser, as a better yield per unit land area reduces the need for extra (forest) land. These recommendations are shared by Schroth et al. (2016) and found that shade levels up to 55% are still compatible with high yields. On the contrary, Kolavalli and Vigneri (2017) argue that removing shade improves yields and yields can be raised further with fertiliser applications, potentially reducing the environmental impact of cacao plots expansion. Applying fertiliser to safeguard the environment is conflicting with the findings of Ntiamoah and Afrane (2008) and Recanti et al. (2018), who state that the application of fertiliser has to be reduced, because fertilisers are a major contributor of environmental impacts of the cacao production. All in all, strategies to produce environmentally friendly cacao have been subject of intense debate. The aim of the my study was to shine new light on these debates, by an examination of many aspects related to cacao production. Although a better understanding of the environmental aspects of cacao production needs to be developed, I expect that my results help the cacao growing industry to formulate climate change mitigation strategies.

7. References

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Appendix I – Overview of required data

Table 19 Overview input data

IBM model			
Input data	Expressed in	Data source	Section
Cacao tree biomass			
Aboveground biomass	Kilogram per tree	Literature	2.3.1.
Woody biomass	Kilogram per tree	Literature	2.3.1.
Leaf biomass	Kilogram per tree	Literature	2.3.1.
Belowground biomass	Kilogram per tree	Literature	2.3.1.
Dry matter wood	Percentage dry material	Literature	2.3.1.
Dry matter leaf	Percentage dry material	Literature	2.3.1.
Dry matter fruit	Percentage dry material	Fieldwork	2.7.4.
Dry matter beans	Percentage dry material	Fieldwork	2.7.4.
Dry matter husk	Percentage dry material	Fieldwork	2.7.4.
Carbon wood	Percentage dry material	Literature	2.3.1.
Nitrogen wood	Percentage dry material	Literature	2.3.1.
Carbon leaf	Carbon fraction	Literature	2.3.1.
Nitrogen leaf	Nitrogen fraction	Literature	2.3.1.
Carbon roots	Carbon fraction	Literature	2.3.1.
Nitrogen roots	Nitrogen fraction	Literature	2.3.1.
Carbon fruit	Carbon fraction	Literature	2.3.1.
Nitrogen fruit	Nitrogen fraction	Literature	2.3.1.
Carbon husk	Carbon fraction	Literature	2.3.1.
Nitrogen husk	Nitrogen fraction	Literature	2.3.1.
Percentage husk	Percentage husk of fruit in dry matter	Fieldwork	2.7.4.
Percentage beans	Percentage beans of fruit in dry matter	Fieldwork	2.7.4.
Unsuitable fruits	Percentage unsuitable fruits	Literature	
Decomposition wood	Decomposition parameter *k*	Literature	2.3.3.
Decomposition litter	Decomposition parameter *k*	Literature	2.3.3.
Decomposition root	Decomposition parameter *k*	Literature	2.3.3.
Decomposition fruit	Decomposition parameter *k*	Literature	2.3.3.
Decomposition husk	Decomposition parameter *k*	Literature	2.3.3.
Pruning	Percentage of dry woody biomass	Fieldwork	2.7.5.
Management practices			
Pruning regime	Number of years ago	UTZ survey	2.3.2.
Cacao husk	Percentage burnt	UTZ survey	2.3.2.
	Percentage left under the trees	UTZ survey	2.3.2.
	Percentage composted	UTZ survey	2.3.2.
Unsuitable fruits	Percentage burnt	UTZ survey	2.3.2.
	Percentage left under the trees	UTZ survey	2.3.2.
	Percentage composted	UTZ survey	2.3.2.
Pruning residues	Percentage burnt	UTZ survey	2.3.2.
	Percentage left under the trees	UTZ survey	2.3.2.
	Percentage composted	UTZ survey	2.3.2.
Litter	Percentage burnt	Literature	2.3.2.
	Percentage left under the trees	Literature	2.3.2.
	Percentage composted	Literature	2.3.2.
CFT			
Data input	Expressed in	Data source	Section

Chemical fertiliser	Kg nitrogen per hectare	UTZ survey, supplemented with literature	2.4.1.
Foliar fertiliser	Kg nitrogen per hectare	UTZ survey, supplemented with literature	2.4.1.
Organic fertiliser	Kg nitrogen per hectare	UTZ survey, supplemented with literature	2.4.1.
Temperature	Average temperature (1987-2016)	ISRIC	2.4.2.
Soil texture	Classification	ISRIC	2.4.2.
Soil organic matter	Fraction organic matter	ISRIC	2.4.2.
Soil moisture	Classification	ISRIC	2.4.2.
Soil drainage	Classification	ISRIC	2.4.2.
Soil acidity	Soil pH	ISRIC	2.4.2.
Shade trees			
Data input	Expressed in	Data source	Section
Shade tree biomass	Volume per hectare	Literature	2.5.1.
Wood density	Kg per m^3	Literature	2.5.1.
Carbon content	Percentage carbon	Literature	2.5.1.
Number of shade trees	Trees per hectare	UTZ survey, supplemented with literature	2.5.2.
Deforestation			
Data input	Expressed in	Data source	Section
Land use change	Previous land use	UTZ survey	2.3.2.
Litter stock	Kg carbon per hectare before change	Literature	2.6.
Litter stock	Kg carbon per hectare after change	Literature	2.6.
Organic carbon stock	Kg carbon per hectare before change	Literature	2.6.
Organic carbon stock	Kg carbon per hectare after change	Literature	2.6.

Appendix II – Overview cacao biomass data

Table 2 Data on cacao biomass

ID	Site	Age_y	AGBbranch_kg	AGBstem_kg	AGBleaf_kg	AGBwoody	totalAGB	BGBroot_kg	TotalBiomass_Kg	density_trees_ha	Study	Method	System
240	Ghana	2									Acquaye & Smith, 1964	Measured	Agroforestry
186	Costa Rica	5	3.63636	2.52025	2.67327	8.82988			17.55	1111	Alpízar et al., 1986	Calculated	Under shade
187	Costa Rica	4.5	2.72727	2.25923	2.54725	7.53375			17.55	1111	Alpízar et al., 1986	Calculated	Under shade
236	Brazil	1		0.068	0.066			0.029	0.173		Alves dos Santos et al., 2018	Destructive	Monoculture
236	Brazil	1		0.067	0.053			0.034	0.159		Alves dos Santos et al., 2018	Destructive	Monoculture
336	India	10									Apshara, 2017	Measured	Monoculture
337	India	10									Apshara, 2017	Measured	Monoculture
298	Brazil	0.2		0.0012	0.0013			0.0011	0.00358		Baligar & Fageria, 2017	Destructive	Monoculture
299	Brazil	0.2		0.00172	0.0029			0.00154	0.00624		Baligar & Fageria, 2017	Destructive	Monoculture
300	Brazil	0.2		0.00148	0.00706			0.00124	0.00516		Baligar & Fageria, 2017	Destructive	Monoculture
56	Costa_Rica	5	3.60036	2.52025	2.70027	6.12061	8.82088				Beer et al., 1990	Calculated	Under shade
57	Costa_Rica	10	21.6022	7.38074	3.3	28.9829	32.2829				Beer et al., 1990	Calculated	Under shade
58	Costa_Rica	5	2.70027	2.25023	2.52025	4.9505	7.47075				Beer et al., 1990	Calculated	Under shade
59	Costa_Rica	10	15.2115	6.12061	3.15032	21.3321	24.4824				Beer et al., 1990	Calculated	Under shade
60	Venezuela	30	17.4912	8.30389	4.41696	25.7951	30.212	12.898	43.11		Beer et al., 1990	Calculated	Under shade
234	Ghana	15					55.7	15.6	71.3	1111	Borden et al., 2017	Calculated	Monoculture
367	Ghana	15					54.7	10.4	65.1	1111	Borden et al., 2017	Calculated	Under shade
368	Ghana	15					56.1	12.9	69	1111	Borden et al., 2017	Calculated	Under shade
189	Cameroon	30				10				1000	Boyer, 1983	Destructive	Agroforestry
181	Republic of Côte d'Ivoire	19			6.00434	32.6958	38.7001	9.79456	48.4947	1333	Calvo Romero, 2018	Destructive	Agroforestry
366	Republic of Côte d'Ivoire	19			8.90012	76.4806	85.3807	27.2023	112.583	1333	Calvo Romero, 2018	Destructive	Agroforestry
369	Republic of Côte d'Ivoire	19			4.03216	44.5589	48.591	12.9794	61.5704	1333	Calvo Romero, 2018	Destructive	Agroforestry
178	Republic of Côte d'Ivoire	1.5			0.22932	0.62089	0.85021	0.26177	1.11198	1333	Calvo Romero, 2018	Destructive	Intercrop
360	Republic of Côte d'Ivoire	1.5			0.13759	0.5588	0.69639	0.13961	0.836	1333	Calvo Romero, 2018	Destructive	Intercrop

361	Republic of Côte d'Ivoire	1.5			0.11466	0.5381	0.65276	0.13961	0.79237	1333	Calvo Romero, 2018	Destructive	Intercrop
179	Republic of Côte d'Ivoire	5			6.27948	36.4253	42.7047	10.7544	53.4591	1333	Calvo Romero, 2018	Destructive	Monoculture
180	Republic of Côte d'Ivoire	10			4.11124	37.4808	41.592	16.6442	58.2362	1333	Calvo Romero, 2018	Destructive	Monoculture
362	Republic of Côte d'Ivoire	5			12.2723	27.381	39.6533	14.0701	53.7235	1333	Calvo Romero, 2018	Destructive	Monoculture
363	Republic of Côte d'Ivoire	5			8.46397	31.0029	39.4668	11.3434	50.8102	1333	Calvo Romero, 2018	Destructive	Monoculture
364	Republic of Côte d'Ivoire	10			7.97339	38.557	46.5304	10.8853	57.4156	1333	Calvo Romero, 2018	Destructive	Monoculture
365	Republic of Côte d'Ivoire	10			5.00312	38.0603	43.0634	14.7246	57.7879	1333	Calvo Romero, 2018	Destructive	Monoculture
253	Brazil	0.5		0.02029	0.02445			0.01257	0.0573		Da Silva Branco et al., 2017	Destructive	Monoculture
254	Brazil	0.5		0.02045	0.01301			0.00646	0.03999		Da Silva Branco et al., 2017	Destructive	Monoculture
261	Brazil	0.5		0.02733	0.02516			0.01666	0.06916		Da Silva Branco et al., 2017	Destructive	Monoculture
262	Brazil	0.5		0.02246	0.01264			0.00847	0.04327		Da Silva Branco et al., 2017	Destructive	Monoculture
241	Ghana	3								1500	Dawoe et al., 2010	Measured	Agroforestry
242	Ghana	15								1100	Dawoe et al., 2010	Measured	Agroforestry
243	Ghana	30								900	Dawoe et al., 2010	Measured	Agroforestry
210	Costa Rica	2.5								1111	Ewell et al., 1982	Measured	Monoculture and agroforestry
371	Ecuador	1	0.09633	0.02985	0.24774	0.12618	0.37392	0.10087	0.47479	1500	Fisher, 2018	Destructive	Monoculture
372	Ecuador	1	0.14475	0.0214	0.50126	0.16615	0.66741	0.12247	0.78988	1500	Fisher, 2018	Destructive	Monoculture
373	Ecuador	1	0.05803	0.03266	0.57299	0.09069	0.66368	0.09477	0.75845	1500	Fisher, 2018	Destructive	Monoculture
374	Ecuador	1	0.07535	0.03777	0.30287	0.11312	0.41599	0.04909	0.46508	1500	Fisher, 2018	Destructive	Monoculture
375	Ecuador	1	0.08187	0.01726	0.32917	0.09913	0.4283	0.07531	0.50361	1500	Fisher, 2018	Destructive	Monoculture
376	Ecuador	6	5.29461	0.55551	1.87059	5.85011	7.72071	2.86186	10.5826	1500	Fisher, 2018	Destructive	Monoculture
377	Ecuador	6	3.77199	0.40667	2.03945	4.17866	6.21811	1.83554	8.05365	1500	Fisher, 2018	Destructive	Monoculture
378	Ecuador	6	6.40434	0.55394	2.32915	6.95828	9.28743	2.41233	11.6998	1500	Fisher, 2018	Destructive	Monoculture
379	Ecuador	6	8.0921	0.8964	2.05434	8.98851	11.0429	2.828	13.8708	1500	Fisher, 2018	Destructive	Monoculture
380	Ecuador	6	6.21409	0.75615	3.05466	6.97024	10.0249	2.83366	12.8586	1500	Fisher, 2018	Destructive	Monoculture
381	Ecuador	11	16.9694	3.12553	2.4996	20.095	22.5946	9.73649	32.331	1130	Fisher, 2018	Destructive	Monoculture

