Impact and response to local dynamics for climate adaptation investments

An agent-based modelling study combined with top-down climate scenarios to explore interventions for climate adaptation in developing countries, applied to the Dutch Development Bank's cocoa investments in Ghana

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IMPACT AND REPONSE TO LOCAL DYNAMICS FOR CLIMATE ADAPTATION INVESTMENTS

An Agent-Based Modelling study combined with top-down climate scenarios to explore interventions for climate adaptation in developing countries, applied to the Dutch Development Bank's cocoa investments in Ghana

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Executive Summary

Development Finance Institutions have been established to provide finance for long-term economic development in low and middle-income countries. However, these investments are exposed to climate-related risks: (1) physical risks due to long-term shifts in weather patterns (chronic) or extreme events such as flooding and drought (acute); and (2) transition risks, because moving towards low carbon economies entails technological, institutional and economic changes resulting in financial or reputational risks.

This means that Development Finance Institutions need to explore climate adaptation interventions to secure financial returns and societal benefits, particularly in view of the fact that developing countries themselves have few resources for climate adaptation. The mandate of Development Finance Institutions includes sustainable development, therefore also protecting developing countries from climate change.

Effectively financing climate adaptation starts with mapping the potential climate impacts of various scenarios, as recommended by the Task Force on Climate-related Financial Disclosures and in European Guidelines on reporting climate-related information. However, to really understand the effects of climate change and support impactful climate adaptation investment, it is essential to take the next step from climate risk assessments towards site-specific impact and adaptation. Literature shows that: (1) translating global climate scenarios to local impact with a top-down approach is indisputably accompanied by major uncertainties, and therefore many assumptions are made; (2) climate models are lacking that include the bottom-up perspective of how individuals respond to climate change; and (3) interventions with climate adaptation are a relatively new development and there is less experience about what is the most robust way to ensure that investments are climate resilient. A complementary study of top-down climate scenarios and bottom-up human responses can be a tool to map these site-specific characteristics and define tailored adaptation investments. This problem is stated in the following research question:

How can Development Finance Institutions achieve long term sustainable investments under climate change?

This thesis aims to establish how, using an agent-based model, Development Finance Institutions can achieve long term investments by financing climate adaptation, while creating societal benefits and financial returns. This implies positively contributing to society, for example by creating jobs, generating a stable income, and supporting the resilience of households, while securing profitability for development banks. Agent-based modelling is a method that is used to illustrate the local dynamics in the value chain and allows to experiment with interventions under different climate scenarios. An investment by the Dutch Development Bank FMO in the cocoa sector in Ghana serves as a case study. This investment was selected based on the banks' strategy, exposure to physical risks and modelling requirements.

Three main steps are followed in the study: (1) translating global climate scenarios at the local level; (2) capturing local behaviour in a bottom-up model; and (3) testing Development Finance Institutions' interventions.

The first step shows that cocoa production in Ghana is exposed to an increased temperature and uncertain precipitation patterns under climate change. Downscaling a global climate model into a local, high resolution map with a downscaling method shows that some regions of Ghana become unsuitable to production and require adaptation, under both optimistic and pessimistic climate scenarios (RCP2.6 and RCP8.5).

In the second step, it becomes clear that cocoa farmers act according to their livelihood strategies. Cocoa households generate an income from the combination of intense cocoa production, diversification with other sources of income and (temporary) migration. These strategies are challenged by climate change and households adapt to the new situation, making choices based on their aversion to change. Literature shows that three groups of cocoa farmers can be distinguished: those who adopt new innovations easily, those who trust the government; and those who are averse to change and therefore rely on their traditions.

The third step shows that Development Finance Institutions can intervene in different ways to achieve sustainable investments. They have to consider the trade-offs between the most viable and the most affected regions depending on their strategy (secure the supply of cocoa beans, or support smallholders to avoid the

economic uncertainty of migration). Development Finance Institutions can also intervene in a proactive way to prevent any losses of production or in a reactive way to specifically target individual farms, and they also need to decide on the type of intervention: pest management, shade trees or subsidies.

The resulting analysis reveals that proactively investing climate adaptation with shade trees in Western and Central Ghana (the most viable regions) appears to be the most robust intervention over time in terms of cocoa bean production, income of cocoa farmers and additionality (Δ income generated by intervening). This can be explained by the share of farmers supplying to FMO's investment in these regions (61%) as well as by the effectiveness of shade trees in protecting cocoa beans.

The ambition could also be to help cocoa farmers out of their unsustainable way of living, and enable them to stay on their land and within their community while avoiding the uncertainty of migration. In that case, giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) who are about to migrate (reactive) appears to be an effective intervention. It reduces migration to 12% compared to 21% with no intervention. It should be noted that migration appears to be a long-term effect and is only starting around 2032 under a scenario where climate change highly affects the loss of production. In case migration starts, it will have a social influence, resulting in a peak of migration.

The analysis also shows that acting proactively is not always the most suitable strategy as it would be intuitively perceived. Proactively giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) is not as effective as reactive, because of the level of uncertainty: it is difficult to know beforehand which farmers will ultimately be highly impacted. This level of uncertainty is higher in the most affected regions and therefore a reactive timing is more useful, while the most viable regions will benefit more from proactive interventions.

FMO is recommended to take into account these trade-offs when deciding on the best strategy for cocoa investments in Ghana. Given the high level of uncertainty how the future will evolve, FMO is also recommended to use adaptive interventions for the cocoa sector in Ghana. They could, for instance, run the model regularly with the most recent climate information to assess timing and likelihood of migration.

This step-by-step framework has four benefits for Development Finance Institutions: (1) It helps to understand the complexity behind climate adaptation interventions. Climate change has specific effects on smaller scale, and therefore there is no 'one-size-fits-all' strategy. (2) The framework goes broader than the physical impact and financial implications of climate change by systemically exploring the socio-technical system around a potential investment, such as a supply chain, technical innovations, and changes in the environment. (3) It would also help Development Finance Institutions to look at the long-term view. The impact of climate change is not clearly visible at present, but it has clear consequences for the long term. (4) This modelling exercise quantifies the trade-offs with financial and societal consequences, in line with the additionality mandate of Development Finance Institutions.

Considering the benefits Development Finance Institutions are recommended to apply this framework in their decision-making process. It can be used as a 'conversation starter' to trigger discussion on how Development Finance Institutions want to position themselves in terms of the prioritization and timing of interventions, and societal and financial returns. This could be a complementary tool to provide information at the due diligence stage or to assess opportunities for climate adaptation investments for specific cases, for example when exploring opportunities in new regions or sectors.

From a scientific point of view, this study proposes a framework that connects three key elements which generate insights how to achieve these sustainable investments on a system level that is not apprehended by existing models. First, including the feedback loop of the bottom-up response to top-down climate models accounts for adaptive strategies of humans in response to climate change, which generates complementary insights and makes the climate scenarios more comprehensive by capturing effects beyond only physical and financial effects. This research also took a broader view on climate adaptation by modelling the heterogeneity of households, their individual behavior in response to climate change and the impact on income and livelihood.

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List of Abbreviations

ABM	Agent Based Modelling
AR	Assessment Report
CMC	Cocoa Marketing Company
CO_2	Carbon Dioxide
COCOBOD	Ghana Cocoa Board
CSA	Climate Smart Agriculture
DFI	Development Finance Institution
ESG	Environmental, Social and Governmental
ETP	Potential Evapotranspiration
FMO	Dutch Entrepreneurial Development Bank (in Dutch: Nederlandse Financierings-Maatschappij voor Ontwikkelingslanden)
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAM	Integrated Assessment Model
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LBC	Licensed Buying Company
LCA	Life-Cycle Assessment
LID	Living Income Differential
MDB	Multilateral Development Bank
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathway
TCFD	Task Force on Climate-related Financial Disclosures
UNEP FI	United Nations Environment Programme Finance Initiative
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction to development banks and climate-risks

1.1 Societal relevance: The mandate of Development Finance Institutions in the context of climate change

Development Finance Institutions (DFIs) were established to provide finance for economic development in low- and middle-income countries (EDFI, 2019). Their projects promote the creation of jobs, sustainable economic growth, reduction of inequalities, and climate action. Such projects sometimes have relatively high risks and would otherwise be unable to acquire funds from commercial lenders (EDFI, 2019; Bruck, 1998). DFIs, therefore, have the opportunity to address market imperfections and generate social benefits (Bruck, 1998).

These projects in low- and middle-income countries are increasingly exposed to the effects of climate change (Monasterolo, Zheng & Battiston, 2018). Climate change is an issue that has an unequal distribution of responsibility and impact (Füssel, 2010). While developing countries generally have lower carbon dioxide emissions per capita, they are the most vulnerable countries when it comes to the effects of climate change (Füssel, 2010). These climate-related risks have two components (TFCD, 2019):

(1) Physical risks such as floods, droughts and cyclones can affect the operations and financial performance of companies' assets as well as communities and are therefore a financial risk for DFIs (European Banking Authority, 2019).
(2) Challenges for DFIs in relation to the transition towards a low-carbon economy. As a result, markets are changing (TCFD, 2019); climate policies set up by governments, shifts in supply, and changing choices of customers are putting additional pressure on existing markets.

The first essential step for dealing with the abovementioned climate-related risks is to measure exposure (European Banking Authority, 2019). The Task Force on Climate-related Financial Disclosures (TCFD) recently recommended that banks use *scenario analysis* (DNB, 2018). This recommendation is widely recognized as being authoritative guidance and is encouraged in the non-binding guidelines on non-financial reporting of the European Commission (European Commission, 2019).

Scenario analysis aims to communicate visions of what the future holds (Rounsevell & Metzger, 2010). It aims to better understand the environment of a business under various future conditions. In the case of climate change, scenarios can help to gain insights into how climate-related risks might impact businesses (TCFD, 2017). They are a helpful tool in structuring our thinking about the future without the bias of personal experiences and prejudice (Rounsevell & Metzger, 2010).

A climate-risk assessment using scenario analysis can lead to various actions. For most commercial banks and products, high climate risks in a country or region can mean limited future investments to reduce exposure. These commercial economic actors also have a short-term horizon ranging from 2-3 years and a maximum of a decade, a period which is not in alignment with the long-term character of climate change (Bank of England, 2015). However, DFIs should act differently since their mandate is to support developing countries that require international assistance. These countries have fewer social, technical and financial resources to make adaptations (EDFI, 2019; UNFCCC, 2007).

DFIs are faced with the dilemma of acting within their mandate on the one hand and the uncertainty of climate risks affecting their business on the other hand. They still have an important role to play in regions highly exposed to climate change, and are trying to balance their commitment to Sustainable Development Goals (SDG) 8 Decent work and economic growth with SDG13 Climate action (DNB, 2017). Most banks adopted the globally recognized International Finance Corporation's (IFC) Performance Standards and the Equator Principles to manage environmental, governmental and social (ESG) risks (World Resources Institute, 2020). Climate risk, however, is not yet integrated in these ESG risk frameworks (ESG Clarity, 2019).

Therefore, DFIs are not yet prepared for the physical and market impacts of climate risks on their investments and are therefore seeking how to achieve sustainable investments using climate adaptation. This is the next step after scenario analysis. How can DFIs prepare best for climate-related risks while making long-term investments in developing countries? What kind of interventions can be applied to balance the financial returns of the investment and support the most affected countries and sectors with societal benefits?

1.2 Research objective: Securing financial returns and societal benefits under climate change

Thus, the main objective of this study is to explore how development banks can achieve long term sustainable investments in developing countries under climate change. This implies positively contributing to society, for example creating jobs and supporting the resilience of households, while securing financial returns for the development bank. Most banks have recently started to use climate scenarios in their decision-making. These analyses, however, are not sufficiently detailed to account for sector and local variabilities (TCFD, 2017). This study will therefore: (1) translate global climate scenarios to the local level; (2) capture local behaviour in a bottom-up model; and (3) help DFIs to identify opportunities. Climate adaptation can be a strategy for reducing vulnerabilities and increasing the resilience of investments (EBRD, 2019).

The objectives of this study are linked to the MSc programme Engineering and Policy Analysis, because working on the SDGs making use of engineering skills is the main topic of this study. This thesis contributes to SDG 13 Climate Action by exploring climate adaptation interventions as well as to SDG 8 Decent Work and Economic Growth by providing finance to foster employment and production, and therefore results in economic growth, in line with the additionality mandate of Development Finance Institutions.

1.3 Research scope

This study uses both a top-down and bottom-up perspective to ensure sustainable investments. The end goal of DFIs is to empower local entrepreneurs in emerging markets and therefore understanding the specificity of the local context and individuals' response is key to really make an impact (FMO, 2018a). It is essential to explore the impact of global climate scenarios, as well as the response of individuals at local level, to design tailored interventions. The case study selected for this purpose is an investment in the cocoa sector in Ghana.

1.4 Structure of this study

This study is structured as follows: chapter 2 consists of a literature review and identifies three main knowledge gaps. This leads to setting out the main research question, the approach to be taken and the sub questions in chapter 3. The answers to the sub questions are provided in chapters 4 to 11. The final two chapters, 12 and 13, reflect on the outcomes and summarize the contributions and recommendations.

2. Literature review on climate impacts on investments

This chapter outlines the current literature about scenarios on a local, investment level and the response to climate change by individuals and DFIs. This exploration of literature leads to the identification of the knowledge gaps presented in section 2.4. The explanation of core methodological concepts and the identification of knowledge gaps subsequently leads to the formulation of a research question in Chapter 3.

2.1 Resolution of climate scenarios is challenging

Global climate scenarios are used to explore the impact of climate change, but there is a need to break them down to the local level. *Climate scenarios* are multiple plausible descriptions of how the future might develop, exploring a range of climate-related impacts (Rounsevell & Metzger, 2010). They could, for instance, describe a world that has a temperature increase of 2°C. This is explicitly different to *forecasts* which are trying to predict what will happen in the future and mostly rely on past data. Global scenarios (Section 2.1.1) are therefore translated into local impact (section 2.1.2).

2.1.1 Global climate scenarios: Representative Concentration Pathways

Representative Concentration Pathways (RCPs) are global climate scenarios that were published by the Intergovernmental Panel on Climate Change (IPCC) in their Fifth Assessment Report (AR5) in 2014 for the first time (Van Vuuren et al., 2018). There are four different pathways with future GHG concentrations and emissions (Figure 1).

RCP2.6 is the most optimistic pathway, in line with the Paris Agreement, aiming for a 1.5ºC temperature rise and a maximum of 2ºC in 2100. It assumes climate policy with a drastic reduction of GHG emissions from 118 to 78% compared to 2010 (Van Vuuren et al., 2014; Van Vuuren et al., 2018; IPCC, 2014).

RCP8.5 is the most pessimistic pathway, representing a business-as-usual scenario: a future with no changes in policy to reduce emissions (IPCC, 2018). This will result in a 3.2-5.4ºC temperature rise in 2100 relative to 1850-1900 (Van Vuuren et al., 2011).

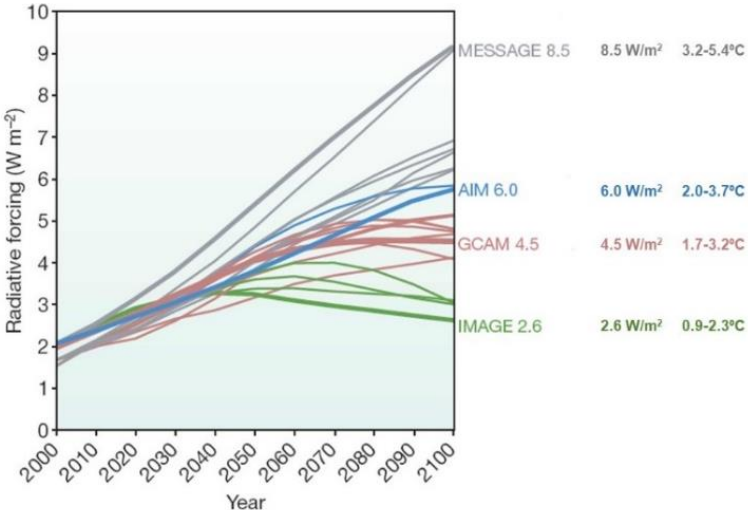


Figure 1 Four radiative forcing trajectories, based on Moss et al., 2010

2.1.2 Challenge to translate global RCPs into local impact

The outcomes of the RCPs are global variables such as global mean temperature and sea level rise (Flato et al., 2013). They are all focused on physical risks including both acute risks from extreme weather conditions as well as chronic risks from shifts in the longer term, such as higher sea levels (TCFD, 2017).

The grid cells of these global climate models (GCMs) are typically coarse (> 100 km), and not granular enough to assess local impact at investment level, for example (Anandhi et al., 2011). In global climate models, regions of approximately the size of the Netherlands only have a few grid points. For that reason, top down approaches are developed to *downscale* information to a spatial scale < 100 x 100 km (Hewitson et al., 2014).

Figure 2 shows the global to local climate process which involves additional data and assumptions in every step. It leads to further uncertainties in the results (Trzaska & Schnarr, 2014).

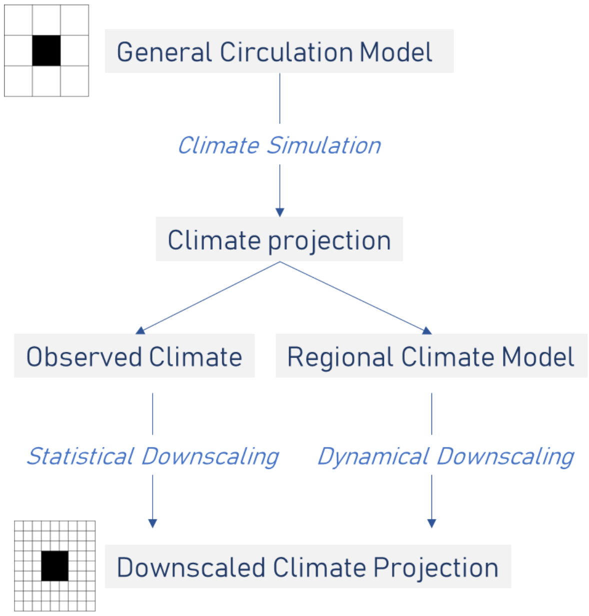


Figure 2 Conceptual illustration of downscaling (based on Daniels et al. 2012)

Downscaling methods assume that local climate is a combination of (a) large-scale features (e.g. global, continental, regional), and (b) local conditions (e.g. water bodies, land surface). There are two major techniques for producing higher resolution climate scenarios with (a) large-scale features and (b) local conditions (Mearns et al., 2001). First, in statistical downscaling a cross-scale relationship between large-scale variables (predictors) and local climate variables (predictands) is developed. This is a statistical regression method (Wilby, 2010). A second way of downscaling is by nesting a regional climate into an existing GCM. This global model provides the boundary conditions for driving the regional climate model (Rounsevell & Metzger, 2010).

Despite the widely recognized use of both downscaling methods, the models run under boundary conditions of GCMs which leads to limited predictive ability (Van den Hurk, 2015). These limitations in the results are not often mentioned in a transparent way, leading to users believing that results are valid (Trzaska & Schnarr, 2014). For these reasons, some researchers argue for bottom-up methods in the scientific debate (Evans, 2015).

2.1.3 Gap 1: Global to local scenarios

To conclude, physical risks might lead to business interruptions and could be felt across many international supply chains (UNEP FI, 2019). It is therefore relevant to study physical climate scenarios. However, downscaling methods translating global into local information are run under many boundary conditions and the necessary data comes from different sources using other assumptions which leads to uncertainties. For these reasons, scientists should reflect on assumptions when using climate models for strategic decisions. Reliable local climate information at the asset level is material that DFIs can use to make their investments more climate-proof.

This has led to an ongoing debate about using bottom-up models, which will be introduced further on in section 2.2.3. These are sufficiently equipped to capture local variations such as policy development, social reaction and technology penetration in response to climate change. They also account for adaptation (Mendelsohn, Morrison, Schlesinger & Andronova, 2000) which is necessary to assess individual investments.

2.2 Behaviour under climate change

The breakdown to the local level is critical, because DFIs need to understand the effects of climate change in a local context on the specific investment (EBRD, 2019). This is only possible taking into account human behaviour which drives (1) adaptive strategies (section 2.2.1) and (2) market behaviour (section 2.2.2).

2.2.1 Need to include adaptive strategies

Many methodologies only quantify exposure to climate-related risks, i.e. the loss or gain of value (UNEP FI, 2019). However, these conventional risk approaches are challenged as a result of the complexity of climate change. In general, complex systems show non-linear behaviour due to the interactions of subsystems. Therefore, the behaviour of people in response to climate change cannot be predicted. It is essential to first understand how people interpret risks and how this is shaped by their experiences, values and cultural beliefs (Eiser et al., 2012). For example, the rural population in Ghana has proven to be dynamic and innovative, having previously been able to generally cope and adapt to changes in their environment by adopting various strategies (Jarawura & Smith, 2015). It is therefore essential to include human behaviour and responses (i.e. adaptive strategies) in climate-risk approaches.

2.2.2 Need to include transition risk

However, macro-economic models such as the Integrated Assessment Models (IAMs), on which Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) are based, do not account for adaptive strategies. According to Patt et al. (2010), most models that include adaptation are much more detailed, specific to a sector or region. The global IAMs are not designed for this and a great deal of work is needed to close this gap. However, DFIs also want to assess local socio-economic impact, because these trends may affect the financial performance of their investees (TCFD, 2017). The socio-economic setting is changing with the transition to low carbon economies which requires policy action and technology shifts. Closing the gap between global IAMs and the local level, where socio-economic trends are driven by human behaviour, is essential in climate-related assessments for banks (Patt et al., 2010).

2.2.3 Bottom-up approaches to include behaviour

Bottom-up studies such as agent-based models are a way to represent variation in local contexts (Hewitson et al., 2014). According to Conway et al. (2019), the essential elements of bottom-up approaches are: a finer geographical scale, current sensitivity to weather and climate, exploring all options for adaptation, risk measures normative to vulnerable populations.

The top-down approach with local spatial information (gap 1) and the bottom-up approach on behaviour can generate complementary insights into who and what is at risk (Conway et al., 2019). First, the top-down approach takes the global climate pathways and downscales these into smaller geographical impacts. Second, the bottom-up approach focuses on the human response to climate change. Integrating the results of both approaches is a much-needed step, according to Cornway et al. (2019).

2.2.4 Gap 2: Complexity of climate change requires bottom-up approaches

In short, the complexity of climate change suggests that it is not a well-defined problem suited to traditional assessments (Adger, Brown & Surminski, 2018). In a complex system with non-linear behaviour, it is essential to understand human behaviour as a driver of adaptive strategies and socio-economic changes. For these reasons, considering both a bottom-up and top-down approach will generate complementary insights (Conway et al., 2019). This is lacking in previous literature and a much-needed step to help DFIs effectively choose their inventions adjusted to the local context.

2.3 Climate-proof investments

Effectively choosing the interventions is crucial because reducing the risks posed by climate change is part of the mandate of DFIs (Section 2.3.1). This funding, however, is a relatively new field (Section 2.3.2).

2.3.1 Mandate of DFIs

The mandate of DFIs is to support developing countries, and they still have an important role to play in regions that are highly exposed to climate change. Developing countries in particular require international assistance since they have fewer social, technical and financial resources to adapt (UNFCCC, 2007). Supporting these countries in the physical impacts of climate change goes beyond climate mitigation (measures to reduce net emissions), which most DFIs are already focusing on. Interventions with climate adaptation are a way to reduce the risks posed by climate change and to increase resilience (EBRD, 2019). It is necessary to make investments climate-proof.

According to the World Bank (2019b), 70% of the total climate financing for 2018 by multilateral development banks (MDBs) was devoted to investments in climate change mitigation, while the remaining 30% was invested in adaptation efforts. Recent developments, however, show an increasing focus on commitments towards climate adaptation. In September 2019, nine multilateral banks announced that they would raise investments and their joint adaptation finance is expected to double to around $18 billion annually by 2025 (Energy Live News, 2019). It can be concluded that there is willingness and funds to invest in climate adaptation and it is therefore essential to identify the relevant interventions.

2.3.2 Climate adaptation interventions

As climate adaptation is a relatively new field for DFIs, they lack knowledge in assessing which financing activities can best contribute to climate resilience (EBRD, 2019). International Financial Institutions have recently announced that they will develop principles to evaluate climate change resilience when investing in climate adaptation (Climate Home News, 2019), but they are still questioning how to correctly use measurements and metrics.

Furthermore, it is difficult to opt for certain interventions in the uncertain context of climate change (Kwakkel, Haasnoot & Walker, 2015). Some interventions have to be taken now so that options can be kept open to adapt if needed in the future.

2.3.3 Gap 3: New focus on finance to adapt to climate change

In conclusion, DFIs have the mandate to support developing countries. Interventions with climate adaptation are one way to reduce the risks posed by climate change and to increase resilience (EBRD, 2019). Finance for climate adaptation is a relatively new topic and is still under development as a way to ensure robustness by assessing which financing activities best contribute to climate resilience.

2.4 Conclusion academic research gap

As stated in the above sections, most studies agree that further work is required to develop and improve methodologies on how to deal with climate-related risks. DFIs aim to make their investments climate-proof by using climate adaption interventions. The essential elements for these interventions are: detailed information about physical climate impact under different scenarios on a local level; human behaviour as a driver of adaptive strategies and socio-economic changes; and robustness of interventions.

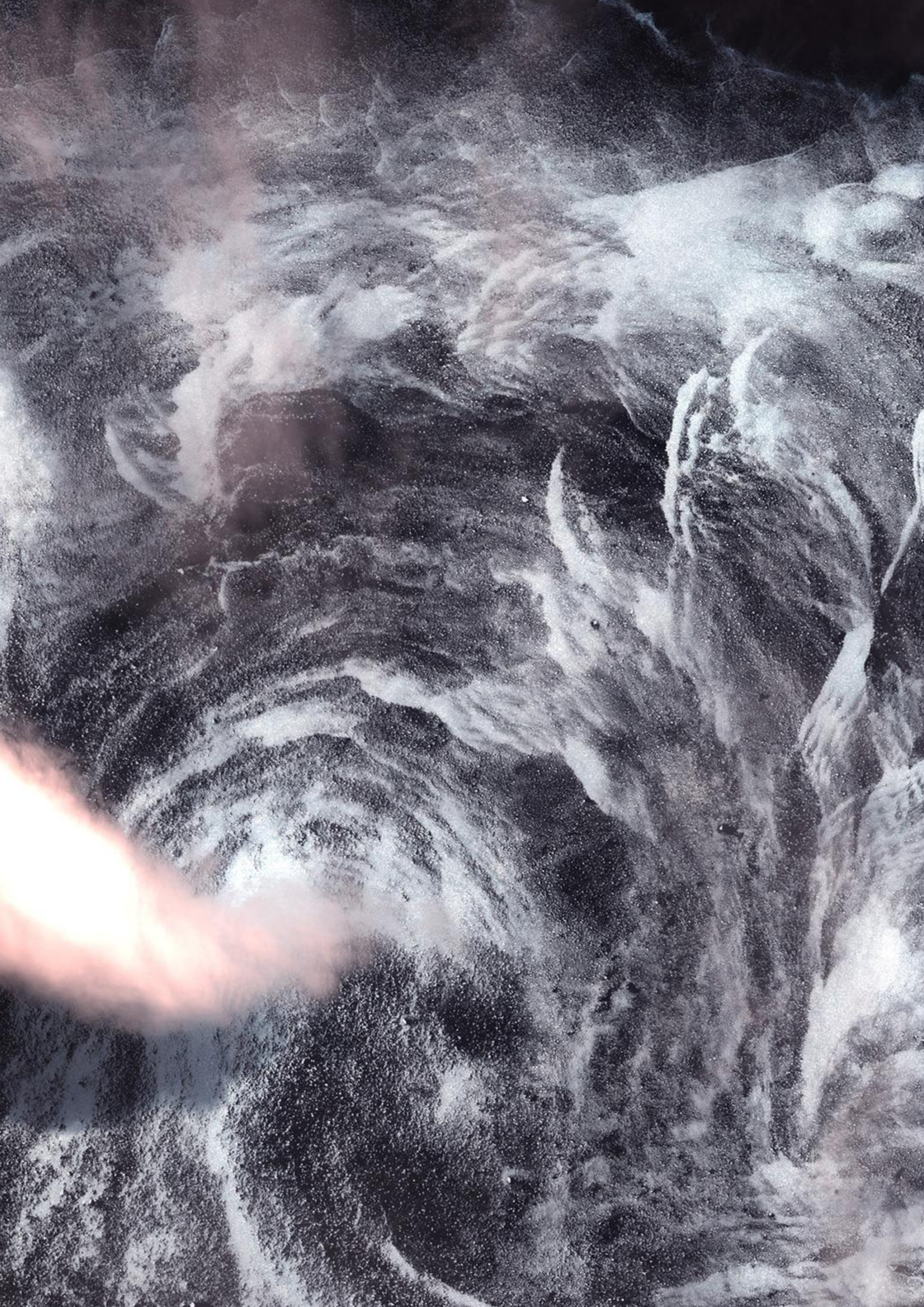
Sections 2.1, 2.2 and 2.3 above demonstrate that the main academic research gaps are:

- Top-down methods that **downscale global into local information are limited by boundary conditions** to capture the local variations of climate change manifestations (Moss et al., 2010). This local information is relevant because DFIs want to explore the opportunities to make their investments more climate-proof at the asset level.

- There is a **need to understand adaptive strategies of humans** to be able to protect them from climate-related impact through interventions by DFIs. More detailed models are required instead of global Integrated Assessment Models to account for adaptation and socio-economic trends, because these can affect the performance of local businesses. **Human behaviour as a driver of adaptation and market behaviour can be captured in a bottom-up model**. A bottom-up approach with human behaviour and a top-down approach as explained in Gap 1 can generate complementary insights into who and what is at risk (Conway et al., 2019).

- DFIs have the mandate to support developing countries. **Intervening with climate adaptation** is a relatively new development and **knowledge is lacking on metrics** for how to assess which financing activities best contribute to climate resilience

The above-mentioned challenges are the driving forces behind this research. Its outcomes will give development banks insight into how to achieve long term sustainable investments with finance for climate adaptation, while balancing financial returns and societal benefits. The next chapter discusses the research approach to fulfil these gaps.



3. Research Design

From the literature review in Chapter 2, it becomes apparent that existing literature has identified problems regarding the translation of global to local climate scenarios, impact on socio-economic elements, adaptive strategies of humans and robustness of interventions to make an informed decision for Development Finance Institutions (DFIs). As the research gap is significant, Section 3.1 describes the scope of this study. The following Section 3.2 then describes the main research question. The third section of this chapter discusses the overall research method, visualized in a research flow diagram. The associated five sub-questions including the specific methods are discussed in Section 3.4. Finally, the chapter ends with a conclusion.

3.1 Scope: cocoa in Ghana

The objective of this study to explore opportunities for climate-proof investments for DFI under different scenarios is tested on a case provided by FMO. FMO is the Dutch Development Bank with energy and agriculture as focus sectors for their investments (FMO, 2018a).

The case study is selected using the following approach:

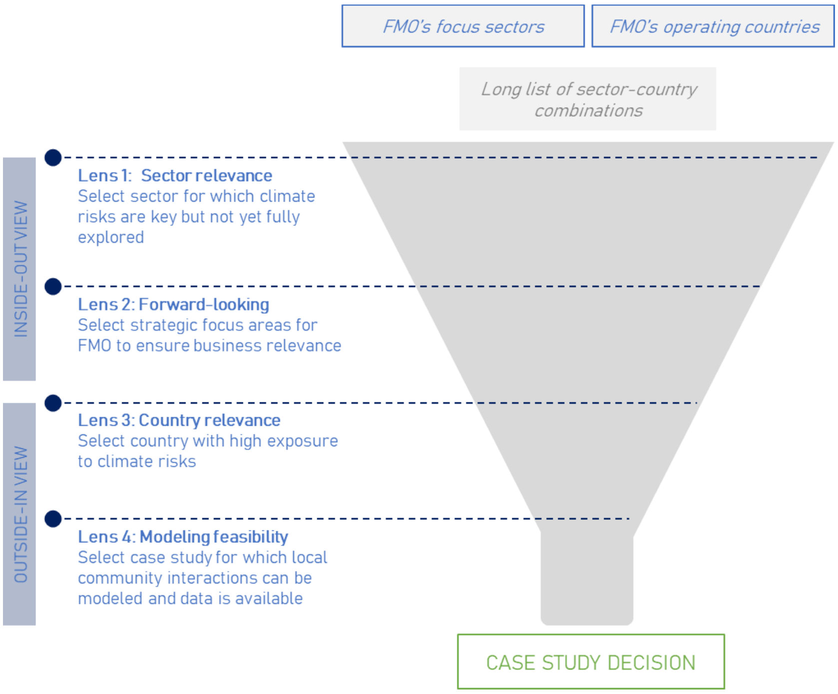


Figure 3 Case study selection approach

The selection started with a list of FMO's main sectors and countries. The selection main criteria are (1) a sector for which climate risks are not fully explored yet in previous publications and (2) a case that remains relevant in the future strategy for FMO. Two additional criteria are (3) the exposure to climate risks and (4) modelling feasibility.

First, the agricultural sector is chosen because there is a limited number of published scenario analysis for this sector, while many banks already explored the energy sector. Second, eight countries were selected where FMO has a large outstanding portfolio and has the opportunity to do further business. In addition, the country should be classified as a low- or middle-income country, in line with the additionality mandate of development banks. Third, the remaining countries and sector were analysed whether they have a high exposure to climate change. Finally, the cases were tested on data availability and the suitability to model local communities in a bottom-up model. A cocoa investment in Ghana is the best suitable option according to these criteria.

Ghana is a Lower-Middle Income Country with few resources to adapt to climate change, which makes it a representative case for DFIs (World Bank, 2019a). The cocoa plant is sensitive to differences in changes in climate circumstances such as temperature and rainfall while contributing to 16% of Ghana's total GDP, and 68% of the GDP in the primary sector (Bunn et al., 2019). Finally, the cocoa production is driven by smallholders and the rural populations prove themselves to be dynamic, having previously been able to generally cope and adapt to changes in their environment with various strategies (Jarawura & Smith, 2015).

The choice of the case is explained in more detail in Confidential Appendix A.

3.2 Main research question

The main research question addresses the identified knowledge gaps in Section 2.4. The following research question can be raised:

How can Development Finance Institutions achieve
long term sustainable investments under climate change?

3.3 Research methodology

Different research methods are used to answer the main research question. The research flow diagram, an aggregated as well as detailed version (Figures 4 and 5), show how the various steps of the approach are connected and how the report is structured.

3.3.1 An agent-based model research design with a case study

Agent-Based Modelling (abbreviated as ABM) as proposed by Van Dam, Nikolic & Lukszo (2013) is chosen for this study, because of its possibility to simulate how system behaviour emerges from the behaviour of individuals at the bottom level (Van Dam et al., 2013). Using ABM, behaviour in response to climate change scenarios based on the previously described case study can be modelled. The method's suitability can be demonstrated, for example, individual decisions to migrate due to climate change often produce nonlinear effects at the population level (Klabunde & Willekens, 2016). It is an attempt to fill one of the research gaps: more bottom-up analysis to incorporate the behaviour of people and businesses in response to climate change. It is academically interesting to combine this with the downscaled scenarios from a top-down approach as it generates complementary insights into who and what is at risk (Conway et al., 2019).

In addition, climate change effects manifest on different levels, each level having its own dynamics. There are considerable local differences that can be captured with ABM.

However, there are some challenges related to this approach. A major challenge is to obtain relevant data to validate the model, especially when situational influences are included. The heterogeneity of agents and the possibility of new patterns emerging as a result of agent interactions make model validation difficult (Pullum & Cui, 2012). Another challenge is the large number of rules and parameters required to set up the model. The bottom-up perspective can be too detailed to simulate over a long period, while a long-time horizon is a characteristic of climate change (Berger & Troost, 2014). Awareness of this issue is required in the implementation phase.

Open interviews are used to motivate the behavioural thresholds in the agent-based model. These focused unstructured interviews are aimed to gather in-depth information of the local context and do not have a pre-planned set of questions, but in times of deviating away from the main issue, the interviewer refocuses the respondent towards key subject (Gray, 2004).

The second approach is a case study. The climate scenarios and corresponding behaviour are tested on a cocoa investment project of the Dutch Development Bank FMO, which helps to gain understanding to what extent integration is possible with real data (Harrison et al., 2017). Easy access to data is one of the advantages of the case study approach, while a common criticism is that the findings only apply to the investment being studied (Johannesson & Perjons, 2014).

