ECONADAPT

The Economics of Adaptation

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Deliverable 9.2: Case Study Findings

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Executive Summary

This document is comprised of three separate chapters:

Chapter One:	Project Appraisal for Climate Mainstreaming in Rwanda's Tea and Coffee Sectors
Chapter Two:	Adaptation decision-making in Zanzibar's clove plantations: a cost benefit analysis extended to "light touch" uncertainty treatment
Chapter Three:	Adapting to Climate Change in Zanzibar's Seaweed Farming Sector

The case studies across the two developing countries – Rwanda and Zanzibar – are designed to have practical use in determining future adaptation investments. Thus, the four products – coffee, tea (Rwanda); seaweed, cloves (Zanzibar) – were selected in conjunction with the principal stakeholders: primarily government ministries, producers and exporters. This process – reported in detail in D9.1 – ensured that the research is more likely to be incorporated in respective sectoral development plans. It also provided a means with which to ensure that adaptation options were developed in the wider policy context that investment decisions are made. An indicator of the effectiveness of this approach is the fact that evolved versions of the coffee and tea analysis undertaken in Rwanda are now being used as the basis for part of an application by the Rwandan Government to the Green Climate Fund established by the UN.

Other principal conclusions are outlined in the following paragraphs.

First, consistent with current practice in development economics, the analyses illustrate the continued importance of estimating shadow prices – market and non-market – for a range of parameters included in the economic analyses. The main market parameters for which shadow prices include the wage rate, distributional weighting, and the discount rate. All constitute a significant form of uncertainty in the analyses, additional to climate change scenarios. Non-market shadow prices include carbon prices and ecosystem damages.

By way of highlighting this point, the seaweed analysis demonstrates the importance of non-market values in climate adaptation interventions. Across all scenarios, appraisals including non-market costs and benefits present much higher returns than financial cash flows alone. This indicates that the adaptation options generate significant social value. Economic, environmental and social benefits of all interventions provide ample opportunity for productive public investment in the sector. Similarly, while global damage assessments have long recognised inequities in climate impacts across regions in the world and between national income groups, they have been less prominent in local analyses. The seaweed case study highlighted gender impacts as an important distributional dimension in the assessment. With distributional weights included in economic valuation, the appraisal demonstrates how a political consideration can be included quantitatively alongside other costs and benefits.

Second, the case studies serve to illustrate that economic decision-support methods that have been developed to better incorporate non-probabilistic uncertainties, of the type presented by climate change projections, can be applied in developing country contexts. In each of the three case studies, these methods – Portfolio Analysis in Rwanda, Real Options Analysis in Zanzibar – are shown to add a further, additional, level of insight to the information that conventional methods such as Cost-Benefit Analysis can convey.

However, third, and as a caveat to the second conclusion, the resource requirements associated with undertaking these more sophisticated methods remain considerable. In the case of the Portfolio Analysis of tea-planting strategies, the data processing was very time-consuming and required a relatively high level of numeracy. The applications of Real Options Analysis – whilst simplified into a decision-tree approach – also required a relatively high degree of knowledge of these methods. It seems, therefore, that the holy grail of “light touch” methods are not quite yet in sight. Certainly, future research needs to focus on simplified approaches to the treatment of uncertainty in adaptation appraisal, as well as effective communication of the results of these appraisals.

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ECONADAPT
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Chapter One: Project Appraisal for Climate Mainstreaming in Rwanda's Tea and Coffee Sectors

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Executive Summary

The objectives of this work package are to:

- Undertake a case study on the economics of adaptation in the context of international development support.
- Undertake this work on a real case study example aligned to developing country adaptation flows and analysis.
- Consider lessons learned and transferability of the case study to methods and guidance.

Consistent with international pledges, there will be very large increases in European overseas development assistance to developing countries, and a likely greater need to demonstrate that these financial resources are being used effectively. This assistance will be dispersed through bi-lateral and multi-lateral arrangements, and range from support for national processes through to individual projects. This work package investigates the economics of adaptation in relation to these flows and policy contexts. The analysis is undertaken in collaboration with developing country partners in real applications looking at project and programme level adaptation implementation. Two country studies are selected: Rwanda tea and coffee production, and; Zanzibar seaweed and clove production.

Task 9.2:

This task undertakes three case studies, examining the prioritisation of adaptation at the national programmatic and project levels, respectively. The analysis is aligned to examples of programmes and projects that – as identified in Task 9.1 – are likely to emerge from international climate funds. These two areas therefore parallel those adopted in the case studies to be undertaken in WP6 and WP7. Common components of analysis include:

1. Policy-focused framing of decision context, including a literature review and a policy dialogue (Link to WP1 and WP12).
2. Application of decision support tool; including identification of adaptation actions; Estimation of benefits (monetary and/or non-monetary); Estimation of resource costs (Inputs from WP1-2; providing input to WP10, WP12 and WPs1-4).
3. Assessment of application of decision rule(s) incorporating treatment of uncertainties (drawing on work from and providing information to WP4).
4. Application of transfer, scaling and aggregation protocols to national and regional contexts (drawing on work from and providing information to WP3).

However, the methods are not identical: there has been a need to adapt these for the developing country context for a number of reasons. First, there is a much greater focus on addressing existing climate variability (the adaptation deficit) in developing countries. Second, there is a formal requirement to estimate the additionality of adaptation needs over development funding. Third, there are substantial challenges in terms of data availability, governance and institutional capacity in developing countries, which make the application of complex methods more difficult and the emphasis on streamlining and simplifying analytical methods and tools.

Assumptions

Exchange rate:	**1 USD = 800 RWF**
Inflation:	Constant (2016) prices
Social discount rate:	0% to 13%

List of Abbreviations

BAU = Business as usual (no change)
c21 = 21st Century
CBA = cost-benefit analysis
CIAT = International Centre for Tropical Agriculture
CMIP = Coupled Model Intercropmarison Project
GDP= Gross Domestic Product
ENSO = El Niño-Southern Oscillation
GCM = Global climate model
GoR = Government of Rwanda
Ha = Hectare(s)
IIASA = International Institude for Applied Systems Anlaysis
IPCC = Intergovernmental Panel on Climate Change
IRR = Internal rate of return
MAM = March-April-May (Rwanda's short rainy season)
Masl = meters above sea level
NAEB = National Agricultural Export Development Board (Government of Rwanda)
NPV = Net present value
RoR = Republic of Rwanda
PA = Portfolio analysis
PRICE = Project for Rural Income through Exports
RCP = Representative Concentration Pathway
ROA = Real options analysis
RWF = Rwandan Francs
SOND = September-October-November-December (Rwanda's long rainy season)
SWC = Soil and water conservation
TWFA = The Wood Foundation Africa
USD = US Dollars
WHO = World Health Organisation

1. Introduction

Investment outline

The Government of Rwanda has developed tea expansion maps as part of the strategy to expand tea plantations through public-private investment e.g. Annex 1. These maps highlight areas suitable for growing tea in today's climate and define tea plantation boundaries for investors. The strategic information from these expansion maps facilitates public-private sector investment that will help achieve the Government of Rwanda's EDPRS II targets (Republic of Rwanda, 2013a).

However, the Government's tea expansion maps do not account for potential changes in future climate. This is important because of the longevity of tea plantations; they are similar to infrastructure investments with large sunk costs and can remain economically viable for over 50 years (Republic of Rwanda, 2016a). As part of mainstreaming climate change into the tea expansion plans, the project appraised here aims to invest in updated tea expansion maps that show areas suitable for growing tea in both current and possible future climates. The climate risk maps will cover both local and national levels.