382	Ecuador	11	14.9946	2.05207	3.73815	17.0467	20.7849	6.63251	27.4174	1130	Fisher, 2018	Destructive	Monoculture
383	Ecuador	11	13.1653	2.44964	2.57994	15.6149	18.1948	7.3655	25.5603	1130	Fisher, 2018	Destructive	Monoculture
384	Ecuador	11	14.292	0.9538	2.59627	15.2458	17.842	5.16117	23.0032	1130	Fisher, 2018	Destructive	Monoculture
385	Ecuador	11	17.3499	3.80392	1.76262	21.1539	22.9165	6.02686	28.9433	1130	Fisher, 2018	Destructive	Monoculture
192	Ghana	0.3		0.01	0.0149		0.0339	0.009			Isaac et al., 2011	Destructive	Under shade
49	Ghana	8					20.75			1100	Isaac et al., 2007-a	Calculated	Monoculture
385	Ghana	8					20.75			1100	Isaac et al., 2007-a	Calculated	Monoculture
385	Ghana	8					36			1100	Isaac et al., 2007-a	Calculated	Under shade
385	Ghana	8					20.07			1100	Isaac et al., 2007-a	Calculated	Under shade
385	Ghana	8					37.28			1100	Isaac et al., 2007-a	Calculated	Under shade
385	Ghana	8					21.97			1100	Isaac et al., 2007-a	Calculated	Under shade
385	Ghana	8					27.99			1100	Isaac et al., 2007-a	Calculated	Under shade
385	Ghana	8					19.71			1100	Isaac et al., 2007-a	Calculated	Under shade
248	Ghana	1		0.0985	0.1289			0.0705		2500	Isaac et al., 2007-b	Destructive	Artificial shade
252	Ghana	1		0.117	0.1168			0.0864		2500	Isaac et al., 2007-b	Destructive	Artificial shade
246	Ghana	1		0.0688	0.074			0.0329		2500	Isaac et al., 2007-b	Destructive	Intercrop
247	Ghana	1		0.0989	0.0955			0.0402		2500	Isaac et al., 2007-b	Destructive	Intercrop
250	Ghana	1		0.0939	0.0788			0.0379		2500	Isaac et al., 2007-b	Destructive	Intercrop
251	Ghana	1		0.0985	0.0801			0.0451		2500	Isaac et al., 2007-b	Destructive	Intercrop
245	Ghana	1		0.0972	0.0747			0.0449		2500	Isaac et al., 2007-b	Destructive	Monoculture
249	Ghana	1		0.1253	0.098			0.0464		2500	Isaac et al., 2007-b	Destructive	Monoculture
221	Bolivia	13							48.48	625	Jacobi et al., 2014	Calculated	Agroforestry
227	Bolivia	14.25							18.72	625	Jacobi et al., 2014	Calculated	Agroforestry
222	Bolivia	9.5							40.16	625	Jacobi et al., 2014	Calculated	Monoculture
323	Cameroon	24								1207	Jagoret et al., 2017	Calculated	Agroforestry
324	Cameroon	33								1568	Jagoret et al., 2017	Calculated	Agroforestry
325	Cameroon	30								1771	Jagoret et al., 2017	Calculated	Agroforestry
269	Ecuador	7					3.4796				Jaimez et al., 2017	Destructive	Monoculture
358	Ghana	17									Lockwood, 1979	Measured	Agroforestry
61	Indonesia	6			3.76	22.32		5.74	31.8	1000	Moser et al., 2010	Calculated	Under shade
62	Indonesia	6			4.76	26.49		8.26	39.1	1000	Moser et al., 2010	Calculated	Under shade

322	Nigeria	0.6									Ndubuaku and Kassim, 2003	Calculated	Under shade
237	Bolivia	5								625	Niether et al., 2018	Calculated	Monoculture
238	Bolivia	5								625	Niether et al., 2018	Calculated	Under shade
239	Bolivia	5								625	Niether et al., 2018	Calculated	Under shade
235	Nigeria	0						0.00099	0.00336		Oladele, 2015	Destructive	Monoculture
236	Nigeria	0						0.00117	0.00434		Oladele, 2015	Destructive	Monoculture
236	Nigeria	0						0.00121	0.00509		Oladele, 2015	Destructive	Monoculture
236	Nigeria	0						0.00085	0.00309		Oladele, 2015	Destructive	Monoculture
193	Ghana	3								5x10ft spacing	Opoku and Jordan, 1966	Measured	Under shade
211	Indonesia	24.3				2.6		2.5		895	Abou Rajab et al., 2016	Calculated	Monoculture
212	Indonesia	20				3		2		1047	Abou Rajab et al., 2016	Calculated	Under shade
213	Indonesia	23				2		1.2		1384	Abou Rajab et al., 2016	Calculated	Under shade
346	Bolivia	2.8								625	Schneider et al., 2016	Measured	Average monoculture + agroforestry
347	Bolivia	4.5								625	Schneider et al., 2016	Measured	Average monoculture + agroforestry
281	Malaysia	2.3									Shamshuddin et al., 2011	Measured	Monoculture
202	Indonesia	15					44.6163	27.7431		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
203	Indonesia	12					37.1487	23.1959		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
204	Indonesia	9					40.2709	25.0994		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
205	Indonesia	5					27.9983	17.5951		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
206	Indonesia	4					8.3949	5.42206		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
207	Indonesia	3					12.0131	7.69604		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
208	Indonesia	2.5					15.2601	9.72315		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
209	Indonesia	2					3.53968	2.33151		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
196	Indonesia	8					23.8252	15.0276		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
197	Indonesia	5					6.81224	4.4208		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
198	Indonesia	4					8.27392	5.34569		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
199	Indonesia	3					17.6378	11.2012		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
200	Indonesia	1.5					0.53078	0.36502		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
201	Indonesia	1					0.202	0.142		1111	Smiley and Kroschel, 2008	Calculated	Agroforestry
194	Ghana	2									Smith, 1964	Measured	Monoculture

318	Cameroon	30.3								1048	Sonwa et al., 2017	Measured	Agroforestry
319	Cameroon	30.3								1283	Sonwa et al., 2017	Measured	Agroforestry
320	Cameroon	30.3								1173	Sonwa et al., 2017	Measured	Agroforestry
321	Cameroon	30.3								1168	Sonwa et al., 2017	Measured	Agroforestry
370	Brazil	16.5	12.4	5.6	1.2	17.6	19.2	0.1	19.3		Subler, 1994	Calculated	Agroforestry
191	Malaysia	5					36.1				Thong and Ng, 1978	Destructive	Monoculture
326	Nigeria	1									Wessel, 1971	Measured	Monoculture
327	Nigeria	2									Wessel, 1971	Measured	Monoculture
328	Nigeria	3									Wessel, 1971	Measured	Monoculture
329	Nigeria	4									Wessel, 1971	Measured	Monoculture
330	Nigeria	1									Wessel, 1971	Measured	Monoculture
331	Nigeria	2									Wessel, 1971	Measured	Monoculture
332	Nigeria	3									Wessel, 1971	Measured	Monoculture
333	Nigeria	4									Wessel, 1971	Measured	Monoculture

Appendix III – Overview of carbon and nitrogen in cacao organs

Table 3 Dry matter, carbon and nitrogen content in percentage

Leaf dry biomass	Wood dry biomass	Fruit dry biomass	Cwood	Nwood	Cleaf	Nleaf	Cfruit	Nfruit	Croot	Nroot	Source
						1.38					Isaac et al., 2007-b
						1.67					Isaac et al., 2007-b
				1.5		1.5					Isaac et al., 2007-b
				1.68		1.68					Isaac et al., 2007-a
		wet:dry 2.25-3.38									Apshara, 2017
								1.8978			Boyer, 1983
								7.07			Aranguren et al, 1982
								3.4			De Oliveira Leite and Valle, 1990
								3.1			Thong and Ng, 1978
			45.00								Smiley and Kroschel, 2008
						1.46					Isaac et al., 2007-b
						1.67					Isaac et al., 2007-b
						1.4					Shamshuddinet al., 2011
						2.6					Shamshuddinet al., 2011
						2.4					International Fertilizer Industry Association, 1992
				1.47							Baligar and Fageria, 2017
				2.43							Baligar and Fageria, 2017
						1.86					Wessel, 1971
								3.5			Hartemink, 2005
								1.489			Hartemink, 2005
								2.807			Hartemink, 2005
			47.5*		47.5*		47.5*				Silatsa et al., 2017
						1.38					Isaac et al., 2007-a
						1.8					Isaac et al., 2007-a
								2.1			Zuidema et al., 2005
											Van Vliet and Giller, 2017
								3			Described by: Van Vliet and Giller, 2017

								4.5			Described by: Van Vliet and Giller, 2017
		80									Bart-Plange and Baryeh, 2002
		92.5									Bart-Plange and Baryeh, 2002
				0.61 (branch) 0.37 (trunk)		1.88					Alpízar et al., 1986
				1.04 (branch) 0.50 (trunk)		2.08					Alpízar et al., 1986
						1.11**					Pérez-Flores et al., 2017
						1.28**					Pérez-Flores et al., 2017
			50*								N'Guessa N'Gbala et al., 2017
				0.63		1.88		1.29			Fassbender et al., 1988
				2.07		1.73		1.44			Fassbender et al., 1988
								0.16			Santana and Cabala-Rosand, 1982
						1.6		2.313			Afrifa et al., n.d.
17			48.52	0.65	46.67	2.4978			48.23	0.64	Calvo Romero, 2018
17	37.00	29.70	48.96	0.31	46.58	2.199	47.76	1.152	48.16	0.78	Calvo Romero, 2018
17	45.00	27.00	49.26	0.21	47.12	1.681	47.635	1.157	48.68	0.46	Calvo Romero, 2018
17	42.00	30	49	0.32	46.92	2.105	46.97	1.36	48.25	0.62	Calvo Romero, 2018
							49.75***	4.2			Craven et al., 2007
		23.4		0.90 (branch)		1.115					Heuveldop et al., 1988
		23.1		1.42 (branch)		1.35					Heuveldop et al., 1988
			42		42		42		42.00		Mohammed et al., 2016
	41.33	**43.67**	**48.32**	**1.127**	**45.858**	**1.82**	**49.92**	**2.55**	**47.06**	**0.63**	

* All aboveground biomass

** Litter

*** Cacao powder

Appendix IV – Transformation of management practices

Interval of pruning

Survey	Model
I don't know	Every three years
Other	Every three years
Not	Do not prune
Once a year	Every year
During/after harvest	Every year
Less than once every two years	Every three years

Pruning waste

Survey	Model
I do not prune my trees	Do not prune
I leave it in the field	Prun_soil
I use it in a field somewhere else	Prun_away
I burn it	Prun_burn
Other	Prun_away

Fruit waste

Survey	Model
Not used	Pulp_soil
Used for composting	Pulp_comp
Used for animal feed	Pulp_away
Other	Pulp_away

Infected fruits

Survey	Model***
I do not have infected fruits**	Fruit_away
I do not know whether fruits are infected**	Fruit_away
I leave infected fruits on the trees	Fruit_away
I leave infected fruits on the trees and spray	Fruit_away
I remove infected fruits from the trees and leave it in the plot	Fruit_soil
I remove infected fruits from the trees and burn it in the plot	Fruit_burn
I remove infected fruits from the trees and burn it in a hole	Fruit_burn
I remove infected fruits from the trees and burry it	Fruit_soil
I remove infected fruits from the trees and spray it	Fruit_soil
Other****	Fruit_compost

** In case famers state they do not have infected fruits, the modelled infected fruits are treated as a farm output. In this way, these fruits are climate neutral and therefore do not affect the outcomes in terms of GHG emissions negatively. The same applies to the cases in which farmers chose none of the options.
*** In case farmers chose more than one option, all practices are considered of equally percentage.
**** In the clarification farmers state they compost the fruits.