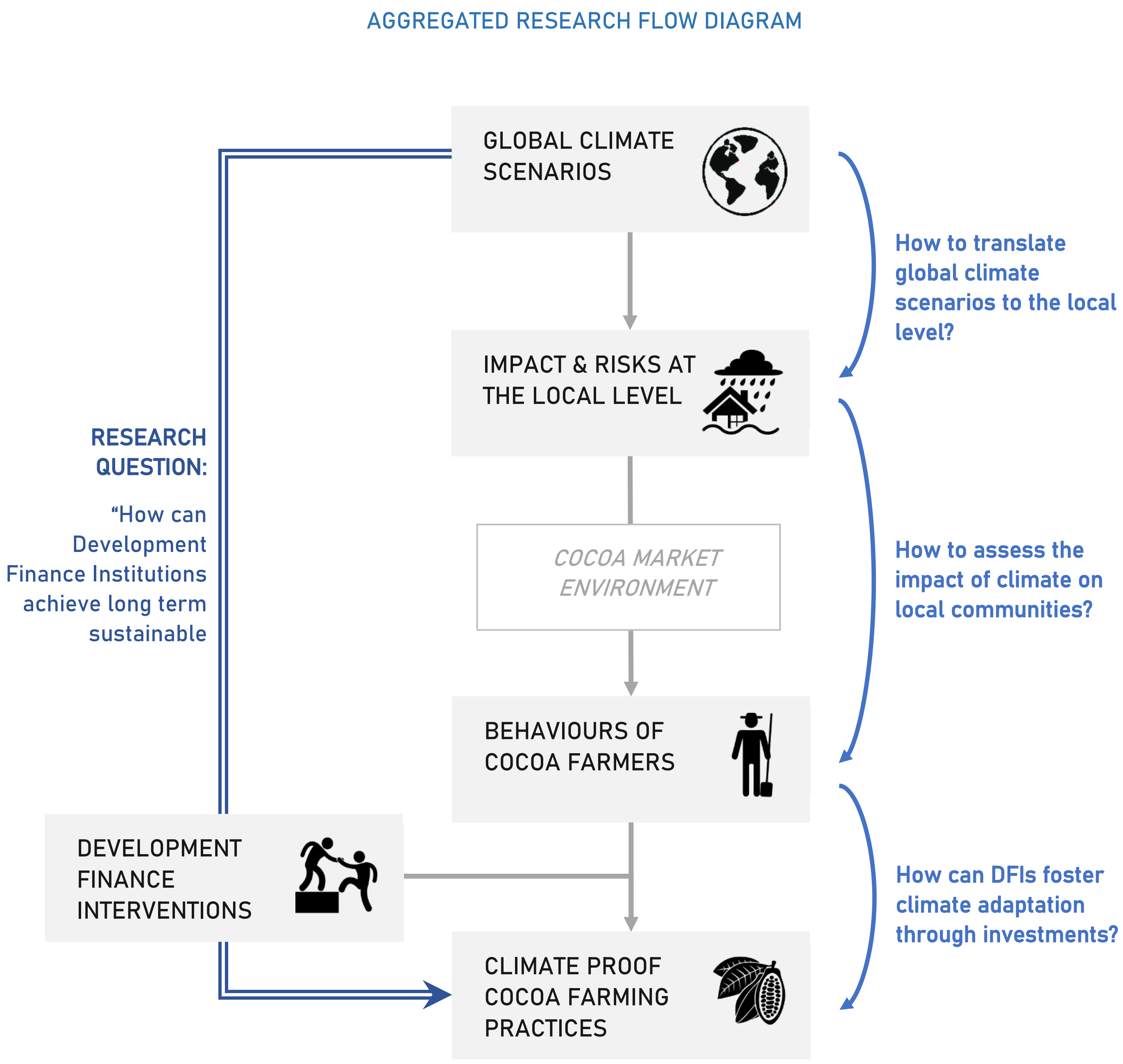


Figure 4 Aggregated research flow diagram

DETAILED RESEARCH FLOW DIAGRAM

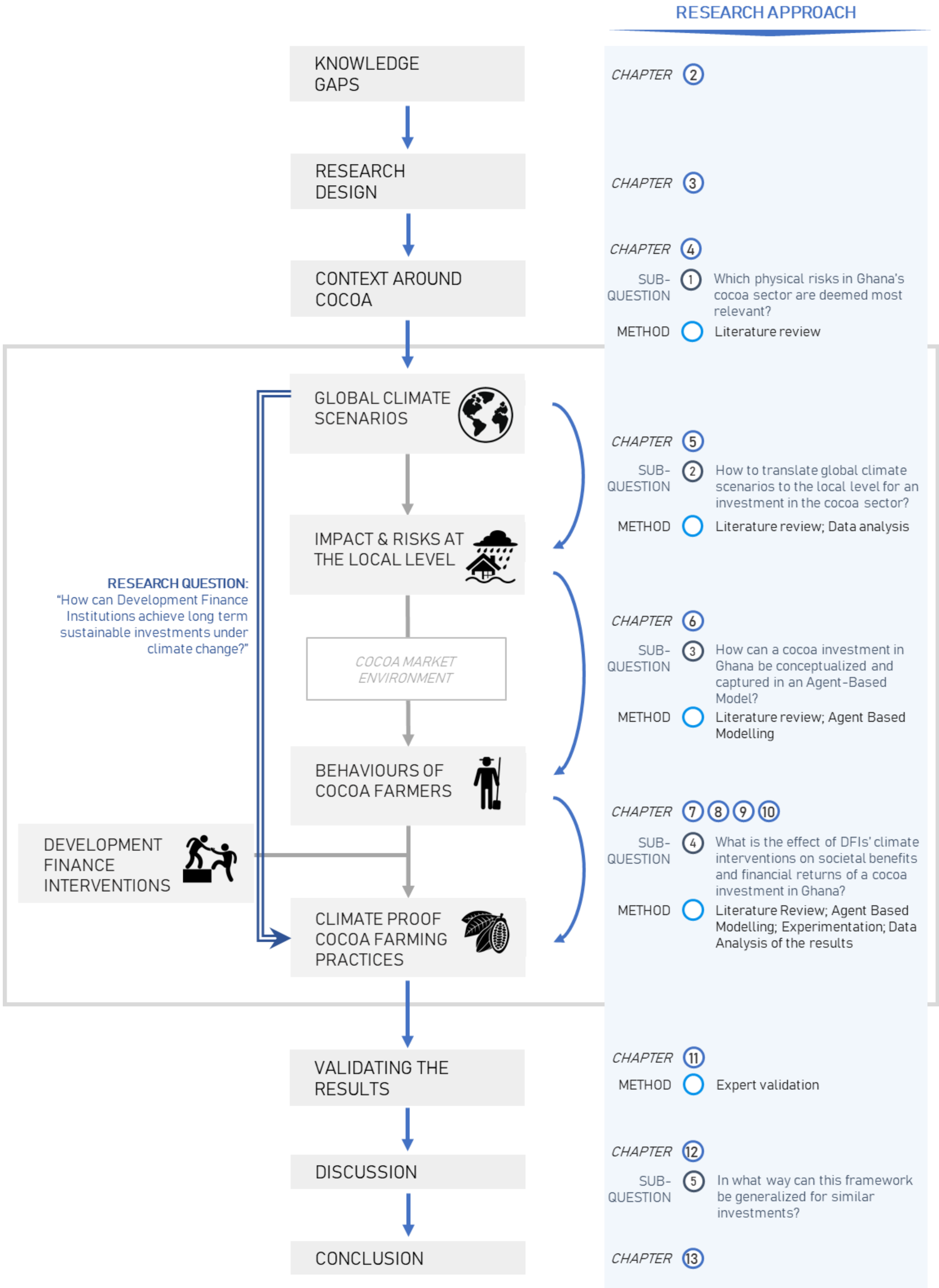


Figure 5 Detailed research flow diagram

3.4 Sub questions and corresponding research methods

The main research question is divided into sub-questions, as presented below. The following subsections discuss each sub-question with corresponding research methods.

Sub question 1 Which physical climate risks in Ghana's cocoa sector are deemed to be the most relevant?

Sub question 2 How to translate global climate scenarios to the local level for an investment in the cocoa sector?

Sub question 3 How can a specific local cocoa investment in Ghana be conceptualized and captured in an Agent-Based Model?

Sub question 4 What is the effect of different interventions on societal benefits and financial returns of a specific local cocoa investment in Ghana under several climate scenarios?

Sub question 5 In what way can this framework be generalized for similar investments?

3.4.1 Sub question 1

Which physical climate risks in Ghana's cocoa sector are deemed to be the most relevant?

The first sub-question aims to identify the most relevant physical climate risks in the cocoa sector which can be acute risks as floods, droughts, cyclones or more continuing risks as uncertain rainfall and temperature. It depends on the cocoa crop characteristics. Those elements are identified during desk research and are improved with information from experts.

3.4.2 Sub question 2

How to translate global climate scenarios to the local level for an investment in the cocoa sector?

The next step is to translate global climate scenarios to local and high-resolution scenarios. Within the local climate scenarios, only the most relevant physical risks for cocoa farming are taken into consideration. The data is retrieved from a recent publication of Bunn et al. (2019) and adjusted with data analysis in ArcGIS.

3.4.3 Sub question 3

How can a specific local cocoa investment in Ghana be conceptualized and captured in an Agent-Based Model?

In the previous sub-questions, the model environment is determined. *Who* and *what* is in the model, a story on how agents interact and software implementation is the next phase of development of the Agent-Based Model (Van Dam et al., 2013). The behaviour of agents is based on the Sustainable Livelihood Framework for rural farmers combined with expert interviews. Agents are grouped into profiles according to the Diffusion of Innovation Theory (Rogers, 1962). Other input data is collected from FMO and desk research. The conceptualisation is aided by the utilization of a XLRM diagram, a flow-chart, and a visualisation of the value chain. Based on this conceptualization a model can be constructed in Netlogo.

3.4.4 Sub question 4

What is the effect of different interventions on societal benefits and financial returns of a specific local cocoa investment in Ghana under several climate scenarios?

FMO has to intervene with climate adaptation under a range of plausible climate scenarios in Ghana. These experiments with climate adaptation provide insight into the system's response. Experimental design and setup must be well thought out in order to investigate system behaviour (Van Dam et al., 2013). Moreover, experimentation is based using data from different sources with probably different underlying assumptions, so deep understanding of the climate change field is required (Mietzer & Reger, 2005). The main results from running the scenarios and experiments are visualized using Python and statistical tests are performed to check whether the results are significant.

3.4.5 Sub question 5

In what way can this framework be generalized for similar investments?

Firstly, verification of the model implementation is performed using an extensive code walk thourgh, single agent testing and extreme value testing. The second step is validation using sensitivity analysis and face validation with experts to determine how *useful* the model is. Validation of the model outcomes with "real" world behaviour is not possible, because the model explores scenarios until 2050 (Van Dam et al., 2013). Validation of agent-based models is also difficult due to the heterogeneity of agents and the possibility of new patterns emerging as a result of agent interactions (Pullum & Cui, 2012). Experts with a diverse backgrounds and responsibilities are invited to reflect on the main findings. The results as presented in Chapter 9 are including one iteration round based on the feedback from the validation workshop.

3.5 Summary chapter 3

The chosen research approach comprises agent-based modelling and a case study of a cocoa investment project of FMO in Ghana. The combination of top-down climate models as input for a bottom-up study to incorporate the behaviour of cocoa households in response to climate change generates complementary insights into who and what is at risk. By subsequently using exploratory modelling of climate adaptation interventions under a wide range of climate scenarios, the main research question can be answered.

Before this model can be built, it should be clear which physical risks are deemed the most relevant for the cocoa sector Ghana. This is discussed in the next chapter.

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4. Context around cocoa production

The Dutch Development Bank FMO has invested in the cocoa sector in Ghana which is exposed to climate change. This chapter consists of two parts. The first part provides background information about the cocoa sector and climate in Ghana (Section 4.1 and 4.2), followed by an explanation of the investments in section 4.3. The second part shows the impact of climate change under climate change. The most relevant climatic drivers on changes in relative climatic suitability for cocoa are identified in Section 4.4.

4.1 Cocoa industry in Ghana

Ghana is currently the second largest cocoa-producing country, after Côte d'Ivoire. The cocoa industry in Ghana is the second largest source of export earnings, accounting for approximately 30% (Wiah & Twumasi-Ankrah, 2017). Furthermore, cocoa contributes to 16% of Ghana's total GDP, and 68% of the GDP in the primary sector (Bunn et al., 2019). Negative impacts of climate change on cocoa production can therefore have serious consequences for the Ghanaian economy and especially rural development. The industry employs approximately 800,000 farm families and the livelihoods of approximately 2 million of additional Ghanaians depend indirectly on the industry (Cocobod, 2020). Cocoa is grown on mainly smallholders' farms and is spread across six regions, as shown in the below map: Eastern, Ashanti, Brong-Ahafo, Central, Volta and the Western region (Cocobod, 2020).

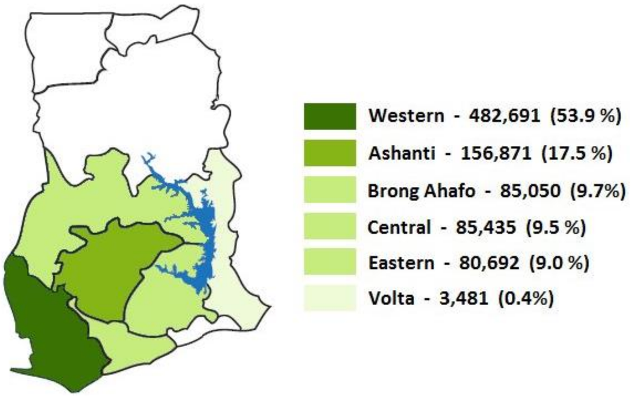

Figure 7 Cocoa growing by region (Monastyrnaya, Joerin, Dawoe & Six, 2016)

4.1.1 Cocoa supply chain

Ghana has a hybrid system where all exports are being controlled by the government and private companies compete for the purchase of cocoa bean volume in the cocoa growing region. Usually two harvests are made in Ghana: the main cropping season is from September to March, and a mid-crop cycle from May to August (Fairtrade, 2016). The mid-crop beans are typically smaller in volume, but the same quality is cultivated.

Once the cocoa is harvested and dried, the beans are collected, inspected, weighed, and bagged by one of the approximately 27 *Licensed Buying Companies (LBCs)* (Sutton & Kpentey, 2012). These cooperatives are appointed by the government and pay the farmers based on the weight of cocoa beans. LBCs receive a commission on every kilogram they deliver and are incentivised to secure high volumes. The public *Ghana Cocoa Board* (COCOBOD) tries to protect the farmers against short-term price volatility and sets the cocoa price for farmers at the start of the season (Aidenvironment & Sustainable Food Lab, 2018). COCOBOD can determine this price for farmers because their subsidiary *Cocoa Marketing Company* (CMC) is the monopolist exporter and already sells 70-80% of the next season's beans in advance with forward contracts. This system provides farmers with a stable income.

After transportation by LBCs and storage in COCOBOD's warehouses the beans are ready for delivery at processing facilities. Most of the cocoa beans are exported before being processed, with support of the exporter CMC, while the remainder is processed locally. There are currently ten processing companies active in Ghana (ILO, 2018). Investments in local processing capacity are hampered by a small domestic demand, inadequate reliability of energy and transport, and weak entrepreneurial skills (World Bank, 2017).

The cocoa beans are then processed into primary products such as cocoa liquor, butter and powder. The food industry is responsible for the final production step where the primary products are transformed into confectionary products such as chocolate bars, spreads and drinks. Only 10 percent of the locally processed cocoa is used by domestic manufacturers (FAO, 2013). The remainder is exported for the final production step. The supply chain ends with the retailers and customers.

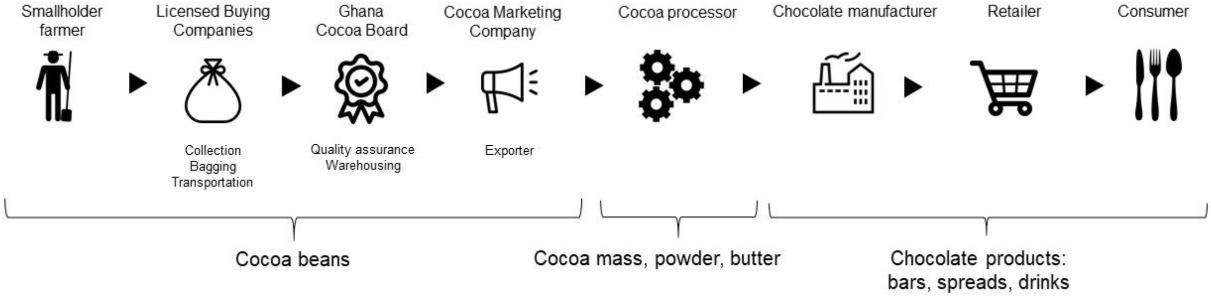

Figure 8 Supply chain of cocoa in Ghana (based on Clear Trade Cocoa, 2020)

4.1.2 Recent developments in the cocoa sector

The Guinean rainforest of West Africa, as shown in Figure 9, has been reduced to 18% of its original area since 2011 (Gockowski & Sonwa, 2011). The deforestation is driven by the expansion of smallholder agriculture in the cocoa, cassava and oil palm sectors. Expansion of cocoa cultivated land occurs as the global demand for cocoa increases. Additionally, there is decreasing productivity and limited ability to improve plantations (World Bank, 2017). Most cocoa smallholders cannot improve their plantations due to low incomes. Plantation challenges include diseased trees, limited access to inputs, and limited ability to invest in new agricultural practices.

Moreover, additional pressure is put on forest resources as the climatic suitability of land currently used for cocoa might decline due to climate change. For that reason, it is important to give priority to climate adaptation and ensure that new cocoa farms are established on previously cleared land over new planting (Schroth et al., 2016).

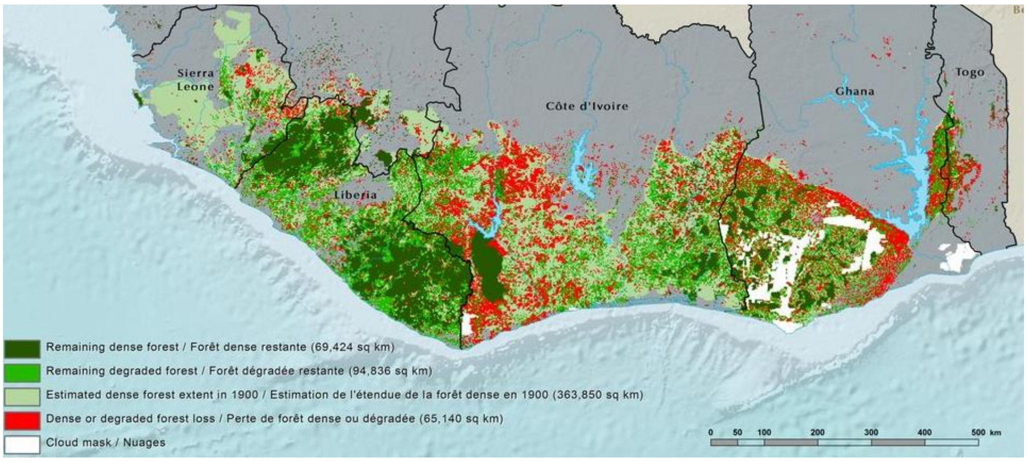

Figure 9 Upper Guinean Forest change from 1975 to 2013(USGS, 2013)

Cocoa growers today receive about 6% of the value of the final product (World Bank, 2017). With current incomes of $0.78 a day, cocoa farmers are usually very poor (Fontain, 2018). Farmers have difficulties paying for fertilizers and pesticides, and this uneven distribution of margins results in other problems as well. It hinders investments in farms, causes young people to leave their farms and move to urban areas, and productions are prone to child labour. Some supply chain actors believe child labour has been addressed through certifications, but others believe it is still a major problem for the sector (Borg & Selmer, 2012).

For the above-mentioned reasons, in June 2019, the governments of Ghana and Côte d'Ivoire proposed to harmonize their prices and raise farmer incomes with a cocoa floor price of 2600 USD per ton, also called Living Income Differential (LID) (Fairtrade, 2019). The two countries produce more than 60% of the world's cocoa supply and now propose an income premium of $400 per tonne to be added to the 2020/21 price.

4.2 Cocoa's growing conditions

Cocoa grows particularly well in countries around the equator such as Côte d' Ivoire, Ghana, Indonesia and Nigeria. Cocoa trees respond well to (Wiah & Twumasi-Ankrah, 2017):

- relatively high and constant temperatures (min. 18-22°C and max. 30-32°C);
- high rainfall, well distributed through the year (annual rainfall in the southwest: 2100mm);
- high humidity;
- wind protection.

Ghana's climate has a strong regional variability: most regions (including the southwestern region where cocoa is mainly grown) have a tropical climate but the northern region, close to the Sub-Sahara, is semi-arid. Ghana has two rain seasons from April to July and a short period from September to October (Cocoa from Ghana, 2019). Cocoa cultivation in Ghana is predominantly rainfed: it relies on rainfall for irrigation (USAID, 2017a). This makes the production sensitive to changes in temperature and precipitation, which are likely due to climate change. Understanding the crop characteristics, such as minimum water requirements and maximum temperature, allows testing and comparison against future climate conditions.

4.3 FMO's investments in the cocoa sector in Ghana

The description of FMO's investment in the cocoa sector are descripted in Confidential Appendix B.

In this thesis, the scope is limited to the Ghanaian cocoa sector. Global exports, retailers and consumers are not included in the scope, because (1) it is difficult to model these indirect, induced effects and their interactions, and (2) the highest climate risk is at the farmer level.

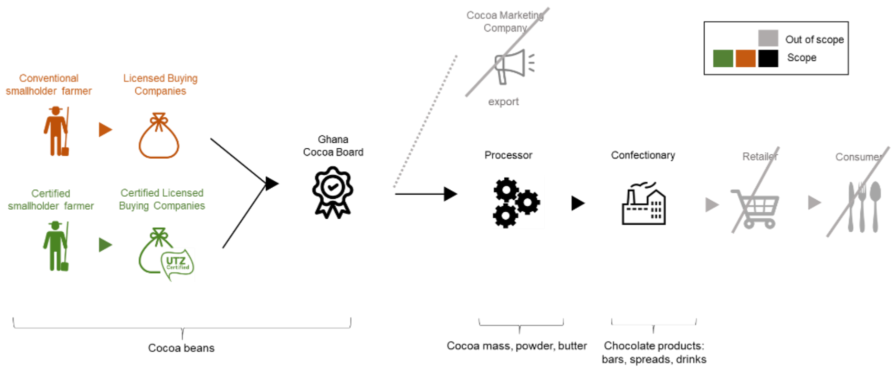

Figure 10 Scope of the supply chain in this study (based on Clear Trade Cocoa, 2020)

4.4 Physical risks in the cocoa sector

This study only focuses on the largest climate-related risk for FMO's cocoa investment: temperature increase and uncertain rainfall patterns, leading to a decrease in cocoa harvest. The motivation for this focus is explained in Confidential Appendix C.

Wiah and Twismasi-Ankrah (2017) examined the impact of climate variables on the total cocoa yield in Ghana. They calculated the relative contribution of each variable to the total historic yield. This can be measured with R^2: a statistical measure that represents the proportion of variance for a dependent variable, cocoa yield in this case, explained by an independent variable such as temperature or rainfall (Wiah & Twismasi-Ankrah, 2017). It can be concluded that four variables explain 48.5% of the total variation in the yield of cocoa: the minimum and maximum annual temperature, precipitation and the number of rainy days. The scope of this study will therefore only include those variables.

Many other studies have also shown that cocoa production is particularly sensitive to precipitation and temperature extremes, especially because cocoa cultivation is rainfed agriculture. These are critical variables dictating the ability of the cocoa tree to produce flowers and fruit (Friedman, 2014). According to Läderach et al. (2013) the balance between temperature and precipitation can best be reflected in the variable 'potential evapotranspiration' (ETP) in mm/day. Temperature increase has an indirect effect on cocoa by increasing the ETP and thus influencing the water availability to the plants. The ETP value could be compensated by increasing rainfall. According to the study of Läderach et al. (2013), ETP contributes 41.1% to the total variability of the predicted shifts in cocoa.

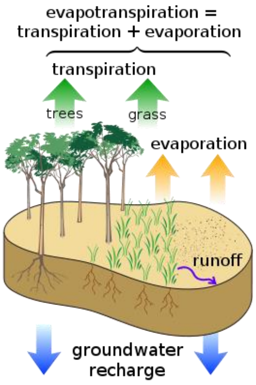

Figure 11 Schematic overview of evapotranspiration process (Wikipedia, 2020)

These crop sensitivity variables are the same ones expected to be challenged by climate change: uncertain precipitation patterns and increasing temperatures (Bunn et al., 2019). Rainfall has a high variability, even between the growing regions within Ghana. A late onset or early end of the rainy season can negatively impact the growing cycle of the crops (Olesen et al., 2013). Bunn et al. (2019) concluded in their paper that a possible reduction of cocoa suitability is likely caused by increased potential evapotranspiration during the short dry season, not compensated by increasing rainfall, which in turn increases the risk of drought, to which cocoa is very susceptible.

An increased ETP trend can already be found in historic climate data over 41-years (1971-2012) for four stations in the Upper East Region of northern Ghana (Limantol, Keith, Azabre & Lennartz, 2016). Data in Figure 12 indicates a rising trend in temperature, but no long-term changes in rainfall, thereby possibly increasing levels of evapotranspiration. The projected effect of rainfall, temperature and ETP on cocoa under different future climate scenario is explained in Chapter 5.

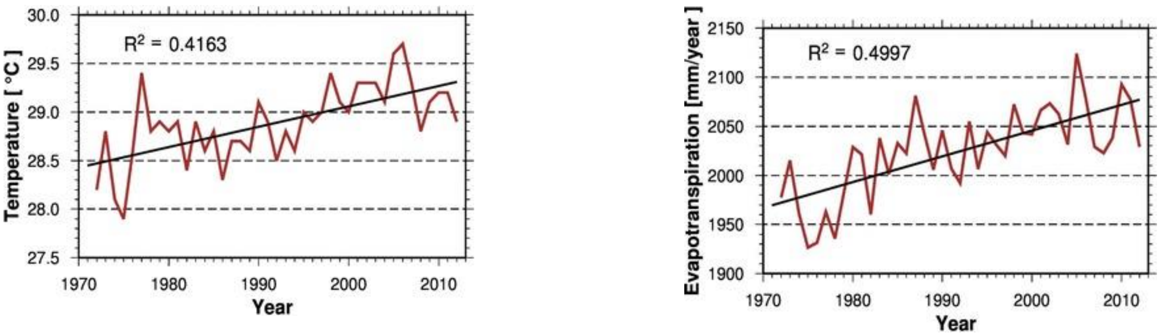

Figure 12 Annual temperature (left) and evapotranspiration (right) trend in Upper East Region of Ghana (Issahaku, Campion & Edziyie, 2016)

New pests and diseases
Another consequence of climate change is that new pests and diseases are reducing cocoa yields (Rainforest Alliance, 2019a). Climate change could alter the rate of development for cocoa pests and pathogens. The host resistance can also be modified, resulting in changes in the physiology of the host pathogen or pest interaction (Codjoe, Ocansey, Boateng & Oforti, 2013). Reduced cocoa yield translates into reduced income for farmers and their families.

The answer to sub question 1, *Which physical risks in the cocoa sector in Ghana are deemed the most relevant?*, can now be formulated. Increased temperature and uncertain precipitation patterns due to climate change, which influence the potential evapotranspiration, are the bioclimatic variables that contribute the most to cocoa yield variability. The reduced cocoa suitability is a key risk for shifts in cocoa supply.

4.5 Summary chapter 4

This chapter first introduced the context of the cocoa industry in Ghana and then defined the boundaries of physical risks in this study. Only temperature and precipitation, affecting the potential evapotranspiration of the cocoa plant, are included in the model. The next chapter discusses the interventions which influence the suitability of cocoa under climate change.


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5. Global to local climate scenarios

The previous chapters have discussed the central knowledge gap, the research approach and the most relevant physical risks for the cocoa sector. Given that increased temperature and uncertain precipitation patterns driven by climate change will affect cocoa production, the question is now how these global scenarios can be translated at the local scale to explore the impact on cocoa in Ghana.

The selected climate scenarios are explained in Section 5.1, followed by a description of policy necessary to achieve an optimistic climate scenario. The data gathering and modification process is described in Section 5.3 and 5.4.

5.1 Selection of global climate scenarios

The global climate scenarios considered in this study are an optimistic and pessimistic scenario. These scenarios represent the two extreme Representation Concentration Pathways (RCP) 2.6 and 8.5 as modelled by the IPCC, therefore providing the boundaries of a range of different outcomes.

The pessimistic scenario gives insight into a world without action on climate mitigation. RCP8.5 represents high GHG concentrations with a radiative forcing reaching 8.5 W/m^2 towards 2100 (Van Vuuren et al., 2011). This means that global temperature will rise with 3.2-5.4°C and certain cocoa growing regions will be become unsuitable or only suitable with specific adaptation measures.

The optimistic scenario is in line with the Paris Agreement, where efforts are taken to drastically reduce the amount of GHG emissions with a radiative forcing of 2.6 W/m^2 in 2100. A global temperature rise of 1.5-2°C corresponds to this scenario. Changes in cocoa suitability will be not as extreme as in the pessimistic scenario.

5.2 Policy risk in the optimistic climate scenario

However, climate mitigation measures should be taken to achieve this optimistic scenario and those measures could also affect the cocoa supply chain. Carbon pricing is one of the considered options. Ghana has a controlled cocoa system and the public COCOBOD is a powerful actor in the supply chain, which is able to change policies, also regarding climate change. This policy risk is also included in the scenarios and can be switched on/off in the ABM model.

For the RCP2.6 scenario, three scenarios for carbon pricing are considered, in line with the analysis of the International Monetary Fund (IMF): US$25, $50 and $75/t$CO_2$ by 2030 (IMF, 2019).

(1) The scenarios with $25 and $50/t$CO_2$ by 2030 are analysed to include the possibility that less ambitious carbon pricing may be combined with other policy instruments (IMF, 2019).

(2) $75/t$CO_2$ is the median of the range of carbon price estimated by the High Level Commission on Carbon Prices of the World Bank (US$50–100/ t$CO_2$ by 2030) which would support the achievement of the Paris Agreement (Stiglitz et al., 2017).

The exact parametrization per year can be found in Appendix A.

Carbon pricing as policy is not included in the pessimistic RCP8.5 scenario, because this scenario shows a future with the highest greenhouse gas emissions in absence of climate change policy (Riahi et al., 2011). The carbon price is therefore set at its current level in Ghana, which is 0 USD/ton.

5.3 Downscaling to local climate scenarios

The selected optimistic and pessimistic global climate scenarios (Section 5.1) have an inappropriate spatial resolution to detect local climate patterns in the future. Grid cells of about 100x100 km are used (Läderach et al., 2013). This is especially the case for Ghana with heterogeneous landscapes as forest and mountain areas.

To assess local impact on cocoa suitability downscaled climate data is required. A previous study on climate impact on cocoa in Ghana carried out this downscaling exercise, which gives the opportunity to use this data for this study. Figure 13 shows the downscaling process of Bunn et al. (2019):

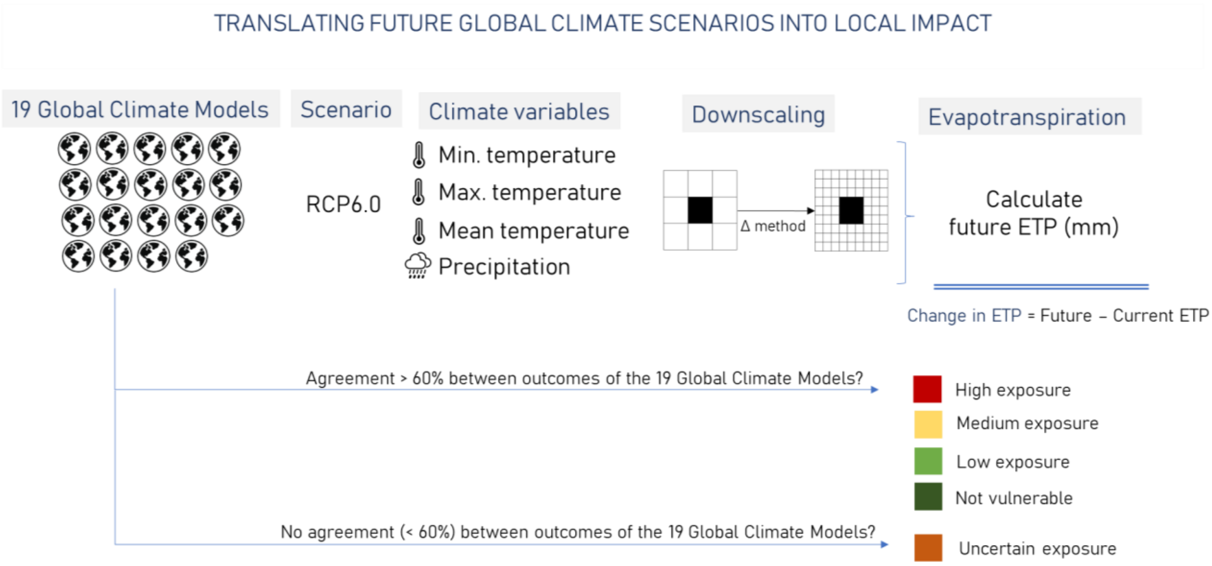


Figure 13 Translating future climate scenarios into local impact (based on Bunn et al., 2019)

Bunn et al. (2019) used future climate data from 19 Global Circulation Models (GCMs) from the Fifth Assessment Report (AR5) of the IPCC. The climate variables affecting the evapotranspiration of cocoa – minimum, maximum, mean temperature and precipitation – are downscaled using the delta method to a detailed level for the RCP6.0 scenario, an intermediate scenario between the more optimistic RCP2.6 and pessimistic RCP8.5. These downscaled datasets of the temperature and rainfall are publicly available on the website of the International Centre for Tropical Agriculture (CIAT) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (Navarro-Racines, Tarapues, Jarvis & Ramirez-Villegas, 2020). The downscaling exercise resulted in a 1 km resolution grid, which can more accurately predict the impacts of climate change for cocoa in Ghana.

Change in cocoa suitability can be estimated based on the variation of evapotranspiration, i.e. the difference between current and future evapotranspiration (Bunn et al., 2019). The 19 GCMs generated a variability in outcomes. If the agreement between the 19 models was higher than 60%, the outcome for this 1x1 km grid is categorized according to the degree of impact: dark green for no vulnerability until red for high exposure. When the 19 global climate models had an outcome with a higher variability than 40%, the exposure of this grid is classified as uncertain and marked with an orange colour. The results of RCP6.0 in 2050 is shown in the map below.

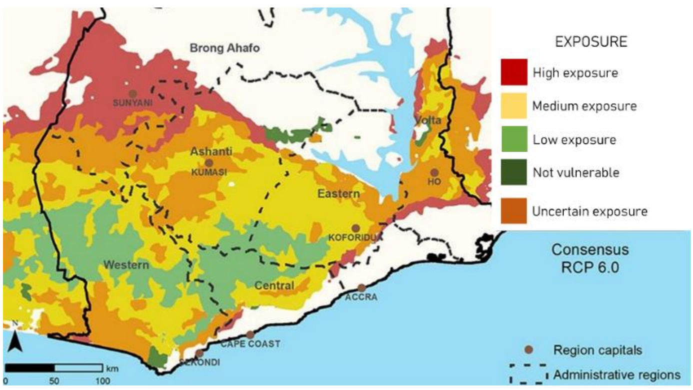


Figure 14 Cocoa suitability and adaptation necessary under RCP6.0 in 2050 (based on Bunn et al., 2019)

This thesis takes the downscaling methodology used by Bunn et al. (2019) for RCP6.0 as a basis for downscaling climate scenarios RCP2.6 and RCP8.5 in this study for multiple reasons:

(1) First, the availability of high-resolution downscaled climate scenarios for Ghana is limited. Many studies have been conducted for global climate data, as climate change happens through interconnected phenomena in a worldwide system. Yet, zoom-in at local level requires also taking into account local characteristics and feedback-loops, which might be more difficult to assess. The downscaled datasets of the temperature and rainfall can be publicly retrieved from the website of the CGIAR Research Program on Climate Change, Agriculture and Food Security (2020).
(2) Second, Bunn et al. (2019) also took temperature and rainfall into account, affecting the evapotranspiration, as most sensitive variables for cocoa. They also neglected other parameters affecting the cocoa yield (answer on sub question 1). The exercise to transform these downscaled datasets to evapotranspiration values and then to geographic values is done by Bunn et al. (2019). Researcher Christian Bunn was willing to share his data for the purpose of this thesis.
(3) Finally, the identified research gap after the site-specific impact study of Bunn et al. (2019) is to focus on behaviour in response to climate change and the adoption of adaptation measures, which is the purpose of this case study.

Since these datasets plays an important role in this research, the most critical assumptions are clarified:

- To identify the current climate, the World Clim dataset of Hijmans et al. (2005) is used with monthly precipitation, minimum and maximum temperatures and 19 bioclimatic variables.
- Bunn et al. (2019) used the Delta Method for statistical downscaling. This method produces an interpolated surface of changes in climates and applies this to the baseline climate. It assumes that relationships among variables are maintained towards the future (Läderach et al., 2013).

5.4 Results of the data modification process

Rough ASC datasets of RCP2.6 and 8.5, shared by researcher Christian Bunn, are converted into maps to identify the affected regions with geographic information system ArcGIS. Appendix B discusses all steps taken to gather and modify this data. The maps (Figure 15 and 16) show the exposure in 2050.

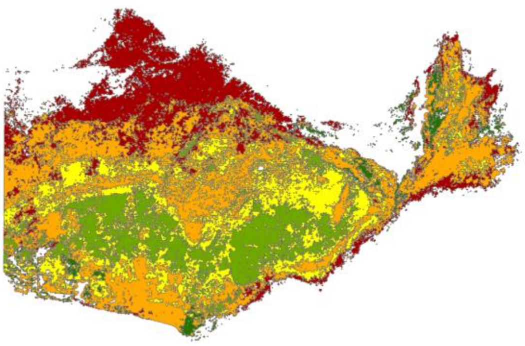


Figure 15 Overview of cocoa in Ghana under climate scenario RCP2.6

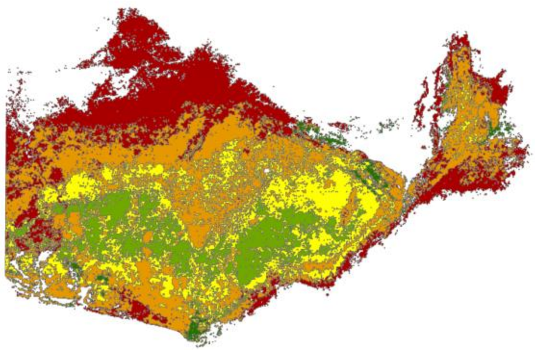


Figure 16 Overview of cocoa in Ghana under climate scenario RCP8.5

The surface (km^2) of the affected regions shown in the maps is measured and included in Table 13 in Appendix C. In all regions, except Ashanti, the share of the surface with high exposure is higher in the pessimistic (RCP8.5) than in the optimistic (RCP2.6) climate scenario. However, the differences between the scenarios are not so large. This can be explained by the trend of the graphs until 2100. RCP8.5 is a continuous rising line, while RCP2.6 first peaks in radiative forcing and then declines to 2.6 W/m^2 in 2100. The results for 2050 are a snapshot where the optimistic curve started to decline just after the peak.

The next step was to plot the location of the cocoa farmers investigated, on the map prepared. FMO's client does not have a traceability system in place to know where its suppliers are located. Therefore, the client's suppliers are mapped across regions, proportionally to national sourcing (COCOBOD 2018). In this process, the exposure category 'highly uncertain' (no agreement between 19 global climate models) as suggested by Bunn et al. (2019) is divided evenly over the other categories: no, low, medium, high exposure, i.e. ¼ each (Appendix D). This results in the following definitions of exposure categories:

- No exposure
- Low exposure: climate will remain suitable besides increased pest and disease pressure
- Medium exposure: climate will remain suitable, but increased droughts & pest and disease pressure
- High exposure: no longer suitable for cocoa; give up cocoa or lose their crop to drought

Figure 17 Definition of exposure to climate change

Table 1 shows the climate impact on the cocoa farms supplying to FMO's client (scale 1:100) under the pessimistic and optimistic scenarios in 2050. In both scenarios, approximately 25% of the cocoa farms are highly exposed in 2050 which means that their location is no longer suitable for cocoa due to droughts. Most of the farms, approximately 63%, is low or medium exposed which means that climate adaptation is essential to cope with both droughts and the increased pest and disease pressure. Finally, 10% of the cocoa farms is not exposed to significant climate change impact. Zooming in on the regions shows that there are large differences: Brong Ahafo has for example a high share in highly exposed farms, while Central is less exposed.