This study focuses on the benefits and costs of climate risk mapping at a local scale, before scaling up to account for wider benefits and costs at a national scale. At the local scale, a representative analysis of investing in 3,415ha of smallholder tea plantations is carried out. This scale represents the smallholder tea plantations that will be implemented by The Wood Foundation Africa and smallholders in four sectors of the Nyaruguru District. A Services Company jointly owned by smallholders (49%) and The Wood Foundation Africa (TWFA) (51%) will implement the tea plantations, with additional co-financing from Unilever and the UK Department for International Development (DfID). A total investment of USD 70 million is planned over 10-15 years, with USD 14 million allocated to the Services Company. (DfID, 2016).

This study considers how climate risk mapping may alter the tea planting decisions at this individual 3,415ha expansion site, with a particular focus on the altitude at which tea is planted. The benefits and costs for this local context are then scaled up to capture the total area of land needed to achieve the Government of Rwanda's tea expansion targets. This approach shows the uncertainty that climate risk mapping may quantify at a local scale, and also the public information value generated by climate risk mapping at a national scale.

Decision support tool: Portfolio Analysis

Portfolio analysis can be applied to risky investment decisions outside of finance, including climate change adaptation (MEDIATION, 2013). This economic decision support tool is therefore used to appraise the climate risk mapping investment. This investment falls under the remit of climate change adaptation because tea yield and quality are sensitive to climate. In Kenya, tea's optimum altitude band is currently between 1500 and 2100 (masl) above sea level (CIAT, 2011). However, the International Centre for Tropical Agriculture (CIAT, 2011) project that this optimal band will shift to between 2000 and 2300 masl by 2050 as a result of climate change. Given the proximity of Rwanda to Kenya, locations in Rwanda that are suitable to grow tea today may not be suitable in future climate scenarios This study evaluates this hypothesis.

Altitude is used as a proxy for temperature in this analysis, with different elevation bands representing investment options for new tea plantations. As temperature decrease 0.65ºC for every 100 meters climbed (ICAO, 1993), different altitude bands are expected to be better suited for growing tea. The suitability of a particular altitude band for growing tea is also expected to change over time, depending on the future climate scenario. This study evaluates different combinations (portfolios) of altitude bands in which tea can be planted. The proposition is that climate risk mapping can better inform tea investors about where to plant tea in order to achieve returns that are robust across a range of future climate scenarios.

The difference in returns for the smallholder tea plantations with and without climate risk mapping is evaluated. Without climate risk mapping, tea plantations may be implemented at altitude bands that are optimal for today's climate but sub-optimal for the future climate. The investment into climate risk mapping should provide information about the performance of different altitude bands in different future climate scenarios and help avoid the lock-in associated with establishing new tea plantations at sub-optimal altitudes.

Traditionally, portfolio analysis uses historical returns to assess the mean return and variance of assets (Markowitz, 1952). However, an alternative "light touch" approach has been developed in this study. Portfolios are selected using analysis of tea plantation performance in altitude bands, an understanding of the decision problem and heuristics. In addition, only two climate scenarios are analysed; the highest and lowest annual mean temperature projections for Rwanda. This approach captures the full range of scenario and model uncertainty whilst minimising the complexity of the analysis.

Portfolio Analysis is a decision support tool originating from financial asset management. Markowitz (1952) first developed portfolio selection theory, as an analysis of the mean returns and variance of returns for individual assets (mean-variance analysis). Different assets have different expected returns and variance of returns (risk). Therefore, the expected return and risk of a portfolio depends on the underlying expected returns and risk of each asset held in the portfolio, and how much of each asset is held in the portfolio. Markowitz (1952) developed the "efficient frontier" hypothesis, which evaluates portfolios that have the highest expected return for a given level of risk (Figure 1).

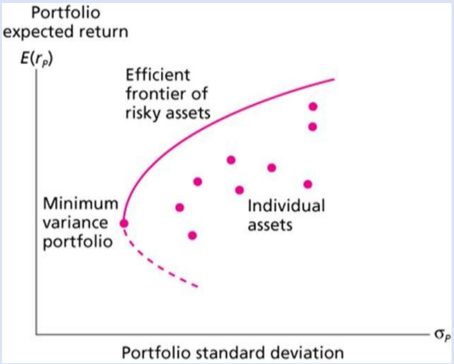

Figure 1: The efficient frontier for traditional portfolio analysis, illustrating the trade-off between risk and return (Source: Blogspot, 2010)

Along the efficient frontier, the level of risk is minimised for a given expected return. The portfolios along this line are known as "efficient portfolios". The leftmost point on the line represents the minimum variance portfolio i.e. the efficient portfolio with lowest risk. There is a clear trade-off between the level of risk and the expected return on the efficient frontier; portfolios with higher expected returns also have a higher level of risk. Therefore, the decision about which efficient portfolio to invest in depends on the level of acceptable risk to the investor(s).

In this study, deciding which combination of adaptation options to invest in is the same as choosing a portfolio. This "adaptation" portfolio's return and difference in returns (uncertainty) between climate scenarios depends on the underlying adaptation options. However, there is a range of possible future climate scenarios (IIASA, 2014) and adaptation options' benefits and costs can vary between these scenarios. For example, flood defences are likely to have higher benefits if they protect against an increase in flood events in the future. Therefore the adaptation portfolio's return and difference in returns (uncertainty) will depend on the plausible future climate scenarios.

Box 1: Origins of portfolio analysis and its application to climate finance (Source: Markowitz, 1952)

2. Methodology

Standard economic decision support tools, including cost-benefit analysis and cost-effectiveness analysis, either assume future outcomes are known with certainty or assign probabilities to these future outcomes to evaluate the “expected” outcome. These decision support tools attempt to identify the “optimal” choice from a set of options. However, climate change is characterised by deep uncertainty because of the complex interactions between human and biophysical systems. Therefore, standard economic decision support tools may not be suitable for informing decisions that account for climate change. (Watkiss et al., 2015)

This case study uses extensions of the normal economic decision support tools. Instead of evaluating the “optimal” choice for one climate scenario, these decision support tools recommend options that are “robust” in the face of deep uncertainty about how the future climate might change. The decision criteria used in this study are the financial internal rate of return (IRR) and economic efficiency (NPV and BCR). These criteria are tested for multiple investments across a range future climate scenarios.

The decision support tools used in this study have been chosen to reflect the level of uncertainty and the type of adaptation options. For adaptation options that address the adaptation deficit in the tea and coffee sectors, cost-benefit scenario analysis is used for a range of plausible (short-term) future climate scenarios. For the near-term problem of choosing where to implement new tea plantations (climate-smart planning), portfolio analysis is used to evaluate the investment into climate risk mapping. The results from these decision support tools for the different adaptation investments are then combined to evaluate the project’s overall outcome.

As climate data in Rwanda is limited (Jones et al., 2015), “light-touch” versions of these decision support tools have been developed. Probabilities are not used to weight the likelihood of outcomes in different climate scenarios (full uncertainty). This case study recognises that traditional cost-benefit and portfolio analysis require probabilities to provide expected returns, but it is hoped that this modification will allow this decision support tools to be used more widely used in contexts where climate information is limited.

In order to use these decision support tools in the context of climate change, the components in Figure 1 are evaluated. These four components allow the interactions between climate, crop output and adaptation options to be assessed.