Appendix V – Simple sensitivity analysis

A sensitivity analysis determines how independent variables affect dependent variables. A parameter is sensitive when a minor change in either a biomass parameter or MP has a strong effect on the GHG emissions. Identifying sensitive parameters provides an useful indication to see which parameters require further research. Two sensitivity analyses are carried out: one for biomass related parameters and one for MP related parameters.

Additional to the modelled GHG emissions, the elasticities of parameters are calculated. Elasticities are calculated as following: $elasticity = \frac{\%\Delta Y}{\%\Delta X}$ (Pannell, 1997). The elasticities provide an indication of the parameters to which the GHG-emission is most sensitive (Pannell, 1997).

Sensitivity analysis biomass

The plant parts are multiplied with 1.10 and 0.90 to indicate the effect of changing plant parts on the GHG emissions in ton per hectare. A simple sensitivity analysis regarding biomass is conducted with biomass data obtained from Supplementary information S2, provided by Ledo et al. (2018). The values of the fruit, wood, leaf and fruit biomass are multiplied with 1.1 and 0.9 to assess their sensitivity. All MP are assumed to be applied in the modelled GHG emissions, to get a representative effect for all the biomass parts.

The outcomes of the sensitivity analysis are shown in Table 4. The outcomes show that changes in the wood, leaf and root biomass weight only have a limited effect on the GHG emissions in ton per hectare. Albeit only a small effect, the fruit-parameter has the strongest effect on the GHG emissions. Nonetheless, a 10% change in plant part parameters does not affect the coefficients extremely.

Table 4 Changes in GHG emissions for alterations in multiple parameters biomass

Biomass	**GHG emissions in ton per hectare**		**Elasticity**
Standard		647,321	
Biomass part	+10%	-10%	-
Fruit	712,050	582,592	-0.9999521
Wood	647,321	647,321	0.0000000
Leaf	647,322	647,320	-0.0000154
Root	647,319	647,323	0.0000309

Sensitivity analysis management practices

A simple sensitivity analysis regarding the MP was conducted with biomass parameters provided by Ledo et al (2018). All the MP were compared to the default practice of plant residues as an farm output. To illustrate, when burning pruning and tree waste is set to 25%, the remaining 75% is seen as a farm output. It is important to bear in mind that the outcomes are modelled with standard data, and do not represent actual practices.

The outcomes of the sensitivity analysis are shown in Table 22. The outcomes show a high variance of the effect of MP on the GHG emissions. For example, composting a higher percentage of the fruits has a strong effect on the GHG emissions leading to higher GHG emissions, whereas leaving pruning waste under the trees has a much smaller effect on the GHG emissions. The results show a higher level of GHG emissions when empty pods and unsuitable fruits are composted in an enclosed technology than in an open technology. Surprisingly, for composting litter the technology did not make a difference. This is probably due to an error. Because litter is not commonly composted in an enclosed technology, no attention is paid to this error. For waste management, practices regarding the empty pods and unsuitable fruits have a relative strong influence on the GHG emissions when compared to pruning and tree waste. Furthermore, the effect of manure and fertiliser has only a limited effect on the GHG emissions. However, the outcomes regarding manure and fertiliser must be interpreted with caution because standard data provided by the Cool Farm Alliance (2016) was used. All in all, it can be concluded that the management of empty pods and unsuitable fruits has the strongest effect on the GHG emissions.

Table 5 Changes in GHG emissions for alterations in multiple parameters MP

Management practices	**GHG emissions in ton ha^{-1}**				**Elasticity**
Standard				-24	-
	25%	50%	75%	100%	-
Plant management					
Pruning	-24	-24	-24	-24	0
Gapping	-	-	-	-25	0.0004
Waste management					
Empty pods and unsuitable fruits – left under the trees	-144,608	-289,192	-433,775	-578,359	60.2733
Empty pods and unsuitable fruits – composted open	2,653,224	5,306,472	7,959,721	10,612,969	-1,106.0729
Empty pods and unsuitable fruits – composted enclosed	-13,117,910	-2,296,403	8,525,104	19,346,610	-2,016.2825
Pruning and tree waste – left under the trees	-43	-62	-81	-100	0.0317
Pruning and tree waste – composted	20	63	107	151	-0.0729
Pruning and tree waste – burnt on the field	0.3	25	49	73	-0.0404
Litter – left under the trees	-1,313	-2,601	-3,890	-5,179	2.1479
Litter – composted open	6,807	13,638	20,470	27,301	-11.3854
Litter – composted enclosed	6,807	13,638	20,470	27,301	-47.3733
Litter – burnt on the field	28,400	56,824	85,248	113,672	-0.0001
Type of fertiliser					
	2500 kg	5000 kg	7500 kg	10000 kg	-
Chicken manure	-23.8	-23.8	-23.7	-23.7	-0.0001
Cattle manure	-23.9	-23.8	-23.8	-23.8	-0.0001
Chemical fertiliser	-23.4	-21.4	-12	-18.6	-0.0023

Appendix VI – Cacao fruit data from literature

Table 6 Information on cacao fruits

Yield in kg dry beans ha^{-1} $year^{-1}$	Yield in kg fresh fruits ha^{-1} $year^{-1}$	Fresh fruit weight in g per fruit	Percentage pulp	Percentage seed	Source
626	1,500*			21% fresh; 42% dry	Fassbender et al., 1988
712	1,730*			20% fresh; 41% dry	Fassbender et al., 1988
458	1,041**			44%	Vanhove, Vanhoudt & van Damme, 2015
		400		40-44%***	Abenvega & Gockowski, 2003
400	4,000	475		10%***	Vriesmann et al., 2011
		400-600		30-50%****	Rucker, 2009
			8.7-9.9%	21-23%	Campos-Vega et al., 2018
		23-38*****		17% fresh; 61% dry	Zuidema et al., 2005
		200-1000		33%	Campos-Vega et al., 2018
				12%	Jagoret et al., 2017
		350-480			Apshara, 2017
		38-1195			Carvalho Santos, Luiz Pires & Xavier Correa, 2012
626	1,454	5,822******			Heuveldop, et al., 1988
3,339		614			Tan, 1990

* Only beans and husk
** Not clear if it is per hectare
*** Dry beans as a percentage of total weight of the pod
**** Pulp and seeds together
***** Immature and semi-mature
****** Only the husk

Appendix VII – Map of field experiment

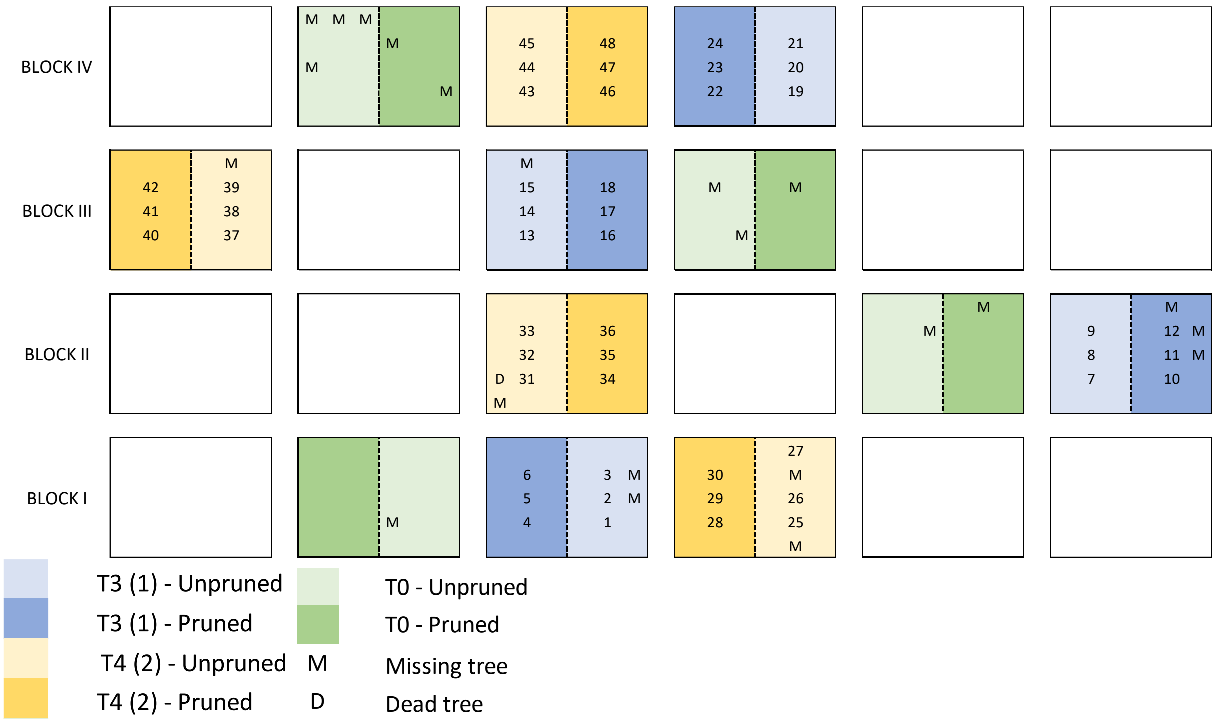

Figure 14 Overview of the field experiment

Appendix XIII – IBM cacao biomass script

```
# Model to parametrice the biomass accumulation curves for the IBM model

cropdata <-read.csv(file="...", header=TRUE, sep = ',')
cdat<-cropdata
colnames(cdat)<-c("ID","species",  "Age",  "AGBfruit",  "AGBbranch","AGBstem",  "AGBleaf",  "AGBwoody",  "totalAGB",
"totalBGB", "TotalBiomass", "IR", "FER","Title")
year<-c(1:  max(cdat$Age))
cdat

# Defining/fitting functions
#AGB  model as a function  of age       (kg per tree per year, cummulative)
nls.control(maxiter = 500, tol = 1e-05, minFactor = 1/1024)
fitpwlAGB_AGE <- nls(totalAGB~a * Age^b, data=cdat,start=list(a=1,b=1))
EST_AGB<-function(age){coef(fitpwlAGB_AGE)[[1]]*age^(coef(fitpwlAGB_AGE)[[2]])}
plot(cdat$Age,cdat$totalAGB)
lines(EST_AGB(0:40),col="blue")

#AGB model of woody parts (branches, trunk) - excluding leaves and apples (kg per tree per)
fitpwlAGBW_AGE<-nls(AGBwoody~a* Age^b, data=cdat,start=list(a=1,b=1))
EST_AGBW<-function(age){coef(fitpwlAGBW_AGE)[[1]]*age^(coef(fitpwlAGBW_AGE)[[2]])}
plot(cdat$Age,cdat$AGBwoody, xlab="year",ylab="woody AGB")
lines(EST_AGBW(0:40),col="blue")

#BGB  model as a function  of age       (kg per tree per year, cummulative)
fitpwlBGB_AGE<-nls(totalBGB~a*Age^b,data=cdat,start=list(a=1,b=1))
EST_BGB<-function(age){coef(fitpwlBGB_AGE)[[1]]*age^(coef(fitpwlBGB_AGE)[[2]])}
plot(cdat$Age,cdat$totalBGB)
lines(EST_BGB(0:40),col="blue")

#Leaves model as a function of  woody AGB     - cummulative values, they are evergreen
fitpwlLEAF_AGB<-nls(AGBleaf~a*  AGBwoody^b,data=cdat,start=list(a=1,b=1))
EST_LEAF<-function(bio){coef(fitpwlLEAF_AGB)[[1]]*bio^(coef(fitpwlLEAF_AGB)[[2]])}
plot(cdat$AGBwoody,cdat$AGBleaf)
lines(EST_LEAF(0:150),col="blue")

summary(fitpwlAGB_AGE)
summary(fitpwlBGB_AGE)
summary(fitpwlLEAF_AGB)
summary(fitpwlAGBW_AGE)
```