Table 1 Climate exposure in 2050 for individual farms

Optimistic scenario: number of farms (1:100)

Region	high	medium	low	no		
Brong Ahafo	50	5	2	2	59	10%
Ashanti	34	39	17	11	101	18%
Eastern	7	27	14	8	56	10%
Central	8	19	25	3	55	10%
Western	37	113	105	33	288	51%
Volta	2	2	0	0	4	1%
Total	138	205	163	57		
	25%	36%	29%	10%		

Pessimistic scenario: number of farms (1:100)

Region	high	medium	low	no		
Brong Ahafo	52	4	2	1	59	10%
Ashanti	34	38	17	12	101	18%
Eastern	9	29	11	7	56	10%
Central	10	21	21	3	55	10%
Western	46	114	94	34	288	51%
Volta	3	1	0	0	4	1%
Total	154	207	145	57		
	27%	37%	26%	10%		

The tables and maps show the exposure in 2050, but there is easily accessible yearly data available. The 30-year trend from the current situation (2020) to the affected farms in 2050 is therefore assumed to be linear. The exposure of each farm evolves step by step: the farms becoming highly exposed first go through the low and then the medium exposed stage. This process follows the logic of a Markov chain, where cocoa farmers go through a sequence of events. The timeframe being 30 years (2020-2050), it has been assumed for the model that a shift occurs every 10 years. This is visualized in the below Figure 18. Appendix E.1 explains the mathematical logic behind this linear trend in detail and shows the dataset corresponding to this approach.

As mentioned earlier, the difference between RCP2.6 and RCP8.5 are not so large until 2050. Therefore, to explore the effects on the longer term, a logarithmic trend is included to illustrate the situation of 2050 earlier. In this trend the exposure to climate change rises sharply in the beginning and then decreasingly increases up to a plateau in 2038. Appendix E.2 shows the logic of tangents behind this logarithmic trend with a corresponding table of exposed cocoa farms per year.

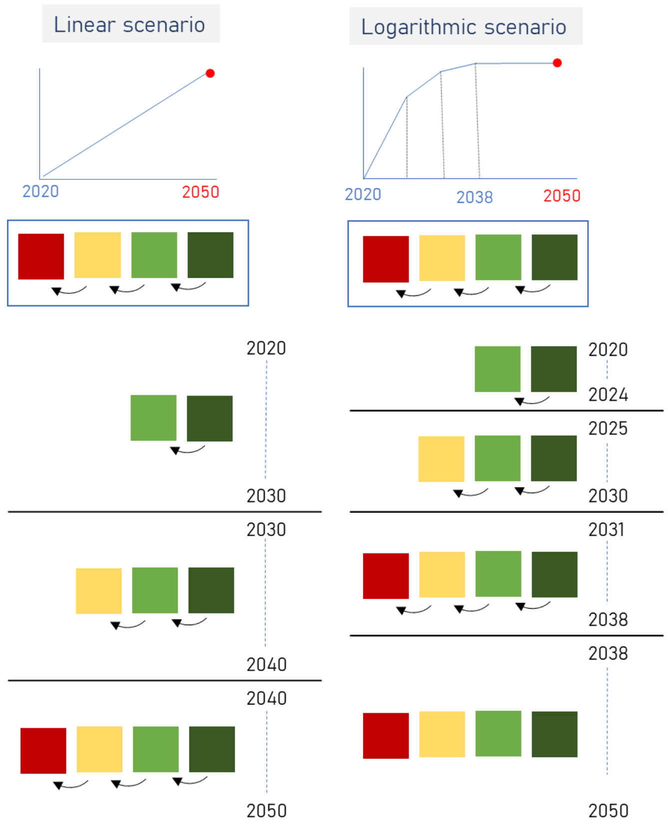


Figure 18 Climate scenario trends till 2050

The second sub-question, *How to translate global climate scenarios to the local level for an investment in the cocoa sector?,* can now be answered. Nineteen Global Climate Projections for 2050 are downscaled with the delta method into local impacts for temperature and precipitation, affecting the potential evapotranspiration of the cocoa plant. This dataset from CGIAR Research Program on Climate Change, Agriculture and Food Security is used in this study. The location of cocoa farms of FMO's client is plot on the maps prepared. These farms are mapped proportionally to national COCOBOD sourcing data, resulting in the climate exposure specific to each cocoa farm in 2050. The pathway from 2020 until 2050 is modelled with a linear trend, following the logic of a Markov chain. To explore the effects on the long-term, a logarithmic trend is included to illustrate the situation of 2050 already in 2038.

5.5 Summary chapter 5

This chapter first introduced the risks driving the scenarios: physical risk for cocoa and policy risk in terms of carbon pricing. The optimistic RCP2.6, in line with the Paris Agreement, and pessimistic RCP8.5 scenario are both included in the model to explore the range of behaviour on these extreme scenarios. This study uses the downscaled dataset of CGIAR Research Program on Climate Change, Agriculture and Food Security where 19 Global Climate Projections are downscaled with the delta method into local impacts on temperature and precipitation, affecting the potential evapotranspiration of the cocoa plant. The results of the data modification process in ArcGIS shows that all regions will become partly unsuitable for cocoa in 2050, ranging from 12% till 85%. In terms of cocoa farms this means that 25% in RCP2.6 and 27% in RCP8.5 is highly exposed and will give up or lose their crop to drought. The pathway from 2020 until 2050 is modelled with a both a linear trend, following the logic of a Markov chain. A logarithmic trend which ends up in the situation of 2050 already in 2038 is included to explore the effects on the long term. Achieving the RCP2.6 scenario include climate mitigation policies as carbon pricing, which is also included in this scenario development. Carbon pricing can be switched on/off in the ABM model. The next chapter discusses the behaviour of cocoa households under these downscaled climate scenarios.

6. Conceptualizing behaviour for agent-based modelling

The previous chapter discussed the climate scenarios, downscaled to the cocoa growing region in Ghana. This chapter discusses the behaviour of cocoa farmers in the current situation as well as under climate change. It revolves around the third sub-question how to conceptualize and capture a specific local investment in an agent-based model. The behavioural rules are based on interviews and frameworks.

In this chapter, the focus is first on showing a high-level conceptualisation for the agent-based model. This is followed by Section 6.2 where a portrait of a Ghanaian cocoa farmer – the central agent in the model – is sketched by describing its livelihood strategies and behavioural profiles. The boundaries are defined in Section 6.4 The next section 6.4 gives an overview which individuals and what properties are the system, and a story how they interact. The final section explains the key performance indicators which would be used to inform FMO.

6.1 High level conceptualisation

In this study, Robust Decision Making (RDM) is used to test interventions of DFIs against multiple future climate scenarios taking into account the behaviour of cocoa farmers (Lempert, 2019). This approach is chosen based on the circumstances of deep uncertainty affecting the financial returns and societal benefits of FMO's investments. The XLRM framework contains the following components: exogenous uncertainties (X) at the left, policy levers (L) on top, relationships (R) as intermediate component and measures (S) at the right. All steps of RDM are included in Appendix G. The below Figure 19 demonstrates the high-level conceptualisation for this study with the corresponding chapters.

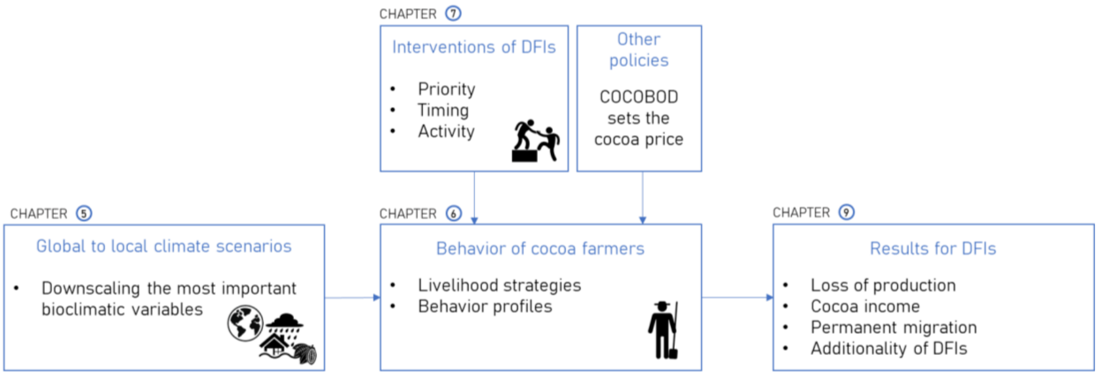


Figure 19 High-level conceptualisation of the agent-based model

In this study, the climate scenarios are the exogenous uncertainties (X) outside the control of DFIs, the interventions with climate adaptation are the policy levers (L) that DFIs want to explore with the famer gate price of the governmental agency COCOBOD; the behaviour of cocoa farmers represent the relationships in the system (R) and finally, the results that DFIs use to make trade-offs between interventions represent the measures (M).

6.2 Portraying a Ghanaian cocoa farmer

This section explains the behaviour of a cocoa farmers with respect to livelihood strategies, as described by the Sustainable Livelihood Framework (Bell, Calvo-Hernandez & Oppenheimer, 2019). It is not realistic to entitle every farmer with the same behavioural profile: farmers will behave in a different way, depending on the location and exposure of their farms, their beliefs, and their resilience to change. For that reason, for the purpose of the study, various group of farmers' profiles are defined in section 6.2.2. In study, a cocoa farmer represents a household with the size of 5.9 members on average (Bymolt, Laven & Tyszler, 2018c)

Figure 20 Main characteristics of a Ghanaian cocoa smallholder household: one household consist of 5.9 individuals on average

6.2.1 Sustainable Livelihood Strategies

The Sustainable Livelihood Framework is a way of looking at the complexity of poor people's livelihoods (Serrat, 2017). A "sustainable livelihood" refers to a livelihood that can cope with and recover from stress and shocks (Hussein & Nelson, 1998). Individuals and households may work to achieve this sustainable livelihood with so-called *livelihood strategies*.

Previous research commonly suggests three main livelihood strategies that are often used in rural contexts: (1) *agricultural intensification*, (2) *diversification across different activities*, and (3) *migration to other places* (Bell, Calvo Hernadez & Oppenheimer, 2019). It might result in more income, reduced vulnerability or improved food security (Serrat, 2017).

(1) Agricultural intensification

Agricultural intensification is a strategy to increase productivity and gain more output per hectare by investing more capital or labour in a farm. Governmental agencies, companies and NGOs agree that that training is an important way to improve productivity levels, for example coaching about spraying and pruning and accessing seedlings (Bymolt, Laven, Tyszler, 2018b).

(2) Diversification across different activities

Diversifying activities is a way to raise income and reduce exposure to environmental risks deriving from heavy dependence on cocoa. The Ghanaian economy is highly dependent on the cocoa production and it is not easy to find alternative sources of income because the infrastructure of new markets is not as good developed. At the moment, 30% of the income of cocoa households is earned from diversification: 10% of the income of cocoa households comes from trading and very little percentages from sale of livestock products and 20% from the sale of other crops. Palm oil, cashew and rubber are the main cultivated crops and farmers gradually gain experiences with these new crops alongside cocoa (Läderach et al., 2013).

(3) Migration

Migration is another strategy for a sustainable livelihood of poor households, consisting in moving to another location for a short or long time. *International migration* is mostly not feasible for cocoa households due to high costs (personal communication, 15 Jan 2020, Appendix L). Yet, migration is not new to the Ghanaian population as 12.5% of the population has experienced *internal migration* (Duplantier, Ksoll, Lehrer & Seitz, 2017), migrating to a city within Ghana with more opportunities for income. This livelihood strategy generally refers to *temporary migration:* approximately 9% of the income of cocoa households is earned from remittances from friends and family living away from the household, and from salary employment in government job or with a company. *Permanent migration* has high economic barriers. First, cocoa landowners believe that income from cocoa production is more profitable than selling the land and serves as income for their retirement (Bymolt, Laven, Tyszler, 2018a). Second, cocoa trees are also a long-term investment. For those reasons, smallholders are not likely to leave their cocoa farm earlier than their optimal productive age (Binam et al., 2008).

6.2.1.1 Livelihood strategies in practice

Household try to achieve the most optimal outcomes with these livelihood strategies and interviewee 2 (Appendix L) suggests that the strategies are simultaneously in practice. It is more fluid than one strategy at the time: nearly all households have multiple income sources and several household members typically engage in income generating activities to support the household (Bymolt, Laven & Tyszler, 2018c). Cocoa households derive, on average, 61% of their income from cocoa, 30% is earned from diversification and 9% from permanently migration. For example, the farmer might attend a training of the certification program on shade trees or fertilizer use (*intensification*), while the woman often work in trade, for example selling peanuts at the market, and the children walk around to sell lollipops (*diversification*). Some cocoa farmers also go to the city to find work in other business sectors as transport or construction for a few months during times of low farm activities (*migration*) (Monastyrnaya, Joerin, Dawoe, & Six, 2016).

6.2.2 Behaviour of farmers groups

The use of livelihood strategies varies across households depending on their behaviour profile. For example, a cocoa farmer over 80 years old will not change his agricultural practices due to a training on intensification from a governmental agency, company or NGO (personal communication, 17 Jan 2020, Appendix K). A household with children studying in the city might be more willing to innovate.

These different groups of cocoa households can be distinguished using behavioural change theories such as the Theory of Planned Behaviour, the Diffusion of Innovations theory and the Value Belief Norms theory. Since this situation concerns the choice of households in response to decreased harvests and their willingness to adopt innovations, the Diffusion of Innovations theory is applied in this study (Rogers, 1962). The other two theories were less relevant here, because the Theory of Planned Behaviour is more focused on intentions and the Value Belief Norms theory is more concerned with the relation between personal norms and green behaviour of consumers.

Rogers (1962) suggests five categories of adopters: *(1) Innovators*: willing to take risks, allowing them to adopt technologies that may fail; *(2) Early adopters*: have more financial liquidity and advanced education than late adopters; *(3) Early Majority*: adopt an innovation after longer time than innovators and early adopters; *(4) Late Majority*: adopt an innovation after an average participant. These individuals are sceptical and have below average social status; *(5) Laggards*: last to adopt an innovation, typically aversion to change. They can be focused on traditions, have low liquidity and are the oldest.

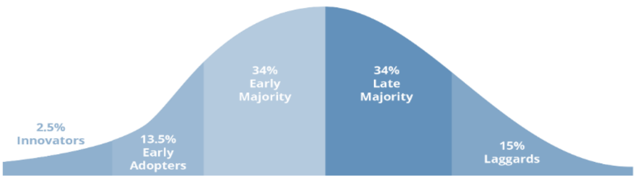


Figure 21 Diffusion of Innovations theory (Rogers, 1962)

During an interview (Appendix K), a social scientist of the KIT Royal Tropical Institute further specified these categories for the cocoa sector in Ghana. She distinguished three groups: *early adopters*, *farmers relying on the government*, and *farmers relying on tradition*. The group *relying on the government* is a group that represents an average cocoa farmer that follows the trends suggested by the government, because Ghana has a hybrid governmental controlled cocoa system. This classification can be interpreted as an aggregation of the Innovation Diffusion theory categories:

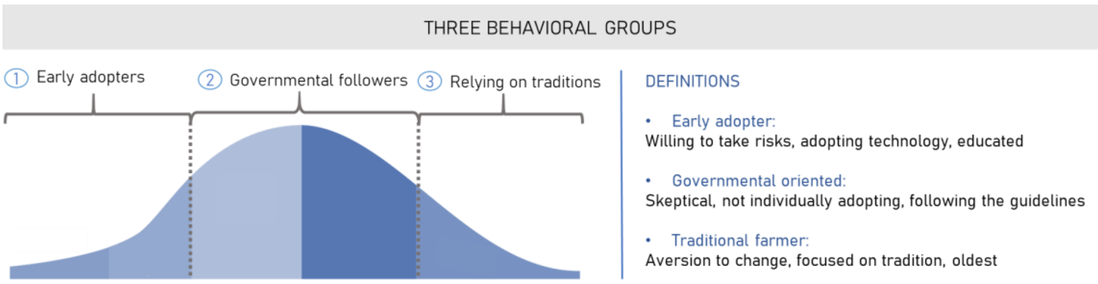


Figure 22 Three behavioural profiles

In this study, a household is assumed to have one behavioural profile. In other words, no distinction is made for different household members while in reality differences probably exist when for example a daughter studying in the city is likely to be an early adopter while her father can be more in favour of traditional agriculture practices.

Four community groups are defined, with a diverse composition of households' behaviour profiles (Table 2). As the cocoa production in Ghana is their main exporting crop for over 81 years and dominated by many smallholders and almost no large-scale farms, the proportion of early adopters is assumed to be lower compared to the governmental and traditional farmers. The farms within scope of this study are assumed to be equally spread across these four communities.

Table 2 For every region four communities are specified

		Early adopters	Relying on the government	Relying on traditions
Community 1	¼	10%	50%	40%
Community 2	¼	0%	60%	40%
Community 3	¼	20%	40%	40%
Community 4	¼	10%	40%	50%

Each group is triggered by different threshold to adopt one of the livelihood strategies as described in section 6.2.1. For example, an early adopter household (profile 1) will start to focus on diversification when a harvest decreases slightly (for example to lower than 300 kg/ha); a household relying on traditional agricultural practices (profile 3) will only diversify when they do not have any other option anymore (for example productivity lower than 200 kg/ha); while a household relying on the government (profile 2) might only diversity when the government supports this measure.

6.3 Defining the boundaries

Now that the portrait of a cocoa farmer is defined in Section 6.2, the boundaries of the system captured in the agent-based model can be defined in this section. All assumptions are listed in Appendix H and the most critical boundaries are shown below:

- Time frame
  The applied time frame is a period of 30 years, from 2020 till 2050. The average term that DFIs have an outstanding loan is 8 years, however supporting climate adaptation means that DFIs should aim for climate-proof investments over the lifetime of an asset (TCFD, 2019). The timeframe is also based on the availability of downscaled climate data until 2050. In the model, time is represented by ticks. One tick corresponds to one year.
- Scale of the model
  In the model, 1% of the farms supplying to FMO's investment are included to save running time: 563 farms.
- Cocoa trees
  The age of cocoa trees in Ghana are split into four categories: 0-10 years (25.7%), 10-20 years (25.7%), 20-30 years (25.7%) and older than 30 years (23%). because. Most of the cocoa farms were planted in the 1980s when the government revived the sector. They estimate that 23% of the cocoa tree stock is older than 30 years and therefore less productive (Pandey, 2017). This means that Ghana deals with an age problem (Wessel & Quist-Wessel, 2015)
- World market price
  Two options for the world market price are included in the model. On June 12, 2019, the governments of Ghana and Cote d'Ivoire announced a floor price of 2600 USD per ton cocoa beans (Rainforest Alliance, 2019b). This floor price could be set because the two countries are responsible for 65% of the world market.
  (1) The first option in the ABM model is to run with this floor price of 2600 USD per ton, constant over the years.
  (2) The second option is to run the model with historical fluctuations over the past 15 years (ICCO, 2020). The yearly averages of daily cocoa prices are retrieved from the International Cocoa Organization. Prices smaller than 2600 USD per ton are manually adjusted to 2600 (according to the recently announced floor price).
- Climate scenario
  The system will run for two climate scenarios: the optimistic RCP2.6 and pessimistic RCP8.5.

- Climate scenario trend till 2050
  The 30-year trend from the current climate till 2050 is assumed to be linear. To explore the effects on the long-term, a logarithmic trend is also included to illustrate the situation of 2050 already in 2038.
- Carbon price
  The system boundary includes three options for carbon pricing in the optimistic RCP2.6 scenario which assumes high efforts for climate mitigation. The carbon price of \$25, \$50 and \$75 per ton CO_2 can be selected (Section 5.1).

The above-mentioned assumptions optimistic or pessimistic climate scenario, trend of the climate scenario, world market price, and carbon price are subject to model exploration in Section 9.1.

6.4 Properties of agents and interactions

Figure 23 shows a flow chart of the behaviour of cocoa farmers under climate change. The chart shows four main behavioural thresholds which are different for the three behavioural profiles early adopters, relying on the government and relying on traditions. The figure shows the behaviour in absence of interventions.

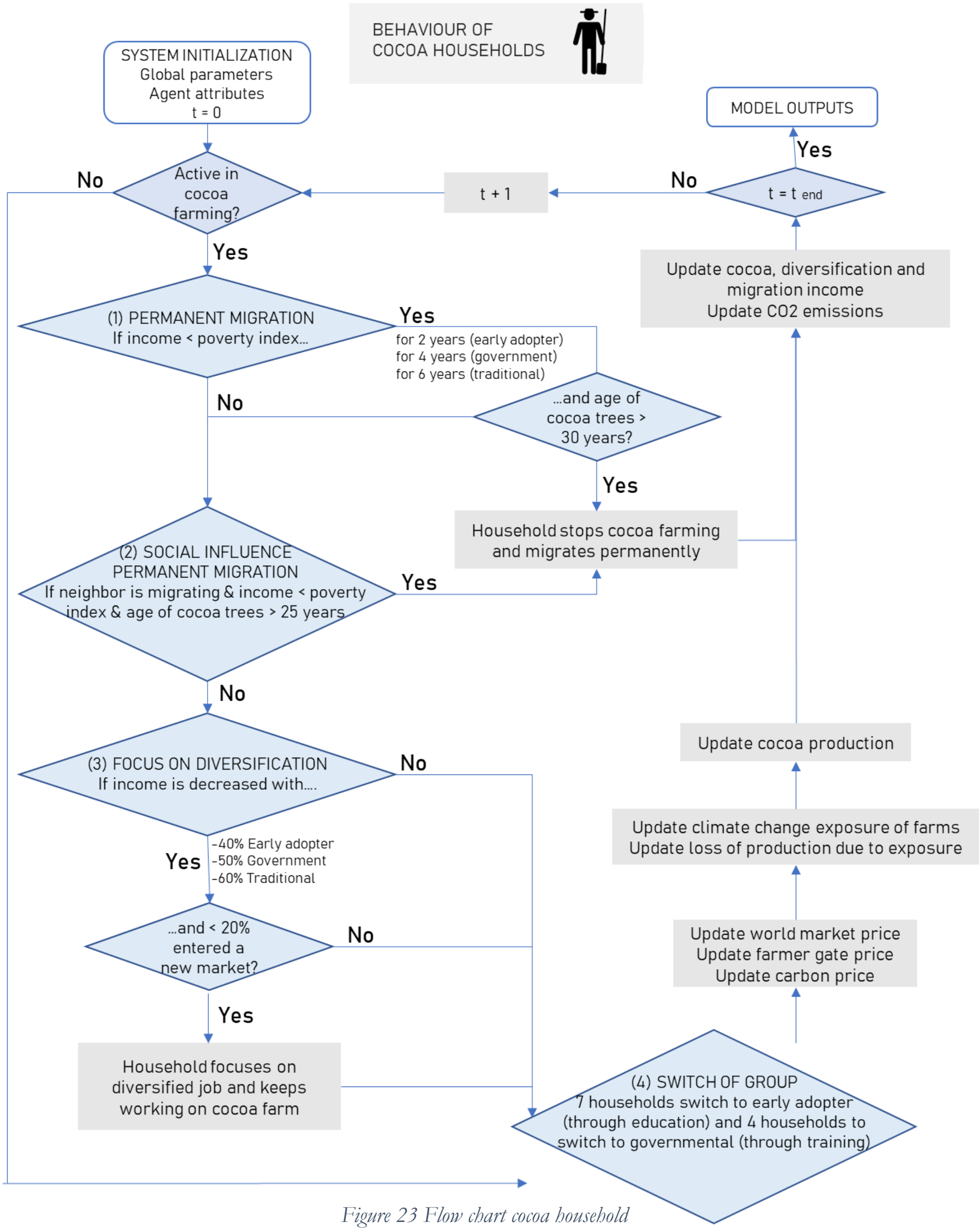


Figure 23 Flow chart cocoa household

Initially, the 563 cocoa farmers (scale 1:100) supplying to FMO's investment are not exposed to climate change. The smallholders are categorized in a region according to the COCOBOD sourcing data. They also belong to one of the three behavioural profiles and gain for 61, 30 and 9% of their income from cocoa, diversification and temporarily migration (Bymolt, Laven & Tyszler, 2018c). The farm size is homogenous with 4 ha. All assumptions on farm size, productivity, household size and costs are listed in Appendix H.

Once the model starts running, their cocoa production becomes not, low, medium, or high exposed to regional changes in climate. This results in a loss of production according to the estimates of Bunn et al. (2018): 10-20% for low, 30-50% for medium and 60-100% for high exposed regions. The effects of these ranges are tested in the sensitivity analysis.

(1) The first behavioural threshold shows that cocoa households will permanently migrate if their cocoa trees are older than 30 years and their income is lower than the poverty index for 2 (early adopters), 4 (governmental) or 6 (traditional) years. This threshold is set based on an interview with researcher who wrote a PhD thesis on migration in Ghana (personal communication, 15 Jan 2020, Appendix L). He argued that cocoa households will survive a substantial decrease of cocoa production for three reasons: (1) Ghana is generally food secure even though it is a poor community within a middle-income country (Darfour, Bernard & Kurt, 2016). (2) Cocoa households believe that the income generated from cocoa production is more profitable than selling the land (Bymolt, Laven, Tyszler, 2018a). (3) Cocoa trees are a long-term investment for 30 years and smallholders would only leave their cocoa trees once they passed their optimal productive age (Binam et al., 2008). The differences in years of low production before permanently migration are based on the willingness to take risks for early adopters and the aversion to change of traditional farmers (Rogers, 1962; Interview 1, Appendix K). The new source of income and location of these migrated farmers is out of scope due to lacking data.

(2) Permanent migration influences neighbouring cocoa farmers. Due to this social component, the thresholds for migration are set a bit lower: neighbours will migrate if their income is lower than the poverty index and their cocoa tree stock is older than 25 years. This age of cocoa trees is varied in the sensitivity analysis to explore the effects of this assumption.

(3) The cocoa households still active in cocoa production will experience a lower production due to climate change impacts. They could therefore decide to change the initial proportion of income earned through the three livelihood strategies (61, 30 and 9% cocoa production, diversification and temporary migration). When their cocoa income is decreased with 40% (early adopter), 50% (governmental) or 60% (traditional) the cocoa farmers start to focus on producing another crop or trading other commodities. These differences are again based on willingness to take risks for early adopters and the aversion to change of traditional farmers (Rogers, 1962; Interview 1, Appendix K). This would increase their diversification income and decreasing the cocoa income a bit due to the change of focus area. An expert however stated in an interview that an economic infrastructure for other crops than cocoa is lacking Ghana (personal communication, 17 Jan 2020, Appendix K). For that reason, only 20% of the farmers can enter a new market in the model. The sensitivity for this bottleneck is tested in Appendix S.

(4) Since the literacy rate in Ghana is increasing, more households have educated children and therefore 7 households per year move towards the early adopter group (explanation in Assumption 29 in Appendix H.2). The governmental controlled COCOBOD is also providing trainings to farmers which results in 4 more governmental oriented households per year (argumentation in Assumption 28 in Appendix H.2).

During the model run, COCOBOD is the agent that guarantees the farmers a stable income. This public body is controlling the cocoa system and provide the farmers with 70% of the world market price with a minimum of the farmer gate price of 2600 USD/year as recently announced (explanation in Assumption 31 in Appendix H). The role of FMO's investment in this storyline is explained in Confidential Appendix D.

At the end of the model run, the production of cocoa beans and income of cocoa farmers are calculated. Please note that is an aggregated narrative and the values for these economic calculations are based on an extended anthropologic research 'Demystifying the Cocoa Sector in Ghana and Côte d'Ivoire' by Bymolt, Laven & Tyszler (2018). The effects of climate change strike according to the graphs suggested in Chapter 5.

The extended narrative can be found in Appendix J.2. The influence of interventions is discussed in the next chapter. All variables related to the described agents are also listed in Appendix J.1.

6.5 Key Performance Indicators

The system behaviour is evaluated based on four Key Performance Indicators (KPIs). FMO is interested in both the financial risk they are exposed to, the social impact on livelihoods and to what extent they use their mandate of additionality.

The main KPI that reflects the financial risk for FMO is *loss of production (%/year)*. This serves as a proxy of the financial performance of FMO's client and therefore FMO's credit risk. The purpose of FMO is to make their investments more resilient against climate change impact with certain interventions. The effectiveness of interventions on financial performance is reflected in this KPI.

The other KPIs reflect the societal benefits of investing:

The second KPI, *Average income of households who are still active in cocoa (USD/household/year),* shows the impact of climate change on smallholders. Providing finance to support cocoa farmers helps to foster employment and production, and therefore results in economic growth (SDG8: Decent Work and Economic Growth)

Some households might decide to leave their cocoa farms due to poor harvests and the social influence of migrating neighbours. This migration flow is captured in the third KPI *Permanent migration (households per year)*. It reflects the societal change in the country due to climate change and the additional pressure on current economic infrastructures. It is also an indicator how people leave unsustainable ways of living and might require support.

The final KPI is related to the *Additionality of interventions (USD household income generated through FMO)*: what is the added value of intervening in the cocoa sector? For example, investing in a region with migrating households with no or low incomes might have more added value than investing in cocoa households that would still have income anyway. The difference (Δ) between the income with and without intervention will therefore differ and will be used a proxy to represent additionality.

The answer to sub question 2, *How can a specific local cocoa investment in Ghana be conceptualized and captured in an Agent-Based Model?,* can now be visualized. The figure shows the high-level conceptualization of the agent-based model. In this study, the climate scenarios represent the uncertainties outside the control of DFIs; the interventions with climate adaptation are the policy levers that DFIs want to explore given the policy of the famer gate price of the governmental agency COCOBOD; the behaviour of cocoa farmers represent the relationships in the system and finally, the results that DFIs use to make trade-offs between various interventions represent the measures.

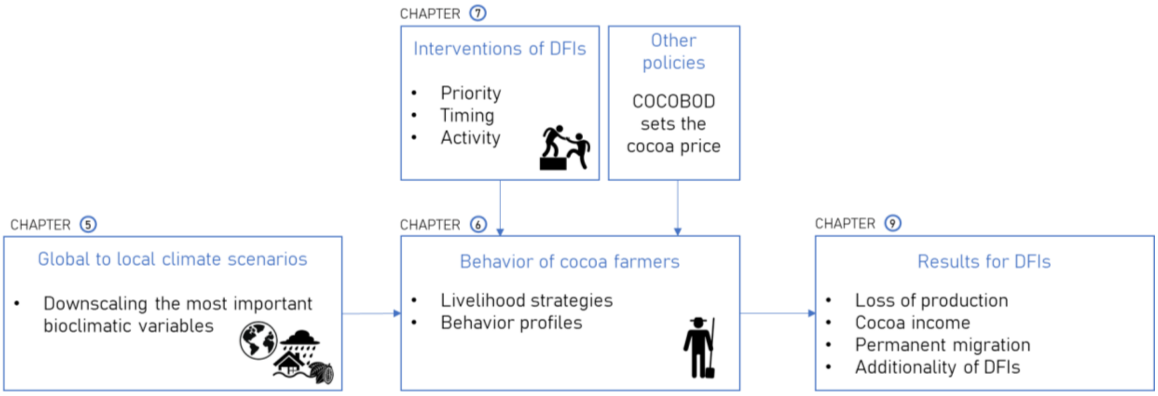


Figure 24 High-level conceptualization

Focusing on the cocoa farmers as most important agents, their behaviour is conceptualized by connecting two frameworks (the Sustainable Livelihood Framework and the Diffusion of Innovation theory) to represent the livelihood strategies influenced by behaviours, and by defining a clear scope and behaviour rules and thresholds (based on input from interviews with anthropologists and literature review) to guide the decisions, reactions and interactions of the agents.

6.6 Summary chapter 6

This chapter first introduced the main characteristics of the cocoa farmer in Ghana, adapting to new circumstances with agricultural intensification, diversification, and migration strategies. Their willingness to adopt to new innovations or their aversion to change is captured in three behavioural profiles 'early adopters', 'governmental oriented' and 'traditional' farmers. Different thresholds for decision are set-up for these groups, driven by the loss of income due to climate change as well as the age of the cocoa tree stock. The lack of alternative markets in Ghana is a bottleneck in the system. The next step will discuss the possible interventions in the cocoa market under climate pressure.

7. Interventions

This chapter discusses the interventions FMO can take to support the client's financial returns and strengthen societal benefits under climate change. These climate adaptation interventions are applied in a situation with the downscaled climate scenarios and livelihood strategies specific to a behaviour profile as constraints in the agent-based model.

Several interventions in line with the DFIs practices are tested against a wide range of plausible futures in order to help DFIs exploring the most *robust* option for long term financial and societal benefits. Deciding on an *optimal* intervention is irrelevant for the uncertain context of climate scenarios and the use predictions can be counterproductive in a complex world (Lempert, 2019).

Section 7.1 describes the interventions, which are context-specific, followed by a description of intervention strategies which differ in terms of priority and timing. The third section explains the implementation of interventions.

7.1 Context-specific interventions

The starting point is that all climate adaptation interventions follow the context-specific approach: due to the heterogeneity of potential physical risks and responses (variability in e.g. onset, duration, frequency, occurrence), the adaptation needs should be defined specific to the context (EBRD, 2018). For the case of cocoa in Ghana three actions could be implemented:

1. In regions with low adaptation needs, pest management as minor intervention could help tackle changing pest and disease patterns (Bunn et al., 2019).
2. Using more shade trees or the adjustment of shade trees can reduce the vulnerability of cocoa to dry season temperatures (Schroth, Läderach, Martinez-Valle, Bunn & Jassogne, 2016).
3. In regions where the climate is found to be unsuitable in the future for cocoa, farmers could be supported to set up a diversified income stream with subsidies.

If the use of the above-mentioned context-specific solutions is neglected, there is a high chance of resources being used inefficiently for dysfunctional interventions.

7.2 Intervention strategies

The three above-mentioned activities (e.g. climate adaptation with pest management, shade trees or subsidies) could be implemented depending on priority (regions getting support from DFIs) and timing (proactive or reactive).

7.2.1 Priority of interventions

These three suggest climate adaptation interventions could be approached via different investment strategies. In an email conversation, Christian Bunn (personal communication, April 2020) suggested two investment strategies (column 1, Table 3).

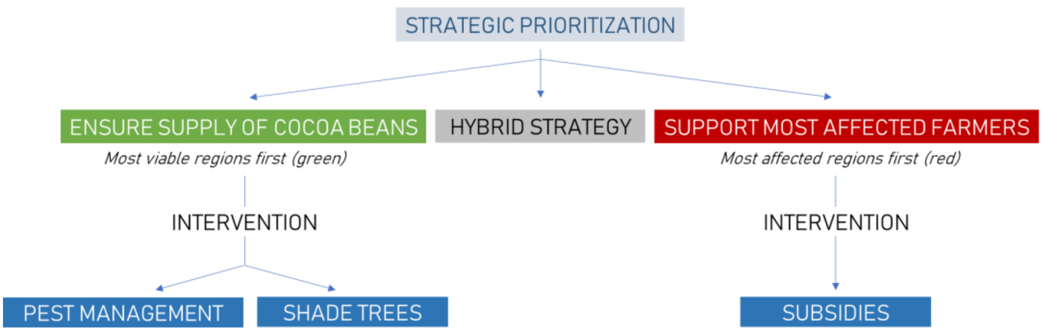


Figure 25 Choices for investment strategies

The first option is to invest in the most affected regions, the red regions, to support the farmers in challenging conditions. These farmers will experience severe effects of climate change, resulting in reduced incomes and could therefore be eager to permanently migrate to live in the city or move to the most viable, green regions to start a new cocoa farm. A migration flow towards the most viable regions will put additional pressure on the available land and might result in deforestation. Households who migrate also experience multiple stresses including the loss of social support, adjustment to new circumstances and economic uncertainty (Bhugra & Becker, 2005). For these reasons, investing in households in the most exposed regions with a subsidy to set up a diversified income stream could potentially be a solution. The coffee sector is also being affected by climate change and smallholders are highly dependent on coffee production. On-farm diversification is being used to provide cash flow as well as for own consumption.

Another strategy is to invest in the most viable regions for cocoa to ensure FMO's client supply of cocoa beans. This study selected the pest management and shade trees as potential climate-smart-agriculture (CSA) measures. Drip irrigation is excluded because of the complex implementation: the dependence on a well and the pollution of water due to mining in Ghana were put forward as limitations in an interview with a social scientist (Appendix K) and during the validation workshop by an expert in resilience in Africa.

As DFIs are trying to balance financial returns and societal benefits, a hybrid strategy is included in the agent-based model. This strategy entails 50% of the budget is spent on ensuring the supply of cocoa beans in the most viable regions and the second 50% is spent on a subsidy to set up a diversified income stream in the most affected regions.

7.2.2 Timing of interventions

FMO has the choice to start investing in climate adaptation in a reactive or proactive way (row 1, Table 3) both with advantages and disadvantages.

In the reactive strategy, the climate conditions and production of cocoa farmers should be monitored and once the production decreases, climate smart agriculture is set in place. The advantage of this strategy is that the affected cocoa farms can be specifically targeted for climate adaptation investments: therefore, having more impact. It is particularly an advantage due to the uncertainty of climate scenarios. The disadvantage of reactive investing is that farmers have already suffered from production losses.

The proactive investment strategy ensures that farms are supported before climate change has a major impact, so large production losses are avoided. On the other hand, specific knowledge on the effect and timing of climate change at individual farm level is hard to estimate. Given the uncertainty of climate scenarios, farmers might receive support which may not need it in the end.

Table 3 Investment strategies with timing and priority categories

			Timing of response	
			Reactive	Proactive
	Strategic level	*Operational level*		
Priority	Viable regions	Pest management Shade trees	Timing: once the most viable regions become exposed Intervention: climate smart agriculture to ensure supply (e.g. pest management or shade trees)	Timing: support several farmers per year in the most viable regions, before they are exposed to climate change Intervention: climate smart agriculture to ensure supply (e.g. pest management or shade trees)
	Affected regions	Subsidies	Timing: once the farmers from the most affected regions are starting to migrate Intervention: encourage them to stay with a subsidy to set up a new market and prevent climate refugees	Timing: support several farmers per year in the most affected regions to prevent the decision to migrate Intervention: encourage them to stay with a subsidy to set up a new market and prevent climate refugees

7.3 Implementation of intervention

To allow for a fair comparison between the interventions in terms of effectiveness, the budget constraint is set at 5 MLN USD for 30 years after consultation with an investment officer. This order of magnitude is in line with the size of the climate adaptation fund FMO is currently managing. It is the Dutch Fund for Climate and Development (DFCD) of the Dutch Ministry of Foreign Affairs, aiming to invest in climate adaptation in developing countries (DFCD, 2020).