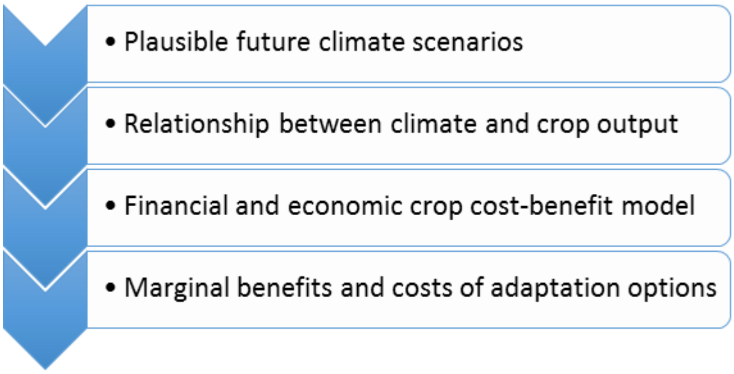

Figure 1: Components used for assessing the impact of climate and adaptation options on crop production

2.1 Climate scenarios

Projections

Plausible future climate scenarios need to be identified so that the impact of future climate on the project's outcome can be modelled. This case study reviewed climate projections from multiple sources (Table 1). Seasonal or monthly climate projections are transformed to annual projections so that the different sources can be compared. This annualised approach is also suitable for a light touch appraisal; by smoothing the noise associated with seasonal and monthly climate variability the results can be more easily interpreted.

Source	Republic of Rwanda (2011)	UK Met Office (2016)	Climate Info Portal (2016)	WHO Country Profile (2015)	Climate-Fact-Sheets (2015)
Baseline	1960 – 90	1970 - 99	1979 - 2000	1961 - 90	1961 - 90
Projections	CMIP3	CMIP5	CMIP5	CMIP5	CMIP3&5
Scenarios	A1B	RCP6.0	RCP4.5/8.5	RCP2.6/8.5	SRES A2/B1 & RCP2.6/4.5/8.5
Models	19 GCMs	18 GCMs	10 GCMs	20 GCMs	31/46 GCMs
Downscaled	N/K	No	Yes (Stat)	Yes (Dyn)	Yes (Stat)
Δ °C Midc21	+1.1 to +2.8	+0.2 to +1.4	+1.2 to +2.0	+0.5 to +3.0	+1.4 to +2.7
Δ °C Endc21	+2.0 to +4.0	0 to +4.0	+1.8 to +3.7	+0.5 to +6.0	+1.5 to +5.1
%Δ Rain Midc21	-5 to +25	-3 to +23	-1.8 to +2.0	N/K	-1.0 to +6.0
%Δ Rain Endc21	-7 to +35	-6 to +44	-3.9 to -2.1	N/K	-1.0 to +11.0

Table 1: Different sources and features of climate projection for Rwanda (Sources: Climate-Fact-Sheet, 2011; Climate Information Portal, 2016; Republic of Rwanda, 2011; UK Met Office, 2016; WHO, 2015)

For temperature, all the climate projections in Table 1 agree that mean annual temperature will either increase or remain the same by the end of the 20th Century. This means there is little uncertainty about the direction of change for temperature. However, the actual amount that temperature is projected to change varies between the different sources, emissions scenarios and models. The projections for rainfall are much more uncertain; not all the climate projections agree on the direction of change (positive or negative) and the magnitude of change varies significantly between different sources, emissions scenarios and models. Therefore, choosing between these contrasting projections is difficult. In order to capture a wide range of the information provided by the full list of projects, the following criteria are used to decide which projections to use in the climate scenarios:

Baseline data period:	**At least 30 years**
Projection models:	Latest available (CMIP5)
Emissions scenarios:	Latest, highest (RCP8.5) and lowest (RCP2.6) to capture scenario uncertainty
Global circulation models:	Ensemble, to capture inter-model uncertainty
Bias correction:	Preferably dynamically downscaled (Dyn), otherwise statistically (Stat)
Reliable and accessible:	Accredited data/models and easy to interpret

Temperature

This case study uses WHO Country Profile (WHO, 2015) climate projections for mean annual temperature. This is because they use the latest climate projections available (CMIP5), consider both a high (RCP8.5) and low (RCP2.6) emissions scenario, test a sufficient number of global circulation models (20 GCMs) and are dynamically downscaled (bias corrected) using meteorological data from a weather station in Kigali, Rwanda. This means a wide range of scenario and model uncertainty is captured in these projections, and the data is up-to-date and corrected using observed temperatures in Rwanda. Figure 2 below shows the temperature projections from the WHO Country Profile.

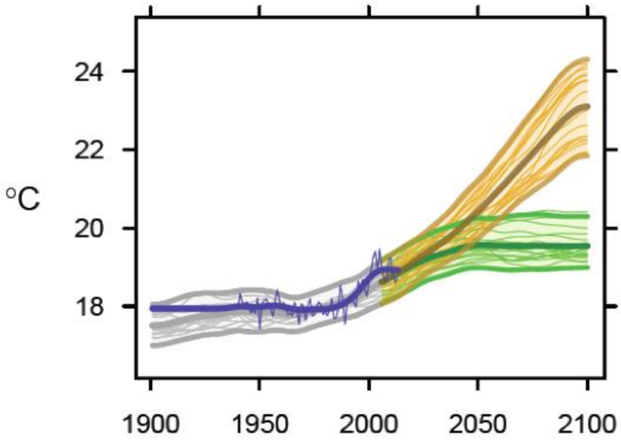

Figure 2: Mean annual temperature projections for Rwanda in emissions scenarios RCP2.6 and RCP8.5 (Source: WHO, 2015).

As Figure 2 shows, the models project a reasonably similar change in mean annual temperature before 2050 in both emissions scenarios. However, by 2100 the projected change is significantly different between the emissions scenarios. Therefore, two points in the future, 2050 and 2100, are used to assess the relative change in temperature compared to when the project will be implemented (2016). To capture scenario (emissions) and model uncertainty, the 90th percentile temperature in emission scenario RCP8.5 (top-most thick yellow line) and 10th percentile temperature from emission scenario RCP2.6 (bottom-most thick green line) are used in the analysis. By taking these extremes, this method excludes outliers, captures a wide range of uncertainty associated with current climate information and minimises the number of scenarios that need to be analysed. This approach is useful in a developing country policy context, as appraisals are often completed in short timeframes without overcomplicated analysis.

Scenarios	Relative Change in Temperature	
	2050	2100
1 – RCP2.6, lowest projection	0%	0%
2 – RCP8.5, highest projection	+11.84%	+28.95%

Table 2: Projected temperature change (relative) for Kigali in emissions scenarios RCP2.6 (10th percentile) and RCP8.5 (90th percentile) (Source: WHO, 2015).

The temperature projections in 2050 and 2100 are compared to the (smoothed) observed temperature in Kigali in 2016 (thick blue line). The relative change in temperature is used so that projections can be calibrated to different project locations at different altitudes relative to Kigali. The temperature projections in each scenario are linearly interpolated between 2016-2050-2100, so that the suitability of temperature for growing tea and coffee can be estimated for all future years. Table 2 shows the two scenarios used for the temperature.

From Table 2, it is clear that Scenario 1 is the same as a “no climate change” scenario; the mean annual temperature is projected to remain the same by 2050 and 2100 when compared to the mean annual temperature in 2016. However, the mean annual temperature in Scenario 2 is projected to increase 11.84% by 2050 and 28.95% by 2100.

It should be noted that the change in mean temperature could be higher or lower than shown in these scenarios. However, the temperature scenarios characterised here capture the extremes of the climate information available today in order to measure the full range of uncertainty about how the future climate might change.

Rainfall

The WHO Country Profile for Rwanda does not provide mean annual precipitation projections (WHO, 2015). In addition, the range of projections for rainfall is extremely wide (Table 1) and the interactions between rainfall and tea and coffee output are not well documented. Therefore, this case study assumes that the direction and magnitude of change for mean annual precipitation is fully uncertain i.e. not known. Instead, the case study assesses how the seasonal distribution rainfall is expected to change as a result of climate change, and what impact this might have for tea and coffee production.