Appendix IX – Pruning percentage obtained during fieldwork

Table 7 Pruning percentage expressed as fresh pruning weight divided by the fresh woody biomass

Tree number	Circumference	Diameter	Woody Biomass kg	Fresh pruning weight kg	Pruning percentage
4	44	14.0056	41.08594023	5.54	13
5	61	19.4169	56.9600535	13.36	23
6	54	17.1887	50.42365391	9.42	19
10	35	11.1408	32.68199791	3.87	12
11	47	14.9606	43.88725433	6.28	14
12	59	18.7803	55.09251076	9.12	17
16	37	11.7775	34.54954065	3.52	10
17	53	16.8704	49.48988255	10.52	21
18	57	18.1437	53.22496802	5.16	10
22	66	21.0085	61.62891034	8.78	14
23	47	14.9606	43.88725433	3.73	8
24	58	18.462	54.15873939	11.26	21
28	53	16.8704	49.48988255	11.38	23
29	30	9.5493	28.01314106	1.24	4
30	68	21.6451	63.49645308	21.72	34
34	65	20.6901	60.69513897	9.2	15
35	38	12.0958	35.48331201	10.84	31
36	58	18.462	54.15873939	12.56	23
40	42	13.369	39.21839749	3.84	10
41	52	16.5521	48.55611118	12.5	26
42	54	17.1887	50.42365391	9.38	19
46	64	20.3718	59.7613676	18.16	30
47	43	13.6873	40.15216886	5.7	14
48	64	20.3718	59.7613676	9.3	16