All combination of these intervention strategies and timings are analysed in the agent-based model. The effects of the interventions are however strongly related to the way of implementing. In this study, Western and Central are selected as most viable regions, and Brong Ahafo and Ashanti as the most affected regions based on an analysis in Appendix M1. Proactive climate adaptation is available for six farmers (scale 1:100) per year in the most viable regions and nine of the most affected farms receive this support. The underlying argumentation is also documented in Appendix M2. The intervention definitions are made as specific as possible in an attempt to align as much as possible with local impact.

A disclaimer should be made about the costs and effectiveness of pest management and shade trees. These numbers are based on assumptions from literature (Appendix M3) but are very hard to validate for two reasons (1)It is very site-specific: it heavily depends on current agricultural practices, use of fertilizer, various shade tree species, density levels and geography. (2) No accurate data is currently available. Because the first pilot with climate adaptation in Ghana is planned for this year (Dalaa, Kofituo & Asare, 2019).

The answer to sub question 4: *What kind of interventions can development finance institutions implement in the cocoa sector in Ghana to achieve sustainable finance under climate change?* can be answered. On a more strategic level DFIs can choose to support the cocoa sector with a balance between supporting the cocoa bean supply and supporting the most affected smallholders, and opting for a proactive or reactive action. On a more operational level, they can choose between different interventions, financing climate smart agriculture, such as pest management and shade trees or providing subsidies to support diversification.

7.4 Summary chapter 7

This chapter describes a selection of eight possible interventions FMO can take in the cocoa sector to achieve financial returns and societal benefits. The aim is to identify robust interventions under a large set of plausible futures. There are important trade-offs between securing the supply of cocoa beans and supporting highly affected farms, as well as between proactively and reactively investing in climate adaptation measures. FMO can support farmers with pest management, shade trees and providing subsidies to set up a diversified income stream. All combinations in terms of timing and priority and hybrid strategies are included in the model. The next chapter first presents a brief overview of the agent-based model implemented in software before the results of the just described interventions are discussed in chapter 9.

8. Model implementation and verification

In this chapter the implementation of the conceptual model (Figure 23 in Section 6.1) as agent-based model in Netlogo is described. The first section shows the model interface and specifies the scenario settings, input parameters and outcomes. The second section describes the verification process to ensure that the conceptual model is correctly translated into modelling language.

8.1 Model implementation

The concepts regarding climate scenarios (Chapter 5), behaviour of cocoa farmers (Chapter 6) and climate adaptation interventions (Chapter 7) are first transformed into pseudo-code (Appendix J.2) and then implemented in Netlogo.

Figure 26 shows the interface of the agent-based model in Netlogo. The green grid represents the cocoa growing region Ghana, close to the Atlantic Ocean in blue. The colours of the cocoa farms change from dark green to lime, yellow and red according to their exposure to climate change. The representation of the cocoa farms in Netlogo is not according to GIS coordinates. Their region is determined based on the 'region' of the property of the farm.

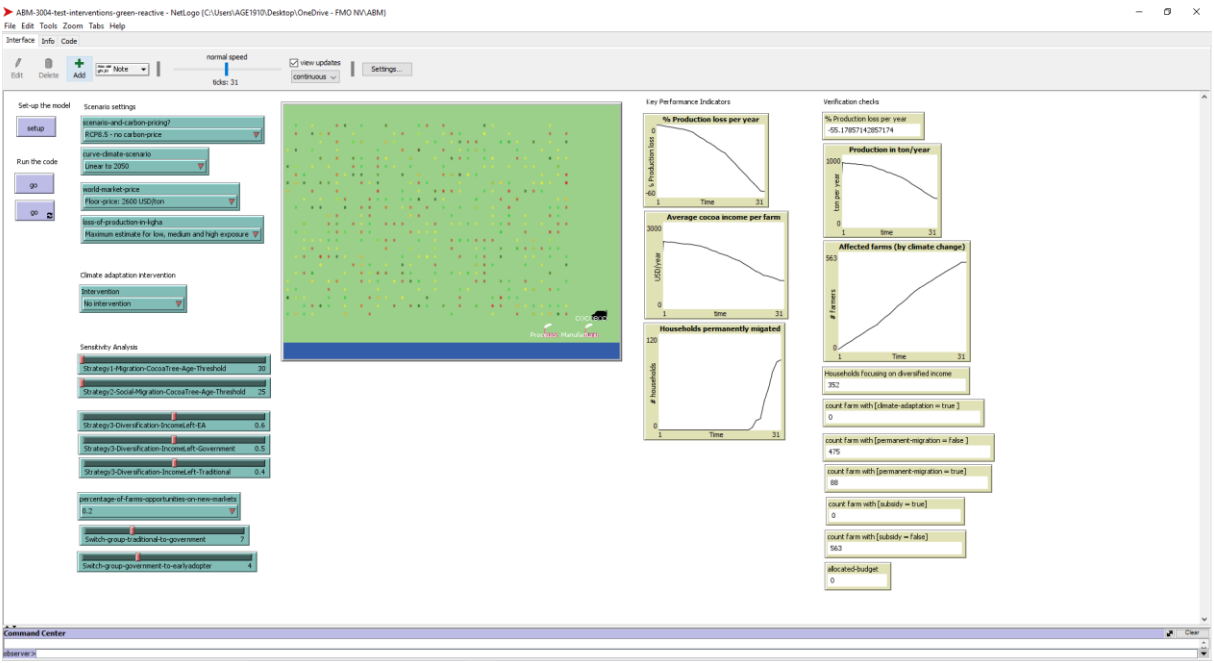


Figure 26 Model interface

The buttons, sliders and switches on the left represent the inputs to run the model, grouped into four categories:

(1) The first group are the model setup buttons. The set-up button can be used to set-up the model environment with cocoa growing region and 563 cocoa farms (scale 1:100). The 'go' button enables the user to run the model from 2020 until 2050 (30 ticks).

(2) The second group are the scenario settings to explore the model under a wide range of plausible futures:
   a. A pessimistic or optimistic climate scenario: RCP2.6 or RCP8.5
   b. A low, medium or high carbon price as climate mitigation measure to achieve RCP2.6
   c. The price of cocoa is plotted according to historical fluctuations with a minimum of 2600 USD per year, or the price of cocoa is a flat curve at 2600 USD during the runtime.
   d. The sensitivity of production for each exposure category (no, low, medium, high exposure): the minimum or maximum estimate in the range.

(3) The third input category is the selection of the climate adaptation interventions. It is possible to run the model with and without interventions. All combinations of timing (proactive or reactive),

priority (regions getting support from DFIs), and activities (e.g. climate adaptation with pest management or shade trees) are included in the model.

(4) The final group are the sliders used for sensitivity analysis with behaviour thresholds:
   a. The age of the cocoa tree stock as condition to consider migration
   b. The age of the cocoa tree stock as condition to consider migration influenced by neighbours who leave their cocoa farm
   c. The decrease of cocoa income due to climate change (compared to a reference income) as condition to start focusing on diversification, for:
      i. Early adopters
      ii. Governmental oriented farmers
      iii. Traditional farmers
   d. The percentage of cocoa farmers able to diversify due the limited market infrastructure in the Ghanaian economy

The model output and visualisations are placed at the right in the model interface:

(1) The Key Performance Indicators
   a. The loss of cocoa bean production per year
   b. Average cocoa income of farmers still active in cocoa per year
   c. Number of households that are permanently migrated
   d. The additionality of DFIs
(2) Outputs to verify the model while running

8.2 Verification

To check whether the conceptual model is correctly translated into the model code, three verification tests are executed (Van Dam et al., 2010). These tests are executed both iteratively during the model development and once the model building phase was finished.

First, the behaviour of agents is verified by walking through the code. Redundant variables such as the Licensed Buying Companies transporting the cocoa beans are excluded from the model. Second, the states of agents is recorded every tick. This verification test shows that the cocoa farmers behave as expected under normal input. The third verification test is an extreme value test. Example of the latter is that increasing capacity for diversification in Ghana to 100% of the cocoa farmers shows that the majority of farmers focus on other sources of income instead of cocoa producing.

It is not possible to test the interaction between agents in a minimal model with a minimal set of agents, because the exposure of climate change of each individual farm is calculated in an Excel model and then manually added to Netlogo. Changing the initial number of cocoa farmers will give many errors because the climate input is not working anymore.

After conducting the verification tests, it can be concluded that the model works as expected. A more elaborated description of the verification is given in Appendix N.

8.3 Summary chapter 8

This chapter described the implementation of the conceptualisation in the Netlogo software. The model interface shows cocoa growing regions with the scenario settings and behaviour thresholds subject to sensitivity analysis on the left, and the model outcomes on the right. Three verification tests show that the model works as expected. The next chapter describes the results of experimentation with this agent-based model.

9. Results

This chapter discusses the experimentation of interventions in the agent-based model. First, the effects of scenario settings are explored. Second, this range of future outcomes can be used to show how robust the climate adaptation interventions are. The subsections start with a design to show the setup of experiments.

The results are generated in Netlogo with the BehaviourSpace feature and then visualized in Python with the pandas, seaborn and mathplotlib libraries.

9.1 Scenario settings

9.1.1 Design of experiments with scenario settings

The scenario settings are analysed to show their influence on the model behaviour (Table 4). They have been combined in 32 scenarios and are analysed based on the three KPIs *Loss of cocoa production*, *Cocoa income* and *Migration* to show the full range of potential future outcomes (full factorial design, Table 25, Appendix O). After looking at the aggregated view of 32 scenarios, the individual scenario setting (disaggregated) responsible for extreme outcomes are identified.

This analysis is performed without any intervention. The fourth KPI additionality is therefore not shown.

Table 4 Experimental design with all scenario settings

	Variable	Settings	Runs per scenario
1	Climate scenario	RCP2.6 RCP8.5	100
2	Carbon price	Low Medium High	100
3	Trend of climate scenario 2020-2050	Linear curve till 2050 Logarithmic curve with peak in 2035	100
4	World market price	Floor price Historical fluctuations	100
5	Sensitivity of production	Minimum estimate for production losses under low (-10%), medium (-30%) and high exposure (-60%) Maximum estimate for production losses under low (-20%), medium (-50%) and high exposure (-100%)	100

9.1.2 Results of experimenting with scenarios

Firstly, the following boxplot (Figure 27) shows the full range of cocoa bean production losses under all 32 scenarios with each 100 runs. Without any intervention the cocoa bean production decreases over time due to climate change, and results in 30 to 50% production loss in 2050. The uncertainty of future production losses is very small in the first years, and diverges up to an extreme range of 40% cocoa production loss in 2038. In the final years from 2038 to 2050, the range converges again.

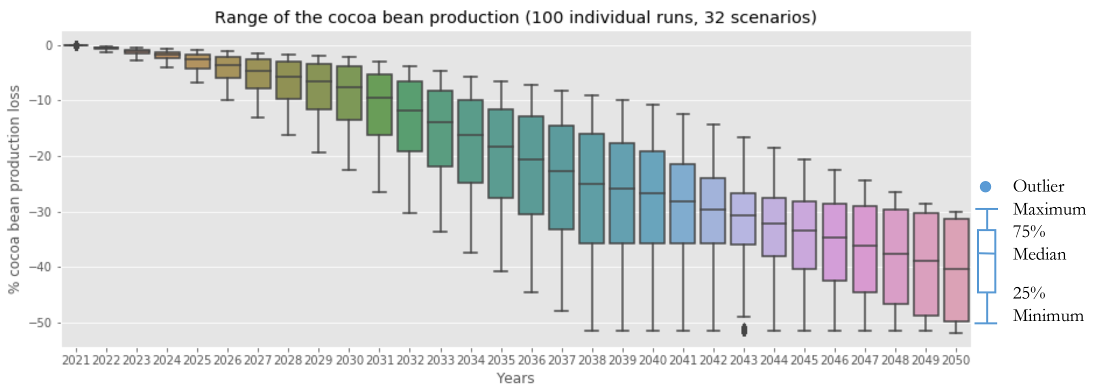


Figure 27 Boxplot showing the full range of plausible cocoa bean production losess under climate change without interventions

Inspecting the loss of production under the five individual scenario settings from Table 4 shows that three out of five scenario settings are not responsible for this range of outcomes. Logically, the carbon price and world market price (setting 2 and 4, Table 4) have no effect on the production of cocoa (in ton/year). The optimistic RCP2.6 and pessimistic climate scenario RCP8.5 (scenario setting 1, Table 4) do influence the range of future cocoa production, but it is not an extreme effect (Figure 50 in Appendix P). The difference in cocoa production under RC2.6 and RC8.5 increases over time, but it is not large (at maximum 2.5%). Therefore, the remaining scenario analysis only considers pessimistic climate scenario RCP8.5.

Two scenario settings are highly responsible for the wide range of future outcomes: the sensitivity of production (scenario setting 5, Table 4) and the trend of the climate scenario (scenario setting 3, Table 4), captured in 4 scenarios:

On the one hand, the sensitivity of production (scenario setting 5, Table 4) is responsible for the wide range of possible cocoa bean production (Figure 27). Schreyer, Bunn, & Castro-Llanos (2018) estimated that climate change can affect production to a greater or lower extend, varying from 10 to 20% for low exposure, 30 to 50% for medium exposure and 60 to 100% for high exposure. Figure 28 shows that the minimum estimates (in blue) result in approximately 32% production loss in 2050, while the maximum estimates (in pink) lead towards approximately 50% less cocoa bean production in 2050. The below boxplot (Figure 28) also shows that the uncertainty of future production follows the same trend as Figure 27: small uncertainty in the first years, diverges up to an extreme range in 2038, and then converges till 2050 again.

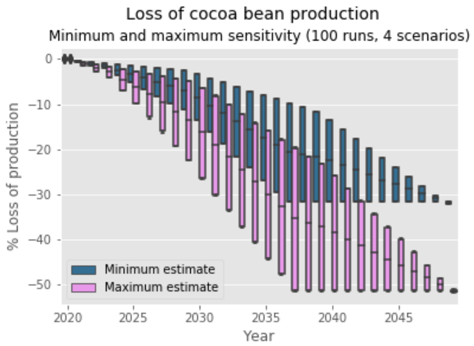


Figure 28 Range of cocoa bean production due to climate change (Figure 27) is highly influenced by the sensitivity: minimum blue, maximum in pink

On other hand, the range for the loss of production (Figure 27) can be explained by the trend of the climate scenario (scenario setting 3, Table 4). Figure 29 shows that under the linear climate trend, highlighted in yellow, the production is granularly decreasing, while the logarithmic climate trend in orange has a steeper decrease of production in the beginning and stabilizes at a tipping point in 2038. The production then ranges between -32 and -52%. This orange logarithmic climate trend was defined as scenario to illustrate the situation of 2050 already in 2038, aiming to explore the effects on the long term.

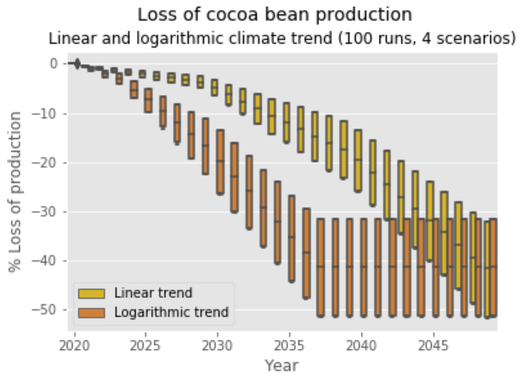


Figure 29 Range of cocoa bean production due to climate change (Figure 27) is highly influenced by the trend: linear in yellow, logarithmic in orange

.

Second, the full range of the cocoa income of farmers households under all 32 scenarios (full factorial design, Table 25) is shown in Figure 30 and follows the same decreasing trend as the loss of production (Figure 27). However, the income is not only a continuously decreasing trend but there is more variation with ups and downs per year. The boxplot shows that the uncertainty is high in those peaking years.

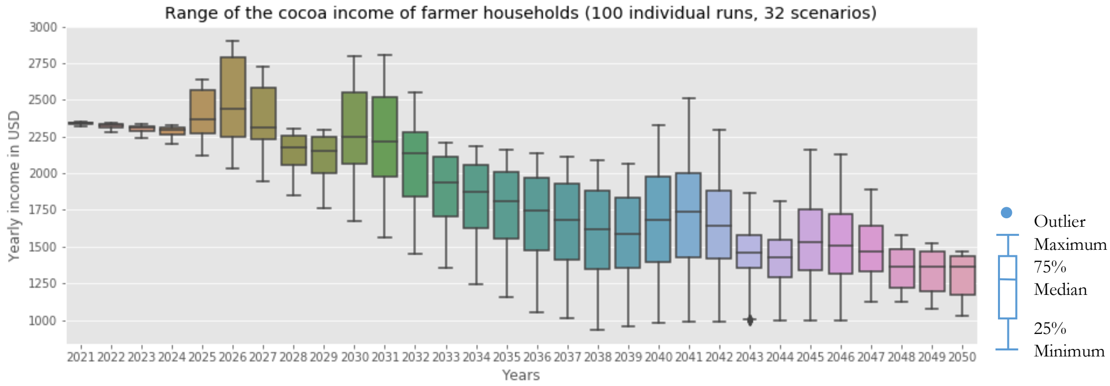


Figure 30 Boxplot showing the full range of plausible incomes generated from cocoa production under climate change without interventions

Inspecting the cocoa income under the five individual scenario settings from Table 4 shows that only the world market price is responsible for the extreme outcomes (scenario setting 4, Table 4). A historical fluctuating world market price result in four peaks in the cocoa income of smallholders, while a cocoa floor price of 2600 USD/ton results in a more stable trend, shown in Figure 31.

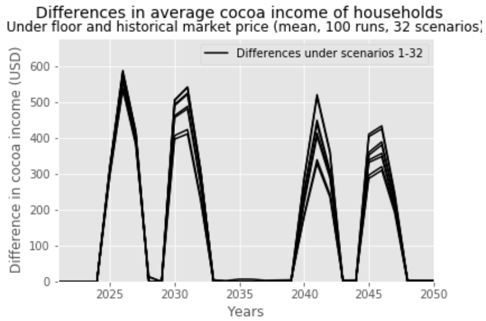


Figure 31 The differences in yearly income of cocoa farmers with a fluctuating or floor price under climate change, under all 32 scenarios

In contrast, the low, medium and high carbon price (scenario setting 2, Table 4) does not result in a different cocoa production after visual inspection. The statistical test ANOVA (Appendix Q) shows that carbon prices do not result in scientifically different outcomes and is therefore not used for exploration in the remaining analysis.

Despite this direct influence of the world market price, the cocoa income boxplot (Figure 30) follows the same trend as the loss of production (Figure 27) because the KPIs are closely connected, and therefore, only the floor price is considered in the remaining analysis.

Finally, the full range of cocoa smallholders leaving their farm under all 32 scenarios (full factorial design, Table 25) shows that migration could potentially start around 2033 (Figure 32). When it starts, the range of households migrating is very large while the median remains low. For example, in 2050 the number of migrating smallholders (scale 1:100) ranges between 0 and 123 households but the median is 20 households. The high number of outliers indicate that *bifurcations* (i.e. a sudden change in behavior) might occur. For that reason, three types of model behavior are identified: (1) flat; (2) exponential; (3) bouncing effect.

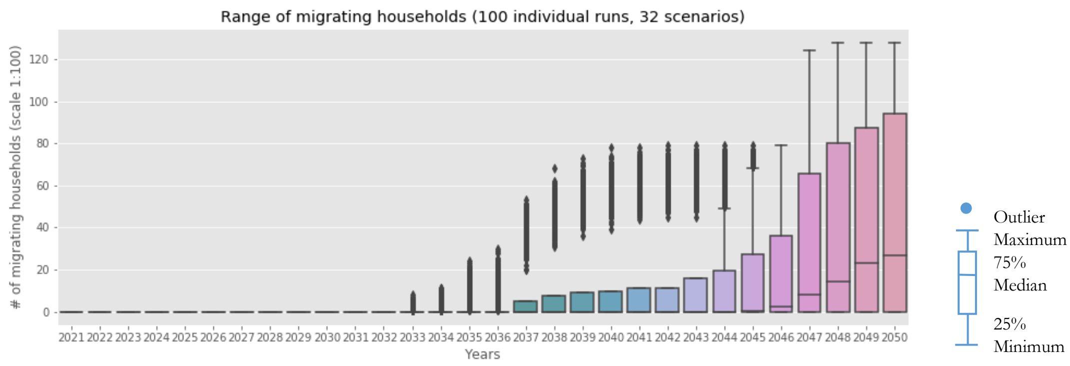
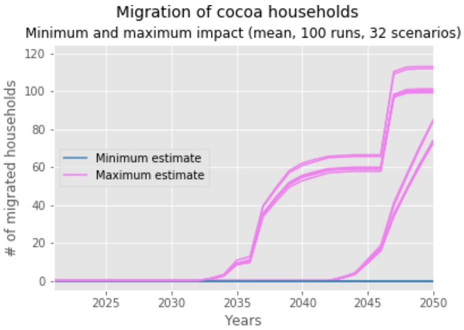


Figure 32 Boxplot showing the full range of plausible smallholders leaving the cocoa farm under climate change without interventions (scale 1:100)

The first scenario setting causing the sudden change in behaviour is the sensitivity of production (scenario setting 5, Table 4). When the cocoa production is minimal sensitive (blue), the migration trend is flat which indicates that no cocoa household will leave their farm (Figure 33). When this first type of model behaviour is taken out of the scenarios (flat curve caused by minimum sensitivity), Figure 34 with 16 scenarios still shows large uncertainties and some outliers. There are still two *bifurcations* under the maximum estimates (pink): an exponential and a bouncing effect.



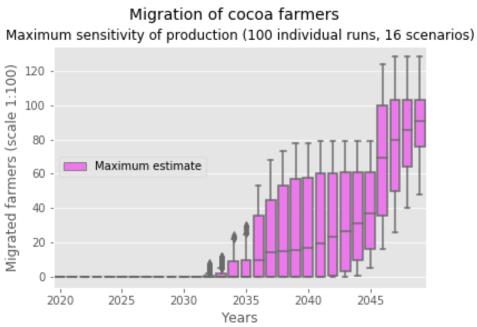
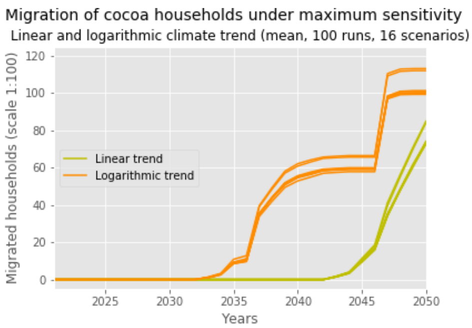


Figure 33 Average migrating smallholders (scale 1:100) with a flat trend under minimum estimates, and an increasing trend under maximum estimates
Figure 34 Boxplot after taking out the minimum estimate (flat curve) shows the range of migration under maximum sensitivity of production

Second, the climate trend (scenario setting 3, Table 4) appears to be the responsible scenario setting for this *bifurcation*. The following Figure 35 is plotted with only maximum estimates because of the previous conclusion. This results in 16 scenarios.

In the linear climate trend, the migration pattern starts in approximately in 2042 and shows an exponential increase (Figure 35). In the logarithmic climate scenario, migration starts already in 2032 and the trend shows a bouncing effect: three jumps and plateaus until a tipping point. This scenario setting, aiming to show the long term effects, results in a higher number of migrating cocoa households (scale 1:100 smallholders). The boxplot (Figure 36) gives insight in the migration trend once the minimum sensitivity of production and the linear climate trend are removed (8 scenarios left). It does not indicate any other bifurcations.



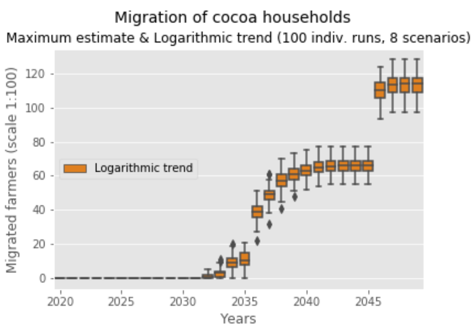


Figure 35 Average migrating smallholders due to climate change (scale 1:100): linear in yellow, logarithmic in orange
Figure 36 Boxplot after taking out the linear trend (exponential curve) shows the range of migration under the logarithmic climate trend

9.1.3 Conclusion scenario settings

The exploration with scenario settings show that:

- The scenario settings (3) climate trend (linear or logarithmic) and (5) sensitivity of production (minimum or maximum estimate) are highly affecting the model behaviour.
- The scenario settings for (1) optimistic or pessimistic climate scenario and (4) world market cocoa price do not affect the model behaviour but only result in different outcomes.
- The scenario setting (2) carbon price does not result in scientifically different outcomes.

9.2 Experiments with interventions

9.2.1 Experimental design of interventions

The experiments are designed to show which climate adaptation intervention is the most robust option to secure financial returns and create societal benefits. The model variation with scenario settings (Section 9.1) shows that some scenario settings were of limited influence. As full factorial design of all 9 interventions under all 32 scenario combinations is not feasible under the scope of the study, only the most extreme scenarios are included which together show the full range of outcomes (motivation in Section 9.1.3). Based on the findings in Section 9.1, the other scenario settings are kept identical.

Table 5 Most extreme scenarios to test interventions

	Scenario A	Scenario B
Climate trend till 2050	Linear	Logarithmic
Sensitivity of production	Minimum	Maximum
Climate scenario	RCP8.5 – pessimistic	
World market price	Floor price of 2600 USD/ton	
Carbon price	No price	

The following nine interventions are subject to exploration under scenario A and B with 100 runs:

Table 6 Overview of interventions explored

	Priority	Activity	Timing
1	No intervention		
2	Most affected regions (red)	Subsidies	Reactive
3	Most affected regions (red)	Subsidies	Proactive
4	Most viable regions (green)	Pest management	Reactive
5	Most viable regions (green)	Pest management	Proactive
6	Most viable regions (green)	Shade trees	Reactive
7	Most viable regions (green)	Shade trees	Proactive
8	Hybrid: 50% green and 50% red	Pest management, shade trees, subsidies	Reactive
9	Hybrid: 50% green and 50% red	Pest management, shade trees, subsidies	Proactive

9.2.2 Results of interventions per KPIs

This section discusses the model behaviour of the four KPIs *Loss of production*, *Cocoa income*, *Migration* and *Additionality* under two extreme scenarios A and B, and under the influence of climate adaptation interventions from Table 6.

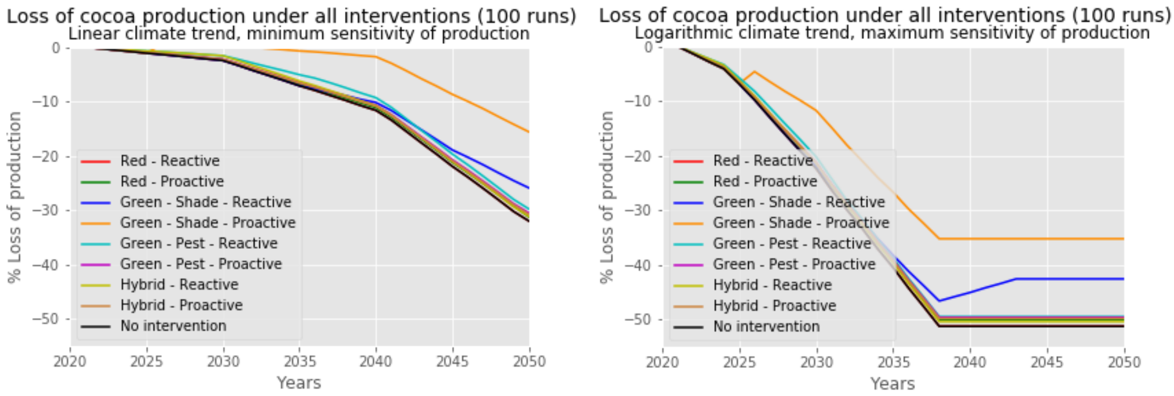


Figure 37a,b All interventions, showing the loss of cocoa production, in scenario A (linear climate trend with minimum sensitivity of production) and scenario B (logarithmic climate trend with maximum sensitivity of production)

First, the effect of interventions on cocoa production are shown in figures 37a and 37b. When looking at scenario A (linear and minimum) it can be noticed that all interventions follow a similar trend. However, seven out of nine interventions have an almost identical trends, while two interventions are standing out: green shade - reactive (blue) and green shade proactive (orange). Green shade reactive (blue) reaches a loss of production of 25%, and green shade proactive (orange) of 15%, while other interventions have a production loss of approximately 30% in 2050. Scenario B (logarithmic and maximum) results in much higher loss of cocoa (around 50% in 2050) but has a similar order of the interventions. Green shade - reactive (blue) and green shade proactive (orange) are distinct with respectively 42% and 35% production losses compared to 50% of the seven identical trends.

These blue and orange lines, meaning planting shade trees either a reactive or proactive way, show a small peak in cocoa production. The blue line first displays a decrease in production, and then slightly increases around 2037 up to a plateau in 2043, while the orange line peaks already in the first 10 years before it decreases and becomes stable in 2037.

In both scenario green shade proactive reduces the loss of production respectively three and two times more than green shade reactive.

Table 7 The standard deviation of interventions affecting the loss of cocoa production under both scenarios

	Scenario A (linear, minimum)			Scenario B (logarithmic, maximum)		
	2030	2040	2050	2030	2040	2050
Red – Reactive	0.00	0.00	0.00	0.07	0.11	0.11
Red – Proactive	0.05	0.13	0.30	0.25	0.38	0.38
Green – Shade – Reactive	0.00	0.00	0.14	0.08	0.23	0.24
Green – Shade – Proactive	0.00	0.00	0.01	0.07	0.08	0.08
Green – Pest – Reactive	0.00	0.01	0.02	0.08	0.10	0.10
Green – Pest – Proactive	0.06	0.08	0.04	0.13	0.10	0.10
Hybrid – Reactive	0.00	0.00	0.01	0.08	0.09	0.09
Hybrid – Proactive	0.05	0.11	0.13	0.20	0.28	0.28
No intervention	0.00	0.00	0.00	0.06	0.10	0.10

Table 7 provides an overview how close the individual runs are from the mean values (σ) in 2030, 2040 and 2050. It can be observed that all standard deviations have the same order of magnitude. When comparing scenarios A and B, it is clear that the standard deviation is lower under a linear climate trend with a minimum sensitivity of production (scenario A). Closer inspection of scenario A shows that both no intervention (black) and red reactive (red) do not have any deviation, i.e. every single run has the same outcome.

Second, the interventions show the same trend for the cocoa income as for the loss of production, which is concluded in Section 9.1. The two KPIs are highly connected because there is a ripple-effect from cocoa production to income of farmers. The graphs and table with standard deviations are therefore shown in Appendix R.

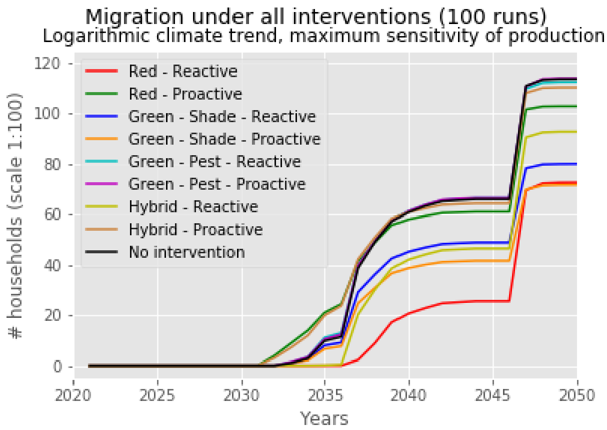


Figure 38 The migration trend with all interventions under scenario B with a logarithmic climate trend and maximum sensitivity of production

Third, there is no migration of cocoa farmers under scenario A due to the minimum sensitivity of production and therefore this graph is not shown. In scenario B, showing the effects on the long term and a maximum sensitivity of production, the starting point of migration is in 2030 and the trend shows three bouncing effect and plateaus until a tipping point (Figure 38). There is first an increase from 2030, another logarithmic increases in 2035, and then the final migration increase starts in 2047.

All interventions follow the same migration trend, but the differences between the interventions are higher than for the production (KPI). Red reactive, i.e. giving subsidies to the most affected farmers (red line), and green shade proactive (orange line) result both in the lowest number of migrating households in 2050. They reduce migration to 12% compared to 21% without intervention.

Green shade reaction (blue), hybrid reactive (yellow) and red proactive (green) are also reducing migration to respectively 14, 16 and 18%, while the other interventions seem to not differ from no intervention.

Figure 38 also shows that investing in a reactive way (red, turquoise line) results is less migration compared to proactive interventions (green, purples lines), except for investing in shade trees (blue and orange lines).

Sharing the budget between the most affected and viable regions, i.e. hybrid interventions, have intermediate results.

When comparing the type of intervention in the most viable regions, Figure 38 illustrates that using shade trees (blue and orange lines) leads to less migration than pest management (turquoise and purple lines) with a difference of approximately 9%.

Table 8 The standard deviation of interventions affecting the number of migrating households under scenario B

	Scenario B (logarithmic, maximum)		
	2030	2040	2050
Red – Reactive	0	6.6	5.7
Red – Proactive	0	5.2	5.7
Green – Shade – Reactive	0	5.9	5.9
Green – Shade – Proactive	0	5.2	5.7
Green – Pest – Reactive	0	5.7	6.6
Green – Pest – Proactive	0	6.0	5.1
Hybrid – Reactive	0	5.5	6.1
Hybrid – Proactive	0	6.3	5.8
No intervention	0	6.6	6.2

Table 8 provides an overview how spread out the number of migrating households are under the different interventions. In 2030, the deviation is 0 because Figure 38 shows that no migration peak is started yet. All interventions in 2040 and 2050 have a similar distribution in relation to the mean.

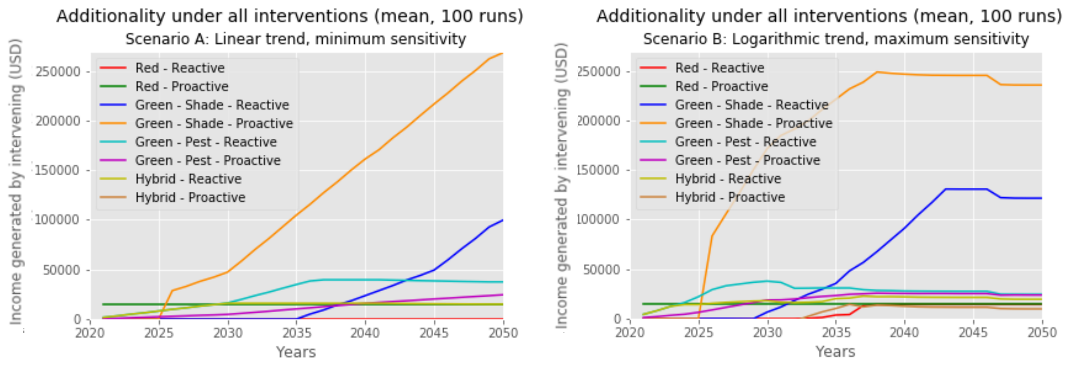


Figure 39a,b Additionality of DFIs under scenario A (linear trend, minimum sensitivity) and scenario B (logarithmic trend, maximum sensitivity)

Finally, the average outcomes for additionality, i.e. the income increase generated through interventions (Δ), are illustrated in Figure 39a and 39b. When looking at scenario A (linear, minimum), it can be noted that interventions have different trends. Two interventions, green shade reactive (orange) and green shade proactive (blue), show a sudden increase in 2025 and 2035. The increasing line of green shade reactive (orange) results in 2,5 times more income generated in 2050 compared to proactive (blue).

Reactively investing in pest management (turquoise) shows a slower increase until 2037, before slightly decreasing. This turquoise line is two times less additionality than the blue line and four times less compared to the orange line. The other interventions have a lower and relatively constant additionality and red reactive (red line) even has a flat line for additionality.

Scenario B (logarithmic and maximum) has a similar order of interventions. A difference with scenario A is that interventions with shade trees (blue and orange) are not only increasing but show a plateau and a small decrease in the final years. Another difference is that red and hybrid reactive (red, brown line) are not flat anymore in this scenario but increase around 2033. In scenario B (Figure 39b) less income is generated in 2050 compared to scenario A (Figure 39a) although the additionality usually starts earlier in scenario B.

A comparison between prioritizing the viable regions (blue, orange, turquoise, purple) and most affected regions (red and green line) show that the additionality is higher in the most viable regions under both scenarios. Hybrid interventions appear to have a limited impact.

Within the green, viable regions, climate adaptation with pest management (turquoise and purple lines) generates less cocoa income for smallholders than investing in shade trees (blue and orange lines).

Figures 39a and 39b also show that planting shade trees in proactive way (orange) results in more additionality compared to a reactive intervention (blue), while it is the opposite for pest management (turquoise vs. purple) and subsidies in the most affected regions (red vs. green).

*Table 9 The standard deviation of interventions affecting the additionality (Δ income generated in USD), *10^1*

* 10^1	Scenario A (lin., min.)			Scenario B (log., max.)		
	2030	2040	2050	2030	2040	2050
Red – Reactive	0	0	0	0	0	0
Red – Proactive	0	0	0	0	0	0
Green – Shade – Reactive	0	0	22	22	40	16
Green – Shade – Proactive	8	4	15	13	93	46
Green – Pest – Reactive	0	17	30	35	70	17
Green – Pest – Proactive	93	13	67	82	17	50
Hybrid – Reactive	0	0	19	30	69	18
Hybrid – Proactive	88	17	22	91	82	83

Table 9 indicates the how spread the additionality is for different interventions. When looking at scenario A, it can be observed that investing in the most affected regions (red reactive and red proactive) have no deviation. Also, the reactive interventions (red, shade, pest and hybrid reactive) have no deviation in the first years because the interventions have not started yet (Figure 39a). In scenario B most deviations start relatively low in 2030 in 2050, and increase in 2040. What stands out in the table, is no standard deviation for the interventions in the most affected, red region. This result can be explained by the way of calculating, which is explained in detail in Section 10.2.

9.2.3 Results of interventions connected across KPIs

The results for each KPIs are discussed in the previous subsection. These KPIs are also connected due to the ripple-effects from cocoa production to farmers' income, which in turn influences the migration decision.

Even though the KPIs are highly connected, the differences between interventions vary for each KPI (spread). For the cocoa production (Figure 37), 7 out of 9 interventions have almost identical trends, except green shade proactive (orange) and green shade reactive (blue) which are outperforming. This is also the case for cocoa income (Figure 51, Appendix R). For additionality and migration, the differences between interventions trends are larger. The same outperforming trends can be identified for additionality (Figure 39), while migration displays a different pattern, with red reactive (red line) having the most effect (Figure 38).

When observing both cocoa production and migration (Figures 37 and 38), it can be concluded that the cocoa production decreases with maximum 30% in 2050 under scenario A (linear, minimum), but does not result in a migration trend. When observing scenario B, Figure 37 shows that production decreases with maximum 35% from 2020 to 2032, while the migration trend is a flat line. The first migration peak starts between 2032 and 2037. In that period, the cocoa production experiences a loss between 35% and 52%. Another migration peak starts in 2047, when the cocoa production is at a stable loss for a longer period.