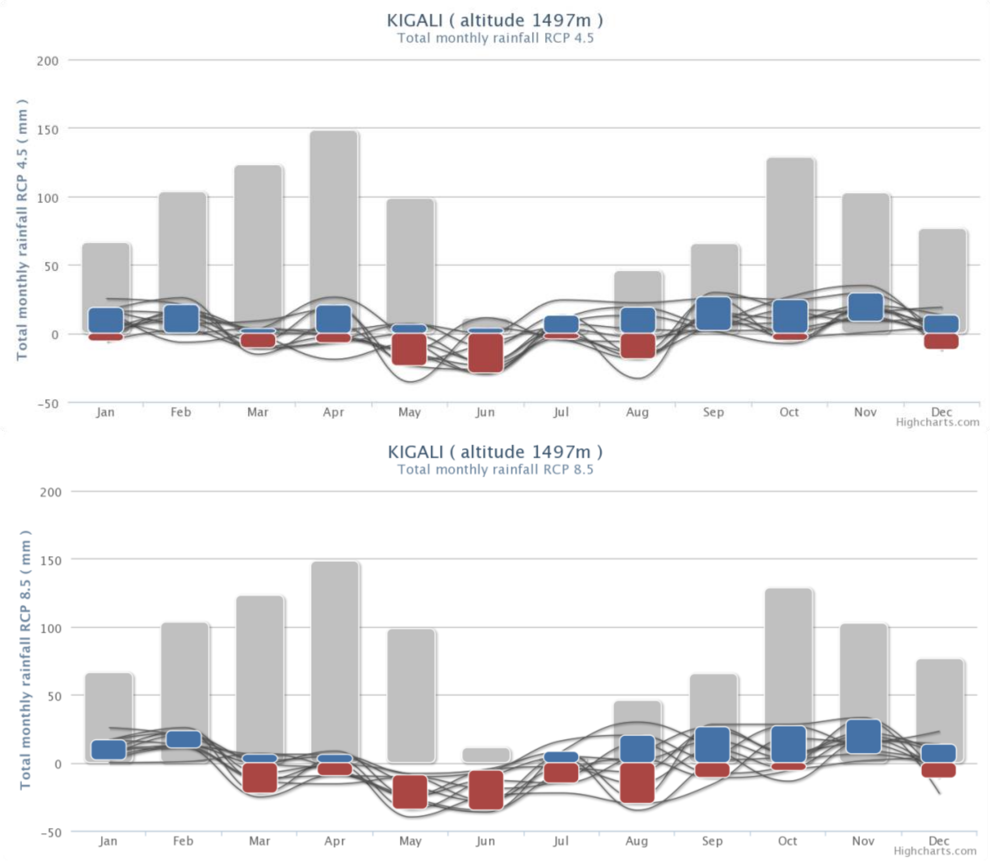

Figure 3: Total monthly rainfall projections between 2040 and 2060 for emissions scenarios RCP4.5 (3a, top) and RCP8.5 (3b, bottom) (Source: Climate Information Portal, 2016).

Using the Climate Information Portal (2016), projected changes in distribution of monthly rainfall are analysed. Figures 3a and 3b show projected changes in total monthly rainfall (mm) for a medium (RCP4.5) and high (RCP8.5) emission scenario across 10 GCMs. The uncertainty about the direction and magnitude of change in total rainfall is still clear at a monthly scale; the model range for some months covers both an increase (blue bars) and a decrease (red bars). However, the projections seem to indicate an increase in rainfall during the two rainy seasons (March-April-May and September-October-November-December) and that the dry season may become longer and more pronounced by the middle of the 21st century. These signals extend to the end of the century. (Climate Information Portal, 2016)

These projections suggest Rwanda's rainy seasons may become shorter and more intense, with a longer and more pronounced dry season. This may be explained by the physical relationship between temperatures and atmospheric moisture content; as temperature increases, the atmosphere can hold more water vapour, which may cause more intense rainfall (IPCC, 2007). However, translating these changes to impacts on crop production is difficult due to the variability in incidence, frequency and magnitude of extreme rainfall events. Therefore, this case study uses the temperature scenarios defined by WHO projections to consider changes in rainfall distribution.

Using the temperature scenarios, Scenario 1 (RCP2.6, 10th percentile) assumes temperature will remain the same by 2050 and 2100. For simplicity, monthly rainfall distribution is also projected to remain constant in Scenario 1. However, Scenario 2 (RCP8.5, 90th percentile) assumes temperature will significantly increase by 2050 and 2100. Therefore, the seasonal distribution of rainfall is likely to become increasingly polarized in Scenario 2. As a result, the damage to crops from soil erosion, landslides and floods is likely to increase in Scenario 2. The climate projections used in this case study capture this effect through an annual yield loss (soil erosion) parameter. The calibration of this parameter is discussed in the *Climate Suitability Function* section, and the projected change of this parameter for the two climate scenarios is shown in Table 3. These projections are linearly interpolated between 2016-2050-2100 to create annual yield loss parameters for each year in the model. The projections provide conservative estimates of how the rate of soil erosion might change as a result of changing seasonal distributions of rainfall distribution in the two climate scenarios.

Scenarios	Annual yield loss	
	2050	2100
1 – RCP2.6, lowest projection	0%	0%
2 – RCP8.5, highest projection	10%	20%

Table 3: Annual yield loss projections as a result of changing seasonal distributions of rainfall (Sources: Climate Information Portal, 2016; IPCC, 2007)

The long-term suitability of future climate for growing tea and coffee can be captured by the above annual temperature and rainfall projections (Tables 2 and 3). However "shocks" from extreme weather events, such as floods and landslides, and pest and disease outbreaks are difficult to model. This is due to the lack of information on hectares at risk (incidence), the frequency of these events (probability) and their severity (yield/quality impacts). Therefore, such events have been excluded from the analysis. However, it should be noted that this might positively skew the returns for the project.

2.2 Climate Suitability Functions

This case study develops climate suitability functions for both tea and coffee. These have been developed through a literature review and expert consultation. The functions translate changes in the projected future climate to effects on tea and coffee production. The output for each crop is defined in two ways: yield (quantity) and quality (price). Both yield and quality are determined by a number of factors, including climate, soil type, nutrient and water availability, vegetative cover, cultivar, and management (Ahmed et al., 2010, 2012, 2013; Lin et al. 2003). Moreover, there are trade-offs between yield and quality in tea and coffee production; the slower a crop matures, the lower its yield and the higher its quality. Both temperature and rainfall effect the rate of maturation and the amount of nutrients each crop is able to process, and subsequently their yield and price[1]. The climate suitability functions therefore use temperature and rainfall to define the yield and price output for each crop in a given scenario.

The climate suitability functions developed in this case study attempt to isolate the impact of climate on the tea and coffees' yield and quality. They do so by defining tea and coffee yield and price relationships with temperature and rainfall.

Temperature

Temperature affects the growth rate and quality of tea and coffee (Ahmed et al., 2014; DaMatta, 2006; FAO, 2015; Gay et al., 2006; Läderach et al., 2011). Within certain temperature thresholds, higher temperatures are usually associated with higher yield and lower quality. This reflects the trade-off between price and quantity. Outside of these temperature thresholds, crop production is assumed to be zero (no yield). For both tea and coffee, normalised yield-temperature and price-temperature functions have been developed. They are normalised so that they can be calibrated to different growing locations with varying yields, prices and temperatures.

Tea: Yield-Temperature

Tea can be grown between 12°C and 30°C, providing there are no other limiting factors (nutrients and water), with an optimum yield temperature of 19.2°C (FAO, 2015). Outside of this range, the yield-temperature suitability function assumes yield is zero. Within this range, the function defines yields at different temperatures as a proportion of yield at the optimal temperature (Table 4 and Figure 4a). The gradient of the function around the optimum is taken from the FAO (2015). From 14°C to 19°C it is assumed the yield increases by 3.19pp of the optimal yield for every +1°C and beyond 19.2°C the yield decreases by 3.19pp of the optimal yield for every +1°C (FAO, 2015).