Appendix X – IBM script regarding MP

```
# IBM Model
cropdata<-read.csv(file="...", header=TRUE)
cdat1<-cropdata

cdat1
cdat1$nr <- 1:nrow(cdat1)
# output lists
datalist = list()
indbio_list = list()
indbioAnnual_list = list()
indbioCum_list = list()
indC_list = list()
indCAnnual_list = list()
indCCum_list = list()
CO2_list = list()
N2O_list = list()
CH4_list = list()
CO2eq_list = list()
Control_list=list()
GHG_list=list()

cat("runnumber, ID, area, BaseYear, AGB [kg/ha],woodyAGB [kg/ha],prunings [kg/ha],actualWAGB [kg/ha],BGB [kg/ha],leaves [kg/ha],fruits [kg/ha],TOTindbio [kg/ha],\n", file=".../indbioCum.csv")
cat("runnumber, ID, area, BaseYear, AGBC [kg/ha],woodyAGBC [kg/ha],pruningsC [kg/ha],actualWAGBC [kg/ha],BGBC [kg/ha],leavesC [kg/ha],fruitsC [kg/ha],TOTindC [kg/ha],\n", file=".../indCCum.csv")
cat("runnumber, ID, area, BaseYear,AGB [kg/ha],woodyAGB [kg/ha],prunings [kg/ha],actualWAGB [kg/ha],BGB [kg/ha],leaves [kg/ha],fruits [kg/ha],TOTindbio [kg/ha],\n", file=".../indbioAnnual.csv")
cat("runnumber, ID, area, BaseYear,  AGBC [kg/ha],woodyAGBC [kg/ha],pruningsC [kg/ha],actualWAGBC [kg/ha],BGBC [kg/ha],leavesC [kg/ha],fruitsC [kg/ha],TOTindC [kg/ha],\n", file=".../indCAnnual.csv")
cat("runnumber, ID, area, year, woodyAGB [kg/ha], leaves [kg/ha], roots [kg/ha], prun_burn [kg/ha],prun_chipsoil [kg/ha],prun_comp [kg/ha],litter_burn [kg/ha],litter_soil [kg/ha],litter_comp [kg/ha],fruit_soil [kg/ha],fruit_comp [kg/ha],pulp_soil [kg/ha],pulp_comp [kg/ha],pulp_burn [kg/ha],CO2TOT [kg/ha],\n", file=".../CO2.csv")
cat("runnumber, ID, area, year, woodyAGB [kg/ha], leaves [kg/ha], roots [kg/ha], prun_burn [kg/ha],prun_chipsoil [kg/ha],prun_comp [kg/ha],litter_burn [kg/ha],litter_soil [kg/ha],litter_comp [kg/ha],fruit_soil [kg/ha],fruit_comp [kg/ha],pulp_soil [kg/ha],pulp_comp [kg/ha],pulp_burn [kg/ha],N2OTOT [kg/ha],\n", file=".../N2O.csv")
cat("runnumber, ID, area, year, woodyAGB [kg/ha], leaves [kg/ha], roots [kg/ha], prun_burn [kg/ha],prun_chipsoil [kg/ha],prun_comp [kg/ha],litter_burn [kg/ha],litter_soil [kg/ha],litter_comp [kg/ha],fruit_soil [kg/ha],fruit_comp [kg/ha],pulp_soil [kg/ha],pulp_comp [kg/ha],pulp_burn [kg/ha],CH4TOT [kg/ha],\n", file=".../CH4.csv")
cat("runnumber, ID, area, year, woodyAGB [kg/ha], leaves [kg/ha], roots [kg/ha], prun_burn [kg/ha],prun_chipsoil [kg/ha],prun_comp [kg/ha],litter_burn [kg/ha],litter_soil [kg/ha],litter_comp [kg/ha],fruit_soil [kg/ha],fruit_comp [kg/ha],pulp_soil [kg/ha],pulp_comp [kg/ha],pulp_burn [kg/ha],CO2eqTOT [kg/ha],\n", file=".../CO2eq.csv")
cat("runnummer, ID,area, year,CO2 [kg/ha],N2O [kg/ha],CH4 [kg/ha],CO2eq [kg/ha],\n",file=".../GHG.csv")

Runnumber <- nrow(cdat1)

#count <- 0
count <-1
for (count in cdat1$nr)
 {
cdat<-cdat1[count,]
#cdat =cdat1[]

#MODEL INPUTS -for this example
crop  =   "cocoa"
GWP = "Myhre2013"
area = cdat$AreaPlot
Nind = cdat$Nind
Nyear = 70
```

```
pruning= "YES"
pruning_yearago = cdat$prun_yearago
pruning_farm_values= "YES"
PrunP_start=6
pruning_weight="NO"
Pruntha  <-c(rep(NA,Nyear))
pruning_perc="YES"
PrunPer=c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0)
Basejaar <- cdat$BaseYear-pruning_yearago
PruningTimes <- as.integer((Basejaar-PrunP_start)/3)
PruningStartTime <- Basejaar - (PruningTimes*3)
vector1 <- (1:PruningTimes)
length(vector1) <- length(vector1)+1

for (i in 1:length(vector1)){
   PrunPer [PruningStartTime] <- cdat$PrunPerBase
   PruningStartTime <-PruningStartTime + 3
   i <- i+1
 }

yieldyear=
c(0,0,50,50,60,70,70,80,80,80,70,70,60,60,55,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,
50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50) # extended to 70 years
yieldyear[] <-cdat$BaseYield
Perbad= 0.30
PNdie= 0
gaping="NO"

#RESIDUES
# Pruning
burn_prun= cdat$burn_prun
PERburn_prun = cdat$PERburn_prun
soil_chip_prun = cdat$soil_chip_prun
PERchipsoil_prun = cdat$PERchipsoil_prun
com_chip_prun= cdat$com_chip_prun
PERchipcom_prun = cdat$PERchipcom_prun
prun_away = cdat$prun_away
PERprun_away= cdat$PERprun_away

#Trees that die during the period
burn_dead = "YES"
PERburn_dead = 50
soil_chip_dead = "NO"
PERchipsoil_dead= 0
dead_away = "YES"
PERdead_away= 50

# Trees end cycle
burn_tree="YES"
PERburn_tree= 90
soil_chip_tree="YES"
PERchipsoil_tree=10
tree_away = "NO"
PERtree_away= 0

# Litter
soil_litter="YES"
PERsoil_litter=100
burn_litter="NO"
PERburn_litter=0
```

```
com_litter="NO"
PERcom_litter=0
open_compost="NO"
enclosed_comp="NO"
litter_away="NO"

# Unsuitable fruits
burn_fruit=cdat$burn_fruit
PERburn_fruit =cdat$PERburn_fruit
soil_fruit=cdat$soil_fruit
PERsoil_fruit =cdat$PERsoil_fruit
comp_fruit = cdat$comp_fruit
PERcomp_fruit=cdat$PERcomp_fruit
open_compost="YES"
enclosed_comp="NO"
fruit_away = cdat$fruit_away
PERfruit_away=cdat$PERfruit_away

# Fruit pulp
depulp="YES"
soil_pulp= cdat$soil_pulp
burn_pulp=cdat$burn_pulp
PERburn_pulp=cdat$PERburn_pulp
PERsoil_pulp=cdat$PERsoil_pulp
comp_pulp=cdat$comp_pulp
PERcomp_pulp= cdat$PERcomp_pulp
open_compost="YES"
enclosed_comp="NO"
pulp_away=cdat$pulp_away
PERpulp_away= cdat$PERpulp_away

# Selecting the suitable submodel
if (crop == "apple"){submodel="IBM"}
if (crop == "citrus"){submodel="IBM"}
if (crop == "cocoa"){submodel="IBM"}
if (crop == "coffee"){submodel="IBM"}
if (crop == "tea"){submodel="IBM"}
if (crop == "willow"){submodel="IBM"}
if (crop == "poplar"){submodel="IBM"}

# Select GWP values
if(GWP=="IPCC2001"){(GWPCH4<-25) & (GWPN2O<-298)} else if
(GWP=="Myhre2013"){(GWPCH4<-34) & (GWPN2O<-298)}

# Model internal parameters for IBM
if(submodel=="IBM"){
  #pruning values
  PrunP=10
  PrunP_start=6
  #Decomposition parameters
  k_chip=1.27
  k_litter=0.63
  k_fruit=1.64
  k_root=1.0
  k_pulp = 1.64
}

# Model internal parameters -CROP PARAMETERS
# parameters for the IBM
if(submodel=="IBM"){
    if (crop=="cocoa"){
```

```
   drymatterwood=0.413
   drymatterfruit= 0.2
   drymatterbeans=0.92
   drymatterpulp = 0.15
   drymatterleaf= 0.38
   Cwood=0.4832
   Nwood=0.0117
   Cleaf=0.45858
   Nleaf=0.0181
   Croot=0.4706
   Nroot= 0.0063
   Cfruit=0.4992
   Nfruit=0.025
   Cpulp=0.499
   Npod=0.012
   AGBcoefa = 5.8283
   AGBcoefb = 0.6988
   AGBWcoefa  = 7.4461
   AGBWcoefb =     0.401
   BGBcoefa = 2.7646
   BGBcoefb =        0.5111
   deciduous="NO"
   leaflife=1
   LEAFcoefa = 0.6759
   LEAFcoefb =       0.5941
   depulp = "YES"
   wRf=1
   nRf=1
   Ppulp=0.4
   Pseed=0.6
   #percentage of discarded fruit
   Perbad=0.30
  }

}

# IBM
if(submodel=="IBM"){
  #Store data and results
  #Biomass
  indbio<-matrix(0,  ncol=8,  nrow=Nyear)
  colnames(indbio)<-c("year","AGB","woodyAGB","pruning","actualWAGB","BGB","leaves","fruit")
  indbio[,1]<-c(1:Nyear)
  indbio<-as.data.frame(indbio)
 #Carbon
  indC<-matrix(0,  ncol=8,  nrow=Nyear)
  colnames(indC)<-c("year","AGB","woodyAGB","pruning","actualWAGB","BGB","leaves","fruit")
  indC[,1]<-c(1:Nyear)
  indC<-as.data.frame(indC)
  #Nitrogen
  indN<-matrix(0,  ncol=8,  nrow=Nyear)
  colnames(indN)<-c("year","AGB","woodyAGB","pruning","actualWAGB","BGB","leaves","fruit")
  indN[,1]<-c(1:Nyear)
  indN<-as.data.frame(indN)

  #Functions
  ############
  ##AGB model as a function of age     (kg per individual per year, cummulative)
  AGBmodel<-function(Nyear){AGBcoefa*wRf*nRf*Nyear^(AGBcoefb)}
  indbio[,2]<-AGBmodel(1:Nyear)
  indC[,2]<-AGBmodel(1:Nyear)
```

```
indN[,2]<-AGBmodel(1:Nyear)
##AGB model of woody parts: branches and trunk       (kg per individual per year, cummulative)
AGBWmodel<-function(Nyear){AGBWcoefa*wRf*nRf*Nyear^(AGBWcoefb)}
indbio[,3]<-AGBWmodel(1:Nyear)
indC[,3]<-AGBWmodel(1:Nyear)*Cwood
indN[,3]<-AGBWmodel(1:Nyear)*Nwood

# Pruning            - (kg per individual per year, cummulative)
if (pruning=="YES"){
 if (pruning_farm_values=="YES"){
   #check pruning values are not be greater than woodyAGB
   if(pruning_weight=="YES"){
    Pruntree_year<-(Pruntha*1000/Nind)*drymatterwood        #kg per tree biomass
    check<-indbio[,3]-Pruntree_year
    if(sum(check<0)>=1){print("ERROR.  Pruning  values  too  high")}
   }
 }
 ###PROGRAM SHOULD STOP HERE##
 if (pruning_weight=="YES"){
   Pruntree_year<-(Pruntha*1000/Nind)*drymatterwood          #kg per tree biomass
   #cummulative values Pruntree<-Pruntree_year sumv=  Pruntree[1]
   for (i in 1:Nyear){
    sumv= Pruntree[i]+sumv
    Pruntree[i]<-sumv
   }
   indbio[,4]<-Pruntree
   indC[,4]<-Pruntree*Cwood
   indN[,4]<-Pruntree*Nwood
 }
 if(pruning_perc=="YES"){
   Pruntree_year<-(PrunPer/100)*indbio[,3]
   #cummulative values
   Pruntree<-Pruntree_year
   sumv=  Pruntree[1]
    for (i in 1:Nyear){
     sumv= Pruntree[i]+sumv
     Pruntree[i]<-sumv
     }
   indbio[,4]<-Pruntree
   indC[,4]<-Pruntree*Cwood
   indN[,4]<-Pruntree*Nwood
 }
 if (pruning_farm_values=="NO") {
   Pruntree_year<-c(indbio[,3]*(PrunP/100))
   Pruntree_year<-Pruntree_year[-Nyear]
   Pruntree_year<-c(0,Pruntree_year)
   Pruntree_year[0:(PrunP_start-1)]<-0

 #cummulative values
   Pruntree<-Pruntree_year
   sumv=  Pruntree[1]
 #for (i in 1:Nyear){
 for (i in PrunP_start:Nyear){
   sumv= Pruntree[i]+sumv
   Pruntree[i]<-sumv
 }
 indbio[,4]<-Pruntree
 indC[,4]<-Pruntree*Cwood
 indN[,4]<-Pruntree*Nwood
 }
}
```

```
# Actual woody AGB        (wood - pruning) -kg per individual per year
if (pruning_farm_values=="YES"){
  indbio[,5]<-indbio[,3]-Pruntree
  indC[,5]<-indC[,3]-Pruntree*Cwood
  indN[,5]<-indN[,3]-Pruntree*Nwood
} else {
  indbio[,5]<-indbio[,3]-Prunest_year
  indC[,5]<-indC[,3]-Prunest_year*Cwood
  indN[,5]<-indN[,3]-Prunest_year*Nwood
}

# BGB model as a function of age     (kg per tree per year, cummulative)
BGBmodel<-function(Nyear){(BGBcoefa*wRf*nRf*Nyear^(BGBcoefb))}
BGBaux<-BGBmodel(1:Nyear)

# fine root
fineroot<-((2.73*BGBaux^(-0.841))/100)*BGBaux
indbio[,6]<-BGBmodel(1:Nyear)
indC[,6]<-BGBmodel(1:Nyear)*Croot
indN[,6]<-BGBmodel(1:Nyear)*Nroot

#Leaves model as a function of woody AGB    (kg per tree per year, cummulative)
if (deciduous=="YES"){
  LEAFmodel<-function(agb){LEAFcoefa*agb^(LEAFcoefb)}
  leaves_year<-c(LEAFmodel(indbio[,5]))
  #cummulative values
  leaves<-leaves_year
  sum=  leaves[1]
  for (i in 1:Nyear){
    sum= leaves[i]+sum
    leaves[i]<-sum
  }
  indbio[,7]<-leaves
  indC[,7]<-leaves*Cleaf
  indN[,7]<-leaves*Nleaf
}else{

  #perennial species
  LEAFmodel<-function(agb){LEAFcoefa*agb^(LEAFcoefb)}
  leaves_year<-c(LEAFmodel(indbio[,3]))
  #cummulative values
  leaves<-leaves_year
  for (i in leaflife:Nyear){
    leaves[i]<-leaves_year[i]+leaves_year[i]/3
  }
  indbio[,7]<-leaves
  indC[,7]<-leaves*Cleaf
  indN[,7]<-leaves*Nleaf
}

#now C and N in AGB can be calculated
indbio[,2] <- indbio[,5]+indbio[,7]
indC[,2]<-indC[,5]+indC[,7]
indN[,2]<-indN[,5]+indN[,7]

#Fruits- yield      - (kg per tree per year, cummulative)
yieldbio_year<- (yieldyear/Nind)*drymatterbeans
#cummulative values
yieldbio<-yieldbio_year