A comparison between cocoa production and additionality (Figures 37 and 39) reveals that the downward trend of cocoa production corresponds to the increasing trend of additionality over time. In scenario B (logarithmic, maximum), where the cocoa production is stable from 2032 to 2050 to show the long-term effects of climate change, the additionality shows a similar trend. When comparing the reactive interventions (blue, turquoise, red) under both scenarios, it must be point out that the additionality starts to rise earlier in scenario B than in scenario A. This observation corresponds with the extremer decrease in cocoa production in scenario B.

Investing in green shade proactive (orange line) has a high outcome under both scenarios in terms of cocoa production, cocoa income of households as well as creating additionality. However, in scenario B where a migration trend starts, green shade proactive (orange line) cannot be considered as the most fitting intervention to help migrating cocoa farmers in times of uncertainty.

The second most robust intervention is green shade reactive (blue line) for the three KPIs cocoa production, cocoa income and additionality, but this is also not the case for the KPI migration.

9.3 Summary chapter 9

This chapter discusses the experiments to evaluate the effects of 5 scenario settings and 9 interventions. The exploration with scenario settings show that the climate trend (linear or logarithmic) and sensitivity of production (minimum or maximum estimate) are affecting the most the model behaviour. The exploration of interventions shows that proactively investing in shade trees in the most viable regions Western and Central is the most robust intervention in terms of cocoa bean production, income of cocoa farmers and additionality for DFIs. However, giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) appears to be an effective intervention to reduce migration. It should be noted that migration appears to be a long-term effect and is only starting if production is highly affected. The next chapter discusses the interpretation of these results.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10. Analysis

In this chapter the results are analysed and interpreted. The outcomes are linked to existing patterns or explained as an artefact of the model, and when possible, the behaviour is related to literature. This chapter aims to formulate an answer to the fourth sub question: *What is the effect of different interventions on societal benefits and financial returns of a specific local cocoa investment in Ghana under different climate scenarios?*

Section 10.1 first analyses the scenario settings, followed by an interpretation of the behaviour of interventions. The final section 10.3 explains the trade-offs of the different interventions under the two extreme scenarios.

10.1 Analysis of scenario settings

The results of experimentation with scenario settings (Section 9.1) show in generally that:

- The trend of the climate scenario until 2050, and the sensitivity of production are highly affecting the model behaviour.
- The 'optimistic RCP2.6 and pessimistic RCP8.5 climate scenario', and 'the world market price' only affect the model outcomes (values).
- The carbon price does not have a significant influence on the model outcomes.

The next subsections explain the outcomes per scenario setting.

10.1.1 Analysis of the climate trend until 2050

Two climate trends are analysed: (1) a linear trend, and (2) a logarithmic trend to explore the long term effect, by representing the effects of 2050 already in 2038. Figure 51 (Appendix R) shows that, in the logarithmic climate trend, the cocoa income is decreasing earlier than in the linear scenario. This cocoa income is in this model one of the influential factors in the migration decision (Behavioral threshold 1 and 2, Appendix I). The earlier decreasing cocoa income in the logarithmic scenario causes the migration flow start to accelerate in 2032 instead of 2042 (Figure 35). This means that a high migration peak is a long-term effect.

The 'bouncing' trend of migration under the logarithmic scenario (Figure 36) can be explained by 2 effects: (a) the social effect on migration, and (b) the age of cocoa trees.

(a) When a smallholder leaves the village, neighbors are influenced to consider migration as well (Behavior threshold 2, Appendix I): the migration peak flattens when all neighbors have decided to either migrate or not. Figure 40 shows that this social effect of migration is highly affecting the model behavior. In case the threshold of cocoa trees is set 5 years higher, the trend will flatten at approximately 60 households instead more than 100 smallholders on the move in 2050. This is explained in detail in the sensitivity analysis in Appendix S.

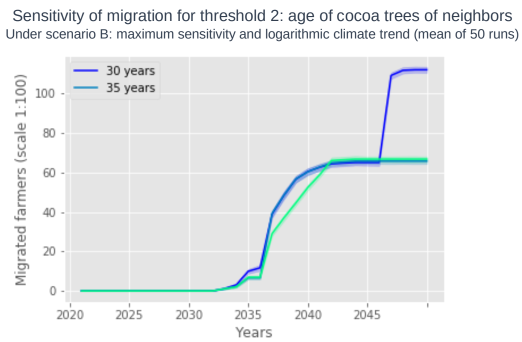

Figure 40 Age of cocoa trees of neighbours as thresholds to decide to migrate affects the migration curve

This social influence of migration is recognized in many studies, for example the recent study of Thober, Schwarz and Hermans (2018). Haug (2008) and Munshi (2003) also show that migrants are influenced by choices of others and that they are dependent on others for help.

(b) The tipping points where behavior suddenly changes from no migration to exponential migration can be explained by the way of modeling the age of cocoa trees. The age of cocoa trees is modelled in three groups, ranging from 0-15, 15-30 and older than 30 years (Assumption 25, Appendix H.2). This means that a full group of farmers become part of the group with trees older than 30 years all at the same time. This age is a tipping point for the willingness to migrate (Behavior threshold 1, Appendix I). These discrete groups are an artefact of the model and in reality, the migration curve is probably smoother.

10.1.2 Analysis of the sensitivity of production

The scenario setting determining the minimum or maximum sensitivity of production is highly influencing the KPIs: Figure 28 shows that running the model with maximum values result in approximately 20% less cocoa bean production compared to minimum sensitivity.

The slope of the cocoa production (Figure29) changes every 10 years. This can be explained by the discrete steps between the exposure categories. In the minimum scenario, the loss of cocoa production is estimated to be 10% under low exposure, 30% under medium exposure and 60% under high exposure in the minimum scenario (Schreyer, Bunn & Castro-Llanos, 2018). In the maximum scenario, it is respectively 20%, 50% and 100% (Assumption 23, Appendix H). These discrete steps mean that a cocoa farm can have loss of production changing from for example 10 to 30% in one year. In reality, the downward trend of cocoa production is smoother and can of course show peaks and plateaus but will probably not follow discrete steps.

Figure 33 shows that no migration takes place under the minimum sensitivity of production. This can be explained by the behavioural thresholds set for migration (Appendix I). An interview with expert in migration in Ghana (personal communication, 15 Jan 2020) revealed high barriers for migration: cocoa production is more profitable than selling the land, it serves as income for their retirement, and the long-term investment makes it hard to leave the farm earlier than their optimal productive age (Bymolt, Laven, Tyszler, 2018a; Binam et al., 2008). In the scenario with minimum sensitivity, the effect of climate change on cocoa production does not outweigh the above-mentioned barriers and therefore no migration starts in this model.

10.1.3 Analysis of the optimistic or pessimistic climate scenario

Figure 50 (Appendix P) illustrates that the optimistic and pessimistic climate scenario, RCP 2.6. and RCP8.5 respectively, have minimal differences in their impact on cocoa production, and therefore on other KPIs (ripple-effects).

The reason why the differences are limited is that the radiative forcing increases continuously until 2100 under the RCP8.5, while RCP2.6's radiative forcing first peaks and then declines to 2.6 W/m² in 2100 (Van Vuuren et al., 2011). The model run until 2050, in which the trends of both RCP2.6 and RCP8.5 are still very close: RCP2.6 just starts to decline. This is conceptually shown in Figure 41:

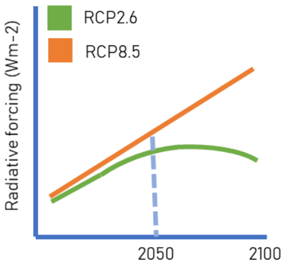

Figure 41 Small differences between RCP2.6 and RCP8.5 in 2050

The differences in model outcomes between the optimistic and pessimistic scenario could possibly be more visible on the longer term (Van Vuuren et al., 2011). Yet, due to data limitations it was not possible to run the climate scenarios until 2100.

10.1.4 Analysis of the world market price

Figure 31 shows that the world market price directly influences the cocoa income. This should be interpreted as trend and not as absolute values, because it is very difficult to forecast the world market price on a long term till 2050.

However, the world market price is not affecting production in this model. This can be explained by the fact that no price-demand feedback loop is included in the model. The loop includes the following causal effects: a reduced supply of cocoa due to climate change and therefore an increasing world market price. This rising world market price will increase farmers' incomes. This is a limitation of this model, which will be reflected upon in Section 12.1. An expert on resilience in Africa explained during the validation workshop that it is likely that, when the feedback loop was included, this increased income of cocoa farmers could attract more farmers to the viable regions to start a cocoa farm there.

Given that migration is triggered by a cocoa income under the poverty index (Appendix I) , as long as the newly set floor price of 2600 USD/ton continues to be used, there will be no more migration than simulated under the floor price scenario. This floor price policy is set in June 2019 by the governments of Ghana and Côte d'Ivoire, responsible for more than 60% of the world's cocoa supply (Fairtrade, 2019) and therefore not likely to change in the near future.

10.1.5 Analysis of the carbon prices

The ANOVA test in Appendix Q shows that the low, medium and high carbon price scenarios create no significant differences on the KPIs and are therefore not further studied. This could be explained by the fact that the production of 1 kg cocoa bean at a farm contributes to only 16% of the total CO2 emissions across the value chain (Ntiamoah & Afrana, 2008). Therefore, the carbon price is not affecting the income of smallholders so much.

10.2 Analysis of interventions

Before analysing the interventions under different scenario settings in Section 10.3, the surprising trends of individual interventions are interpreted in this subsection.

First, investing in shade trees in the most viable regions Western and Central causes a peak in cocoa production (blue and orange lines, Figure 37). The additionality also indicates a peak after 5 years (Figure 39). A delay effect might explain these peaks: shade trees should grow before they can effectively protect cocoa trees (Appendix M.3). However, in reality shade trees usually do not become effective in such an abrupt way after 5 years, but protect the cocoa plant more granularly over time.

Second, Table 7 and Table 27 (Appendix R) provide an overview of the standard deviations for cocoa production and cocoa income, where the amount of variation is higher for scenario B (logarithmic, maximum) compared to scenario A (linear, minimum). A possible explanation for these results may be the sensitivity of production. Figure 28 illustrates that the minimum sensitivity of production ranges at maximum between -9% and -30% in 2038, while the maximum sensitivity shows a higher uncertainty between -19 and 52% in 2038. This spread can in turn be attributed to the discrete exposure categories as described in Section 10.1.2. For example, moving from medium to high exposure is a change of 30% in scenario A, while it is a change of 50% in scenario B.

Interestingly, the red reactive intervention is observed to have no deviation under scenario A. This result may be explained by the fact that no migration peak starts under this scenario, so no subsidies for a diversified income stream (red reactive) are given to farmers willing to migrate. The intervention is not initiated and therefore the standard deviation is 0.

Third, the additionality (Figure 39) show suddenly some peaks for reactive interventions. These tipping points are the moments when farms become exposed to climate change (blue and turquoise lines) or when smallholders want to leave their cocoa farms (red line).

This might also be the reason for no deviation of reactive interventions (Tables 7, 9 and 27) in the first years under scenario A. In 2030 and possibly 2040 there are no farmers to support from climate change exposure, and when DFIs are not intervening, the additionality and its standard deviation remains 0.

Another surprising finding is that the interventions in the red, most affected regions have no standard deviation for additionality under both scenarios (Table 9). Without intervention, these cocoa farms would have migrated. The additionality is therefore calculated by comparing the cocoa income with a fixed income of low-skilled workers in Ghana (Trading Economics, 2020). It is an ambiguous calculation, which explains the low standard deviation. This is contrasting with the green, viable regions where the additionality is calculated by subtracting the runs with interventions from the runs without interventions. This is a highly dynamic outcome, which explains the standard deviation for the green regions.

The next subsection discussed the interventions under the different scenarios, resulting in trade-offs.

10.3 Analysis of trade-offs

Trade-offs in terms of (a) priority (regions getting support from DFIs), (b) timing (proactive or reactive), and (c) activities (e.g. climate adaptation with pest management or shade trees) are taken into consideration while evaluating potential interventions of Development Finance Institutions.

(a) First, investing in climate adaptation with shade trees in the most viable regions Western and Central (blue and orange lines, Figures 37, 51, 39) appears to be the most robust intervention under the full range of scenarios in terms of *cocoa production*, *cocoa income* and *additionality*, compared to investing in the most affected regions Brong Ahafo and Ashanti (green and red lines).

Analysis shows that three dynamics can cause this outcome: (1) The costs of shade trees are relatively low, compared to a subsidy to set up a diversified income stream for multiple years (Appendix M.3). Therefore, a higher number of cocoa farms can receive support within the limited budget, stimulating their production, income and creating additionality. (2) The number of cocoa farms in the most viable regions Western and Central is higher than in the most affected regions Brong Ahafo and Ashanti. (3) Planting shade trees is assumed to be highly effective in protecting the cocoa trees from droughts. It increases the production with 29% when the trees are fully grown (Appendix M.3).

On the contrary, if the ambition is to help cocoa farmers out of their current unsustainable way of living, and enable them to stay on their land and within their community while avoiding the uncertainty of migration, prioritizing the most affected regions with subsidies for farmers who are about to migrate appears to be an effective intervention (Figure 38, red line). It results in a lower *number of migrating households* compared to prioritizing the most viable regions. This migration trend will however not start under the least extreme scenario, while it starts around 2032 and goes up to 20% of the farmers in the most extreme scenario. Given this high level of uncertainty an adaptive intervention, e.g. the model is run regularly with the most recent climate information, could be useful to assess timing and likelihood of migration.

Sharing the budget between the most affected and viable regions, i.e. hybrid interventions, have intermediate results for all KPIs (Figures 37, 38, 39 and 51). The hybrid interventions considered in this study have both the same timing (i.e. both proactive or reactive). However, when looking at the results, hybrid interventions combining proactively acting in the most viable regions and reactively acting in the most affected regions could be a suitable strategy (orange line in Figures 37 and 39, red line in Figure 38). This combination could be subject for future exploration how prioritize the regions getting support from DFIs.

(b) Second, the timing of interventions is analysed. Figure 38 indicates that supporting the most affected regions Brong Ahafo and Ashanti in a reactive way (red line) results in less migrating households than in a proactive way (green line). However, it is the opposite for the most viable regions. Here, acting proactively (orange and purple, Figure 38) results in less migrating cocoa households than acting reactively (blue and turquoise).

This result can be explained by the level of uncertainty: are the farmers proactively receiving support also the ones who are ultimately impacted by climate change? This uncertainty is not so high in the most viable regions, because most farms across the regions are subject to a low level of exposure. However, this uncertainty is higher in the most affected regions. Here, not all farms across the regions are highly exposed to climate change. This means that is more difficult to know beforehand which farmers in the region will be highly impacted, and therefore there is a risk of giving subsidies to farmers which become not as much exposed that they are willing to migrate. Despite the interventions a migration flow is then starting (green line, Figure 38).

(c) Third, the climate adaptation activities for the most viable regions are compared: pest management and shade trees. Using shade trees (blue and orange) results in a higher *cocoa production, cocoa income, additionality*, and less *migration,* compared to pest management (turquoise and purple). This is the case under the full range of future scenarios. The result corresponds with the high exposure of the cocoa growing region as shown in Chapter 5: pest management is a minor intervention with regions with low adaptation needs, which is not enough to tackle increasing droughts (Bunn et al., 2019). Shade trees can reduce the vulnerability to dry season temperatures (Schroth, Läderach, Martinez-Valle, Bunn & Jassogne, 2016).

The fourth sub question, *What is the effect of different interventions on societal benefits and financial returns of a specific local cocoa investment in Ghana under different climate scenarios?* can be answered by the observation that the interventions can create different societal and financial impacts, and when selecting an intervention, DFIs need to carefully assess the trade-offs and decide on their priorities.
Proactively investing in climate adaptation with shade trees in Western and Central Ghana (the most viable regions) appears to be the most robust intervention in terms of cocoa bean production (financial returns), income of cocoa farmers and additionality (societal benefits). This can be explained by the share of farmers supplying to FMO's investment in these regions (61%) as well as by the effectiveness of shade trees in protecting cocoa beans.

The ambition could also be to help cocoa farmers out of their unsustainable way of living, and enable them to stay on their land while avoiding the uncertainty of migration. In that case, giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) who are about to migrate (reactive) appears to be an effective intervention. It should be noted that migration appears to be a long-term effect and is only starting from 2030 on under a scenario where climate change highly affects the cocoa production. Given this high level of uncertainty an adaptive intervention, e.g. the model is run regularly with the most recent climate information, could be useful to assess timing and likelihood of migration.

If the ambition is to balance both societal benefits and financial returns, hybrid interventions combining both proactively inventing with shade trees and reactively giving subsidies could be a suitable strategy. However, the hybrid interventions considered in this model have the same timing (i.e. both proactive or reactive). This suggested combination could be subject for future exploration.

10.4 Summary chapter 10

This chapter aimed to interpret the effects of different interventions on the financial returns and societal benefits under two extreme scenarios. In terms of interventions, DFIs should make the trade-off between prioritizing the supply of cocoa beans to secure financial returns, and ensuring societal benefits in terms of cocoa income of smallholders, helping farmers which are willing to migrate and creating additionality. This next chapter discusses whether these model results can be validated.

11. Validation

The previous chapters discussed the case study of an investment in the cocoa sector in Ghana, for which an agent-based model is built and used to experiment with interventions. This chapter aims to investigate whether the model outcomes are useful using face validation and structural validation.

Section 11.1 first describes the set-up of the validation workshop before presenting the outcomes in Section 11.2. Some of the outcomes are selected for a model iteration step, which is explained in Section 11.3. The final section discusses the structural validation: a sensitivity analysis is used to assess the behavioural thresholds.

11.1 Set-up of validation workshop

In this study, the behaviour of the agent-based model cannot be compared to the "real" system behaviour as validation, because the model explores possible scenarios until 2050. For that reason, the validation focuses on whether the model is useful and convincing (Van Dam et al., 2013). Face validation by organising a workshop is the most commonly used validation approach in agent-based modelling (Van Dam et al., 2013). The focus of the workshop is on validating the interventions, the model results and the added value of the framework.

Due to the corona circumstances it was not possible to organize an extended workshop. The validation is now performed during a Skype meeting, with a small number of people to keep the session as energized as possible. The group consisted of four participants with diverse backgrounds and responsibilities within FMO (Table 10).

Table 10 Participants of the validation workshop

	Function	Organization
1	Investment Officer: Agriculture in Africa	FMO
2	Risk Officer	FMO
3	Expert: Resilience in Africa	FMO
4	Impact Officer	FMO

However, it is hard to validate the outcomes because of the heterogeneity of agents and possibility of new patterns emerging as a result of agent interactions (Pullum & Cui, 2012). Experts might not have an understanding on what may happen in the future and be biased on what happened in the past (Van Dam et al., 2013).

It should be noted that the climate scenarios and model dynamics are not validated within this Skype workshop.

11.2 Validation workshop

The validation workshop included systemically going through three main discussion points, which were indicated in the slides (Appendix T): (1) suggested interventions, (2) model results and (3) added value of the framework for DFIs. Each point was first analysed by the group of experts without sharing the conclusions of the modeller, so their observations could be discussed without any bias.

These three points are subsequently discussed in this section. Please note that some recommendations might be already included in the previous chapter as one model iteration round is performed after the validation workshop.

11.2.1 Validation of suggested interventions

The suggested interventions are defined based on the response (proactive and reactive) and the priority (most affected or most viable regions first) of DFIs.

One of the participants mentioned that FMO cannot ask for these types of strategic interventions from only one client in the cocoa sector due to the scale. The suggested interventions are sector-wide initiatives. Cooperation with the government and other DFIs active in the cocoa sector is therefore essential. This participant suggested further research into this cooperation. Another professional highlighted the added value of this strategic level of interventions as a way for DFIs to make significant social impact.

One participant suggested to also work out the interventions 'green first' in more detail. The intervention is currently based on the assumption of drip irrigation, while an expert mentioned that this is a challenging intervention given its costs and water availability and water pollution in Ghana. They recommended to also explore shade trees in detail, which can be more feasible.

The proposed intervention 'red first' reminded one of the participants of a similar situation in the coffee sector to one of the participants: Coffee farmers in Africa who are highly affected by climate change are helped to set up a diversified income stream.

11.2.2 Validation of model results

The discussion on the model results mainly revolved around (1) the business case behind the interventions, (2) the definition of interventions and (3) the migration stream.

First, the participants were looking for the reason why the intervention 'green first' seems to be the most robust option for KPIs loss of production, cocoa income and permanently migrated households. The share of green farmers is much higher than the share of red farmers and the costs of giving subsidies for several years to the most affected farmers are higher. This makes the intervention in the most viable, green region most robust. As a response to this explanation, a professional recommended adding 'additionality' as a KPI. Her hypothesis is that investing in the most affected regions where households have no, or low incomes might have more added value than investing in the viable regions where households would have had an income anyway (Δ). This KPI would better represent the mission of the DFIs.

There were also questions regarding the definition of the interventions. For example, what is the timeline or level of exposure to be considered as proactive? Which regions should be prioritized, and how many farmers? A professional asked why the proactive strategy was defined as six farms per year receiving support. He expected that this definition highly influences the results and should therefore be clearly communicated.

The third main discussion point was about the results for migration. The expert on resilience in Africa mentioned that the migration flow now starts around 2035 in the case of 'green first', which is not realistic in her view. She expects that farmers from the most affected regions will migrate at an earlier stage if they get to know this group is supported as it is more attractive to work there.

11.2.3 Validation of the added value of the framework for DFIs

The three main steps of the framework suggested in this study consisted of (1) global to local climate scenarios, (2) capturing local behaviour in a bottom-up model, and (3) exploring the opportunities for DFIs' interventions.

- Regarding the scale of this kind of models, a risk professional concluded that the model shows that climate change has different effects at a smaller scale, more than he had expected. It shows that climate adaptation is very site specific and that there is no one-for-all type of intervention. Everything needs to be put in a broader context and that point is really shown in this exercise.

- The added value of these kinds of models are acknowledged by all participants. They feel an urgency to be more active on climate risk, because there is currently no tool for climate risk assessment yet. One of the participants mentioned that this modelling exercise on such a detailed level has a disadvantage of being time consuming. He suggested that an agent-based model can be used to explore the impact of climate change and societal behaviour in new regions or for more risky clients. The 'due diligence' stage before actual investment is a suitable step for these models in the investment process. He also thinks that an agent-based model could not only be run to identify impact and response for current investments, but also to identify highly affected communities or sectors due to climate change. This is where DFIs could make an impact according to their mandate.

- Another professional shared her view on the context of these kinds of models. She said that it is a model and therefore a simplification of reality. This study is a scenario analysis to identify all plausible futures and it should therefore not be interpreted as a predicating tool. However, these models can be used to start a conversation about trade-offs.

- The final remarks on the added value for DFIs were recommendations for implementation. The investment officer thinks that playing with both a short (time of an investment) and long term (which is key to maintain agricultural production) can give relevant insights.

11.3 Iteration of validation outcomes

Some of the comments made by the workshop participants were implemented in an iteration step:

1. The green first intervention which was before assessed as one single 'priority' option, is then split into two operational interventions: pest management and shade trees.
2. A fourth key performance indicator 'Additionality' is added to measure the impact and added value of DFIs intervening in the cocoa sector compared to the baseline. The difference between income of households with and without interventions serves as a proxy for the additionality of DFIs.
3. The results are sensitive for the definition of the interventions. This definition is clearly motivated in Section 7.3 and Appendix M.4.

11.4 Structural validation

To evaluate the effects of the behaviour thresholds set in Section 6.4, a sensitivity analysis is performed. The objective is to test whether another assumption on cocoa smallholders' behaviour retrieved from interviews and literature affects the model outcomes. Based on this analysis it can be concluded that most thresholds and bottlenecks do not affect the model behaviour, except from the social influence of migration. Neighbours are willing to migrate if three criteria are met (Section 6.4). One of the criteria is that their cocoa trees are older than 25 years. When this age is raised, the migration peak will flatten in 2047, instead of causing another peak. The analysis chapter already reflected upon this finding (Section 10.1). The structural validation is discussed in detail in Appendix S.

11.5 Summary chapter 11

This chapter focuses on the question whether the agent-based model for the cocoa in Ghana case study are *useful*. The behaviour of the agent-based model cannot be compared to the "real" system behaviour as validation, because the model explores possible scenarios until 2050. Expert validation is used to go through the interventions, model outcomes and added value of the proposed framework. It should be noted that the climate scenarios and model dynamics are not validated within this workshop. Some comments on this specific case study were implemented in an iteration. The next chapter discusses the reflection of this study.

12. Discussion

The results of the agent-based modelling study – first downscaling global climate scenarios, then capturing human behaviour, and finally exploring interventions for DFIs to achieve sustainable investments under climate change – are considered in this chapter. The framework is applied to an investment in the cocoa sector of the Dutch Development Bank FMO. This investment is exposed to change climate as cocoa plantations are sensitive to temperature increases and uncertain precipitation patterns.

Section 12.1 reflects on the model, which is based on several assumptions, as well as the method and approach. Subsequently, Section 12.2 reflects on the possibility to generalize the framework to similar investments.

12.1 Limitations of the study

It is inherent to this framework that many assumptions have been made in order to devise scenarios. The most important assumptions which are expected to affect the model outcomes are discussed in Section 12.1.1. A full list of assumptions is provided in Appendix H. The limitations of the agent-based model and the suggested framework are outlined in Section 12.1.2 and 12.1.3.

12.1.1 Assumptions

The first assumption made is in the location of cocoa farmers relevant for FMO's investment. The client does not have a traceability system in place to know where its suppliers are located. Therefore, the client suppliers are mapped proportionally to national sourcing data of COCOBOD. Full knowledge about the location of plantations linked to FMO's client would result in a more accurate mapping and regional division. Consequently, the exposure to climate change impact is either overestimated or underestimated in this study. This could in turn affect the preference for certain interventions. For example, if FMO's client is only sourcing from the green, most viable cocoa region, the suggested interventions for highly affected farms are less relevant.

The second assumption is related to the climate exposure classification of cocoa farms (low, medium, high or no exposure). Production loss is linked to these exposures: for example 10% loss of production when a cocoa farm has low exposure and 30% for medium exposure, which means that this classification affects the model outcomes for loss of production in a discrete way, which in turn also influences the cocoa income and migration outcomes. However, these discrete steps are unrealistic, and in reality the exposure evolution of cocoa farmers is expected to be smoother.

The third assumption is related to the exposure category 'highly uncertain' (no agreement between global climate models) as suggested by Bunn et al. (2019). This category represents 35% of the farms. In the parametrization of the model, this has been divided evenly over the other categories: no, low, medium, high exposure, i.e. ¼ each. A different division over the categories would significantly change the farms' climate exposure per region. For example, dividing the highly uncertain category according to the weight of each region with respect to the total number of farmers, shows an overestimation of approximately 18% in the no exposure and high exposure categories, and underestimates in the medium and low categories (calculation in Appendix D). This might mean a different loss of production, cocoa income and migration for 35% of the farmers as well as potentially on the aggregated level, which in turn might require different adaptation interventions.

The definition of neighbours is a fourth assumption in the model. It is assumed that cocoa farmers belonging to the same region and living within a distance of 5 patches are neighbours, who could be socially influenced to make a migration decision. However, this distance ignores regional differences of land and community settlement. The social influence of migration, which is accelerating the permanent migration trend, will therefore be different in reality.

Furthermore, the model assumes that the Ghanaian economy can bear a maximum of 20% cocoa farmers diversifying to start trading in nuts, for example, or growing other crops besides cocoa farming. This bottleneck is set because according to interviews, the market infrastructure in Ghana cannot fully support diversification, farmers need specific skills, the gains are not as high, or the land is not suitable. In the model, this bottleneck means that people will consider migration when no opportunities for diversification exist. If the market in Ghana allows for a threshold over 20%, more people will decide to diversify without the need to migrate.

The sixth important assumption is the efficiency of pest management and shade trees as a means of climate adaptation intervention. Finding estimates on the effect of these measures on the production of cocoa was challenging, as efficiency is very site-specific. It heavily depends on current agricultural practices, use of fertilizer, various shade tree species and geography. These assumed efficiency values have an impact on the effect of the interventions for most viable regions, and an overestimation could mean that this intervention is not as robust on the financial returns and societal benefits as is now assumed.

Another important model boundary is that there is no feedback loop connecting production with the world market price included in this agent-based model. If the global supply of cocoa beans decreases due to the impact of climate change while demand remains at the same level, the world market price will increase. This would in turn increase the income of farmers. Another impact of the world market price which is not captured in the model is that if the cocoa price increases, this will attract more farmers to regions that are suitable for cocoa production. The model outcome for permanent migration would start at an earlier stage. Other market dynamics, for example a collapsing demand for cocoa, are also not included in the model.

Finally, another key assumption is that supporting cocoa farmers in the viable regions with climate adaptation, without supporting the most affected regions, might create an attraction effect. The most affected farmers are expected to be willing to migrate to these supported regions earlier. The permanent migration stream could therefore be started at an earlier stage.

The effect of the above-mentioned assumption on the model outcomes is shown in the table below:

Table 11 Effect of assumptions on KPIs

			Loss of production	Cocoa income	Permanent migration	Additionality
Region	1	Location of farms	++++	+++	++	++
Exposure	2	Discrete method for exposure	+++	++	+	+
	3	Division of highly uncertain categories	+++	++	+	+
Opportunities	5	Alternative markets in Ghana	/	/	++	+
Interventions	6	Efficiency of climate adaptation	+	+	+	+
Demand/supply	7	Feedback loop with world market price	/	++	+	+
Migration	4	Social migration	/	/	++	+
	8	Attraction effect of support green regions	/	/	++	+

12.1.2 Model limitations

The agent-based model (ABM) is built in Netlogo and used for exploratory modelling with interventions under different scenario settings. The advantage of using ABM is that it provides insights into what happens on a local level and this can be used to explore the effect of the behaviour of cocoa farmers in response to climate change on a system level.

However, building an ABM also requires a lot of assumptions. Modelling human behaviour into rules is challenging when it is based solely on literature and without primary data. Due to circumstances surrounding the coronavirus crisis, it was not possible to go to Ghana for fieldwork in order to understand the context of cocoa farmers and climate adaptation interventions. Also, interviews with experts highlight that it is hard to make estimates about behavioural thresholds in the future.

The model assumes, for example, that all cocoa farmers have full knowledge about the age of their cocoa tree stock and whether they live below/above the poverty threshold, which affect their behaviour in relation to diversification or migration. This is a strong assumption as it is something that is more intuitive in reality – farmers observe that they do not have enough money to feed their families, or at some point observe that their cocoa trees are less productive than they used to be.

These assumptions result in variability of model outcomes. The agent-based model should therefore be used a tool to identify trends, rather than to analyse absolute results, also because the model is applied over a long period of time.

12.1.3 Approach

This study follows three main steps: (1) translating global climate scenarios at the local level; (2) capturing local behaviour in a bottom-up model; and (3) testing interventions of DFIs. This suggested approach turned out to be useful for mapping the opportunities for climate adaptation on a local scale, but it also has the drawback of oversimplification.

First, macro-trends such as the political situation and economic developments are not included in this model. Second, the downscaling exercise from global to local scenarios is a statistical method: a cross-scale relationship between global climate projections and observed climate variables in Ghana is developed (Section 2.1). These boundary conditions related to current climate in Ghana lead to limited predictive ability and the potential to look for new trends (Van den Hurk, 2015).

In addition, the interventions could have side effects which are not included in this framework. For example, the ripple effect in the economy due to increased spending and stimulation of other sectors is not included. Also, the approach does not take into account other players in the cocoa sector. The government, as well as big chocolate manufacturers or other financial institutions, might also want to intervene in the system under climate change.

Finally, this framework could only be partial validated. The model explores possible scenarios until 2050, which cannot be compared with a representation in reality. For that reason, the validation is focused on whether the model is useful and convincing: the interventions, the model results and the added value of the framework. The climate scenarios and model dynamics are not validated.

12.2 Generalizability for similar investments

This subsection aims to reflect on the generalizability of the suggested framework. The three steps of the study can be applied to other investments to a certain extent.

Climate risk is becoming a hot issue on which DFIs are increasingly focusing. The bottom-up modelling exercise on an investment's local level is, however, very time-consuming and would therefore be suitable as a complementary tool next to global climate risk models performed at portfolio level. This approach could, for example, be used to explore the impacts of climate change on investments in new countries or sectors.

First, the downscaled climate data is publicly available and can be used for other investments as well. It first requires making a prioritization of which climate variables, such as temperature, rainfall, or more extreme events, are most relevant for that specific investment. This dataset of climate variables can be used to identify the likelihood and impact of climate change to assess the exposure of an investment at a local level.

Second, a bottom-up model, such as an agent-based model, could be used to represent other agents such as households and industries. The behavioural thresholds would be different depending on the country and sector. Fieldwork or interviews with local experts or even surveys would be crucial to capture these assumptions and map local behaviour.

An energy investment is used to illustrate how this framework could be applied on another sector and country. It is first interesting to map the exposure of the project to climate change effects, for example sea level rise, relevant for low-lying coastal energy infrastructure, but also acute events as floods, droughts, and storms. This has an impact across the entire value chain: the production, storage, infrastructure, transportation, and demand of energy (Ebinger & Vergara, 2011). For example, disruption in the supply of construction materials for a wind park, changes in energy consumption due to cold weather patterns, weakening of infrastructure and disruptions in transportation routes.

In the second step, building an agent-based model can help to capture the local behaviour of people under climate change. Due to the energy project the local population got improved access to energy resulting in for example more education, jobs creased and microenterprise development. Climate change could affect both the energy access and the energy consumption. First, climate change can disrupt the energy production, transportation, and distribution, which in turn decreases the created livelihood benefits. Second, the local population can be more or less affected by climate change, their vulnerability or resilience leading to potential migration and change in business activities resulting in different energy consumption patterns.

The final step is to experiment with climate adaptation interventions of DFIs. If climate change disrupts the energy production, interventions could potentially include reconsideration of the design, construction, operation, and maintenance of the wind park, as well as strengthening of the transportation and distribution system (Ebinger & Vergara, 2011). When climate change directly affects the local population, intervening with off-grid solutions and alternative locations for energy production could be interesting to explore in the agent-based model.

Even though the model as such cannot be directly transposed due to the specific dynamics for cocoa in Ghana, this approach can certainly benefit DFIs by exploring effects of climate change at the local level and searching for tailored climate adaptation interventions. It is a way to look at the broader picture of social changes such as migration and other climate impacts in the value chain.

The answer to sub question 5, *In what way can this framework be generalized for similar investments?*, can now be formulated. The three steps – (1) translating global climate scenarios at the local level; (2) capturing local behaviour in a bottom-up model; and (3) testing DFIs interventions – can be applied to similar investments. This framework on the local level can be used as a 'conversation starter' to trigger discussion on how DFIs want to balance their trade-offs. This could be a complementary tool at the 'due diligence' stage when exploring opportunities in new regions or sectors.

The application on similar investments requires prioritizing bioclimatic variables that are most relevant for that specific investment. Second, mapping the behaviour requires country-specific and sector-specific rules about thresholds, culture, and livelihood strategies. For other investments, it is crucial to be aware of this data requirement in terms of fieldwork, interviews with experts or surveys.

This step-by-step approach could encourage DFIs to explore the effects of climate change and the dynamics at the local level, and to design tailored interventions. It is a way to look at the broader picture of social changes such as migration and other climate impacts in the value chain.

12.3 Summary chapter 12

This chapter provided a discussion of the results as well as of the generalizability for similar investments. The assumptions influencing the model outcomes include the location of cocoa farms, the exposure to climate changes, limited opportunities at alternative markets in Ghana, the efficiency of climate adaptation, no feedback loop with the world market price, social migration and the attraction effect of support to viable regions. The limitation of agent-based modelling is that quantifying human behaviour into rules requires many assumptions, and finally the approach did not include macro-trends and potential side effects of interventions.

Reflecting in the second part of this chapter whether the suggested framework can be generalized, shows that it can be used as 'conversation starter' to trigger discussion on how DFIs want to balance their trade-offs. This can be used a complementary tool next to global climate risk models on the portfolio level. It can certainly benefit DFIs in exploring the effects of climate change at the local level and finding tailored climate adaptation interventions.

The next chapter discusses the conclusions, recommendations for DFIs, social and scientific relevance and recommendations for future research.

13. Conclusion, scientific contribution and suggested future research

This chapter presents the conclusions of the study, recommendations for Development Finance Institutions (DFIs), its societal and scientific contributions, and recommendations for future research. First, a synopsis of the research project is given in Section 13.1, followed by answering the main research question as presented in the third chapter. Section 13.3 presents answers to the sub questions. The recommendations for Development Finance Institutions, societal and scientific relevance are reflected upon in Sections 13.4, 13.5 and 13.6 and finally, the chapter concludes with suggestions for future research.

13.1 Synopsis research project

Development Finance Institutions (DFIs) have been established to provide finance for long-term economic development in low and middle-income countries. However, these investments are exposed to climate-related risks: (1) physical risks with impacts due to long-term shifts in weather patterns (chronic) or extreme events such as flooding and drought (acute); and (2) transition risks, because moving towards low carbon economies entails technological, institutional and economic changes resulting in financial or reputational risks.

This means that Development Finance Institutions need to explore climate adaptation interventions to secure financial returns and societal benefits, particularly in view of the fact that developing countries themselves have few resources for climate adaptation. The mandate of DFIs includes sustainable development, therefore also protecting developing countries from the impact of climate change.

Effectively financing climate adaption starts with mapping the impacts of climate change by exploring various global climate scenarios. This was recently recommended by the Task Force on Climate-related Financial Disclosures (TCFD) and in European Guidelines on reporting climate-related information. To fully understand the human response to climate change and to support impactful climate adaptation investment it is interesting to take the next step and move from climate risk assessments towards a site-specific analysis.

The aim of this thesis is therefore to establish how Development Finance Institutions can achieve long term sustainable investments with financing climate adaptation, while securing financial returns and creating societal benefits. For this reason, an agent-based model is developed and an investment by the Dutch Development Bank (FMO) in the cocoa sector in Ghana serves as a case study.

From literature it becomes clear that scaling these global climate scenarios to a local level such as the cocoa sector in Ghana uses a lot of assumptions. Research also highlights that climate models lack the bottom-up response of humans to climate change as feedback loop. Finally, literature shows that interventions related to climate adaptation are still at an early stage of development.

The research approach to address these gaps consists of three steps. (1) Global climate scenarios are downscaled to the local level, specifically for rainfall and temperature affecting the cocoa plant. (2) The behaviour of cocoa farmers is conceptualized with the Sustainable Livelihood Framework and Diffusion of Innovation theory, and then captured in an agent-based model. (3) Potential climate adaptation interventions are evaluated, combining different timing (proactive or reactive), priority (regions getting support from DFIs), and activities (e.g. climate adaptation with pest management or shade trees).