Temperature (C)	Climate Suitability	% of Max Yield
< 12	Not suitable	0%
12 – 14	Marginal	50% – 83%
14 – 19.2	Increasingly optimal	83% – 100%
19.2	Optimal	100%
19.2 – 30	Increasingly suboptimal	100 – 67%
> 30	Not suitable	0%

Table 4: Suitability of temperature for tea yield (Source: FAO, 2015)

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[1] This general trade-off between yield and quality for tea and coffee elicited through correspondence with climate-coffee expert, Peter Baker (2016).

As the function is normalised between 0 and 1, it can be calibrated to the temperatures and yields experienced at different tea plantations. Take, for example, a plantation with an average annual yield of 12,000kg per hectare per year that sits at an elevation between 1,800m and 1,900 meters above sea level (masl). Given the current average annual temperature in Kigali (1,497m) is around 19.8°C (Figure 2), the temperature at the plantation can be estimated by subtracting a multiple of 0.65°C for every 100 meters above the Kigali met station i.e. 17.05°C. By inputting 12,000kg $ha^{-1}y^{-1}$ at 17.05 °C, the calibrated climate suitability function for this plantation is shown in Figure 4b.

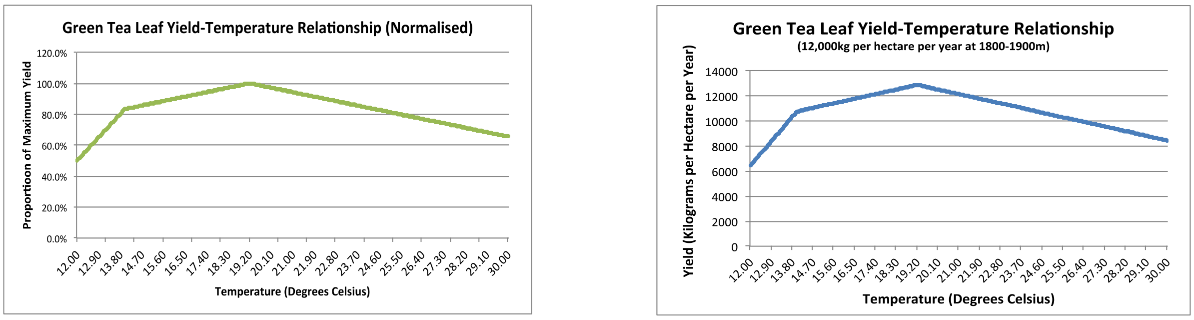

Figure 4: Normalised (4a, left) and calibrated (4b, right) temperature-yield function for tea (Source: FAO, 2015).

Tea: Price-Temperature

For the relationship between tea price and temperature, this case study analysed deflated weekly price data from the Mombasa tea auctions for each tea factory in Rwanda between 2007 and 2016[2]. Having adjusted for inflation and calculated current factory temperatures using the same method as above, a scatterplot for average price (USC/Kg) at different altitudes is shown in Figure 5a.

A logarithmic trend line is fitted to the scatterplot to avoid negative prices at higher temperatures. This relationship was used to estimate the function for green leaf prices received by farmers at different temperatures. A weight conversion factor of 4.5kg of green leaf for every 1kg of made tea, the green leaf price mechanism conversion factor of 40%[3] and the USD:RWF exchange rate[4] were all used to convert the data into green leaf prices received by farmers. It is assumed the maximum price could be achieved at the lower temperature threshold (12°C). The resulting (normalised) price-temperature suitability function shows the price farmers receive per kilogram of green leaf at each temperature, as a proportion of the maximum price (figure 5b). This function can be calibrated to specific project locations in the same way as the tea yield-temperature suitability function.

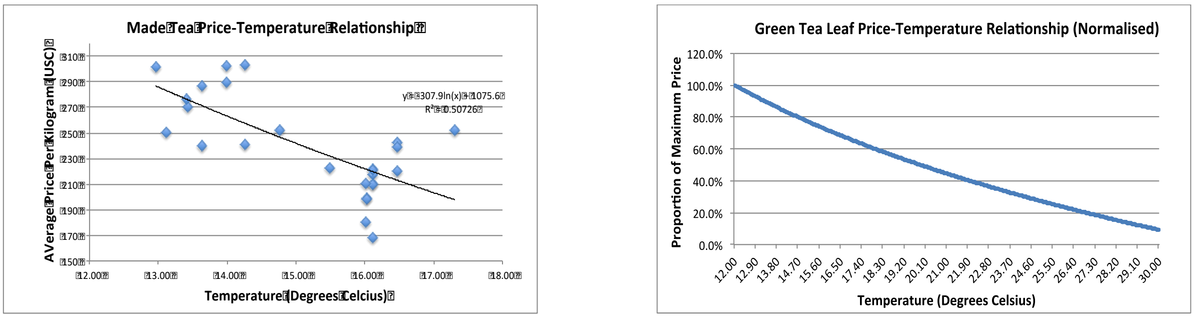

Figure 5: Price-temperature scatterplot for made tea (5a, left)[2] and normalised green leaf price-temperature function (5b, right)[3,4].

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[2] Weekly price data extracted by Combrok Tea Brokers Ltd. from Mombasa tea auctions database (06.6.16).

[3] Green leaf price document for January to March 2016 provided by the NAEB (21.03.16).

[4] Exchange rate data extracted from National Bank of Rwanda (06.09.16).

Coffee: Yield- and Price-Temperature

Arabica coffee can be grown between 15°C and 30°C providing there are no other limiting factors e.g. nutrients and water (Ngabitsinze et al., 2011). However, this range represents the absolute limits and is not suitable for applying to mean annual temperature projections. This is due to variability around the mean; a mean temperature of 15°C would be below 15°C for 50% of the time on average, and a mean temperature of 30°C would be higher than 30°C for 50% of the time on average. Therefore, a more constrained range is needed for mean annual temperature suitability.

Pereira et al. (2008) suggest Arabica coffee can be grown between mean annual temperature ranges of 17°C and 24°C in Brazil. Arabica can withstand temperatures outside this range, but only for certain phonological stages and providing there are no other limiting factors (Teixeria et al., 2014; Morais et al., 2006). In addition, Camargo (1985) states that above 23°C ripening accelerates, whilst a number of authors find the rates growth might decline above 24°C as a result of the effects highlighted in Table 5.

Temperature (C)	Effects
> 23	Ripening accelerates, loss of quality (Camargo, 1985)
> 24 - 25	Photosynthesis and carbon assimilation reduced (Nunes et al., 1968; Wilson, 1985; Descroix & Snoeck, 2004)
> 29 - 30	Soil temp at which feeder roots die (Franco and Munns, 1982)
> 30	Growth depression, increasing leaf, stem and flower abnormalities (DaMatta, 2004; Descroix & Snoeck, 2004)
> 34	Rapid flower aberration (Laffe et al., 1968, 2003[5])

Table 5: Effect of different temperature ranges on coffee trees at various phonological stages.

From this evidence, a "near-optimal" yield range of 18°C to 24°C (mean annual) is defined in this case study, with yield increasing up to the optimal 24°C. The mean annual temperature is assumed to be suboptimal for yield between 16°C and 18°C, and marginal between 15°C - 16°C and 24°C - 30°C. This is shown in Table 6 and Figure 6a.

The price received by farmers for coffee cherries (RWF/kg) is assumed to be highest at the lower yield-temperature bound (15°C), and decrease as temperatures increase. This reflects the trade-off between the rate of berry maturation and quality for increasing temperatures. The rate at which the coffee cherry price falls is modelled to increases beyond 23°C as suggested by Camargo (1985). This is shown in Figure 6b.

Temperature (C)	Climate Suitability	% of Max Yield
< 15	Not suitable	0%
15 – 16	Marginal	0% - 75%
16 – 18	Suboptimal	75% - 95%
18 – 24	Near-optimal	95% - 100%
24	Optimal	100 %
24 - 30	Marginal	100% - 0%
>30	Not suitable	0%

Table 6: Climate suitability function of temperature-yield for coffee.