sum=  yieldbio_year[1]
```

```
 for (i in 2:Nyear){
  sum= yieldbio_year[i]+sum
  yieldbio[i]<-sum
 }

 # the total fruit production Perbad
 indbio[,8]<-yieldbio*(1+Perbad)/Pseed
 indC[,8]<-yieldbio*(1+Perbad)/Pseed*Cfruit
 indN[,8]<-yieldbio*(1+Perbad)/Pseed*Nfruit

########################################
#Annual values
########################################

 indbio_annual<-indbio

 for (i in 2:Nyear){
  indbio_annual[i,2]<-indbio[i,2]-indbio[i-1,2]
  indbio_annual[i,3]<-indbio[i,3]-indbio[i-1,3]
  indbio_annual[i,4]<-indbio[i,4]-indbio[i-1,4]
  indbio_annual[i,5]<-indbio[i,5]-indbio[i-1,5]
  indbio_annual[i,6]<-indbio[i,6]-indbio[i-1,6]
  indbio_annual[i,7]<-indbio[i,7]-indbio[i-1,7]
  indbio_annual[i,8]<-indbio[i,8]-indbio[i-1,8]
 }

indC_annual<-indC

 for (i in 2:Nyear){
  indC_annual[i,2]<-indC[i,2]-indC[i-1,2]
  indC_annual[i,3]<-indC[i,3]-indC[i-1,3]
  indC_annual[i,4]<-indC[i,4]-indC[i-1,4]
  indC_annual[i,5]<-indC[i,5]-indC[i-1,5]
  indC_annual[i,6]<-indC[i,6]-indC[i-1,6]
  indC_annual[i,7]<-indC[i,7]-indC[i-1,7]
  indC_annual[i,8]<-indC[i,8]-indC[i-1,8]
 }

 indN_annual<-indN

 for (i in 2:Nyear){
  indN_annual[i,2]<-indN[i,2]-indN[i-1,2]
  indN_annual[i,3]<-indN[i,3]-indN[i-1,3]
  indN_annual[i,4]<-indN[i,4]-indN[i-1,4]
  indN_annual[i,5]<-indN[i,5]-indN[i-1,5]
  indN_annual[i,6]<-indN[i,6]-indN[i-1,6]
  indN_annual[i,7]<-indN[i,7]-indN[i-1,7]
  indN_annual[i,8]<-indN[i,8]-indN[i-1,8]
 }

########################################################################################
##
##GHGs calculation            - Kg per tree annual values - warning- no cummulative anymore
########################################################################################
##
#Store values - per individual tree values # "pulp_burn", toegevoegd ine in colomn .. gestopt
CO2<-matrix(0,  ncol=19,  nrow=Nyear)
colnames(CO2)<-c("year","woodyAGB","leaves","roots","prun_burn","prun_chipsoil",
"prun_comp","litter_burn","litter_soil","litter_comp","fruit_soil","fruit_comp","pulp_soil","pulp_comp","EPtree_burn",
"EPtree_chip","aux_dead_burn","aux_dead_chip", "pulp_burn")
CO2[,1]<-c(1:Nyear)
```

```
CO2<-as.data.frame(CO2)
N2O<-matrix(0,  ncol=19,  nrow=Nyear)
colnames(N2O)<-c("year","woodAGB","leaves","roots","prun_burn","prun_chipsoil",
"prun_comp","litter_burn","litter_soil","litter_comp","fruit_soil","fruit_comp","pulp_soil","pulp_comp","EPtree_burn",
"EPtree_chip","aux_dead_burn","aux_dead_chip","pulp_burn")
N2O[,1]<-c(1:Nyear)
N2O<-as.data.frame(N2O)
CH4<-matrix(0,  ncol=19,  nrow=Nyear)
colnames(CH4)<-c("year","woodAGB","leaves","roots","prun_burn","prun_chipsoil",
"prun_comp","litter_burn","litter_soil","litter_comp","fruit_soil","fruit_comp", "pulp_soil","pulp_comp","EPtree_burn",
"EPtree_chip","aux_dead_burn","aux_dead_chip","pulp_burn")
CH4[,1]<-c(1:Nyear)
CH4<-as.data.frame(CH4)
CO2eq<-matrix(0,  ncol=22,  nrow=Nyear)
colnames(CO2eq)<-c("year","woodAGB","leaves","roots","prun_burn","prun_chipsoil",
"prun_comp","litter_burn","litter_soil","litter_comp","fruit_soil","fruit_comp", "pulp_soil","pulp_comp","EPtree_burn",
"EPtree_chip","aux_dead_burn","aux_dead_chip","pulp_burn", "chip_prun_annual","litter_soil_annual","pulp_soil_annual")
CO2eq[,1]<-c(1:Nyear)
CO2eq<-as.data.frame(CO2eq)

CO2Cum <-matrix(0, ncol=19, nrow=Nyear)
colnames(CO2Cum)<-c("year","woodyAGB","leaves","roots","prun_burn","prun_chipsoil",
"prun_comp","litter_burn","litter_soil","litter_comp","fruit_soil","fruit_comp","pulp_soil","pulp_comp","EPtree_burn",
"EPtree_chip","aux_dead_burn","aux_dead_chip","pulp_burn")
CO2Cum[,1]<-c(1:Nyear)
CO2Cum <-as.data.frame(CO2Cum)

#Plant balance,CO2 accumulation by the plant - via respiration - in Kg per tree per year
 if (deciduous=="YES"){
   CO2[,2]<-indC_annual[,5]*44/12*(-1)
   CO2[,3]<-0
   CO2[,4]<-indC_annual[,6]*44/12*(-1)
 } else {
   CO2[,2]<-indC_annual[,5]*44/12*(-1)
   CO2[,3]<-indC_annual[,7]*1/3*44/12*(-1)
   CO2[,4]<-indC_annual[,6]*44/12*(-1)
 }

# Fine root decomposition
root_remain<-matrix(0,  ncol=Nyear+1,nrow=Nyear)
colnames(root_remain)<-c("year",names<-1:Nyear)
root_remain[,1]<-c(1:Nyear)
root_remain<-as.data.frame(root_remain)
rootaux<-c(1:Nyear)  #needs  this  auxiliar  vector

#remaining mass each year
 for (j in 1:Nyear){
   for (i in 1:Nyear){
       rootaux[i]<-fineroot[j]*(exp(-1*(k_root)*i))
       root_j<-c(rep(0,(j-1)),rootaux)
         root_j<-root_j[1:Nyear]
       root_remain[,1+j]<- root_j
   }
 }
#annual values
fineroot_remain_annual<-rowSums(root_remain[2:(Nyear+1)])

CO2[,4]<-(indC_annual[,6]+(fineroot_remain_annual*Croot))*44/12*(-1)

# Residuals from prunning, in Kg per tree per year
#check that the 100% of information about residues is here
```

```
###PROGRAM SHOULD STOP HERE##
# Residues are burnt
 if (burn_prun=="YES"){
   CO2[,5]<- (indbio_annual[,4]*(PERburn_prun/100)*1.509)- (indbio_annual[,4]*(PERburn_prun/100)*Cwood*44/12)
   N2O[,5]<-  indbio_annual[,4]*(PERburn_prun/100)*0.00038
   CH4[,5]<- indbio_annual[,4]*(PERburn_prun/100)*0.00568
 }
#the  residues  are  chippedand spread
 if (soil_chip_prun=="YES"){
  #matrix with each year decomposition
  chip_remain<-matrix(0,  ncol=Nyear+1,  nrow=Nyear)
  colnames(chip_remain)<-c("year",names<-1:Nyear)
  chip_remain[,1]<-c(1:Nyear)
  chip_remain<-as.data.frame(chip_remain)
  chipaux<-c(1:Nyear)

 #remaining mass each year
 for (j in 1:Nyear){
  for (i in 1:Nyear){
  chipaux[i]<-indbio_annual[j,4]*(exp(-1*(k_chip)*i))
  chip_j<-c(rep(0,(j-1)),chipaux)
   chip_j<-chip_j[1:Nyear]
  chip_remain[,1+j]<- chip_j
  }
 }
 #annual values
  chip_remain_annual<-rowSums(chip_remain[2:(Nyear+1)])
  CO2Cum[,6]<-chip_remain_annual*Cwood*(PERchipsoil_prun/100)*(-44/12)

  for (i in 2:Nyear){
    CO2[i,6]<-CO2Cum[i,6]-CO2Cum[i-1,6]
  }

 }else{chip_remain_annual=c(rep(0,Nyear))}

# the residues are chipped and taken
if (prun_away=="YES"){
 #nothing, they are carbon neutral
}

# the residues are chipped and composted
 if (com_chip_prun=="YES"){
  if (open_compost=="YES"){
    CO2[,7]<-  ((indbio_annual[,4]*Cwood*(1-(60/100))*-44/12)+
(indbio_annual[,4]/drymatterwood*0.25)+(indbio_annual[,4]*drymatterwood*7.965))*(PERchipcom_prun/100)
    N2O[,7]<- (indbio_annual[,4]/drymatterwood*0.001)*(PERchipcom_prun/100)
    CH4[,7]<- (indbio_annual[,4]/drymatterwood*0.0035)*(PERchipcom_prun/100)
   }
 if(enclosed_comp=="YES") {
    CO2[,7]<-  ((indbio_annual[,4]*Cwood*(1-(60/100))*-44/12)
          +(indbio_annual[,4]/drymatterwood*0.3)+(indbio_annual[,4]/drymatterwood*7.965))*(PERchipcom_prun/100)
    N2O[,7]<- (indbio_annual[,4]/drymatterwood*0.00659)*(PERchipcom_prun/100)
    CH4[,7]<- (indbio_annual[,4]/drymatterwood*0.0009)*(PERchipcom_prun/100)
  }
 }

#Litter, in Kg per tree per year
#check - 100% of information about litter is here
if ((PERsoil_litter+PERburn_litter+PERcom_litter)!=100)
{print("ERROR. Percentage of litter does not equal to 100%")}
###PROGRAM SHOULD STOP HERE##
```

```
#the litter is burnt
 if (burn_litter=="YES"){
   CO2[,8]<- (indbio_annual[,7]*(1-1/(1+1/3))*(PERburn_litter/100)*1.515)-
(indbio_annual[,7]*(PERburn_litter/100)*Cleaf*44/12)
   N2O[,8]<-  indbio_annual[,7]*(1-1/(1+1/3))*(PERburn_litter/100)*0.00007
   CH4[,8]<-  indbio_annual[,7]*(1-1/(1+1/3))*(PERburn_litter/100)*0.027
 }
# the litter is left on the ground
 if(soil_litter=="YES"){
  #matrix with each year decomposition
  litter_remain<-matrix(0,  ncol=Nyear+1,  nrow=Nyear)
  colnames(litter_remain)<-c("year",names<-1:Nyear)
  litter_remain[,1]<-c(1:Nyear)
  litter_remain<-as.data.frame(litter_remain)
  litteraux<-c(1:Nyear)

  #remaining mass each year
  for (j in 1:Nyear){
   for (i in 1:Nyear){
     litteraux[i]<-indbio_annual[j,7]*(1-1/(1+1/3))*(exp(-1*(k_litter)*i))
     lit_j<-c(rep(0,(j-1)),litteraux)
     lit_j<-lit_j[1:Nyear]
     litter_remain[,1+j]<- lit_j
   }
  }
  #annual values
  litter_remain_annual<-rowSums(litter_remain[2:(Nyear+1)])
  CO2Cum[,9]<-litter_remain_annual*Cleaf*(PERsoil_litter/100)*(-44/12)

  for (i in 2:Nyear){
   CO2[i,9]<-CO2Cum[i,9]-CO2Cum[i-1,9]
  }

 }

#litter composted
 if (com_litter=="YES"){
  if (open_compost=="YES"){
    CO2[,10]<- ((indbio_annual[,7]*(1-1/(1+1/3))*Cleaf*(1-(60/100))*-44/12)+ (indbio_annual[,7]*(1-
1/(1+1/3))/drymatterleaf*0.25)+(indbio_annual[,7]*(1-1/(1+1/3))/drymatterleaf*7.965))*PERcom_litter/100
    N2O[,10]<-   indbio_annual[,7]*(1-1/(1+1/3))/drymatterleaf*PERcom_litter/100*0.001
    CH4[,10]<-   indbio_annual[,7]*(1-1/(1+1/3))/drymatterleaf*PERcom_litter/100*0.0035
   }
  if(enclosed_comp=="YES") {
    CO2[,10]<-  ((indbio_annual[,7]*(1-1/(1+1/3))*Cleaf*(1-(60/100))*-44/12)+ (indbio_annual[,7]*(1-
1/(1+1/3))/drymatterleaf*0.3)+(indbio_annual[,7]*(1-
1/(1+1/3))*drymatterleaf*7.965))*PERcom_litter/100/drymatterleaf
    N2O[,10]<- indbio_annual[,7]*(1-1/(1+1/3))*PERcom_litter/100/drymatterleaf*0.00659
    CH4[,10]<- indbio_annual[,7]*(1-1/(1+1/3))*PERcom_litter/100/drymatterleaf*0.0009

   }
 }

# fruits left on the ground- in Kg per tree per year

# fruit is burned.
if (burn_fruit=="YES"){
  CO2[,20]<- (indbio_annual[,8]*(Perbad)*(PERburn_fruit/100)*1.515)-
(indbio_annual[,8]*(Perbad)*(PERburn_fruit/100)*Cfruit*44/12)
  N2O[,20]<-  indbio_annual[,8]*(Perbad)*(PERburn_fruit/100)*0.00007
  CH4[,20]<-  indbio_annual[,8]*(Perbad)*(PERburn_fruit/100)*0.027
```

```
}

 if (soil_fruit=="YES"){
   fruit_remain<-matrix(0,  ncol=Nyear+1,  nrow=Nyear)
   colnames(fruit_remain)<-c("year",names<-1:Nyear)
   fruit_remain[,1]<-c(1:Nyear)
   fruit_remain<-as.data.frame(fruit_remain)
   fruitaux<-c(1:Nyear)
  for  (j in 1:Nyear){
    for(i in 1:Nyear){
      fruitaux[i]<-(indbio_annual[j,8]*Perbad)*(exp(-1*(k_fruit)*i))
      fruit_j<-c(rep(0,(j-1)),fruitaux)
      fruit_j<-fruit_j[1:Nyear]
      fruit_remain[,1+j]<- fruit_j
    }
  }
  #annual values
   fruit_remain_annual<-rowSums(fruit_remain[2:(Nyear+1)])
   CO2Cum[,11]<-fruit_remain_annual*Cfruit*(PERsoil_fruit/100)*(-44/12)

   for (i in 2:Nyear){
     CO2[i,11]<-CO2Cum[i,11]-CO2Cum[i-1,11]
   }

 }

# Pulp
if ((PERburn_pulp+PERsoil_pulp+PERpulp_away+PERcomp_pulp)!=100)
{print("ERROR. Percentage of pulp residues does not equal to 100%")}
###PROGRAM SHOULD STOP HERE##
# pulp is burned.
if (burn_pulp=="YES"){
  CO2[,19]<- (indbio_annual[,8]*(1-Perbad)*Ppulp*(PERburn_pulp/100)*1.515)-
(indbio_annual[,8]*Ppulp*(PERburn_pulp/100)*Cpulp*44/12)
  N2O[,19]<-  indbio_annual[,8]*(1-Perbad)*Ppulp*(PERburn_pulp/100)*0.00007
  CH4[,19]<-  indbio_annual[,8]*(1-Perbad)*Ppulp*(PERburn_pulp/100)*0.027
}

if (soil_pulp=="YES"){
  pulp_remain<-matrix(0,  ncol=Nyear+1,  nrow=Nyear)
  colnames(pulp_remain)<-c("year",names<-1:Nyear)
  pulp_remain[,1]<-c(1:Nyear)
  pulp_remain<-as.data.frame(pulp_remain)
  pulpaux<-c(1:Nyear)

  for (j in 1:Nyear){
    for (i in 1:Nyear){
      pulpaux[i]<-indbio_annual[j,8]*(1-Perbad)*Ppulp*(exp(-1*(k_pulp)*i))