13.2 Answering the main research question

This study aims to formulate an answer to the main research question:

How can DFIs achieve long term sustainable investments under climate change?

To ensure long term sustainable investments under climate change, DFIs need to finance climate adaptation while creating societal benefits and financial returns. This implies positively contributing to society, for example creating jobs, generating a stable income, and supporting the resilience of households, while securing financial returns for development banks.

A way to explore how to achieve these sustainable investments is to set-up a study with three components: (1) translating global climate scenarios at the local level; (2) capturing local behaviour in a bottom-up model because understanding the specificity of the local context and individuals' response is key to really make an impact; and (3) testing climate adaptation interventions. This step-by-step approach could encourage DFIs to capture the impact of climate change and the dynamics at the local level, and to design tailored interventions. It is also a way to take a holistic perspective and look at the broader picture of economic and societal impacts of climate change, and the response across the whole value chain.

13.3 Answering the research sub-questions

To be able to formulate an answer to the main research questions, the following five sub-questions were answered:

1. *Which physical climate risks in Ghana's cocoa sector are deemed to be the most relevant?*

The reduced cocoa suitability is a key risk for changes in cocoa supply. Increased temperature and uncertain precipitation patterns due to climate change, which influence the potential evapotranspiration, are the bioclimatic variables that contribute the most to cocoa yield variability. Therefore, these two variables are considered when assessing climate change exposure of cocoa farms.

2. *How to translate global climate scenarios to the local level for an investment in the cocoa sector?*

This study uses the downscaled dataset of CGIAR Research Program on Climate Change, Agriculture and Food Security (2020) where 19 Global Climate Projections are downscaled with the delta method into local impacts for temperature and precipitation, affecting the potential evapotranspiration of the cocoa plant. The second step is to map the cocoa farms of FMO's client proportionally to national COCOBOD sourcing data, resulting in the climate exposure specific to each cocoa farm.

The optimistic RCP2.6 and pessimistic RCP8.5 scenario show that all regions will become partly unsuitable for cocoa by 2050. In terms of cocoa farms, this means that 25% in RCP2.6 and 27% in RCP8.5 is highly exposed. Due to data availability issues, the pathway from 2020 until 2050 is modelled with a linear trend, following the logic of a Markov chain. To explore the effects on the long term, a logarithmic trend is included to illustrate the situation of 2050 already in 2038.

3. *How can a specific local cocoa investment in Ghana be conceptualized and captured in an Agent-Based Model?*

The below figure 42 shows the high-level conceptualization of the agent-based model. In this study, the climate scenarios represent the uncertainties outside the control of DFIs; the interventions with climate adaptation are the policy levers that DFIs want to explore, given the policy of the famer gate price of the governmental agency COCOBOD; the behaviour of cocoa farmers represent the relationships in the system and finally, the results that DFIs use to rank make the trade-off between interventions represent the measures.

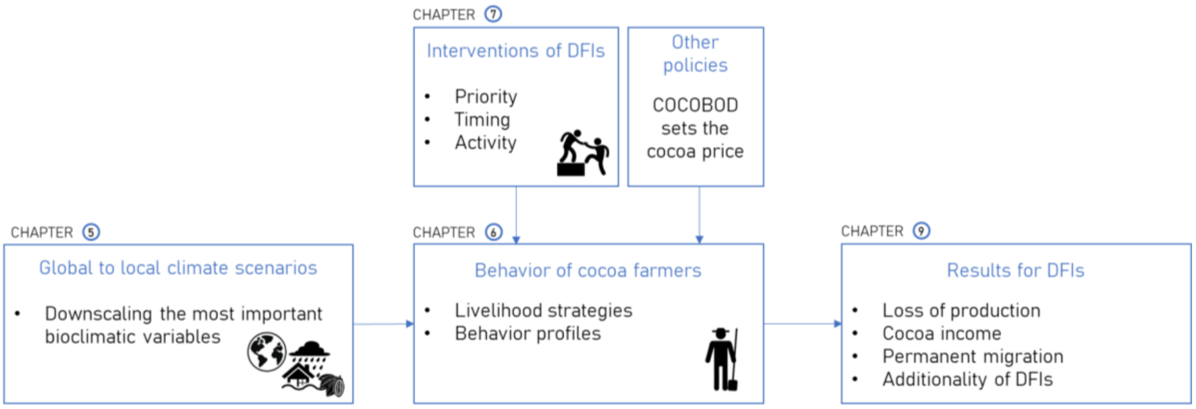

Figure 42 High-level conceptualization

Focusing on the cocoa farmers as most important agents, their behaviour is conceptualized by connecting two frameworks (the Sustainable Livelihood Framework and the Diffusion of Innovation theory) to represent the livelihood strategies influenced by behaviours, and by defining a clear scope and behaviour rules and thresholds (based on input from interviews with anthropologists and literature review) to guide the decisions, reactions and interactions of the agents.

4. *What is the effect of different interventions on societal benefits and financial returns of a specific local cocoa investment in Ghana under climate scenarios?*

Proactively investing climate adaptation with shade trees in Western and Central Ghana (the most viable regions) appears to be the most robust intervention over time in terms of cocoa bean production, income of cocoa farmers and additionality (Δ income generated by intervening). This can be explained by the share of farmers supplying to FMO's investment in these regions (61%) as well as by the effectiveness of shade trees in protecting cocoa beans.

The ambition could also be to help cocoa farmers out of their current unsustainable way of living, and enable them to stay on their land and within their community while avoiding the uncertainty of migration. In that case, giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) who are about to migrate (reactive) appears to be an effective intervention. It reduces migration to 12% compared to 21% with no intervention. It should be noted that migration appears to be a long-term effect and is only starting around 2030 under a scenario where climate change highly affects the loss of production, for example 20% instead of 10% production loss in low exposure. In case migration starts, it will have a social influence, resulting in a peak of migration.

Given this high level of uncertainty, an adaptive intervention, i.e. the model is run regularly with the most recent climate information, could be useful to assess timing and likelihood of migration.

The resulting analysis shows that acting proactively is not always the most suitable strategy as it would be intuitively perceived. Proactively giving subsidies to farmers in Brong Ahafo and Ashanti (the most affected regions) is less effective, because of the level of uncertainty: it is difficult to know beforehand which farmers in the region will ultimately be highly impacted. This level of uncertainty is higher in the most affected regions and therefore a reactive timing is more useful, while the most viable regions will benefit more from proactive interventions.

If the ambition is to balance both societal benefits and financial returns, hybrid interventions combining both proactively investing in shade trees and reactively giving subsidies could be a suitable strategy. However, in this model only the hybrid interventions with both the same timing (i.e. both proactive or reactive) were captured. This suggested combination could be subject for future exploration.

5. *In what way can this framework be generalized for similar investments?*

The three steps – (1) translating global climate scenarios to the local level; (2) capturing local behaviour in a bottom-up model; and (3) testing DFIs interventions – can be applied to similar investments. This framework on the local level can be used as a 'conversation' starter about the trade-offs DFIS have to make. This could be a complementary tool next to current global climate risk models on the portfolio level, and implemented at the 'due diligence' stage when exploring opportunities in new regions or sectors.

First, the application to similar investments requires the prioritization of bioclimatic variables that are most relevant for that specific investment. Second, mapping the behaviour requires country-specific and sector-specific rules about thresholds, culture, and livelihood strategies. For other investments, it is crucial to be aware of this data requirement in terms of fieldwork, interviews with experts or surveys.

This step-by-step framework has four benefits for Development Finance Institutions: (1) It helps to understand the complexity behind climate adaptation interventions. Climate change has specific effects on smaller scale, and therefore there is no 'one-size-fits-all' strategy. (2) The framework goes broader than the physical impact and financial implications of climate change by systemically exploring the socio-technical system around a potential investment, such as a supply chain, technical innovations, and changes in the environment. (3) It would also help Development Finance Institutions in considering the long-term view. The impact of climate change is not clearly visible at present, but it has clear consequences for the long term. (4) This modelling exercise also quantifies the trade-offs with financial and societal consequences, in line with the additionality mandate of Development Finance Institutions.

13.4 Recommendations for Development Finance Institutions

The outcomes for DFIs in relation to both the case study and future climate adaptation interventions are discussed in this section.

The case study on a cocoa investment in Ghana shows the range of what could potentially happen under different scenarios. The cocoa production loss due to climate change ranges from 15 to 32% in 2050, and 35 to 50% on the long term. This causes approximately 12 to 19% of the cocoa households leaving their farms.

The interventions differ in terms of priority (i.e. most viable or affected regions), timing (reactive or proactive) and activity (shade trees, pest management or subsidies). FMO is recommended to take into account these trade-offs to inform decision-making on the best strategy for cocoa investments in Ghana.

If FMO decides to prioritize cocoa production to secure financial returns, it is recommended to invest in shade trees in Western and Central (the most viable regions). Using shade trees also results in the highest cocoa income, therefore creating societal benefits and additionality (income generated by intervening, Δ).

If FMO decides to prioritize the most affected cocoa farmers in Brong Ahafo and Ashanti that are about to migrate (reactive intervention), giving subsidies to set up a diversified income stream appears to be the most effective intervention. This diversified income stream limits the uncertainty of migration for cocoa households by ensuring an income while still breaking through an environmental and financial unsustainable situation. It should be noted that this migration stream is only starting under a scenario where the impact of climate change is heavily affecting the loss of production. Yet, this phenomenon will play a more important role on the long term from around 2032. In case coca farmers decide to give up their farms, social influence would result in a high peak of migration, with up to 20% of the cocoa farmers on the move.

Given the high level of uncertainty, DFIs are recommended to use adaptive interventions. They could, for instance, run the model regularly with the most recent climate information to assess timing and likelihood of migration.

Considering the benefits (Section 13.3, sub question 5), Development Finance Institutions are recommended to apply this framework in their decision-making process. It can be used as a 'conversation starter' to trigger discussion on how Development Finance Institutions want to position themselves in terms of the prioritization and timing of interventions, and societal and financial returns. This could be a complementary tool to provide information at the 'due diligence' stage or to assess opportunities for climate adaptation investments for specific cases, for example when exploring opportunities in new regions or sectors.

13.5 Societal contribution

In the Engineering and Policy Analysis masters program the central focus is on analyzing and solving the UN Sustainable Development Goals (SDGs).

Several studies argue that smallholder farmers might actually be the backbone of many SDGs, because they are the first step in numerous supply chains worldwide (Terlau, Hirsch & Blanke, 2019). More specially, this case study about supporting cocoa smallholders in Ghana contributes to following SDGs:

First, providing finance to support cocoa farmers helps to foster employment and production, and therefore results in economic growth (SDG8: Decent Work and Economic Growth), which is in line with the mandate of DFIs. This is reflected in the KPIs *Loss of cocoa production* (%) and *Cocoa income of households* (USD/year).

Second, this study is related to SDG13: Climate Action. Interventions on climate adaptation such as shade trees and diversification can make developing countries more resilient to the impacts of climate change. The impact of climate adaptation interventions is shown in the KPI *Additionality of DFIs* (USD/year).

Finally, by financing the resilience of developing countries with less resources to adapt, DFIs also contribute to reduce inequalities between countries and therefore contribute to SDG10. This SDG is also linked to the inequalities within Ghana: smallholders in the most affected regions might decide to leave their cocoa farms due to reduced income, and will experience the uncertainty of migration, while other smallholders in the viable regions for cocoa are less exposed to climate risks. This is captured in the KPIs *Permanent migration* but can also be reflected in *Cocoa income of households* (USD/year).

In the EPA masters program these SDGs are analysed with modelling and simulation methods to inform decision-making. In this study, an agent-based model is used to capture the above-mentioned challenges. The modelling exercise shows on a system level what is the impact of climate change and informs DFIs' decision makings to make their investments more sustainable.

13.6 Scientific contribution

This study proposes a framework that connects three key elements: (1) translating global climate scenarios at the local level; (2) capturing local behavior in a bottom-up model; and (3) testing climate adaptation interventions. This approach generates insights for DFIs on a system level that is not apprehended by existing models.

The first connection is from (1) climate impact to (2) human response. The Integrated Assessment Models (IAMs), such as the Shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathways (RCPs), capture the impact of climate change *based on* the socio-economic context. The integrated models use *input* assumptions as population growth and GDP development to drive the model (Clarke et al., 2014). These IAMs can be downscaled to local level, but they still do not account for adaptive strategies of humans in response to climate change. Patt et al. (2010) suggest that these models could be improved by considering more bottom-up characteristics.

This study shows that it is possible to combine top-down and bottom-up models to generate complementary insights into who and what is at risk, which was a much-needed step according to Conway et al. (2019). The global climate scenarios are used as input, setting the context in the agent-based model showing the human response of cocoa farmers. Including the feedback loop of the bottom-up response to climate change helps to make the 'climate scenario' more comprehensive: no system acts independently, and these dynamics between systems should be captured to reflect consequences and dependencies (Van Dam et al., 2013). This was lacking in previous literature and is useful to help DFIs effectively choose their inventions adjusted to the local context.

The other connection is to (3) climate adaptation. Top-down adaptation strategies, for example deriving from the Integrated Assessment Models, are typically based on aggregated costs and benefits of adaptation measures to reach global or national goals (Sanderson, 2016). Even though climate adaptation is a global problem, the impact of climate change and therefore the need for adaptation can vary widely on smaller scale. For this reason, Williams, Crespo and Abu (2019) suggest that adaptation strategies should be context-specific, and that there are no one-size-fits-all strategies. Dickinson (2008) also argues that human behavior should be an essential component in adaptation models: if two farmers have identical climate change information, they will not act in the same way. However, adaptation strategies do not systematically consider these local, societal, and economic perspectives as well as the diversity of beneficiaries.

This research took a broader view on climate adaptation by modelling the heterogeneity of households, their individual behavior in response to climate change and the impact on income and livelihood. It also highlights that adaptation requires trade-offs in timing (proactive or reactive), priority (regions getting support from DFIs), and activities (e.g. climate adaptation with pest management or shade trees). These implications specific for DFIs have not yet been found in existing literature.

13.7 Recommendations for future research

Several interesting themes triggered by this research could be further explored.

First, additional research is suggested that looks at the 19 different global climate models. In this study, 35% of the farms were classified in the high-uncertainty category because there was no agreement (>60%) on the exposure between the 19 global climate models. It would be interesting to explore the differences between the climate models which give a better estimate of the bandwidth of climate change impacts, so the exposure and response to climate change can be better assessed.

Second, there is an opportunity to expand the model with a spatial feature to increase communication purposes. Currently, representation of the cocoa farms in Netlogo is not according to GIS coordinates. Their region is determined based on the 'region' of the property of the farm. It would, however, increase communication when the system effect of where climate hits the most is clearly visible, and where people are deciding to migrate. There are possibilities to add a GIS extension to Netlogo.

Third, the proposed framework can be further refined by paying attention to first climate modelling step. Within this study the climate scenarios are not validated by experts in the field of climate modelling.

In addition, the feedback loop connecting cocoa production with the world market price might be an important area for future research. If the global supply of cocoa beans decreases due to climate change while demand remains at the same level, the world market price will increase. This dynamic is not included in the current study. An increase price will also attract more farmers to regions that are suitable for cocoa production, and therefore including this feedback loop requires future research.

This research investigates the migration trend of cocoa smallholders triggered by climate change, and subsequently explores the effects of a subsidy to set up a new diversified income stream. It is recommended to further explore how migration is perceived in Ghana. On the one hand, migration is a way to get out of an unstainable way of living and it is not new to the Ghanaian population as 12.5% of the population has experienced migration (Duplantier, Ksoll, Lehrer & Seitz, 2017). On the other hand, smallholders leave their farms and communities (economic and social barriers) and a situation of uncertainty starts. Future research should consider all potential perceptions on migration in Ghana more carefully, for example from an anthropological point of view.

Regarding the interventions, multiple directions for future research are identified:

- In this study, the budget for climate adaptation is fixed and the effects of interventions are explored under this constraint. Future research could identify how much budget is necessary to keep the cocoa production at the current level or to prevent migration.

- The effects of pest management and shade trees as a means of climate adaptation interventions on the cocoa production are very site-specific. It heavily depends on current agricultural practices, use of fertilizer, various shade tree species and geography. More research is needed to test these interventions within Ghana.

- The opportunity exists to make an optimization model to find the optimal point between prioritizing support for the most viable and most affected regions. This trade-off between losing farmers and giving subsidies to set up a diversified income stream is now explored with a hybrid strategy, but this could be further explored with an optimization model.

- The hybrid strategies considered in this study have both the same timing (i.e. both proactive or reactive). The findings of this study show that combining proactively investing in shade trees in the most viable regions and reactively in the most affected regions could be a suitable strategy. Future research could investigate this combination.

- Additional research regarding the implementation of interventions is necessary to ensure the effectiveness of climate adaptation measures. This study is focused on the methodological aspects of the problem: what is the impact of climate change, how do people respond to it, and what would be the most robust intervention? The multi-actor context, however, is beyond the scope of this study. Remaining questions are: What kind of cooperation between stakeholders is crucial? How are the government, financial institutions, NGOs, and local parties working together to adapt to climate change? This multi-actor focus could also provide insights into how the dependencies and power between agents is divided.

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Appendix

Appendix A: Carbon price parametrization

RCP8.5: This is a more pessimistic scenario, corresponding with the highest greenhouse gas emissions in absence of climate change policy (Riahi et al., 2011). The characteristic that there are no mitigation measures leads to the assumption that no carbon price can be set until 2050 under this scenario.

RCP2.6: In the agent-based model, carbon pricing can be switched on and off. When carbon-pricing is switched on, the following scenarios are used in line with the IMF (2019):

(1) Scenario with $25/ tCO_2 by 2030 (IMF, 2019). The starting point in 2020 is assumed to be $10/ tCO_2. Ghana doesn't have a carbon price yet. The start value is therefore chosen to be in line with the only African reference point, South Africa, with a carbon tax of $10/ tCO_2 in 2019 (IMF, 2019).

(2) Scenario with $50/ tCO_2 by 2030 (IMF, 2019). The starting point in 2020 is assumed to be $10/ tCO_2, following the same logic as scenario 1.

(3) Scenario with $75/ tCO_2 by 2030. The High-Level Commission on Carbon Prices recommends that a carbon price of at least US$60/$tCO_2$ by 2020 and US$75/$tCO_2$ by 2030 is consistent with achieving the Paris temperature target (Stiglitz et al., 2017). This recommendation is made explicit in the following table. A linear trend of 1.5 USD increase per year is assumed and extrapolated for the years 2030-2050.

Table 12 Carbon pricing scenarios in RCP2.6

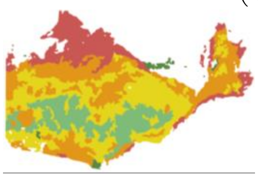
Year	$25/tCO2 in 2030	$50/tCO2 in 2030	$75/tCO2 in 2030
2020	10	10	60
2021	11.5	14	61.5
2022	13	18	63
2023	14.5	22	64.5
2024	16	26	66
2025	17.5	30	67.5
2026	19	34	69
2027	20.5	38	70.5
2028	22	42	72
2029	23.5	46	73.5
2030	25	50	75
2031	26.5	54	76.5
2032	28	58	78
2033	29.5	62	79.5
2034	31	66	81
2035	32.5	70	82.5
2036	34	74	84
2037	35.5	78	85.5
2038	37	82	87
2039	38.5	86	88.5
2040	40	90	90
2041	41.5	94	91.5
2042	43	98	93
2043	44.5	102	94.5
2044	46	106	96
2045	47.5	110	97.5
2046	49	114	99
2047	50.5	118	100.5
2048	52	122	102
2049	53.5	126	103.5
2050	55	130	105

Appendix B: Analysing the climate impact in ArcGIS

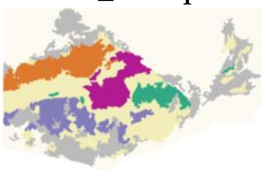
Rough ASC datasets of RCP2.6 and 8.5, shared by researcher Christian Bunn, are converted into maps to measure the size of the affected regions with geographic information system ArcGIS. The geoprocessing tools *define projection, clip*, *raster to polygon*, *calculate geometry*, and *summary statistics* in geographic information system ArcGIS are used for this purpose.

Christian Bunn (author of *Recommendation domains to scale out climate change adaptation in cocoa production in Ghana*, 2019) shared the following datasets:

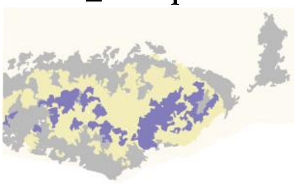
1. **Change_final.lpk** showing the map with changed cocoa suitability for RCP6 in 2050 (difference between current and future)



2. **Current_final.lpk** showing the map of current cocoa regions



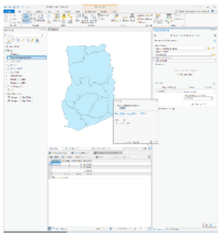
3. **Future_final.lpk** showing the map of future cocoa regions in 2050



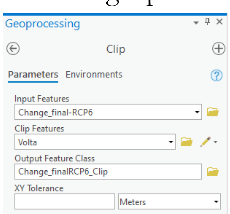
4. ASC dataset for RCP2.6
5. ASC dataset for RCP8.5

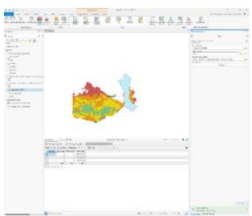
<u>Step 1: Make the above maps (RCP6.0) regional and calculate the areas</u>

- Geoprocessing tool *Feature Class to Feature Class* are used to make separate regional maps based on *Region* Expression. For example, the region Volta:

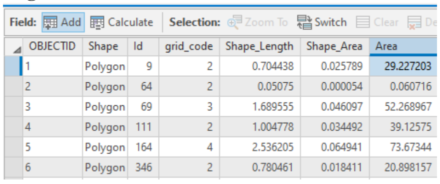


- To make the RCP6.0 map with cocoa suitability differences (**change_final.lpk**) regional, I used the geoprocessing tool *Clip*.

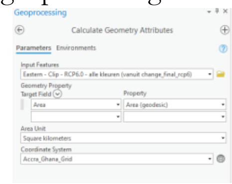




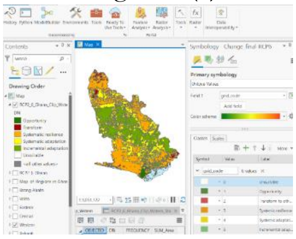
- Based on the coordinates it was possible to calculate the area (km²) for each of the climate regions with the *Attribute table* and the geoprocessing tool *Calculate Geometry Attributes*.



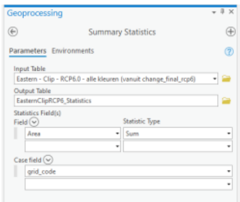
OBJECTID	Shape	Id	grid_code	Shape_Length	Shape_Area	Area
1	Polygon	9	2	0.704438	0.025789	29.227203
2	Polygon	64	2	0.05075	0.000054	0.060716
3	Polygon	69	3	1.689555	0.046097	52.268967
4	Polygon	111	2	1.004778	0.034492	39.12575
5	Polygon	164	4	2.536205	0.064941	73.67344
6	Polygon	346	2	0.780461	0.018411	20.898157



- The symbology of the map is adjusted to get the *DN* or *grid_code* corresponding with the climate regions: (1) not exposed, (2) low exposure, (3) medium exposure, (4) high exposure.



- The next step was to take the sum of the areas per classified region with the *Summary Statics* tool.

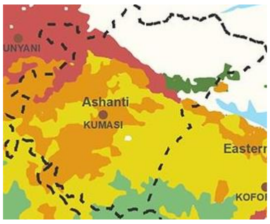


- This resulted in the following table of absolute area (km²) per *grid_code* (meaning climate region):

OBJECTID	grid_code	FREQUENCY	SUM_Area
1	1	3	57.122342
2	2	1	243.571139
3	3	4	658.373935
4	4	4	673.123706
5	5	1	82.371564

The sum of these area (corresponding to *grid_code* 1 till 5) is however not equal to the total area (km²) on Google. For example, 571,… + 2435,… + 6583,… +6731,… + 823,… = 14709,… km² for Ashanti. However, the total area of Ashanti is however 24389 km² according to Google. So, the area is only 14709,…/24389,…= 60% mapped.

This difference can be explained by 30% white remainder, shown in this map. The remainder shows the unsuitable area of Ashanti; it was already unsuitable for cocoa at the start of the model.

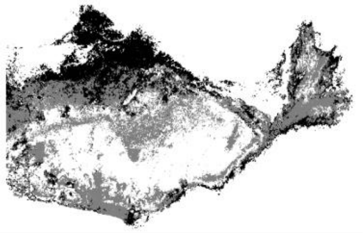
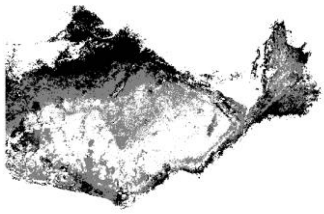


RCP6.0					
Brong Ahafo	0%	71%	26%	3%	0%
Ashanti	3%	14%	38%	39%	5%
Eastern	2%	4%	24%	53%	17%
Central	0%	3%	11%	39%	47%
Western	1%	1%	26%	37%	35%
Volta	2%	25%	54%	19%	0%

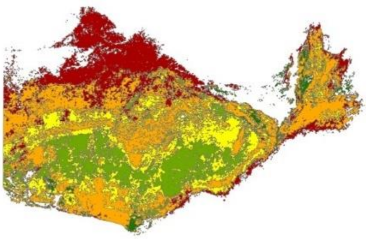
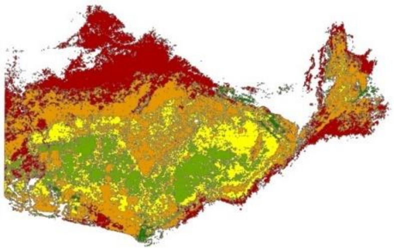
The final step was to calculate the percentages of the region, based on the total area (km²) that has a *grid_code*. For example, the value for no vulnerability is 143.56 for Volta, out of 6618. This means 2% of the area is highly exposed.

Step 2: Loading the RCP2.6 and RCP8.5 files (2050)

- The rough ASC files are first imported in ArcGIS

- Use the *define projection* tool to make the connection between Current_final.lpk and the ASC files
- The symbology of the map is adjusted to get the *DN* or *grid_code* corresponding with the climate regions: (1) not exposed, (2) low exposure, (3) medium exposure, (4) high exposure.
- This resulted in the following maps:

Step 3: Make the RCP2.6 and RCP8.5 maps regional and calculate their cocoa suitability (2050)

- The regional maps for RCP2.6 and RCP8.5 are then transformed into regions.
- The exposure categories within those regions could then be measured. All steps to do so are explained under 'Step 1'.

Appendix C: Exposure per region in 2050

Table 13 Regional exposure to climate change in 2050

RCP2.6: exposure (% km^2 per region), 2050

	high	medium	low	no
Brong Ahafo	85%	7%	4%	4%
Ashanti	34%	37%	19%	10%
Eastern	13%	47%	26%	14%
Central	14%	35%	46%	5%
Western	12%	39%	37%	12%
Volta	36%	23%	17%	24%

RCP8.5: exposure (% km^2 per region), 2050

	high	medium	low	no
Brong Ahafo	91%	3%	3%	3%
Ashanti	34%	37%	16%	13%
Eastern	16%	53%	19%	12%
Central	18%	38%	39%	5%
Western	16%	41%	33%	10%
Volta	59%	18%	10%	13%

Appendix D: Exposure per cocoa farm in 2050

The next step is to plot the location of the cocoa farmers investigated, on the map prepared. FMO's client does not have a traceability system in place to know where its suppliers are located. Therefore, the client's suppliers are mapped across regions, proportionally to national sourcing (COCOBOD, 2018). This calculation is included in Confidential Appendix E, and has the following result:

Table 14 Exposure to climate change on farm level (scale 1:100), with 5 categories in 2050

RCP2.6: number of farms, classified per exposure

Region	(red)	(orange)	(yellow)	(light green)	(dark green)
Brong Ahafo	47	10	2	0	0
Ashanti	23	42	28	7	1
Eastern	3	17	22	10	4
Central	5	12	16	22	0
Western	9	111	85	77	6
Volta	1	2	1	0	0
Total	88	194	154	116	11

RCP8.5

Region	(red)	(orange)	(yellow)	(light green)	(dark green)
Brong Ahafo	49	9	1	0	0
Ashanti	22	47	26	5	1
Eastern	5	15	25	7	4
Central	7	12	18	18	0
Western	18	112	86	66	6
Volta	2	2	0	0	0
Total	103	197	156	96	11

In this process, the exposure category 'highly uncertain' (no agreement between 19 global climate models) as suggested by Bunn et al. (2019) is divided evenly over the other categories: no, low, medium, high exposure, i.e. ¼ each.

Table 15 Exposure to climate change on farm level (scale 1:100), with 4 categories

RCP2.6: number of farms, classified per exposure, 2050

Region	(red)	(yellow)	(light green)	(dark green)
Brong Ahafo	50	5	2	2
Ashanti	34	39	17	11
Eastern	7	27	14	8
Central	8	19	25	3
Western	37	113	105	33
Volta	2	2	0	0
Total	138	205	163	57

RCP8.5, 2050

Region	(red)	(yellow)	(light green)	(dark green)
Brong Ahafo	52	4	2	1
Ashanti	34	38	17	12
Eastern	9	29	11	7
Central	10	21	21	3
Western	46	114	94	34
Volta	3	1	0	0
Total	154	207	145	57

Another method could have been to divide the highly uncertain category according to weights. The different methods have the following over- and underestimations:

Table 16 Over- and underestimating due to distribution method

	(red)	(yellow)	(light green)	(dark green)
RCP2.6	-14.69	+37.70%	+16.77%	-39.78
RCP8.5	-11%	18%	%10%	-70%

Appendix E: Climate trend from 2020 till 2050

E.1 Linear climate trend

The 30-year trend from the current situation (2020) to the affected farms in 2050 is assumed to be linear.

- There are four types of exposure: no, low, medium and high.
- All farms start in no exposure, and end in 2050 in one of the other categories.
- As it is a linear scenario, the time frame is split into 3 intervals of 10 years: together 30 years.

$$t_1 = 10,\ t_2 = 10,\ t_3 = 10$$

- The exposure of each farm evolves step by step: the farms becoming highly exposed first go through the low and then the medium exposed stage. This process follows the logic of a Markov chain, where cocoa farmers go through a sequence of events.
- For example, the exposure in Brong Ahafo in 2050 should look like this:

Region				
Brong Ahafo	50	5	2	2

- For the example, therefore, a total of 50 farmers of no exposure move to low in interval 1, and in interval 2 they will move to medium.
- For the farmers that end in medium, we assume that they will not move forward in the first period.
- This "shifting" is done in a linear manner. Below is the formula for the transfer the first period:

$$\#farmers_2(t) = \frac{50}{t_1} * t$$

$$\#farmers_1(t) = 59 - \#farmers_2(t)$$

- $\#farmers_2$ is the number of farmers in the second exposure category (low) at time t (in years), $\#farmers_1$ is the number of farmers in the first exposure category (no)

- In the second interval of 10 years, we follow the same principle for these 50 farmers.

$$\#farmers_3(t) = \frac{50}{t_1} * (t - t_2)$$

- The number of farmers in the 2nd category (low exposure) is hard to calculate, because there are both incoming farms from no exposure as well as outgoing farms to medium exposure. The formula will therefore look like this:

$$\#farmers_2(t) = \#farmers_2(t_1) - \#farmers_3(t) + \frac{10}{t_2} * (t - t_1)$$

- In other words, the number of farmers you start with are $(b_2(t_1))$, minus the number of farmers transferred to exposure category 3 from 2, plus the farmers shifted to category 2 from 1.
- The number of farmers in the first category (no exposure) is now:

$$\#farmers_1(t) = 59 - \#farmers_2(t) - \#farmers_3(t)$$

- The logic is also applicable for the next steps. For each exposure category it is calculated: what is your initial state, which farmers leave the gradation and which farmers join the category.

This is also visualized in the following figure:

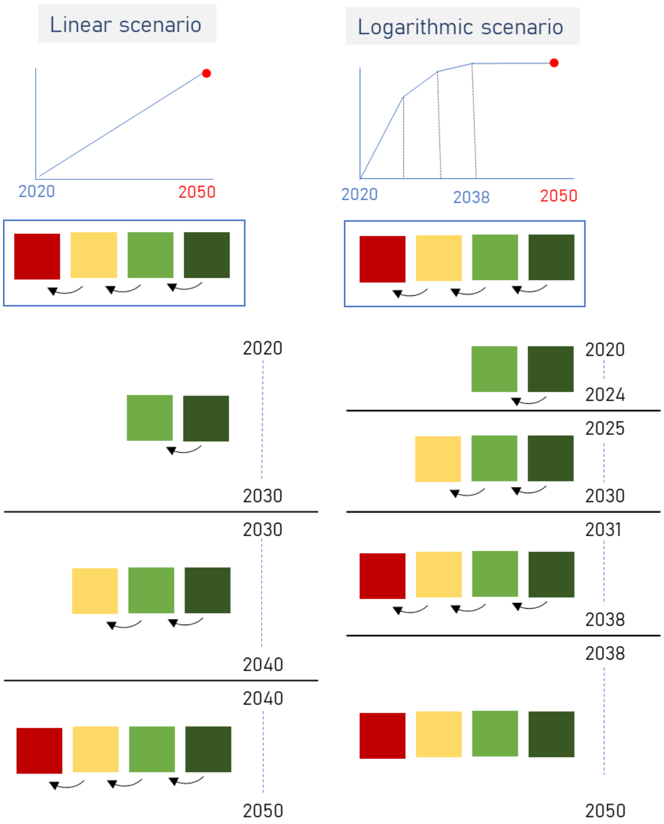


Figure 43 Logic behind exposure categories

E.2: Logarithmic climate trend

To explore the effects on the longer term, a logarithmic trend is included to illustrate the situation of 2050 earlier. In this trend the exposure to climate change rises sharply in the beginning and then decreasingly increases up to a plateau in 2038.

The process from 2020 till 2050 follows the same logic as linear does, except for the following differences:

- All farms start in no exposure, and end in 2038 in one of the other categories.
- As it is a logarithmic scenario, the time frame is split into 3 intervals of 4, 6 and 8 years: together 18 years. The interval of only 4 years results in a steeper curve than for example 8 years to show the logarithmic trend.
  $t_1 = 4,\ \ t_2 = 6,\ t_3 = 8$
- After 2038, all farms do not change their exposure until 2050.

Appendix F: Theory of Change

A conceptualization with the Theory of Change, i.e. mapping the process of social change, is made in the first stage of model development. It helped the conceptualization process by identifying how and when climate change and the livelihood strategies impact.