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[5] Papers cited in unpublished literature review by coffee-climate expert Peter Baker (2016).

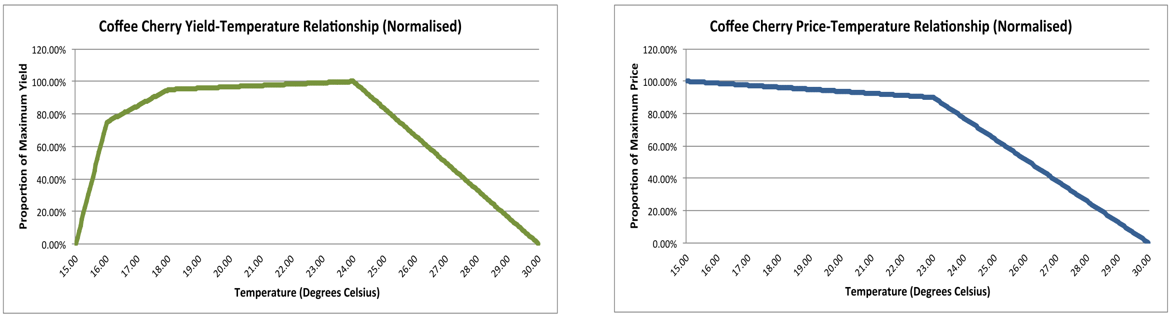


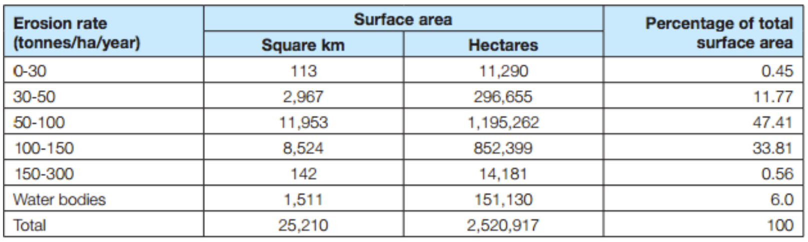
Figure 6: Coffee climate suitability functions for temperature-yield (6a, left) and temperature-price (6b, right).

These functions should be treated with caution as the majority of evidence used in their development is from plantations in South America. Moreover, the coffee price-temperature function is not based on an evaluation of price data, unlike the tea price-temperature function. However, all the climate-suitability functions are based on the best available evidence and are relatively easy to interpret.

Rainfall

Tea bushes require at least 1,200mm of rainfall per year. Ahmed et al. (2014) find higher levels of rainfall are associated with higher yields and lower quality tea during the Chinese monsoon season. This provides further evidence for the trade-off between yield and quality in tea as a result of varying climatic conditions. Despite these findings, quantifying the direct relationship between rainfall and tea yield and price is more difficult than temperature. Similarly, despite evidence suggesting that coffee trees require at least 125mm rainfall per month (Jaramillo, 2005), there is very little quantitative evidence of the direct impact rainfall has on coffee yield and price.

As a proxy for the indirect impact of rainfall on tea and coffee production, this study uses the annual yield loss parameter outlined in the previous section (*Climate Scenarios: Projections - Rainfall*). This parameter accounts for the yield loss each year as a result of soil erosion. A review on soil erosion literature was carried out in order to calibrate this parameter.



Erosion rate (tonnes/ha/year)	Surface area		Percentage of total surface area
	Square km	Hectares	
0-30	113	11,290	0.45
30-50	2,967	296,655	11.77
50-100	11,953	1,195,262	47.41
100-150	8,524	852,399	33.81
150-300	142	14,181	0.56
Water bodies	1,511	151,130	6.0
Total	25,210	2,520,917	100

Table 7: Soil erosion rates in Rwanda based on GIS modelling (Source: UNEP, 2011)

The rate of soil erosion depends on a number of factors, including the amount of vegetation, soil structure and topography of a plantation (*Daba, 2002*). The World Bank (2002) reports soil losses of 35 to 246 tonnes per hectare each year. The United Nations Environment Programme (UNEP, 2011) updated these finding in 2011 (Table 7), categorising the total surface area in Rwanda into different soil erosion rate bands using GIS modelling.

Despite this evidence, translating the loss of soil erosion in tonnes into changes in yield or quality for tea and coffee is problematic. The World Bank (2002) estimates cereal and tuber crops loose 0.167% and 1.167% of yield respectively each year in Rwanda as a result of soil erosion.

However, no estimates for tea and coffee have been found. Therefore, the lower bound of the World Bank estimates (0.167%) is used as a conservative estimate for yield loss per annum is used in this study. This is the baseline (2016) rate at which yield declines year-on-year for tea and coffee.

In scenario 1, the seasonal distribution of rainfall distribution is assumed to remain constant as temperatures remain unchanged. The annual yield loss as a result of soil erosion is therefore assumed to remain the same for all future years at 0.167% (Figure 7). In scenario 2, the seasonal distribution of rainfall is expected to change, leading to a year-on-year increase in the rate of soil erosion (Table 3). As a result, the annual yield loss as a result of soil erosion is modelled to increase 10% by 2050 and 20% by 2100 (Figure 7).

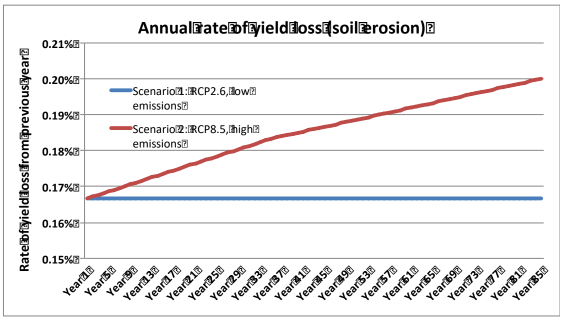


Figure 7: Annual yield loss parameter in Scenarios 1 (RCP2.6) and 2 (RCP8.5)

2.3 Plantation models

Financial model

For both tea and coffee, the financial models have been established in a two-fold process. Firstly, an input and output model for a 1 hectare plantation has been developed which captures the investment, operating and management costs, and the benefits in terms of average annual yield and price. This is the engine of the model. It can be calibrated to specific plantations using price, productivity and climate data. This model can be scaled up to represent the size in hectares of different project locations, which allows to the study to assess the business as usual (BAU) plantations without any interventions from the project.

Secondly, the BAU plantation models are tested in the different climate scenarios (Tables 2 and 3). The impact of the climate scenarios on the crops' outputs (and inputs) is driven by the changes in yield and price associated with different climatic conditions, which are defined by the climate suitability functions (previous section). This is the private financial model for tea and coffee plantations without any intervention. The main financial input and output categories are shown in Tables 8 and 9. These values were attained through consultation with stakeholders in the Rwanda tea and coffee sectors, including the Government of Rwanda and the third sector.

In the financial model land is assumed to have an economic life of 50 years (Wintgens 2009, cited in Bunn et al 2014; Republic of Rwanda, 2016a). Agricultural tools and materials are assumed to have an economic life of 1 to 10 years[6]. These assets are depreciated over their economic life and then incurred as a reinvestment cost once fully depreciated. No tax is included at the smallholder farm level as agricultural inputs and income from agricultural activities that is less than RWF 12m per year are exempt from tax (PWC, 2015).

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[6] Economic life of agricultural assets taken from financial model for coffee provided by MINAGRI (25.04.16), and quality assured by consulting Sustainable Harvest agronomists (08.09.16).