      pulp_j<-c(rep(0,(j-1)),pulpaux)
      pulp_j<-pulp_j[1:Nyear]
      pulp_remain[,1+j]<- pulp_j
    }
  }
  pulp_remain_annual<-rowSums(pulp_remain[2:(Nyear+1)])
  CO2Cum[,13]<-pulp_remain_annual*Cpulp*(PERsoil_pulp/100)*(-44/12)

  for (i in 2:Nyear){
    CO2[i,13]<-CO2Cum[i,13]-CO2Cum[i-1,13]
  }

}else{pulp_remain_annual=c(rep(0,Nyear))}
```

```
 if (comp_pulp=="YES"){
   if (open_compost=="YES"){
     CO2[,14]<-  ((indbio_annual[,8]*(1-Perbad)*Ppulp*Cpulp*(1-(60/100))*-44/12)+ (indbio_annual[,8]*(1-
Perbad)*Ppulp/drymatterpulp*0.25)+ (indbio_annual[,8]*(1-
Perbad)*Ppulp/Pseed/drymatterpulp*7.965))*PERcomp_pulp/100
     N2O[,14]<- indbio_annual[,8]*(1-Perbad)*Ppulp*PERcomp_pulp/100/drymatterpulp*0.001
     CH4[,14]<- indbio_annual[,8]*(1-Perbad)*Ppulp*PERcomp_pulp/100/drymatterpulp*0.0035
   }           else
     if(enclosed_comp=="YES") {
       CO2[,14]<-  (indbio_annual[,8]*(1-Perbad)*Ppulp*Cpulp*(1-(60/100))*-44/12)+ (indbio_annual[,8]*(1-
Perbad)*Ppulp/Pseed/drymatterpulp*0.3)+ (indbio_annual[,8]*(1-Perbad)*Ppulp/Pseed/drymatterpulp*7.965)
       N2O[,14]<-   indbio_annual[,8]*(1-Perbad)*Ppulp*PERcomp_pulp/100/drymatterpulp*0.00659
       CH4[,14]<-   indbio_annual[,8]*(1-Perbad)*Ppulp*PERcomp_pulp/100/drymatterpulp*0.0009
     }
 }

#End - Residuals from the tree, in Kg per tree per year
####################################################
#check that the 100% of information about residues is here
if ((PERburn_tree+PERchipsoil_tree+PERtree_away)!=100)
{print("ERROR. Percentage of dead trees does not equal to 100%")}
###PROGRAM SHOULD STOP HERE##
#the residues are burnt
if (burn_tree=="YES"){
  CO2[Nyear,2]<- 0
  CO2[Nyear,15]<- (indbio[Nyear,5]*(PERburn_tree/100)*1.509)- (indbio[Nyear,5]*(PERburn_tree/100)*Cwood*44/12)
  N2O[Nyear,15]<-  indbio[Nyear,5]*(PERburn_tree/100)*0.00038
  CH4[Nyear,15]<-  indbio[Nyear,5]*(PERburn_tree/100)*0.00568
}
# the residues are chipped
if (soil_chip_tree=="YES"){
  CO2[Nyear,2]<- 0
  #matrix  with  each year decomposition          - NO need
  CO2[Nyear,16]<-(indbio[Nyear,5]*(exp(-1*(k_chip)*1)))*Cwood*(PERchipsoil_tree/100*(-44/12))
}
#the residues are chipped and taken
if (tree_away=="YES"){
  #nothing, they are carbon neutral
}

#auxiliar dead trees
# warning, this is not for a single tree, this is an auxiliar field that will be need
#####################################################################################
###
#check that the 100% of information about residues is here
if ((PERburn_dead+PERchipsoil_dead+PERdead_away)!=100)
  {print("ERROR. Percentage of dead trees does not equal to 100%")}
###PROGRAM SHOULD STOP HERE##

#the residues are burnt
if (burn_dead=="YES"){
  CO2[,17]<- (indbio[,5]*(PERburn_dead/100)*1.509)- (indbio[,5]*(PERburn_dead/100)*Cwood*44/12)
  N2O[,17]<-  indbio[,5]*(PERburn_dead/100)*0.00038
  CH4[,17]<- indbio[,5]*(PERburn_dead/100)*0.00568
}
#the residues are chipped
if (soil_chip_dead=="YES"){
  #matrix with each year decomposition
  dead_remain<-matrix(0,  ncol=Nyear+1,  nrow=Nyear)
  colnames(dead_remain)<-c("year",names<-1:Nyear)
```

```
  dead_remain[,1]<-c(1:Nyear)
  dead_remain<-as.data.frame(dead_remain)
  deadaux<-c(1:Nyear)
  #remaining mass each year
  for (j in 1:Nyear){
   for (i in 1:Nyear){
     deadaux[i]<-indbio[j,5]*(exp(-1*(k_chip)*i))           ###
     dead_j<-c(rep(0,(j-1)),deadaux)
     dead_j<-dead_j[1:Nyear]
     dead_remain[,1+j]<- dead_j
  }
  }
  #annual values
  dead_remain_annual<-rowSums(dead_remain[2:(Nyear+1)])
  CO2[,18]<-dead_remain_annual*Cwood*(PERchipsoil_dead/100*(-44/12))
}

# CO2 eq per tree and year
##########################
CO2eq<-CO2+ (CH4*GWPCH4)+(N2O*GWPN2O)
CO2eq[,1]<-c(1:Nyear)
CO2eqtree<-  CO2eq[,-(17:18)]

#CO2 per tree organ - total
#############################
CO2tree_sum<- colSums(CO2[1:Nyear,])
CO2tree_sum<-CO2tree_sum[-(1:3)]
CO2tree_sum<-CO2tree_sum[-(14:15)]

# things that decompose
#coarse root + fine non-decomposed roots
CO2tree_sum[1]<-(indbio[Nyear,6]+fineroot_remain_annual[Nyear])*Croot*(-44/12)
#chip_soil -only the chips not decomposed last year
CO2tree_sum[3]<-(chip_remain_annual[Nyear])*Cwood*(PERchipsoil_prun/100*(-44/12))
#litter_soil          -only the litter not decomposed last year
CO2tree_sum[6]<-(litter_remain_annual[Nyear])*Cleaf*(PERsoil_litter/100*(-44/12))
#fruit soil -only no decomposed
CO2tree_sum[8]<-(fruit_remain_annual[Nyear])*Cfruit*(PERsoil_fruit/100*(-44/12))
#pulp
CO2tree_sum[10]<-(pulp_remain_annual[Nyear])*Cpulp*(PERsoil_pulp/100*(-44/12))

#CO2 and CO2eq total value end cycle
###################################
CO2tree_END<-sum(CO2tree_sum)
CH4tree_sum<-colSums(CH4)
CH4tree_sum<-CH4tree_sum[-(1:3)]
CH4tree_sum<-CH4tree_sum[-(10:11)]
N2Otree_sum<-colSums(N2O)
N2Otree_sum<-N2Otree_sum[-(1:3)]
N2Otree_sum<-N2Otree_sum[-(10:11)]

CO2eqtree_sum<-CO2tree_sum +(CH4tree_sum*GWPCH4)+ (N2Otree_sum*GWPN2O)
CO2eqtree_END<-sum(CO2eqtree_sum)

######################################################################
#FARM VALUES    - Kg CO2 total
######################################################################
# actual number of trees
ifelse (gaping=="YES", Ntree<-Nind, Ntree<-as.integer(Nind-(Nind*PNdie/100)))
#dead trees
Ndead=as.integer(Nind*PNdie/100)
```

```
#trees that die per year
Ndeadyear=ceiling(Ndead/Nyear)

# Annual values of GHGs per year and plant organ
#############################################################
#CO2 Kg per year
farmCO2_annual<- CO2*Ntree*area
farmCO2_annual[,1]<-c(1:Nyear)
farmCO2_annual<-farmCO2_annual[,-(17:18)]
farmCO2_annual$dead_burn<-CO2[,17]*Ndeadyear
farmCO2_annual$dead_chip<-CO2[,18]*Ndeadyear

#N2O Kg per year
farmN2O_annual<- N2O*Ntree*area
farmN2O_annual[,1]<-c(1:Nyear)
farmN2O_annual<-farmN2O_annual[,-(17:18)]
farmN2O_annual$dead_burn<-N2O[,17]*Ndeadyear
farmN2O_annual$dead_chip<-N2O[,18]*Ndeadyear

#CH4 Kg per year
farmCH4_annual<- CH4*Ntree*area
farmCH4_annual[,1]<-c(1:Nyear)
farmCH4_annual<-farmCH4_annual[,-(17:18)]
farmCH4_annual$dead_burn<-CH4[,17]*Ndeadyear
farmCH4_annual$dead_chip<-CH4[,18]*Ndeadyear

#CO2 eq Kg per year
farmCO2eq_annual<-farmCO2_annual+ (farmCH4_annual*GWPCH4)+(farmN2O_annual*GWPN2O)
farmCO2eq_annual[,1]<-c(1:Nyear)

##GHGs values end cycle per plant organ split
###########################################
farmCO2_organ<-CO2tree_sum*Ntree*area
farmN2O_organ<- N2Otree_sum*Ntree*area
farmCH4_organ<- CH4tree_sum*Ntree*area
farmCO2eq_organ<- farmCO2_organ+ (farmCH4_organ*GWPCH4)+(farmN2O_organ*GWPN2O)

#summary results per organ:
farmGHG_organ<-cbind( farmCO2_organ,farmN2O_organ,farmCH4_organ,farmCO2eq_organ)
colnames(farmGHG_organ)<-c("CO2","N2O","CH4","CO2eq")

##GHGs values end cycle
###########################################
farmCO2_END<-sum(farmCO2_organ)
farmN2O_END<-sum(farmN2O_organ)
farmCH4_END<-sum(farmCH4_organ)
farmCO2eq_END<-sum(farmCO2eq_organ)

#summary results:
farmGHG<-cbind(  farmCO2_END,farmN2O_END,farmCH4_END,farmCO2eq_END)
colnames(farmGHG)<-c("CO2","N2O","CH4","CO2eq")

##GHGs in TONNES
farmGHG_tones<-farmGHG/1000

##7 Tonnes CO2eq per Kg product
###########################################
farm_yield<-sum(yieldyear*Ntree*area)
farmGHG_yield_Tkg<-farmGHG_tones/farm_yield
farmGHG_yield_kgkg<-farmGHG/farm_yield
```

```
}

indbio <-indbio[cdat$BaseYear,]
TOTindbio <-rowSums(cbind (indbio[5]*Ntree,indbio[6]*Ntree,indbio[7]*Ntree), na.rm=TRUE)
names(TOTindbio)<-c("TotalBiomass [kg/ha]")
indbio_kgha <-c(indbio[1],indbio[-1]*Ntree,TOTindbio)
indC <- indC[cdat$BaseYear,]
TOTindC <-rowSums(cbind (indC[5]*Ntree,indC[6]*Ntree,indC[7]*Ntree), na.rm=TRUE)
names(TOTindC) <-c("TotalCinBiomass [kg/ha]")
indC_kgha  <-c(indC[1],indC[-1]*Ntree,TOTindC)
CO2out  <- CO2[cdat$BaseYear,]
N2Oout  <- N2O[cdat$BaseYear,]
CH4out  <- CH4[cdat$BaseYear,]
CO2eqout<- CO2eq[cdat$BaseYear,]
#farmCO2eq_organ <-farmCO2eq_organ[cdat$BaseYear,]

# Annual amount of biomassa and total biomass (actualAGB+BGB+leaves) en C inhoud in kg/ha, op moment van BaseYear
indbio_annualkgha <-c(indbio_annual[cdat$BaseYear,1],indbio_annual[cdat$BaseYear,-1]*Ntree,rowSums(cbind
(indbio_annual[cdat$BaseYear,5]*Ntree,indbio_annual[cdat$BaseYear,6]*Ntree,indbio_annual[cdat$BaseYear,7]*Ntree),
na.rm=TRUE))
indC_annualkgha   <-c(indC_annual[cdat$BaseYear,1],indC_annual[cdat$BaseYear,-
1]*Ntree,rowSums(cbind(indC_annual[cdat$BaseYear,5]*Ntree,indC_annual[cdat$BaseYear,6]*Ntree,indC_annual[cdat$Ba
seYear,7]*Ntree), na.rm=TRUE))
CO2_kgha    <-cbind(CO2out[1],CO2out[-1]*Ntree)
N2O_kgha    <-cbind(N2Oout[1],N2Oout[-1]*Ntree)
CH4_kgha    <-cbind(CH4out[1],CH4out[-1]*Ntree)
CO2eq_kgha  <-cbind(CO2eqout[1],CO2eqout[-1]*Ntree)

# Total emissions of summed plant organs in kg/ha/year of BaseYear.
CO2TOT_kgha   <- cbind(CO2_kgha[1],sum(CO2_kgha[c(-1,-15:-18)]))
N2OTOT_kgha   <- cbind(N2O_kgha[1],sum(N2O_kgha[c(-1,-15:-18)]))
CH4TOT_kgha   <- cbind(CH4_kgha[1],sum(CH4_kgha[c(-1,-15:-18)]))
CO2eqTOT_kgha <- cbind(CO2eq_kgha[1],sum(CO2eq_kgha[c(-1,-15:-18)]))

indbioCum_list[[count]] <- data.frame(count,cdat$ID,area,indbio_kgha)
write.table(indbioCum_list[count],file=".../indbioCum.csv",col.names =
FALSE,quote=FALSE,row.names=F,append=TRUE,sep=",")
indCCum_list[[count]] <- data.frame(count,cdat$ID,area,indC_kgha)
write.table(indCCum_list[count],file=".../indCCum.csv",col.names =
FALSE,quote=FALSE,row.names=F,append=TRUE,sep=",")
indbioAnnual_list[[count]] <- data.frame(count,cdat$ID,area,indbio_annualkgha)
write.table(indbioAnnual_list[count],file=".../indbioAnnual.csv",col.names =
FALSE,quote=FALSE,row.names=F,append=TRUE,sep=",")
indCAnnual_list[[count]] <- data.frame(count,cdat$ID,area,indC_annualkgha)
write.table(indCAnnual_list[count],file=".../indCAnnual.csv",col.names =
FALSE,quote=FALSE,row.names=F,append=TRUE,sep=",")
CO2_list[[count]] <- data.frame(count,cdat$ID,area,CO2_kgha[-(15:18)],CO2TOT_kgha[-1])
write.table(CO2_list[count],file=".../CO2.csv",col.names = FALSE,quote=FALSE,row.names=F,append=TRUE,sep =",")
N2O_list[[count]] <- data.frame(count,cdat$ID,area,N2O_kgha[-(15:18)],N2OTOT_kgha[-1])
write.table(N2O_list[count],file=".../N2O.csv",col.names = FALSE,quote=FALSE,row.names=F,append=TRUE,sep =",")
CH4_list[[count]] <- data.frame(count,cdat$ID,area,CH4_kgha[-(15:18)],CH4TOT_kgha[-1])
write.table(CH4_list[count],file=".../CH4.csv",col.names = FALSE,quote=FALSE,row.names=F,append=TRUE,sep =",")

CO2eq_list[[count]] <- data.frame(count,cdat$ID,area,CO2eq_kgha[c(-15:-18)],CO2eqTOT_kgha[-1])
write.table(CO2eq_list[count],file=".../CO2eq.csv",col.names = FALSE, quote=FALSE,row.names=F,append=TRUE,sep =",")
GHG_list[[count]] <- data.frame(count,cdat$ID,area,CO2TOT_kgha,N2OTOT_kgha[-1],CH4TOT_kgha[-1],CO2eqTOT_kgha[-
1])
write.table(GHG_list[count],file=".../GHG.csv",col.names = FALSE, quote=FALSE,row.names=F,append=TRUE,sep =",")
count = count +1

}
```