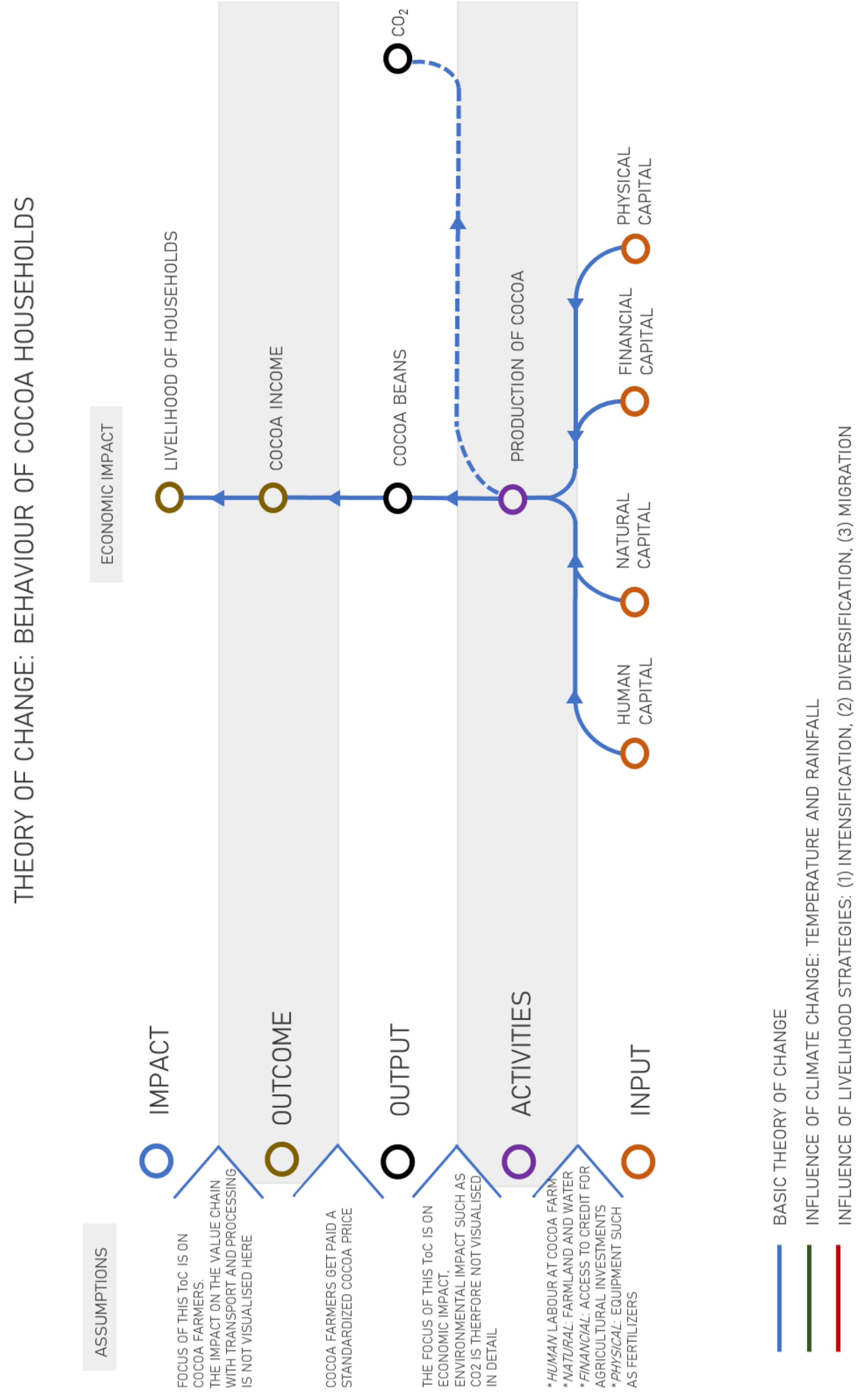


Figure 44 Simple Theory of Change

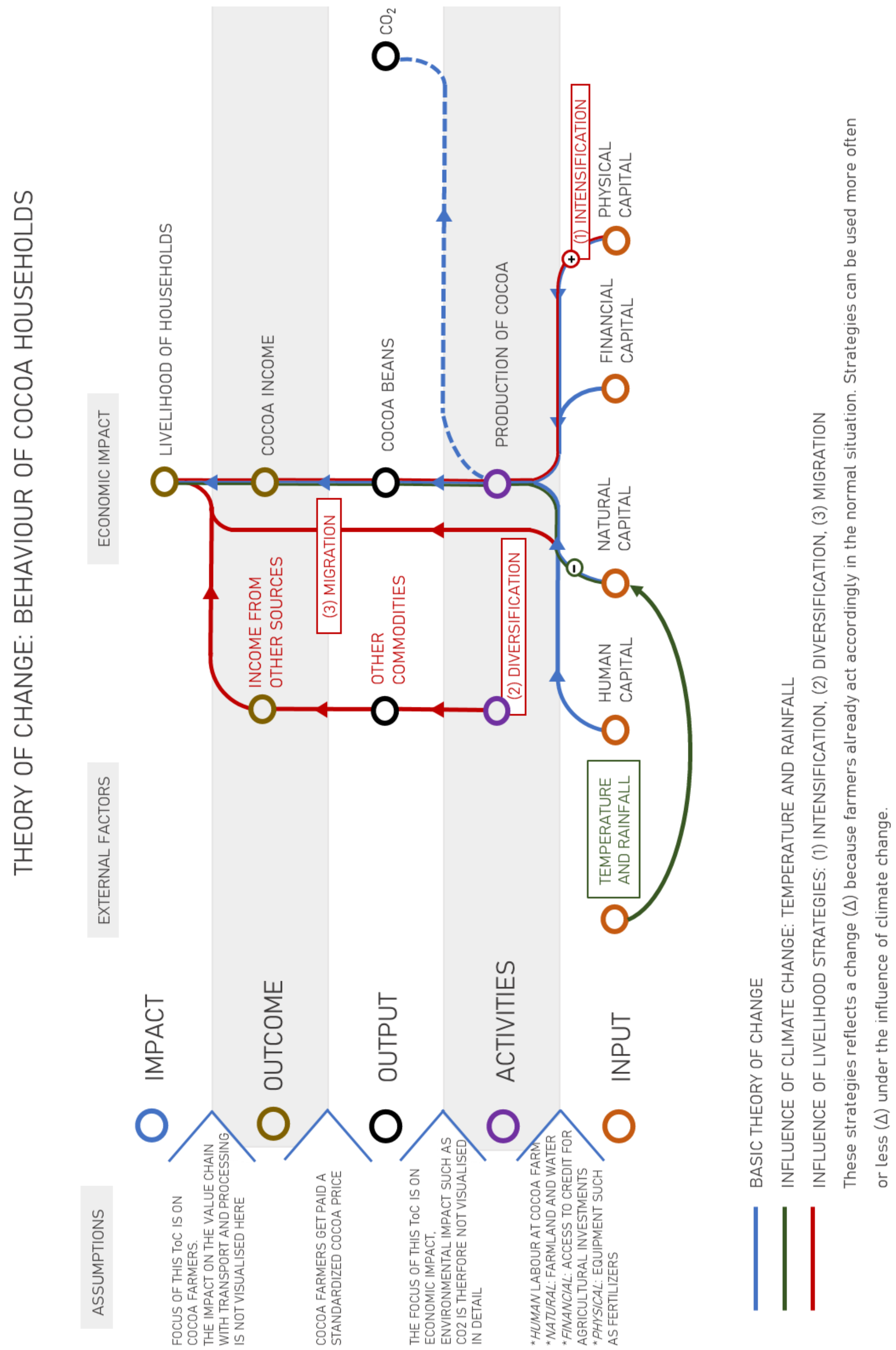


Figure 45 Extended Theory of Change with livelihood strategies and climate impact

Appendix G: Robust Decision Making

The key elements of RDM are explained according to Lempert (2019):

1. Multiplicity of plausible futures;
2. Robust rather than optimal strategies (i.e. well performing interventions compared to other alternatives, over multiple futures);
3. Employ adaptive strategies to achieve robustness (i.e. interventions evolving over time in response to new information);
4. Use the computer to facilitate explorations and trade-off, rather than ordering of strategies.

Appendix H: Assumptions

H.1: Assumptions for scenario development

Table 17 Assumptions about scenarios

ASSUMPTIONS ABOUT SCENARIOS		
Assumption	Topic	Explanation
1	Climate risk on infrastructure	The climate-related risks on infrastructure is beyond the scope of this model. Limited infrastructure and poor access to villages due to heavy rainfall could be a problem when cocoa beans have to be delivered to the LBCs.
2	Land-use	Assumed is that there is no more available land in the scenarios. Climate change is accompanied by increasing population and increasing urbanisation which in turn decreases the amount of available land. The climate scenarios used as model input don't account for these land-use changes, including deforestation.
3	Limited production	Assumption 2 also means that FMO's client is not able to expand the number of supplying farms than their current supplying farms. So, in the model the client's production is limited to the current capacity and will not change over time.
4	Demand for cocoa	Worldwide demand for cocoa is beyond the scope of this model. Increasing demand for cocoa would trigger more production while the available land is limited due to increasing population and deforestation (Wessel & Quint-Wessel, 2015). This complexity is out of scope.
5	Child labour	Child labour is not monitored in this Agent-Based Model, as the model is focused on climate-related effects on cocoa production and climate adaptation opportunities for FMO.

H.2: Assumptions for agent-based model

The value chain agents all have states in the agent-based model. The assumptions are listed per agent in the following tables:

Table 18 Assumptions about agents

ASSUMPTIONS ABOUT SUPPLY CHAIN AGENTS		
COCOA SMALLHOLDERS		
#	Topic	Explanation
		Agents
6	Smallholders	All agents in the model are smallholders as 90% of cocoa is grown by smallholders (FMO, 2018b).
7	Definition of smallholders	Defining a smallholder is a matter of threshold: below a certain size a farmer is called a smallholder (FAO, 1992). In this study, smallholders are farmers with less than 4 ha land.
8	Agent represents a household	The smallholder agent represents a 'cocoa household': households who reported cocoa to be either their most important or second most important crop (Bymolt, Laven & Tyszler, 2018c).
9	Rainfed vs. irrigation	All farms are assumed to be rainfed. A very small percentage farms will use irrigation and are therefore more climate-proof, but it is hard to track the percentage of irrigated farms that supply to FMO's client.
10	Active in cocoa	Initially, every smallholder is active in cocoa farming. Later, it could be possible that they change to other sources of income, resulting in the state 'Active in cocoa farming?' False.
11	# of agents cannot increase	The number of supplying farms to FMO's client cannot increase over the time. This assumption is made because of the scarcity of available land for new farms, especially in cocoa suitable area. Secondly, current farms are already supplying to other companies and competition of this market share is out of scope.
		Cocoa income

12	Cocoa income	The methodology to calculate the cocoa income is based on the calculation of Bymolt, Laven and Tyszler (2018). It consists of the following elements: *productive land* (ha), *productivity* (kg/ha), *cocoa price* (USD/kg), *value of production* (USD/year), *input costs* (USD/year) and *hired labour costs* (USD/year). All of these elements are covered in this study:
12A	Productive land	The initial land productivity is 400kg/ha on farms operating under low technology level (USAID, 2017b). Farms under medium and high production levels are out of scope.
12B	Productivity	The smallholder agent represents a 'cocoa household': households who reported cocoa to be either their most important or second most important crop (Bymolt, Laven & Tyszler, 2018c).
12C	Cocoa price	The price of cocoa differs from the study of Bymolt, Laven and Tyszler and is explained under COCOBOD.
12D	Net cocoa income	The net cocoa income of cocoa smallholders consists of (Bymolt, Laven & Tyszler, 2018d): * Revenues: value of production = *productive land* (ha) * *land productivity* (kg/ha/year) * *price* (USD/kg) * Costs: *input costs* (USD/ha) * *productive land* (ha) + *hired labour costs* (USD/ha) * *productive land* (ha)
12E	Labour costs	The hired labour costs are assumed to be 97 USD per ha per year (Bymolt, Laven & Tyszler, 2018d). Smaller cocoa farmers in Ghana use family labour which might be supplemented by hired labour. On larger farms it is common to have caretakers working fulltime. It becomes increasingly difficult to find laborers since it is physically demanding, and the youth of Ghana migrates from farms to urban areas.
12F	Input costs	The input costs consist of investments such as granular fertiliser, liquid fertilizer, herbicides and pesticides and are assumed to be 41 USD/ha/year on average, while there are also households reporting not doing the activities related to the input above (Bymolt, Laven & Tyszler, 2018c).
13	Poverty	In order to compare the incomes to the poverty lines, the income per person per day is calculated by: net income household / average household size / 365 days. The average cocoa household size in Ghana is 5.9 members (Bymolt, Laven & Tyszler, 2018c). This formula results in USD/person/day. These values need to be converted into PPP, following the methodology of Bymolt, Laven & Tyszler (2018b). The daily income per person in USD is changes to PPP with PPP conversion rates without equivalence scale.
		Household income
14	Income division	Initially, cocoa households earn 61% of their income from cocoa, 30% from diversification and 9% from migration. This is based on a survey of Bymolt, Laven, Tyszler (2018c): - Intensification: 61% sale of cocoa - Diversification: 20% sale of other crops and 10% trading - Migration: sum of remittances from friends and family living away from the household and salary of employment in a governmental job (adding up to 9%)
		Cocoa production
15	Number of farmers	Confidential Appendix E
16	Production cannot increase	Production can only increase if farmers become more efficient
17	Mid and main crop	No division is made between mid and main crop harvest during the year
		Emissions
18	CO2 emissions	A life-cycle assessment (LCA) on the production of 1 kg cocoa bean in Ghana showed that the production step at the farms contributes to 16% of the total CO2 emissions associated with production, transportation and processing (Ntiamoah & Afrana, 2008). The CO2 emissions of the smallholders are therefore assumed to be 0.16 * 0.32286 ≈ 0.0516576 kg CO2 equivalent per kg cocoa beans.
		Migration
19	Income after migration	The new source of income of farmers who completely stop producing cocoa due to disappointing production and income is beyond the scope. The fact that they stop farming and choose for migration, for example, is modelled. However, it is not a geographical migration model with GPS coordinates.
20	Economic migration	Migration is only climate-driven and not political or due to war. Individuals who strive for a high standard of living may be assumed to make different decision than those fleeing from war (Klabunde & Willekens, 2016).
		Regions and climate

21 Spatial distribution — Confidential Appendix E

22 Exposure categories — All farms start in 2020 in the dark green (no exposure) category. Over the years, they may move to light green (low exposure), yellow (medium exposure) or red (high exposure). To end up in red, the farm first needs to go through the low and medium exposure stages (assumption that exposure is increasing linear over time). The full mathematical methodology for the exposure categories is written in Appendix E.

23 Loss of production due to exposure — The exposure to climate change results in a loss of production. Schreyer, Bunn, & Castro-Llanos (2018) did a cost of inaction analysis to produce the following estimate ranges:

Exposure	Loss of production (according to Schreyer, Bunn & Castro-Llanos, 2018)
low exposure	10-20%
Medium exposure	30-50%
High exposure	60-100%

The agent-based model assumes the loss to production to be the first mentioned percentage. The estimate range is tested in the scenario analysis.

Age of cocoa farms

24 Complete replanting — It is assumed that all cocoa trees on a farm have the same age, so there is complete replantation after the lifetime (no phased or partial replantation).

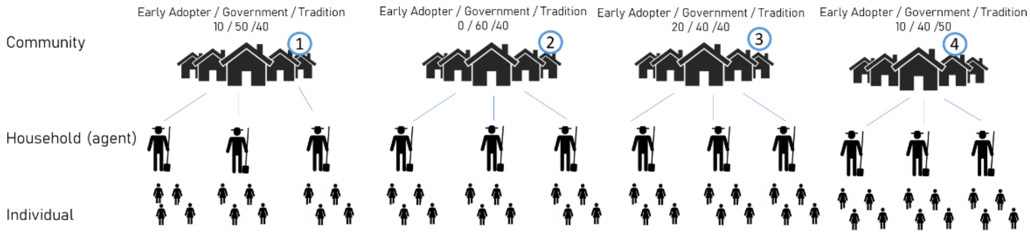
25 Age distribution of cocoa tree stock — Ghana deals with an age problem (Wessel & Quist-Wessel, 2015). Most of the cocoa farms were planted in the 1980s when the government revived the sector. They estimate that 23% of the cocoa tree stock is older than 30 years and therefore less productive (Pandey, 2017). In this model, the age distribution is therefore split in four categories (Dalaa, Kofituo & Asare, 2019):
* young, 0-15 years: 38.5 %
* mature, 15-30 years: 38.5%
* > 30 years: 23%
After 15 years, this group of cocoa farmers goes to the next category. The age distribution is randomly distributed through the cocoa growing region.

26 Old cocoa trees — If a cocoa tree becomes old, the yield will decrease, resulting in a loss of income (Wessel & Quist-Wessel, 2015). In this model, it is assumed that the cocoa trees older than 30 years will be replanted after 15 years. The age of the cocoa tree stock is also a window of opportunity for migration. It is assumed that there is enough credit to buy new seedlings.

Behaviour profiles

27 Initial behavioural profiles — Initially, there are four community types with a different division of behavioural groups. Each of the four communities is present for 25% in the cocoa growing region.

- Community 1: 10% EA, 20% Government, 40% Traditional
- Community 2: 0% EA, 60% Government, 40% Traditional
- Community 3: 20% EA, 40% Government, 40% Traditional
- Community 4: 10% EA, 40% Government, 50% Traditional

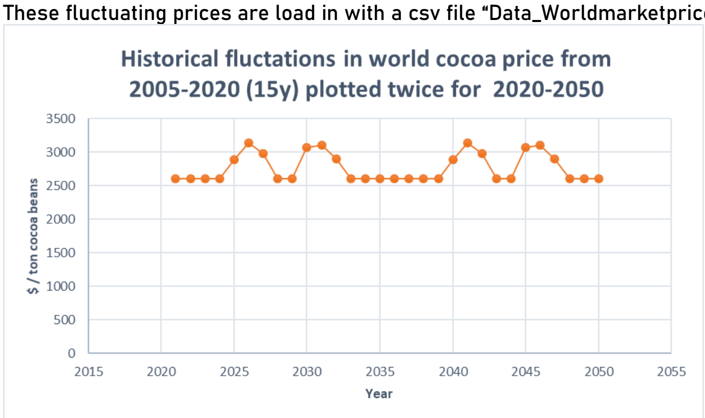


28 Move to governmental profile — Farmers can get access to agricultural training, which means that traditional households can move to more governmental oriented households. 78% of the trainings is provided by the government (Laven CH9).

It is assumed that 7 households will move each year, because results from a survey suggest that 49% has received cocoa training in the past 5 years (Laven chapter 9). This is 9.8% per year. Results from the survey also suggest that only 16% received a training that changes their practices and most trainings were of very low intensity.
Therefore, 563 farmers * (0.49/5) * 0.16 ≈ 7 farmers received intense trainings. Those farmers will move to the governmental behaviour profile.

29	Move to early adopter	Ghana is rapidly moving towards a higher literacy rate. Since most children of cocoa households have access to education (literacy rate of 71% in 2010 (World Bank, 2020), households can also move to early adopters. Research shows that 1 out of 10 of the youth is interested in cocoa farming (Bymolt, Laven & Tyszler, 2017) It is therefore assumed that 563 farmers * 0.71 * 0.1 = 40 households become early adopter. It is not a yearly rate, but it can only happen for the three kids in a household over 30 years. Therefore, the amount is divided by 10 and only 4 households will move to early adopter.

Table 19 Assumptions about COCOBOD

ASSUMPTIONS ABOUT SUPPLY CHAIN AGENTS		
COCOBOD		
#	Topic	Explanation
		Cocoa price
30	World market price	There are two options for the world market price in the model. On June 12 2019, the governments of Ghana and Cote d'Ivoire announced a floor price of 2600 USD per ton cocoa beans (Rainforest Alliance, 2019b). This floor price could be set because the two countries are responsible for 65% of the world market. (1) The first option in the ABM model is to run with the floor price of 2600 USD per ton, constant over the years. (2) The second option is to run the model with historical fluctuations over the past 15 years (ICCO, 2020). The yearly averages of daily cocoa prices are retrieved from the International Cocoa Organization. The numbers from 2005-2020 will run two times for the period 2020-2050 in the model, but prices smaller than 2600 USD per ton are manually adjusted to 2600 (according to the recently announced floor price, see Figure below). These fluctuating prices are load in with a csv file "Data_Worldmarketprice". 
31	Price for farmers	The cocoa price for farmers is set at 70% of the world market price. This is in line with the new announced prices of Ghana and Cote d'Ivoire (Fairtrade, 2019). (1) In case of a floor price of 2600 USD per ton, the farmers will be entitled to 70% which is 1820 USD per ton. (2) In case of the fluctuating world market price, the cocoa farmer price is 70% of this yearly price. These recently announced prices mean that the net income of cocoa farmers is higher than measured in the study of Bymont, Laven and Tyszler (2018a). They used a cocoa price for farmers of 1773 USD/ton.
32	Feedback loop	The world market price will increase if global production of cocoa decreases due to climate change. When the price rises, it is more attractive to start in cocoa again. For example, by starting a farm in the most viable regions with the risk of deforestation. This loop is not included in this model.

The assumptions specific for FMO's client can be found in Confidential Appendix E.

Appendix I: Overview of behavioural thresholds

The main behavioural thresholds are shown in the following Table 20, corresponding with the flowchart in Section 6.4. The motivation for the thresholds is also explained in Section 6.4.

Table 20 Overview of behaviour thresholds

	Topic	Threshold
1	Permanent migration	The age of cocoa trees > 30 years; and The current income < poverty index Additional: - Early adopters: income should be lower than poverty index for 2 years - Government: income should be lower than poverty index for 4 years - Traditional: income should be lower than poverty index for 6 years
2	Social influence of permanent migration	Your neighbour has decided to migrate; and Your current income < poverty index; and The age of cocoa trees > 25 years
3	Focus on diversification	Your income is decreased with: - Early adopters: 40% - Government: 50% - Traditional: 60% compared to your reference income in 2020; and Not more than 20% of the cocoa farmers in Ghana have entered a new market
4	Switch of groups	Select 7 random governmental households that change to early adopter, through education Select 4 random traditional households that change to governmental, through COCOBODs' trainings

Appendix J: Concept formalization and narrative

J.1: Formalization

The conceptual model that is described in chapter 6 is formalized in this chapter. The concepts are converted into computer understandable analogues. Van Dam et al. (2013) made list of these analogues: numbers (both integers and floats), strings (text characters), booleans (true/false), objects (elements containing both data and functions), classes (types of objects), lists and tables (containing data and information) (Van Dam et al., 2013).

The parameters are based on the assumptions in Appendix H.1

Table 21 Concept formalization

CONCEPT FORMALIZATION			
State	Unit	Analogues	Parameter
Productive land	ha	Integer	4
Land productivity	kg/ha/year	Integer	400
Value of production	USD/year	Float	≥ 0
Input costs	USD/year	Integer	96
Labour costs	USD/year	Integer	233
Net household income	USD/year	Float	≥ 0
Income per person per day	PPP/person	Float	≥ 0
Region		String	Brong Ahafo, Ashanti, Central, Western, Eastern, Volta
CO2 equivalent emissions	kg CO2/kg beans	Float	0.0516576
Production	ton/year	Float	≥ 0
Age group	year	Integer	0, 15 or 30
Behaviour group		String	Early adopter; government; traditional
• Active in cocoa farming?		Boolean	Yes; No
Diversification income	USD/year	Float	≥ 0
Migration income	USD/year	Float	≥ 0
Cocoa income	USD/year	Float	≥ 0
Reference cocoa income in 2020	USD/year	Float	≥ 0
Looking for diversification job?		String	No; Done
Community members	Agents	Integer	≥ 0
Reference production in 2020	ton/year	Float	≥ 0
Permanent migration		Boolean	Yes; No
Subsidy given		Boolean	True; False
Supported with pest management		Boolean	True; False
Supported with shade trees		Boolean	True; False
Delay before effectiveness of shade trees	Year	Integer	5
Loss of production, low exposure	%	Integer	10-20%
Loss of production, medium exposure	%	Integer	30-50%
Loss of production, high exposure	%	Integer	60-100%
Additionality	USD/year	Float	≥ 0
Cocoa price			
State	Unit	Analogues	Parameter
Floor price	USD/ton	Integer	2600
Percentage for farmers	%	Float	0.7
Carbon price	USD/ton	Integer	Appendix A
World market price	USD/ton	Integer	Assumption 30, Appendix H

The parametrization specific for FMO's client are listed in Confidential Appendix F.

J.2: Pseudo code

Secondly, the outcome of the model formalization is the model narrative. It describes the setup and model-running procedures.

J.2.1 Setup narrative

Setup environment

Setup an environment containing the cocoa growing region in Ghana
Open the file with data on the worldmarketprice
Set the global variables/climate scenarios

Setup farmers

Create a certain number of smallholder farmers

Locate them randomly in the cocoa growing region, in the southwest of Ghana
Give them a darkgreen color
Set the initial productive land
Set the initial land productivity
Set the initial value of production
Set the initial input costs
Set the initial hired labour costs
Set the initial net income, diversification and migration income
Set the initial CO2 emissions
Let them know they are active in cocoa farming
Let them know they are not migrated and do not receive climate adaptation
Set the age of their cocoa tree stock

Setup regions

Set the regions Ashanti, Brong Ahafo, Eastern, Central, Western and Volta for a fixed number of farms
Give a fixed number of farms per region a behavioural group

Setup COCOBOD

Create one COCOBOD

Locate
Give them a white color
Set the initial world market price
Set the minimal farmer percentage
Set the carbon price

The set-up of FMO's client can be found in Confidential Appendix G.

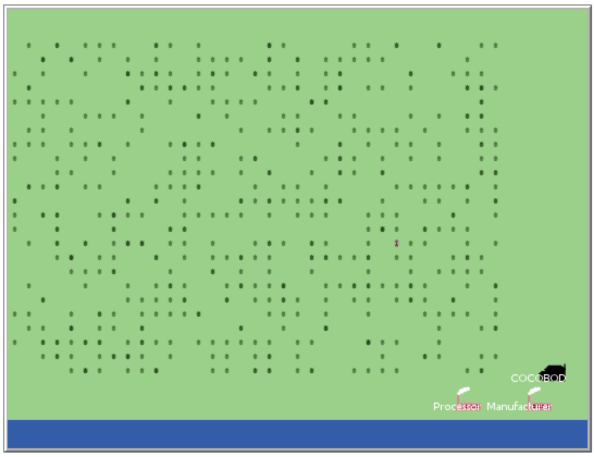


Figure 46 Visualized setup

J.2.2 Setup running of the model

Count another year
Ask farmers with shade tree investments to delay the growing time with one year
New strategy for farmers

Migration strategy
Ask farmers which are still active in cocoa (only when year 1 is over)
If they have a lower income than the poverty index AND their cocoa tree stock is older than 30 years
Ask early adopter farmers if their income was lower than the poverty index last year as well
Stop producing cocoa
Stop diversifying
Start full migration
Ask governmental oriented farmers if their income was under the poverty index for the last three years as well
Stop producing cocoa
Stop diversifying
Start full migration
Ask traditional farmers if their income was under the poverty index for five years in a row
Stop producing cocoa
Stop diversifying
Start full migration

Migration when neighbours also migrate
Ask farmers if they have an income lower than the poverty index AND their cocoa tree stock is older than 25 years
Ask farmers which are still active in cocoa to identify their neighbours within a radius of 5
If there are any community members in the same region that stopped cocoa production
Also stop producing cocoa
Stop diversifying
Start full migration

Behavioural group change
If there is access to new technologies from the government and access to education
Ask 7 random farmers in a traditional group
Set their behaviour group to governmental oriented
Ask 4 random farmers in a governmental oriented group
Set their behaviour group to early adopter

Focus on diversification with reduced income
If the number of farms that are focusing on a new sector don't exceed 20% of all farms
Ask farmers who are active in cocoa farming and are not yet changed to a new sector
If their behavioural group is early adopter
If their income from cocoa farming is lower than 60% compared to 2020
Set diversification income 1,25 times higher
Set looking for new sector 'done'
If their behavioural group is government
If their income from cocoa farming is lower than 50% compared

to 2020

Set diversification income 1,25 times higher

Set looking for new sector 'done'

If their behavioural group is traditional

If their income from cocoa farming is lower than 40% compared to 2020

Set diversification income 1,25 times higher

Set looking for new sector 'done'

Set new yearly prices

Ask COCOCOD

If the worldmarketprice is set as 'Historical fluctuations (2005-2020)'

Load the worldmarketprice of cocoa in from a CSV file

Set the worldmarket price

If the worldmarketprice is set as 'Floor-price: 26000 USD/ton'

Set the worldmarketprice 2600

Set the farmer gate price 70% of the worldmarketprice

If the climate scenario is RCP2.6 with a low carbon price of $25 in 2030

Set the carbon price its current price + 1.5

If the climate scenario is RCP2.6 with a medium carbon price of $50 in 2030

Set the carbon price its current price + 4

If the climate scenario is RCP2.6 with a high carbon price of $75 in 2030

Set the carbon price its current price + 1.5

Set climate

If the climate scenario is RCP2.6 under all of the carbon prices

Ask a fixed amount of farmers per region on a specific tick to

Set their color green, yellow or red for a low, medium or high exposure

If the climate scenario is RCP8.5

Ask a fixed amount of farmers per region on a specific tick to

Set their color green, yellow or red for a low, medium or high exposure

(details of this process are documented in Appendix E)

Impact of climate

Ask farmers who are still active in cocoa

If their color is lime

Set land-productivity to 90% of the original productivity

If their color is yellow

Set land-productivity to 70% of the original productivity

If their color is red

Set land-productivity to 40% of the original productivity

If they receive climate adaptation, the production will increase

Grow cocoa plants

Ask farmers active in cocoa

Ifelse they focus on a diversified job on a new market

Set production of cocoa beans * 0.75

Set production of cocoa beans

Determine the value of production

Determine the CO2 emissions

Determine the income by substracting the value of production with input, labour and carbon costs

Income of farmers

- Set the total household income as a sum of cocoa, diversification and migration
- Calculate the poverty values

Procedures in Confidential Appendix G

Calculate KPIs

- Calculate the average cocoa income of all farms active in cocoa
- Calculate the loss of production by dividing the current production of all farms by a reference production in 2020
- Calculate the permanently migrated households
- Calculate all exposed farms to climate change
- Calculate the additionality
    - If the green or hybrid interventions are on
        - Subtracting the cocoa income from a run without intervention
    - If the red interventions are turn on
        - Multiplying a fixed income of low-skilled workers with the number of migrated households

Aging

- Ask all cocoa farmers active in cocoa
    - Set age +1
    - If the age is 45, the age of cocoa trees are set back to 0

Tick

Stop if ticks = 31

Appendix K: Summary and key-take aways interview 1

Social scientist with expertise in sustainable cocoa (PhD), 17 Jan 2020

Do you already see the impact of climate change in Ghana now?

In the Western region and Brong-Ahafo, farmers complain about unpredictable and delayed rainfall, as well as droughts. This has consequences for the timing of cocoa cultivation, such as planning of applying fertilizers. The planning of your agricultural practices depends a lot on the rain season. The rainfall is more extreme and there are more droughts. In certain areas (especially Western and Brong-Ahafo) farmers really struggle with that. Interviewee 1 has been hearing that for years. If you ask the farmers 'was it a good or bad year?', they will respond that the climate is change and there are pests and diseases.

Farmers are increasingly making the link with deforestation, have more knowledge on Climate Smart Agriculture and the importance of shade trees. The policy around shade trees is a bit confusing. Shade trees provide ecological services for birds and can positively affect climatic conditions by promoting cooler temperatures instead of full sun. In earlier times, the government recommended to remove shade trees, a policy that is now being reversed. So, farmers know there is something going on and they must change something but acting on that is still difficult.

How is the adoption of agricultural practices going?

You always have (1) early adopters, (2) people relying on traditions, and (3) people relying on the government. Overall, the cocoa yield decreased in the past years. They recently published an official map with data on cocoa yield. This reduction has to do with many reasons:

(1) Age of cocoa trees
(2) Pests
(3) Climate

So, it is not only about climate, but overall, you see a trend in decreased yields. The impact of climate is not only related to climate smart agriculture. Regarding practices, in the report '*Demystifying the Cocoa Sector in Ghana and Côte d'Ivoire*' the interviewee questioned a random sample of farmers. Most data you find only concerns farmers related to a certification programs, so it is biased data. According to evaluations, 75-80% of the farmers have access to trainings. This access is not equally spread among farmers. It mainly concerns the male habitat households < 4ha. Programs are always preferred by typical famers. Other groups do not find it interesting, do not have time or are not willing to invest effort in it.

However, the quality of training differs within this 75-80% with access to information. Farmers already respond with 'yes' to this question when they listened to a radio program on agricultural practices or had training in a big room. It would be better if training institutions go to the farms, do coaching there and a follow-up visit. This way of training is much more expensive.

Farmers are the only visitors at training, while there are a lot of migrants working on the farms without training. So, many people still do not have access to training. To better organize these trainings, you should think about your target group. Are you only going to work with motivated farmers?

What are the options for cocoa in Ghana based on the climate projections?

There are three options:

(1) <u>Intensification</u> – more production, most chocolate manufacturers are working on this
(2) <u>Diversification</u> of income - it is about the total income of a household, not only the farmer. Is it a possibility to produce multiple crops? And what are the possibilities to earn more, not from cocoa farming? Ghana is not as strong on other markets.
(3) <u>Conversion</u> – unavoidable.

Most companies are still working on intensification, farmers on diversification and they are not looking at conversion at all. It is however unavoidable. Intensification and diversification will never result in enough production. The core livelihood of many households is dependent on cocoa. Cocoa is the basis for all infrastructures in Ghana. The resilience is therefore low. Cocoa is a seasonal product that is flourishing from September till January. So, there is a very challenging combination of:

- Low resilience
- Climate change
- Seasonal product

Most studies focus on increasing the income of farmers. A better approach towards the cocoa industry is increased *stability for the long term*. Climate change affects this stability. Ghana needs: (*) resilience, (*) income diversification, (*) healthy financial infrastructures, (*) other markets than cocoa, and (*) both man and women. This income diversification is currently executed by women. They mostly work in trading, for example on markets. However, you shouldn't only focus on women. How do you as a household achieve optimum behavior?

What is your expectation about future behavior in response to decreasing yield? Are people for example starting to migrate?

There are still a lot of migrants from the North of Ghana coming to the cocoa growing regions, looking for work. Families dependent on cocoa don't want their kids to work in cocoa forever. However, children do not have too many alternatives. Especially dropouts do not have a better choice than cocoa, so there is still a constant influx of kids working in cocoa. There are also people that went to school but could not find a job. Be aware that the land is valuable, more than the cocoa yield only. Owning land is seen as your retirement income.

In the research of interviewee 1, there is a comparison with other crops because switching to rubber, cashew or palm oil are more resistant to a changing climate. Cocoa is still the most valuable crop. Rubber: you have to wait 5-7 years once rubber is mature; oil palm is more labor intensive. You can always sell cocoa and it is embedded in the country's tradition. Many people will never earn a living income from cocoa, but there is a lack of alternatives.

For example, there are big differences with cocoa in Indonesia. Cocoa is introduced later and not as rooted. If the cocoa price is low, farmers will find another crop. Due to their history people are less likely to adopt. At the same time, the population in growing and households consist of 5-6 people. It would have been better if there were less farmers.

A future scenario with only farmers, resilient to climate change, entrepreneurial with CSA practices and motivated, would be positive.

What is the best way to implement these CSA practices? Would micro finance also be an option?

The standard training packages consist of shade tree management and diversifying. Diversification of income is acknowledging, mostly in programs of LBCs. The government of Ghana is dominating with seedlings. They believe many farmers depend on ageing, unproductive cocoa trees. The government gives climate resilient seedlings and farmers provide feedback on which seedling work the best. There is however very little choice in seedlings and knowing what works.

There is no training program working with irrigation yet. You should be aware that water can be polluted by mining. Regarding options for micro finance, a lot of money is lost due to incorrect matching. It can be the case that all money is spent at the time the funding comes in. Help with financial planning and payment at moment outside high season is necessary.

What is your expectation about the adoption of (drip) irrigation systems?

Irrigation depends on water, which can be polluted by mining (only in some contexts). Climate caused (1) extreme rainfall and (2) problems with planning of cultivation. Irrigation does not solve those two problems.

Key take-aways:

- It would be interesting to include the community and family dynamics in the model and not only the farmers. It is more fluid than one "breadwinner". These dynamics could explain more of their rationales.
- There is already climate impact, for example in Western and Brong-Ahafo. Unpredictable and delayed rain affect the timing of agricultural practices, such as applying fertilizers.
- Most farmers know about the link with climate change.
- Overall, the cocoa yield is decreasing, not only due to climate change, but also the age of cocoa trees and pests.
- Within adoption of practices, there are three groups:
  (1) early adopters,
  (2) people relying on traditions, and
  (3) people relying on the government.
- Be careful with data about the adoption of agricultural practices. It might be not a random sample but biased by farmers in a training program.
- Many farmers say they had access to training on agricultural practices, but the quality of training might be very low. The training is also mostly made for farmers and not caretakers.
- The focus in Ghana is on
  (1) intensification of cocoa production and
  (2) diversification of income.
  Conversion (3) to other crops is out of focus, but unavoidable.
- There is low resilience; many families are dependent on the cocoa industry and all infrastructure is developed around this industry.
- The combination of low resilience, seasonal product and climate change is very challenging.
- Main challenge: How do you as a household achieve optimum behavior? For the long-term stability.
- People will not easily leave their farms, for many reasons:
- Land has a high value, is their income for retirement
- There is a lack of alternatives (also for kids)
- Other crops are not as profitable as cocoa
- You can always sell cocoa
- It is within the country's history and all infrastructure is built around cocoa
- A future with motivated and entrepreneurial farmers, open for CSA, and resilient against climate change is most favorable.
- Shade trees and diversification of income is already in the picture. The government is mainly working on climate-proof seedling, but it is quite random, and farmers don't really have a choice.
- Regarding microfinance, be aware of local dynamics in the context of Ghana. People spend their money immediately and long-term planning is very hard.
- No irrigation programs started yet. Some water in Ghana is polluted due to mining, so be aware. Moreover, climate causes (1) extreme rainfall and (2) problems with planning of cultivation. Irrigation does not solve these two problems.

Appendix L: Summary interview 2

Expert on migration in Ghana (PhD in 2011), currently focusing on the relation between migration and environment. Interview on January the 15th, 2020.

Is the Ghanaian population familiar with migration? And what kind of barriers do play a role?

The Ghanaian population is very familiar with migration. About 20% of the people lives in another region than they are born. Especially West Africa is very mobile. Cultural barriers do not play an important role, however, attachment to their current place and that preferences places a role, but it is not different from other places in the world. It is characteristic from Ghana that people from the north should go to the south for a couple of years. That is perceived as a cool experience to do.

Which factors are important when considering migration within Ghana due to climate impact?

People decide to migrate for many reasons at the same time. It is very much context specific. If the cocoa production decreases due to climate, they will first explore other options to generate income. And once people want to migrate due to scarcity of income, there should be enough capital left to make this uncertain move. Sometimes, rural people are not able to migrate because the situation is already deteriorated too much. Within Ghana you observe many people migrating from the poorer north regions to the south, but international migration is scarce due to limited capital.

How long would it take before cocoa farmers consider migrating?

Cocoa keeps an interesting crop, because it requires a lot of time and money investment, which you will not easily leave. Cocoa trees are very different from crops that need new seedlings every year, for example maze and casava. This is a totally different dynamic. Interviewee 2 does not expect that farmers will leave their cocoa trees if they are still productive. Once the trees are not productive anymore, smallholders have a window of opportunity to do something else. This will not be the case for young plantations. He only expects this dynamic at the borders of the main cocoa growing region in Ghana. In the 80's there were increasing droughts and destroyed harvests in Ghana and these smallholders decided to leave their land.

What are the characteristics of Ghanaian smallholders?

Cocoa smallholder families live in a fluid way, without clear patterns. They are in touch with other family members, who might live somewhere else. When multiple families decide to leave the community, the facilities in terms of transportation and education will deteriorate. Tradition in cocoa farming is important, but the cocoa smallholders in the south are more and more business oriented. If adaptation is efficient and does not require major investments, interviewee 2 expects that people will do that.

The Sustainable Livelihood Framework can be applied on rural farmers, for example when environmental conditions decrease: (1) Intensification, so changing your current way of production. (2) Diversification, making yourself less dependent on one crop. For example, kids are selling lolly's and women sell pindas on the market. (3) Migration. You could for example work in the city for 4 or 5 months and then come back to the cocoa farms. In practice, all three strategies are fluid and active at the same time.

Appendix M: Definition of interventions

M.1: Selection of the most viable and affected regions

The selection of most viable and most affected regions is based on the following tables:

Table 22 Division of farms over regions; informing the selection of most viable and affected regions

Region	high	medium	low	no
Brong Ahafo	85%	8%	3%	3%
Ashanti	34%	39%	17%	11%
Eastern	13%	48%	25%	14%
Central	15%	35%	45%	5%
Western	13%	39%	36%	11%
Volta	50%	50%	0%	0%

Region	high	medium	low	no
Brong Ahafo	50	5	2	2
Ashanti	34	39	17	11
Eastern	7	27	14	8
Central	8	19	25	3
Western	37	113	105	33
Volta	2	2	0	0
Total	138	205	163	57

Brong Ahafo and Ashanti are prioritized as regions with the most highly affected cocoa farms, and Central and Western as region with the highest number of viable farms.