Inputs	Year(s)	Private costs
Establishment Costs		
Land acquisition (50 year lifetime)	1	2,600,000 RWF
Tools and equipment (1-10 year lifetime)	1	225,267 RWF
Nursery establishment	1	235,933 RWF
Seedling preparation	1	320,264 RWF
Plantation preparation	1	1,020,100 RWF
Transplanting seedlings and fertiliser	1	866,762 RWF
De-centering	2	3,600,000 RWF
Operation and Maintenance		
Nursery maintenance and infilling	2+	6,408 – 64,076 RWF
Fertiliser purchase and application	2+	135,548 – 314,119 RWF
Weeding (manual)	2+	1,650 – 16,500 RWF
Maintenance of anti-erosion/drainage ditches	2+	22,500 RWF
Pruning, skiffing and tipping	4+	36,870 RWF
Plucking labour	3+	35 RWF/kg
Transport to factory	3+	10 RWF/kg
Outputs	**Year(s)**	**Private benefits**
Revenues from green leaf payments	3+	100 – 250 RWF/kg

Table 8: 1 hectare financial input and output model for smallholder tea plantation (13,889 bushes)

Inputs	Year(s)	Private costs
Establishment Costs		
Land acquisition (50 year lifetime)	1	2,600,000 RWF
Tools and equipment (1-10 year lifetime)	1	303,000 RWF
Nursery establishment	1	80,950 RWF
Seedling preparation	1	199,750 RWF
Plantation preparation	1	856,500 RWF
Transplanting seedlings and fertiliser	1	875,000 RWF
Formative prune	2	648,000 RWF
Operation and Maintenance (annual)		
Nursery maintenance and infilling	2+	3,865 – 38,650 RWF
Fertiliser purchase and application	2+	330,000 RWF
Pesticide/fungicide purchase and application	2+	50,000 RWF
Weeding (manual)	2+	75,000 RWF
Maintenance of anti-erosion/drainage ditches	2+	22,500 RWF
Pruning	3+	30,000 RWF
Cherry picking	3+	10 RWF/kg
Transport to washing station	3+	10 RWF/kg
Outputs	**Year(s)**	**Private benefits**
Revenues from coffee cherry payments	3+	100 – 300 RWF/kg

Table 9: 1hectare financial input and output model for smallholder coffee plantation (2,500 trees)

Economic conversion factors

The financial model for tea and coffee plantations is converted into an economic model using the assumptions in table 10. These assumptions are also used to convert financial inputs and outputs from the project into economic values.

Category	Assumption and explanation
Opportunity costs:	Next best source of income for tea and coffee smallholders
Exisiting tea/coffee plantations	Net benefits from plantation without project implemented (BAU)
New land used by the project	**USD 400** per hectare each year[7]
Public transfers	**Remove** for economic appraisal, to eliminate distortions of opportunity costs which can affect economic decision making (HM Treasury, 2015)
Depreciation and capital charges	**Remove** as based on sunk costs, which should be excluded from economic decision making
Shadow price conversions:	Adjust market prices for ineffiencies the alter scarcity value (HM Treasury, 2015)
Capital goods	**0.7139**[8] of market price
Unskilled labour	**0.8600**[8] of market price
Skilled labour	**0.7692**[8] of market price
Tea and coffee prices	**None** applied[8] – EAC customs union minimises regional export trade barriers
Income multiplier	**1.053**[9] - Conservative multiplier that quantifies positive externalities associated with additional income generated by a project (HM Treasury, 2015). In Rwanda, these positive externatlities include food security and higher investments into human capital e.g. health and education
Social discount rate	**13%** - Used by Republic of Rwanda to reflect preference for receiving goods and services today rather than tomorrow (HM Treasury, 2015). The analysis here also considers a 0% discount rate as a form of sensitivity anlaysis

Table 10: Economic conversion factors for financial plantation models and project inputs and outputs

Other externalities are assessed after the quantitative analysis in this study due to a lack of quantifiable evidence. The impact of the project on biodiversity, carbon sequestration and off-farm soil erosion are considered.

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[7] Estimated by the UK Department for International Development (DfID) and provided through consultation (May 2016).

[8] Shadow price assumptions for financial inputs and outputs taken from World Bank (2013) Rwanda Second Rural Sector Support Project (RSSP2) Implementation and Completion Report

[9] Revenue multiplier taken from financial model for coffee provided by MINAGRI (25.04.16)

3. Analysis and Results

3.1 Low-regret options: Cost-Benefit Scenario Analysis

The project has allocated 66.67% of funding to hard adaptation options that address current climate variability and the adaptation deficit in the tea and coffee sectors. These adaptation options are soil and water conservation (SWC) measures, which change the physical conditions in which tea and coffee are grown. The measures aim to provide private benefits to smallholders, in terms of improved yield and price that smallholders receive and the recovery of potential earnings lost from soil erosion (Bekele, 2003). However, they also generate off-site benefits through a reduction in the negative externalities linked soil erosion (Telles et al., 2013).

The full list of SWC measures identified for tea and coffee is shown in Table 11. This list was narrowed down through a process of stakeholder consensus, literature reviews on the options' efficacy, and finally benefit-cost assessment. Some of the SWC measures have already been implemented by projects funded by international development assistance (IFAD, 2011), and were therefore excluded from this project in order to diversify the range of suitable options implemented in Rwanda. Mulching is the exception to this rule, due to the weight of evidence in favour of it (Tummakate, 1999). Other options were ruled out as unsuitable for tea or coffee in Rwanda, or not justifiable in terms of adaptation funding. The final SWC measures included in the project design are highlighted in green (Table 11). The benefits and costs of cover crops as a substitute to mulching for coffee are also assessed, but this option is ruled out due to its performance relative to mulching.

Tea	Coffee	Tea
Double digging	✓	✓
Terracing	✓	✓
Anti-erosion / drainage ditches	✓	✓
Hedgerows / grass strips	✗	✓
Shade trees	✓	✗
Tree belts	✗	✓
(Banana) intercropping	✓	✗
Organic composting	✓	✓
Envelope forking	✓	✓
Burying pruned material	✓	✗
Mulching	✓	✓
Cover crops	✓	✗

Table 11: Soil and water conservation measures for tea and coffee assessed in project design phase

In the rest of this section, the tea and coffee plantations chosen to implement SWC measures are evaluated in Scenarios 1 and 2 (see *Climate Scenarios*). This is the BAU case. Then the marginal benefits and costs of implementing the SWC measures highlighted in Table 11 are evaluated for each of the plantations in which they will be implemented.

Existing tea plantations

Business as usual

In the 2009 - 2012 Agriculture Sector Investment Plan (ASIP) the Government of Rwanda set out to increase tea exports by developing 5 new tea factories (Republic of Rwanda, 2013c). In combination with these factories, 5 new smallholder tea cooperatives have been established to supply green leaf tea (Table 12). The plantations developed by these cooperatives are still young (between 3 and 5 years old), and can therefore benefit from soil and water conservation (SWC) measures because they are not as dense as mature plantations.

New Tea Cooperatives	Plantation Size (Ha)	Number of Members
COOTHEGAB	664	996
COOTHEMUKI	1026	3436
COTHEGA	1719	2829
KATECOGRO	1097	859
RUTEGROC	1735	2078

Table 12: Existing tea cooperatives established under phase I of Rwanda's tea expansion plan[10].

For simplicity, this analysis assumes all the cooperative plantations are three years old[11]. The entire 6,240ha are assessed in both Scenario 1 (no climate change) and 2 (climate change) over the next 35 years. The current yields for all the project locations are calibrated at 10,000kgs/ha each year[12]. The price received by smallholders is estimated to be 170 RWF/kg, based on the national average price received from 2007 to 2016[2]. Future yields and prices are calibrated using the altitude of project locations (Annex 2), forecasting temperature at these locations and applying the tea climate suitability function. The results from the business as usual (BAU) analysis are shown in Table 13.