Appendix XI – Fertiliser content and application rates

Table 8 Fertiliser application. Fertiliser types were mentioned in the UTZ survey. The percentage N, the application rate and the total kilograms of N applied are on the basis of literature.

Fertiliser types	N%	kg/ha	Application method	N kg/ha	Source
AsaaseWura	0	375	Broadcast	0	Afrifa et al., 2010
base vital					
Benzai					
Biodepost					
Biopower					
Chicken manure	3.18	1035	Liquid	33	Meyer et al., 2011
Cocofeed	0	375	Broadcast	0	Afrifa et al., 2010
Compost	2.75	6666	Broadcast	183	Koko et al., 2013
Hypercacao					
LDC 023	0	200	Liquid	0	Obtained at CNRA
Nitrabor	15.4	127	Broadcast	20	Yara International, 2019[iii]
NPK 023	0	200	Broadcast	0	Obtained at CNRA
NPK18	18	200	Broadcast	36	Obtained at CNRA
Organic	2.5	370	Broadcast	9	Afrifa et al., 2010
Paracao					
Sidalco	10	120 ml	Foliar		Afrifa et al., 2010
super foliaire	5				Salifou and Kimba, 2017
Supercacao	0	220	Broadcast	0	Yara International, 2019
Supergro	5		Liquid		Salifou and Kimba, 2017
tao-tao					
Terradio					
Uree	46	200	Liquid	92	Obtained at CNRA
Yara	15	295	Broadcast	44	Obtained at CNRA
Other				67	Van Vliet & Giller, 2017

Appendix XII – Cacao fruit biomass by diameter and length

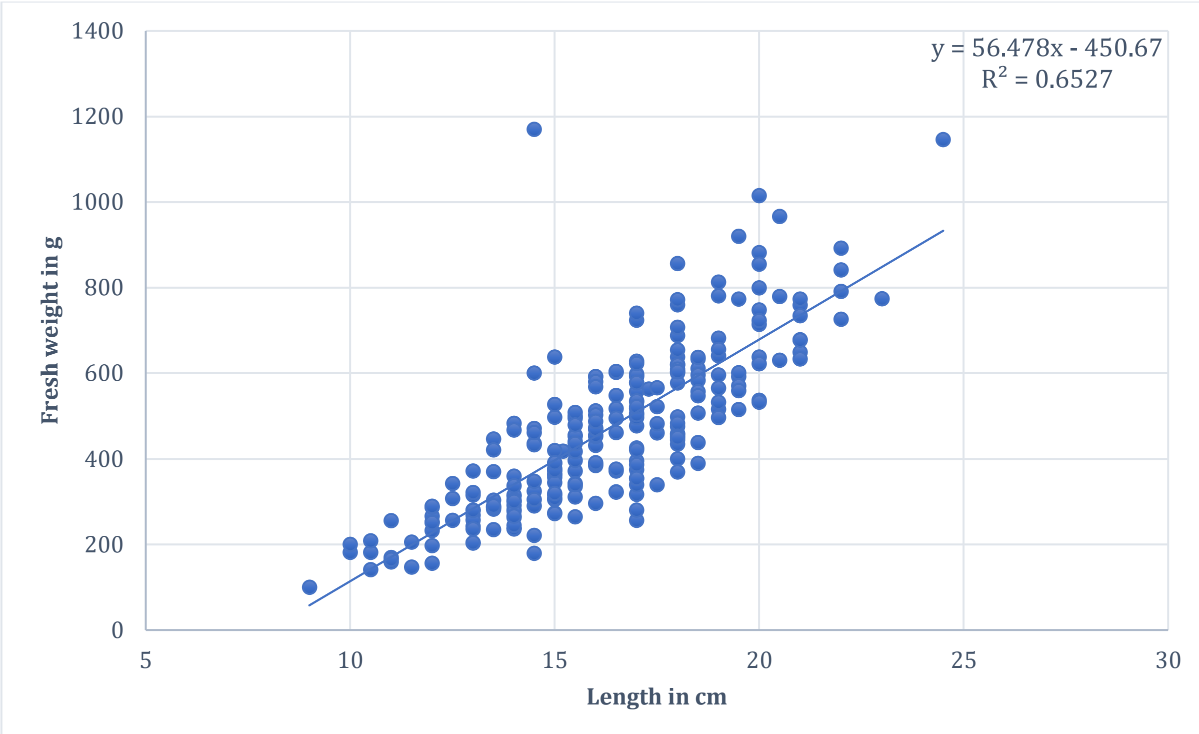

Figure 15 Fresh cacao fruit weight by length

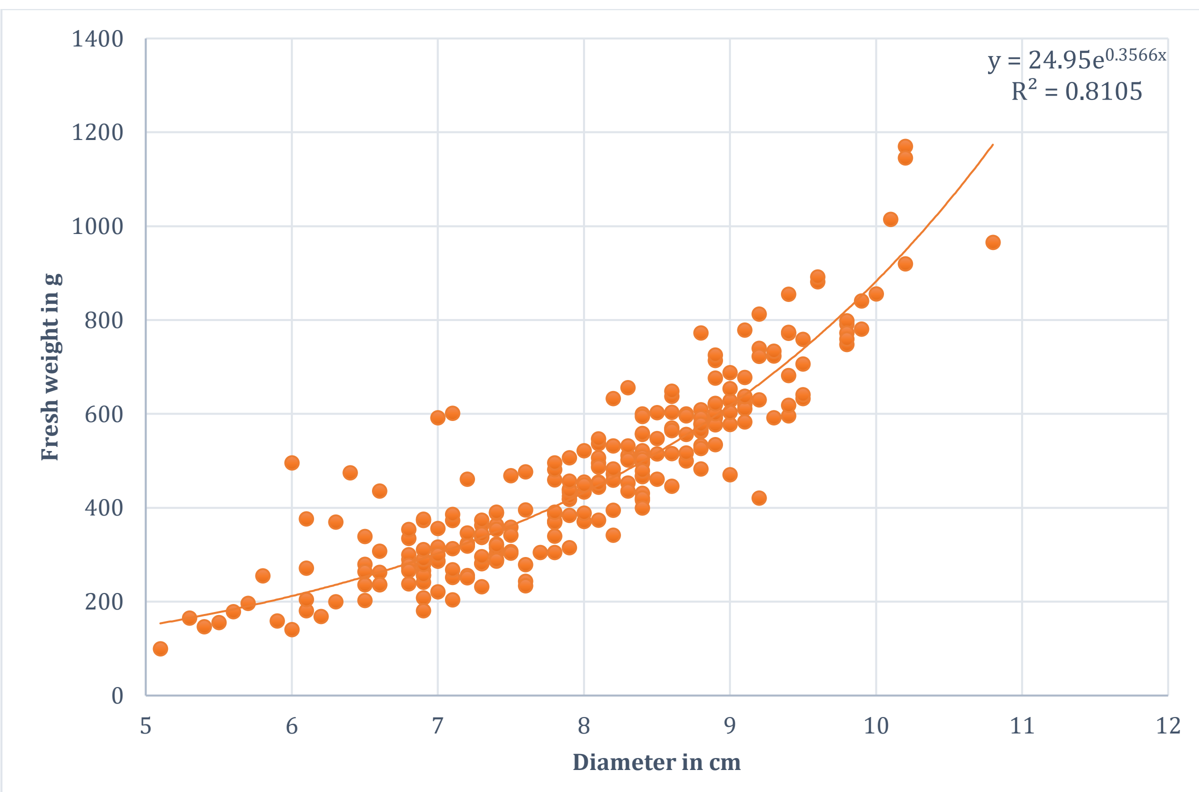

Figure 16 Fresh cacao fruit weight by diameter

Appendix XIII – Correlation between farm characteristics and GHG emissions (GHG-e)

Plantation age (year)

	GHG-e	*year*
GHG-e	1	
year	-0.01052	1

Cacao yield (kg/ha)

	GHG-e	*BaseYield*
GHG-e	1	
BaseYield	0.26986	1

Appendix XIV – Quantifying uncertainties

Uncertainties were quantified by adjusting model parameters (ADF) or data inputs (BCE) with 10% (see Table 9). A change of more than 10% means that the GHG emissions are sensitive to changes in parameters or data inputs.

Table 9 Change in GHG emissions as a result of adjusting parameters or data inputs

	Percentage change	Elasticity
A. DM husk and fruit (-10%)	37	4
B. Cacao yield (+10%)	32	3
C. Shade tree biomass (-10%)	24	2
D. Cacao woody biomass (+10%)	-10	-1
E. Deforestation (+10%)	1	0
F. Excluding Asia and Central and Latin America	-47	-5

[i]https://fr.wikipedia.org/wiki/Départements_de_la_Côte_d%27Ivoire#/media/File:C%C3%B4te_d%27Ivoire_departments.png
[ii] https://www.freepik.com/premium-photo/cocoa-fruit-isolated-white-background_2250402.htm
[iii] https://www.yara.ci/fertilisation/produits-et-solutions-pour-la-fertilisation/yaraliva/yaraliva-nitrabor/