M.2: Definition of proactive investments

The number of farms to be protected in the proactive investment strategy is based on the linear climate scenario graph:

Table 23 Snapshot of one of the climate scenario tables

High	Medium	Low	No	Total	Ticks	Years
0.00	0.00	0.00	288.00	288	0	2020
		4	284	288	1	2021
		7	281	288	2	2022
		11	277	288	3	2023
		15	273	288	4	2024
		19	269	288	5	2025
		22	266	288	6	2026
		26	262	288	7	2027
		30	258	288	8	2028
		33	255	288	9	2029
		37	251	288	10	2030

For the most viable regions:

- In the Western region:
  - 3 or 4 farms become low exposed per year under RCP2.6, linear curve
  - 4 or 5 farms become low exposed per year under RCP8.5, linear curve
- In Central:
  - 0 or 1 farm becomes low exposed per year under RCP2.6, linear curve
  - 1 farm becomes low exposed per year under RCP8.5, linear curve

Conclusion: 6 farms get climate adaptation per year to avoid production losses (intervention: green first, proactive)

For the most affected regions:

- In Brong Ahafo:
    - 5 farms become low exposed per year under RCP2.6, linear curve
    - 5 or 6 farms become low exposed per year under RCP8.5, linear curve
- In Ashanti:
    - 3 or 4 farms become low exposed per year under RCP2.6, linear curve
    - 3 or 4 farms become low exposed per year under RCP8.5, linear curve

Conclusion: 9 farms get a subsidy per year to start a new business and avoid migration (intervention: red first, proactive)

M.3: Price and effectiveness of investments

The price and effectiveness of the interventions is based on the following arguments:

- Pest management helps to avoid pest and disease problems starting from a changing climate. A study of Dormon (2006) on pest and disease management in Ghana shows that pest management costs are yearly 143 USD for a harvest of 1300 kg/ha. As this study assumes a harvest of 1600 kg cocoa beans per hectare, 178 USD are considered as yearly costs.
  Dormon's study (2006) also indicates that pest management increases resulted in an additional income of 240 USD per year for four hectares. When these outcomes are scaled to the scope of this study, it can be assumed that using pest management increases the production with 10%.

- Shade trees help to minimize heat stress by protecting cocoa plants from direct sunlight and potential damage as they modify the crops microclimate and soil water content (Läderach et al., 2013). Moreover, shaded cocoa can also provide a habitat for tropical forest flora and fauna and provide secondary products such as fruits and timber (Greenberg, 2014).
  The costs of shade trees can vary widely, depending on the type of tree. In this study, orange trees are chosen because of (1) good data availability, and (2) orange trees are often used as shade trees in Ghana. A study of O'Connell et al. (2015) shows that the costs of orange trees to use on a plantation are 11.50 USD, and 110 orange trees could fit per acre. Changing this into hectares, with a maximum coverage of 1/3th, results in 717 orange trees on a cocoa plantation. The total investment costs are 1725 USD.
  The effectiveness of shade trees is assumed to be 29%, in line with estimates of Blaser et al. (2018) under a cover of approximately 30%. Due to the growing time of shade tree seedling there is a delay of 5 years before the measure is effective.
  In study, no distinction will be made between percentage shade cover, shade tree density and number of specifies. The average yield also varies across land types, the ones using fertilizers and experiences, which are all beyond the scope due to time limits.

- Subsidies to set up a diversified income stream are set at 2100 USD per year in this study, because the poverty index of a households in Ghana is set around 1900 USD (Appendix H). Below this threshold, cocoa farmers are possibly willing to migrate if it is beyond the productive age of their cocoa trees. The duration of 6 years is chosen in contact with an Investment Officer with experience how long it takes before a new diversified income stream is fully running. The subsidy ensures the smallholders of an income to try another source of income.

M.4: Overview with definitions of interventions

The following Table 24 summarizes the above-mentioned motivations for interventions:

Table 24 Definition of interventions in this study (scale of the model, 1 agent :100 cocoa farms).

Intervention	Definition in this study
Green regions, pest management – Proactive	Western and Central are the most viable regions. Every year, 6 farmers from these regions are selected to receive support for pest management. The price is 178 USD per year and assumed to be 10% effective in increasing the cocoa production.
Green regions, pest management – Reactive	Once farms in the Western or Central regions become low exposed, they will receive support for pest management. The price is 178 USD per year and assumed to be 10% effective in increasing the cocoa production.
Green regions, shade trees – Proactive	Western and Central are the most viable regions. Every year, 6 farmers from these regions are selected to receive shade tree seedlings. The shade trees cost 1725 USD and the effectiveness is assumed to be 29%. Due to the growing time of shade tree seedling there is a delay of 5 years before the measure is effective.
Green regions, shade trees – Reactive	Once farms in the Western or Central regions become low exposed, they will receive support for shade trees. The shade trees cost 1725 USD and the effectiveness is assumed to be 29%. Due to the growing time of shade tree seedling there is a delay of 5 years before the measure is effective.
Red regions - Proactive	Brong Ahafo and Ashanti are the most affected regions. Every year, 9 farms from these regions receive a subsidy of 2100 USD to set up a new diversified income stream to prevent migration. This subsidy last for 6 years.
Red regions - Reactive	Once farms are willing to migrate (reached the permanent migration threshold of old cocoa trees and income lower than the poverty index), these households will receive a subsidy of 2100 USD to set up a new diversified income stream to prevent migration. This subsidy last for 6 years.
Hybrid – Proactive	There is 50% budget, so 2.5 mln USD, for the green first – proactive, so both pest and shade interventions. The other 50% is spent on red first – proactive.
Hybrid - Reactive	50% of the budget is spent on green first – reactive, both pest and shade. The remaining 50% is spent on red first – reactive.

This is all explored with a maximum budget of 5 MLN USD.

Appendix N: Verification

In the following section, verification of the model is performed by using four tests. The tests are executed both iteratively during the model development and once the model building phase was finished. The aim is to check that all agents and relations for the conceptual model have been translated into the agent-based model in a correct way (Van Dam et al., 2010). This can be challenging in an agent-based model because there is a high number of agents and possible interactions and the observed emergent behaviour is not known in advance.

Three types of verification test are performed as suggested by Van Dam et al. (2010). First, the behaviour of agents is verified by (1) walking through the code and by (2) tracking input, outputs and states. Furthermore, single agent behaviour is tested by (3) running the model with extreme values.

It is not possible to test the interaction between agents in a minimal model with a minimal set of agents, because the exposure of climate change of each individual farm is calculated in an Excel model and then manually added to Netlogo. Changing the initial number of cocoa farmers will give many errors because the climate input is not working anymore.

N.1 Recording and tracking agent behaviour

N.1.1 Walk through the source code

The entire code is checked at multiple stages of model development. First, every new part of the code has been tested in a simple agent-based model. If this component behaved as expected, it was included in the full model and checked again if it behaved correctly. Despite this methodology, including the change of behavioural groups (Behaviour threshold 4, Appendix I) was for example still resulting in errors because the run time was lengthened from 30 to 31 in the full model. In this final tick, there were no farmer households in the stock of traditional behaviour were left to change of behavioural group. This error was solved by included an *if any?* statement.

Furthermore, comments in the code are made during the building process. At the end of the project, the comments were reviewed, and some additional comments were made.

When the model was completed, the code was checked whether there were redundant variables in the model. For example, the Licensed Buying Companies (LBCs) were included in the first model as important transportation stakeholder in the value chain, but they did not have a purpose for this model of climate exposure for the farms and were therefore excluded after this verification step.

Finally, a verification check was done to make sure that all Key Performance Indicators and other reporters are measured at the end of the model run when all other commands are executed.

N.1.2 Record the states and outputs of agents

The behaviour of an individual farmer household and COCOBOD are recorded over time.

Agent-tracking farmer household: The left figure 47 shows the setup, in which the farm is attributed to be active in cocoa farming (**confirmed**: active-cocoa? yes) but not producing yet (**confirmed**: production-tonyear 0) with a young cocoa tree stock (**confirmed**: age 0). The farmer household is also not yet exposed to climate change (**confirmed**: no exposure). After the tick, the production is started and all corresponding internal states are therefore updated (**confirmed**: production is updated, world market price is loaded in and internal income states are updates). The age of the cocoa tree stock is increased by 1 year every tick (**confirmed**: age 0 to 1). The cocoa farm is still not exposed to climate change (**confirmed**: color is darkgreen). In tick 8, the exposure of this farm changes to low (**confirmed**: color is lime), resulting in a lower land productivity (**confirmed**: land-productivity 240 instead of 400), production (**confirmed**: production-tonyear is 1.28 instead of 1.6) and therefore lower income states (**confirmed**: cocoa-income is 1777.6 instead of 2360). Some farmer household are prone to change their behavioural group, which is randomly chosen. In tick 13, this agent changed from governmental oriented to early adopting households (**confirmed**, Figure 47). During the entire model run, the income of this farmer household is never lower than the poverty index, which means that the household will not migrate (**confirmed**: active-cocoa? yes).

Since the cocoa income is decreasing due to climate exposure, households are open for focusing on diversification, which is only possible for 20% of the farmers on an alternative market. This agent was apparently fitting within this percentage (**confirmed**: diversification income increased from 1160 to 1450).

Figure 47 Verification farm: tick 0 (set-up)   Tick 1   Tick 8 (climate exposure)   Tick 13 (group change)

Agent-tracking COCOBOD: The first time step shows the setup, in which COCOBOD has determined a fixed cocoa floor price on the world market and a fixed percentage for the cocoa farmers (**confirmed**: floor price is 2600 USD/ton and fraction for farmers is 0.7). During the model run, the states of COCOBOD are not changing.

Figure 48 Verification by tracking COCOBODs behaviour

N.2 Single-agent testing: extreme value testing

As it is now confirmed that the agents behave as expected under normal inputs, the model is now run with extreme values to check whether the behaviour of agents changes in an unexpected way.

The model is run without interventions under the following scenario settings:

- Climate scenario: RCP8.5, no carbon price
- Climate trend: Linear till 2050
- World market price: Floor price of 2600 USD per ton
- Loss of production: Maximum estimate

Age of cocoa trees as condition to migrate: The age is set to 100 years (initial value: 30 years).

Confirmed: the agent behaviour is not affected by this extreme value. None of the agents are permanently migrating, because the cocoa farms will never have a tree stock older than 100 years.

Age of cocoa trees as condition to migrate due to social influences: The age is first set to 1 year and then to 100 years (initial value: 25 years).

Confirmed: the agents do not show unexpected behaviour. Only agents who meet the criteria of migration without social influence are now migrating. The agents socially influenced by the neighbours are not migrating, because the cocoa farms will never have a tree stock older than 100 years.

The cocoa income should be decreased with a certain percentage to choose to focus on diversification: The percentage is set to 100% for cocoa farmers with all behaviour profiles (initial value: -40% for early adopters, -50% for governmental oriented farmers, -60% for traditional farmers).

Confirmed: the agents don't show undesired behaviour. All of the cocoa farmers have *look-for-job?* "not yet done" to show that the cocoa farmer is not diversifying.

Percentage of cocoa farmers that can enter a new market in Ghana: The percentage is first set to 100% (initial value: 20%).

Confirmed: many cocoa farmers now focus on diversification instead of cocoa production, looking at the state *look-for-job?* "done".

Appendix O: Experimental design

The following Table shows the experiments with all five scenario settings, together 32 scenarios (full factorial design). These scenarios illustrate the full range of future outcomes.

Table 25 Full factorial design of scenario settings

	Intervention	Climate scenario	Carbon price	Trend	Sensitivity of production	World market price
1	No intervention	RCP2.6	Low	Linear	Minimum	Floor price
2	No intervention	RCP2.6	Low	Linear	Minimum	Historical average
3	No intervention	RCP2.6	Low	Linear	Maximum	Floor price
4	No intervention	RCP2.6	Low	Linear	Maximum	Historical average
5	No intervention	RCP2.6	Low	Log	Minimum	Floor price
6	No intervention	RCP2.6	Low	Log	Minimum	Historical average
7	No intervention	RCP2.6	Low	Log	Maximum	Floor price
8	No intervention	RCP2.6	Low	Log	Maximum	Historical average
9	No intervention	RCP2.6	Medium	Linear	Minimum	Floor price
10	No intervention	RCP2.6	Medium	Linear	Minimum	Historical average
11	No intervention	RCP2.6	Medium	Linear	Maximum	Floor price
12	No intervention	RCP2.6	Medium	Linear	Maximum	Historical average
13	No intervention	RCP2.6	Medium	Log	Minimum	Floor price
14	No intervention	RCP2.6	Medium	Log	Minimum	Historical average
15	No intervention	RCP2.6	Medium	Lo	Maximum	Floor price
16	No intervention	RCP2.6	Medium	Log	Maximum	Historical average
17	No intervention	RCP2.6	High	Linear	Minimum	Floor price
18	No intervention	RCP2.6	High	Linear	Minimum	Historical average
19	No intervention	RCP2.6	High	Linear	Maximum	Floor price
20	No intervention	RCP2.6	High	Linear	Maximum	Historical average
21	No intervention	RCP2.6	High	Log	Minimum	Floor price
22	No intervention	RCP2.6	High	Log	Minimum	Historical average
23	No intervention	RCP2.6	High	Log	Maximum	Floor price
24	No intervention	RCP2.6	High	Log	Maximum	Historical average
25	No intervention	RCP8.5		Linear	Minimum	Floor price
26	No intervention	RCP8.5		Linear	Minimum	Historical average
27	No intervention	RCP8.5		Linear	Maximum	Floor price
28	No intervention	RCP8.5		Linear	Maximum	Historical average
29	No intervention	RCP8.5		Log	Minimum	Floor price
30	No intervention	RCP8.5		Log	Minimum	Historical average
31	No intervention	RCP8.5		Log	Maximum	Floor price
32	No intervention	RCP8.5		Log	Maximum	Historical average

These scenario settings are visualized in Figure 49:

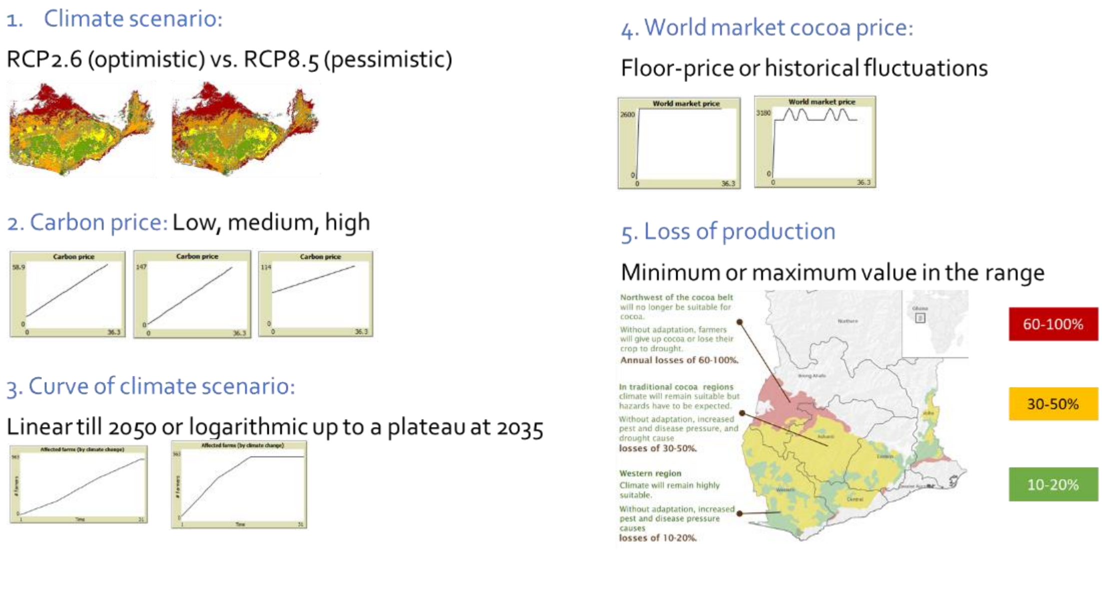


Figure 49 Scenario settings

Appendix P: Optimistic and pessimistic scenario space

Figure 50 shows the lines of the eight most influential scenario combinations on average: climate scenario (RCP2.6/RC8.5, setting 1), trend (linear/logarithmic, setting 3) and sensitivity of production (min/max, setting 5). The optimistic scenario RCP2.6 is marked in green, and the pessimistic climate scenario RCP8.5 in red.

The loss of production follows the same trend under the optimistic and pessimistic scenario. The difference in outcome increases over time, but it is still not large (at maximum 2.5%). Therefore, the remaining scenario analysis only considers pessimistic climate scenario RCP8.5.

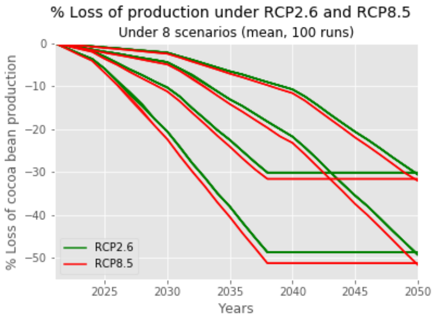


Figure 50 The loss of cocoa production under 8 scenarios on average: min/max sensitivity, linear/logarithmic trend, RCP2.6/8.5

Appendix Q: ANOVA test for carbon prices

The ANOVA test is used to compare low, medium and high carbon prices. The hypothesis is that the groups are equal. When the p-value of the ANOVA test is lower than the alpha of 0.05, the alternative hypothesis of at least one group is different from others is accepted.

For production and migration no significant differences are found. The cocoa income has some values lower than 0.05. Therefore, the Levene test is performed to test ANOVA assumptions. The Levene test checks the homogeneity of variances. As the p-value is not significant, we must conclude that there are no significant differences between the carbon prices.

Table 26 p-values for ANOVA test

Experiment (Table 25)	Loss of production (p-value ANOVA)	Cocoa income (p-value ANOVA)	Cocoa income (p-value Levene test)	Migration (p-value ANOVA)
1-9-17	0.326	0.000	0.30	Nan
2-10-18	0.743	0.012	0.10	Nan
3-11-19	0.430	0.743		0.359
4-12-20	0.575	0.216		0.746
5-13-21	0.484	0.000	0.07	Nan
6-14-22	0.805	0.025	0.25	Nan
7-15-23	0.365	0.001	0.09	0.061
8-16-24	0.466	0.047	0.51	0.430

Appendix R: Results of cocoa income

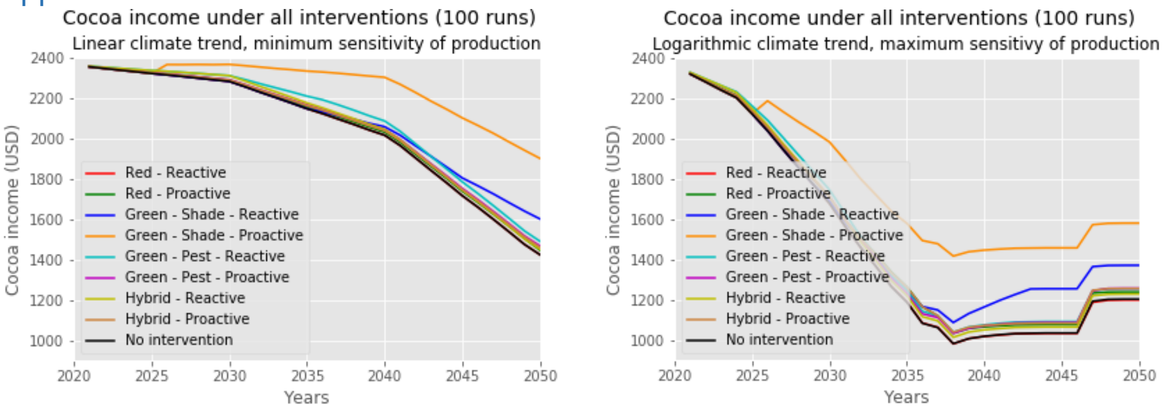


Figure 51a,b All intervention combinations, showing the cocoa income trend, in the linear (left) and logarithmic climate trend (2050 already in 2038)

The cocoa income under all different interventions is shown in Figure 51a and 51b. This KPIs follows the same trend as the loss of production. Green shade proactive (orange) and green shade reactive (blue) appears to be the most robust interventions under both extreme scenarios.

Table 27 Standard deviation of intervention for the cocoa income (USD/year)

	Scenario A (linear, minimum)			Scenario B (logarithmic, maximum)		
	2030	2040	2050	2030	2040	2050
Red – Reactive	0.0	0.0	0.0	2.0	20	22
Red – Proactive	1.5	3.9	8.9	7.3	18	20
Green – Shade – Reactive	0.0	0.0	4.0	2.2	17	21
Green – Shade – Proactive	0.0	0.0	0.1	2.1	20	25
Green – Pest – Reactive	0.0	0.3	0.5	2.4	18	26
Green – Pest – Proactive	1.7	2.5	1.2	3.6	20	21
Hybrid – Reactive	0.0	0.0	0.4	2.4	18	24
Hybrid – Proactive	1.6	3.3	4.1	5.8	20	23
No intervention	0.0	0.0	0.0	1.8	21	24

Table 27 provides an overview how close the individual runs are from the mean values (σ). When comparing scenarios A and B, it is clear that the standard deviation is lower under a linear climate trend with a minimum sensitivity of production (scenario A). Closer inspection of scenario A shows that both no intervention (black) and red reactive (red) do have no deviation, i.e. every single run has the same outcome. These results follow the same trend as the loss of production (Section 9.2).

Appendix S: Sensitivity analysis

The assumptions, and in particular behavioural thresholds are varied one-by-one to show the impact on the model behaviour. This analysis is performed without any intervention. The fourth KPI additionality is therefore not shown.

Table 28 Experimental design sensitivity analysis

	Variable	Value	Change to	Number of runs
1	Migration: Threshold cocoa tree age	30	35	50
2	Social migration: Threshold cocoa tree age	25	30 35	50
3	Diversification: income left early adopter	0.6	0.5 0.7	50
4	Diversification: income left government	0.5	0.4 0.6	50
5	Diversification: income left traditional	0.4	0.3 0.5	50
6	# farmers change to governmental group per year	7	4 14	50
7	# farmers change to early adopter group per year	4	2 8	50
8	Place for new opportunities on Ghanaian market	0.2	0.4	50

The results are shown for the first affected KPI of that threshold. Based on the outcomes of Chapter 9, the behavioural thresholds are tested under the following conditions:

- Climate scenario: Pessimistic RCP8.5
- No carbon price
- Cocoa floor price of 2600 USD/year
- Maximum sensitivity of production
- Logarithmic climate trend

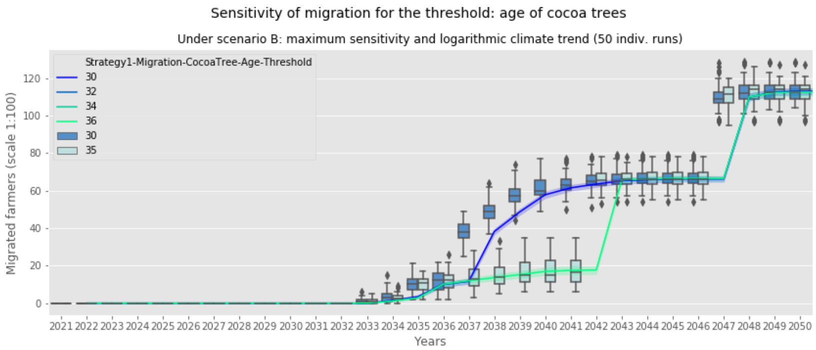


Figure 52 Sensitivity of migration for threshold: age of cocoa trees, changed from 30 to 35 years

Figure 52 shows the results for sensitivity analysis 1 (Table 28): changing the age of the cocoa trees as threshold whether smallholders are willing to migrate results in a similar outcome in 2050. However, the logarithmic trend from 2037 till 2042 when the age is set at 30 years (dark blue) will not take place at the cocoa tree age of 35 years (turquoise). This logarithmic trend is in turn a steep exponential trend in 2042. This means that migration is an effect on the long term when the productive age of cocoa trees is longer but will have an enormous peak in 2042.

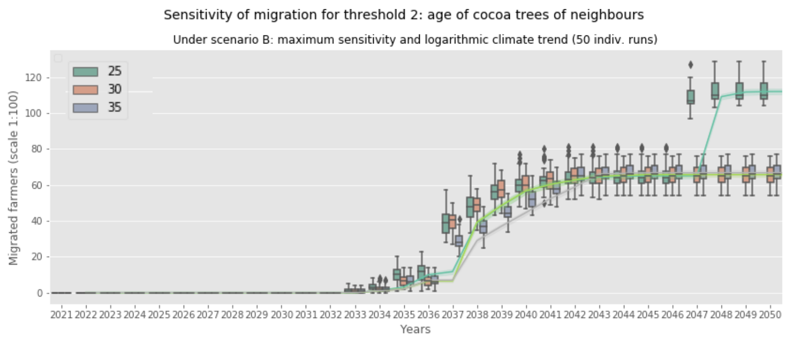


Figure 53 Sensitivity of migration for threshold of neighbours: age of cocoa trees, changed from 25 to 35 years

Figure 53 (sensitivity analysis 2, Table 28) shows that changing the age of the cocoa trees for neighbours of migrating households result in different model behaviour. The increasing trend in 2047 will only happen if neighbours are already willing to migrate when their trees are 25 years old (assumed in the analysis). If this threshold is set to 30 or 35 years, like the initiators of migration have (first sensitivity analysis), the migration trend will flatten. The number of migrating households in 2050 is then 45% lower.

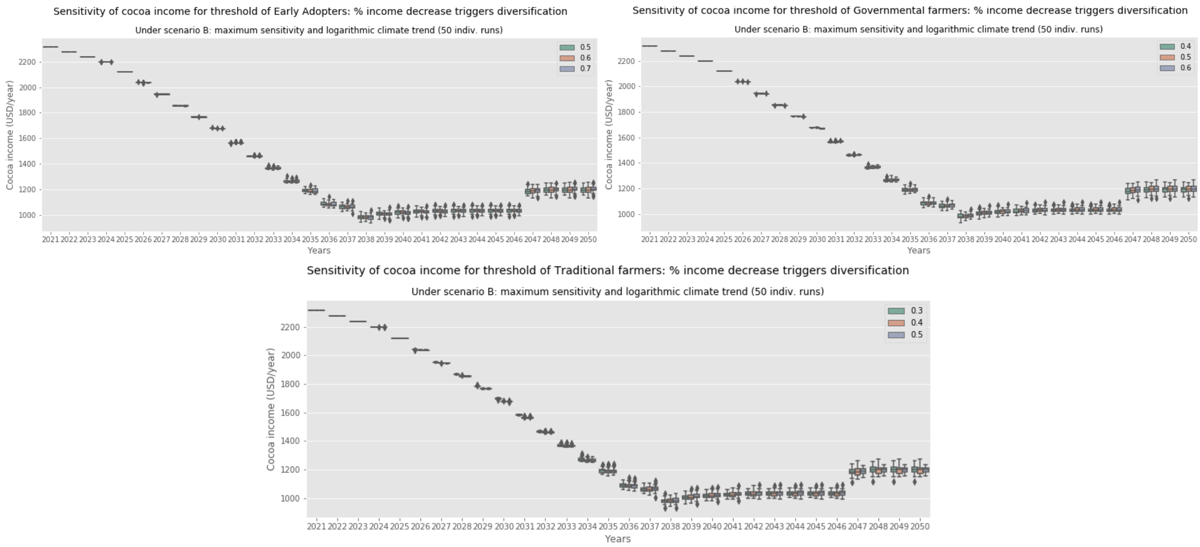


Figure 54 Sensitivity of cocoa income for threshold triggering diversifying: % increase decrease -/+ 10%

The thresholds for diversification are now tested: the decrease of income determines the moment when cocoa farmers will look for a diversified source of income (Behavioural threshold 3, Appendix I). Those thresholds are set differently based on their behavioural profile and corresponding aversion to change. Figure 54 shows that changing the threshold does not have a major result on the Cocoa Income (USD/year) of farmers.

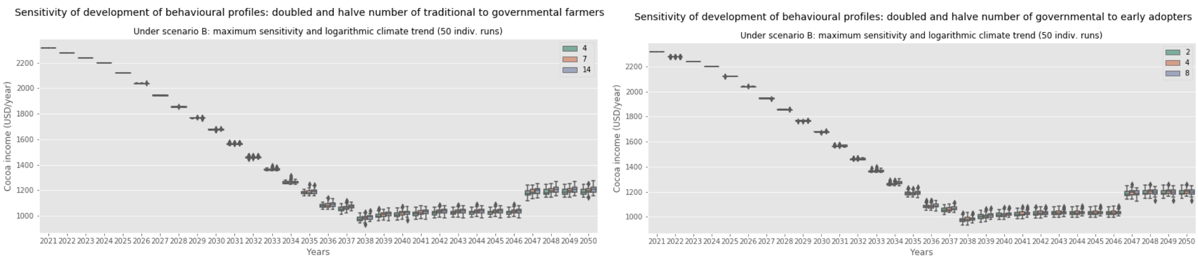


Figure 55 Sensitivity of cocoa income for autonomous development of behavioural profiles through training and education

Sensitivity analysis 6 and 7 change the developments of behavioural profiles. In the model it is assumed that under normal circumstances approximately 7 traditional farmers become governmental through cocoa trainings from COCOBOD, while 4 households become early adopters through education. Doubling and halving these values will not result in different outcomes (Figure 55).

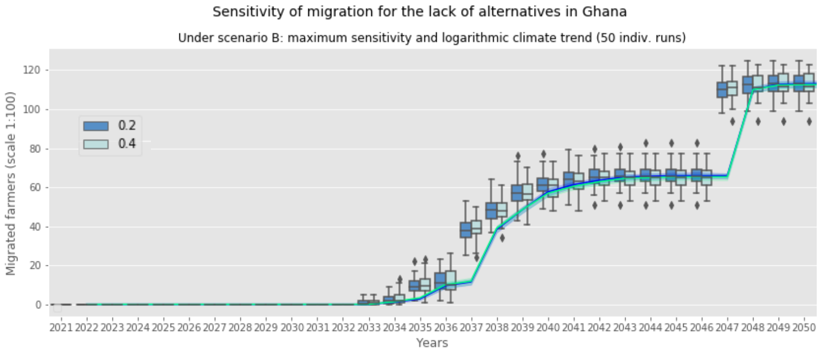


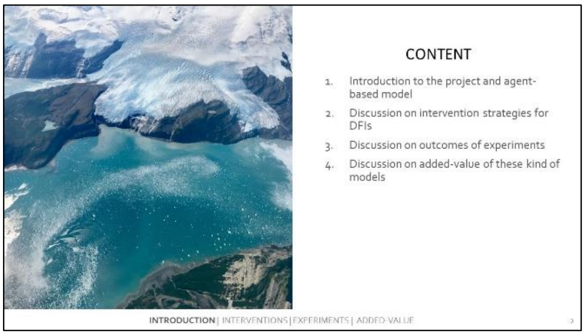
Figure 56 Sensitivity of migration for increasing bottleneck of diversifying alternatives in Ghana besides cocoa farming

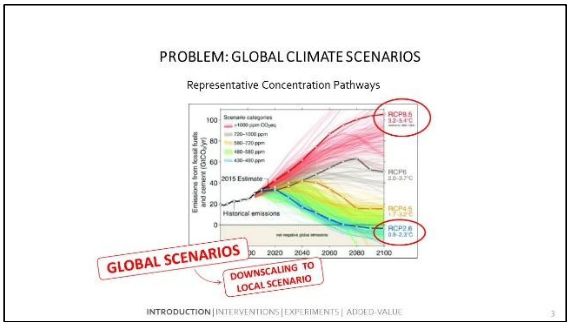
The final analysis tracks the bottleneck in this study: when the income of cocoa smallholders decreases to a certain extent, they will look for new income. As discussed in Section 6.4, there is a lack of alternatives in the Ghanaian and a bottleneck is therefore set at 20%. Increasing the opportunities to 40% of all cocoa farmers (more diversifying alternatives around the cocoa farm) might potentially reduce migration. However, Figure 56 indicates that this bottleneck does not change the model behaviour. A possible explanation is that impact of climate change on production is so high, that a bit diversification income is not enough to compensate.

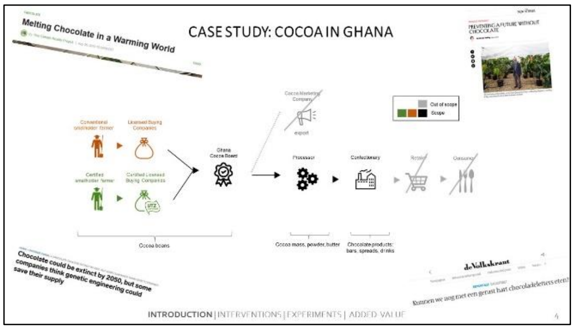
It can be concluded that only the second sensitivity analysis, changing the threshold of the age of cocoa trees of neighbours, results in significant different model behaviour. There will be reflected upon this sensitivity in the analysis chapter (Section 10.1).

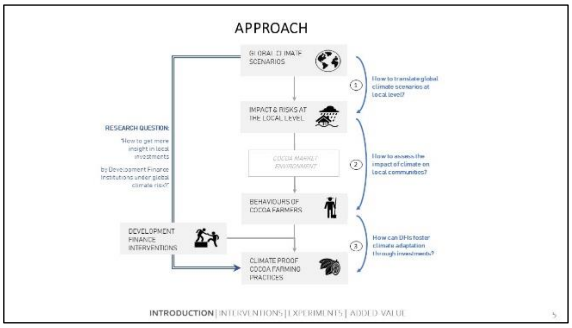
Appendix T: Validation workshop

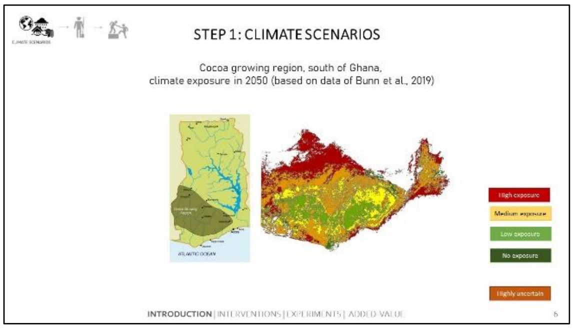
One of the validation methods used is face validation with a workshop via Skype due to the corona circumstances. The slides to facilitate the discussion are attached:

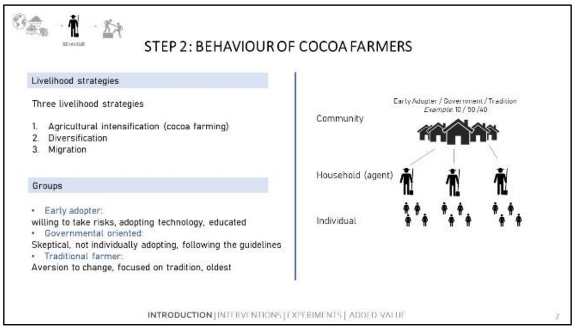


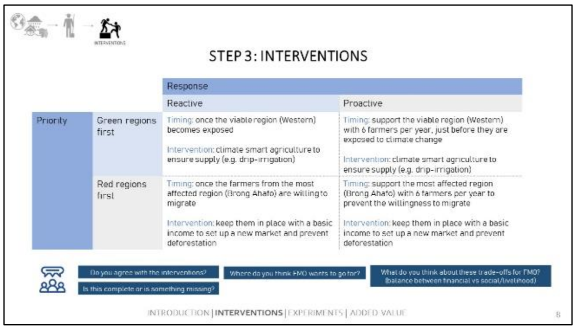


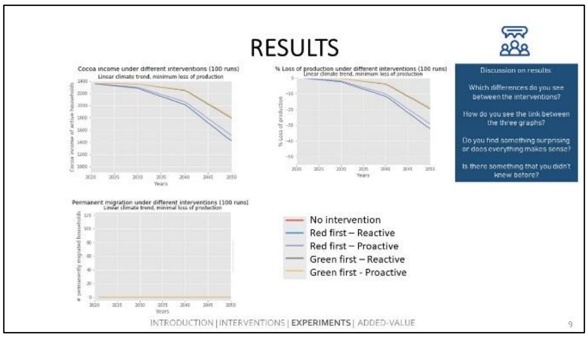


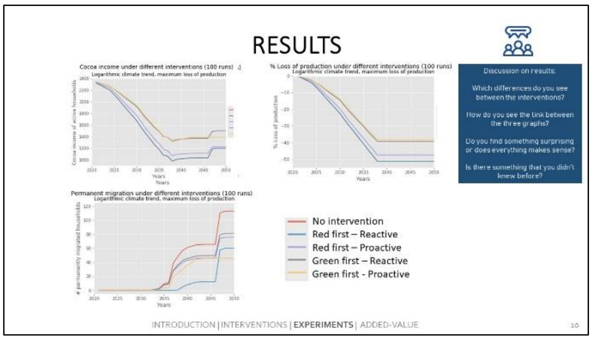


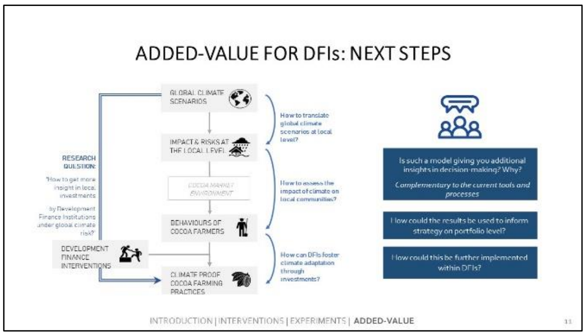







RESULTS
Cocoa income under different interventions (100 runs)
Linear climate trend, minimum loss of production
% Loss of production under different interventions (100 runs)
Linear climate trend, minimum loss of production
Permanent migration under different interventions (100 runs)
Linear climate trend, minimal loss of production
Years
Discussion on results:
Which differences do you see between the interventions?
How do you see the link between the three graphs?
Do you find something surprising or does everything makes sense?
Is there something that you didn't knew before?
No intervention
Red first – Reactive
Red first – Proactive
Green first – Reactive
Green first - Proactive
INTRODUCTION | INTERVENTIONS | EXPERIMENTS | ADDED-VALUE
9


RESULTS
Cocoa income under different interventions (100 runs)
% Loss of production under different interventions (100 runs)
Permanent migration under different interventions (100 runs)
Years
Discussion on results:
Which differences do you see between the interventions?
How do you see the link between the three graphs?
Do you find something surprising or does everything makes sense?
Is there something that you didn't knew before?
No intervention
Red first – Reactive
Red first – Proactive
Green first – Reactive
Green first - Proactive
INTRODUCTION | INTERVENTIONS | EXPERIMENTS | ADDED-VALUE
10


ADDED-VALUE FOR DFIs: NEXT STEPS
GLOBAL CLIMATE SCENARIOS
IMPACT & RISKS AT THE LOCAL LEVEL
COCOA MARKET ENVIRONMENT
BEHAVIOURS OF COCOA FARMERS
CLIMATE PROOF COCOA FARMING PRACTICES
DEVELOPMENT FINANCE INTERVENTIONS
RESEARCH QUESTION:
'How to get more insight in local investments by Development Finance Institutions under global climate risk?'
How to translate global climate scenarios at local level?
How to assess the impact of climate on local communities?
How can DFIs foster climate adaptation through investments?
Is such a model giving you additional insights in decision-making? Why?
Complementary to the current tools and processes
How could the results be used to inform strategy on portfolio level?
How could this be further implemented within DFIs?
INTRODUCTION | INTERVENTIONS | EXPERIMENTS | ADDED-VALUE
11


POINTS OF DISCUSSION?
SEND EMAIL
SKYPE COFFEE 1-1
TUDelft
VALIDATION WORKSHOP | 07-05-2020 | ANNABEL DE GOEDE
FMO