Sensitivity analysis: BAU existing tea plantations (6,240ha)	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
Scenario 1: RCP2.6 / No climate change	146 %	2.63	USD 281.42m	2.57	USD 53.16m
Scenario 2: RCP8.5 / Climate change	145 %	2.55	USD 275.23m	2.54	USD 53.02m

Table 13: Financial and economic returns for 3-year-old tea plantations (6,240ha) in and high emissions scenarios.

The results show that the plantations will generate higher financial and economic returns in Scenario 1. In Scenario 2, private returns are expected to fall by 1 percentage point over the next 35 years. Similarly, the loss in social welfare relative to Scenario 1 is estimated to be between 0.25% and 2.20% depending on which social discount rate is used. For the 10,198 members of these 5 cooperatives, this translates to a loss between USD 14 and 607 per farmer over 35 years. These results are driven by the change in climatic suitability between the two scenarios. In Scenario 2, temperatures are expected to increase by 11.84% by year 35 (Table 2), which may result in a price fall of 13-15% and an increase in the annual yield loss parameter of 10%. However, overall yield is expected to increase by 0-14% over the next 35 years because

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[10] Information provided by Rwanda National Agricultural Exports Board (22.06.16).

[11] In reality the planting scheme is phased, meaning there are some tea bushes that are planted and productive, some that are planted and not productive, and some that are not yet planted.

[12] Output estimated by National Agricultural Exports Board for 13,889 tea bushes per hectare.

of the increase in temperature. Therefore there is a trade-off between yield and price in Scenario 2 as temperatures increase, but the price fall dominates the yield increase. This is a feature of the tea climate suitability function.

To bolster the output of tea in these cooperative in both scenarios, this study considers the following SWC investments for these plantation: grass strips and tree belts. These adaptation options will be implemented in combination with farmer field schools, to improve the efficiency of their implementation and educate farmers about additional SWC techniques.

Grass strips

Anti-erosion or drainage ditches have been constructed at each of the 5 tea cooperatives (6,240ha). This study considers the impact of implementing grass strips along these ditches. The investment into grass strips would contribute to "progressive terracing", whereby hydric and tillage erosion gradually reduces the gradient to create bench terraces (WOCAT, 2013). In addition, the grass adds another layer of protection against surface runoff and topsoil loss. The plant matter produced by the grasses will also provide mulching material to cover the ground between tea bushes whilst the plantations are still young (up to 8 years old)[13]. After the plantations reach maturity, the grasses can be used to provide an alternative source of income through the sale of the surplus plant matter (fodder or mulch), or can be used for mulching other crops owned by the smallholder.

The practice of combining grass lines with trenches is already practiced in Imiringoti, which demonstrates its suitability for Rwandan tea plantations (WOCAT, 2014). A quantitative assessment of the private costs and benefits is provided in Table 14. However, the wider benefits and costs are difficult to quantity, so a qualitative assessment of progressive terracing is provided in Annex 3.

Inputs	**Year(s)**	**Private costs**
Establishment Costs		
Scythes (5 year life)	1/5/10…	8,000 RWF
Seeds	1	3,000 RWF
Land preparation	1	1,080 RWF
Clearing bushes/trees	1	200 RWF
Planting	1	1,350 RWF
1st weeding	1	900 RWF
2nd weeding and watering	1	900 RWF
Operation and Maintenance		
Grass management	2+	30,000 RWF
Mulching or removing fodder	2+	30,000 RWF
Outputs	**Year(s)**	**Private benefits**
Direct change in green leaf yield	5+	+10%
Revenue from grass plant matter	5-35	15,000 RWF

Table 14: Financial (private) benefits and costs of implementation grass strips on a 1 hectare tea plantation.

The costs in Table 14 are based on French Cameroon Grass being implemented as grass strips. It assumes 150 metres/ha of grass strips are planted, with a spacing of 0.5 metres i.e. 300 plants/ha. For the full 6,240ha of cooperative tea plantations, this represents an investment into

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[13] Mulching tea plantation less than 8 years old said to be beneficial in interview with third-sector tea expert (Sanjay Kumar, 25.04.16).

936km of grass strips or 1,872,000 grass plants. The mulch provided by these strips is assumed to boost tea yield by 10% after 5 years (Sandanam et al., 1976). It is also assumed that the progressive terraces developed with the help of these strips reduce the rate of soil erosion by 50% from year 5 onwards. This is a conservative estimate derived from evidence that radical terracing can reduce soil erosion by 78% reduction in Rwanda (Karamage et al., 2016). Further benefits result from the surplus grass matter that can no longer be used as mulch once the tea plantations are mature (after year 5). It is assumed that each plant produces 1kg dry matter each year from years 5 to 35 based on Bodgan's (1977) low maintenance estimates. At 50 RWF/kg of mulch[14], the dry matter benefits are estimated to be 15,000 RWF/ha from years 5 to 35.

The benefit-cost analysis of French Cameroon Grass are shown in Table 15. They show high financial returns in both Scenario 1 and 2. Similarly, they show that the economic net benefits of implementing French Cameroon Grass are high in both scenarios. Interestingly, the economic performance between the two scenarios depends on the social discount rate that is used; with a 0% discount rate the BCR and NPV are higher in Scenario 1, but at the 13% discount rate the BCR ranking is the same but the NPV is higher in Scenario 2.

Sensitivity analysis: Grass strips	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
Scenario 1: RCP2.6 / No climate change	59.74%	3.94	USD 71.85m	3.16	USD 9.24m
Scenario 2: RCP8.5 / Climate change	59.84%	3.80	USD 71.11m	3.12	USD 9.26m

Table 15: Cost-benefit analysis for grass strips on 6,240ha of smallholder tea plantations for high and low emissions climate scenarios.

Tree belts

Tree belts will be implemented at plantations exposed to damage from wind and dust e.g. hilltops and roads. This is assumed to be half of the total area for each cooperative plantation (3,121ha). This study did not find any quantifiable evidence for the direct impact tree belts could have on tea yield or quality. However, there is evidence that tree belts can increase the yield of other crops by 23% to 300% (Bognetteau-Verlinden, 1980; Guyot, 1986; Wang Shiiji, 1988). These improvements in yield are likely to be caused by a reduction in wind speed, which reduces topsoil erosion, damage to crops and conserves water by decreasing the rate of evapotranspiration (FAO, 1989). The trees also help stabilise soil, further reducing soil erosion and the risk of landslides and flooding. This is particularly important because of Rwanda's hilly topography (Bizimana, 2015). Finally, the trees belts yield wood that can be used for firewood or other products.

Table 16 shows the private benefits and costs of investing in tree belts. The costs assume 200 metres/ha of tree belts are planted (2-leg windbreak[15]), with a spacing of 4.5 metres i.e. 44 tree/ha. For the 3,120ha where the project plants to implement tree belts, this represents an investment into 924km of tree belts or 166,000 trees (including a 20% contingency for infilling).

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[14] Estimate taken from spreadsheet provided by MINAGRI (25.04.16).

[15] National Agroforestry Centre's (USDA) Windbreak Series: How Windbreaks Work. Available from: http://nac.unl.edu/documents/morepublications/ec1763.pdf (accessed 20.10.16).

Inputs	**Year(s)**	**Private costs**
Establishment Costs		
Land for nursery	1	468 RWF
Tools and materials (1 - 5 year life)	1+	19,900 RWF
Nursery and seedling establishment	1	3,605 RWF
Transplanting seedlings	1	17,156 RWF
Operation and Maintenance		
Nursery maintenance and infilling	2	1,029 RWF
Pruning trees	5/10/15…	50,000 RWF
Transporting tree biomass	5/10/15…	2,667 RWF
Outputs	**Year(s)**	**Private benefits**
Direct change in green leaf yield	5+	0% to +10%
Revenue from tree dry matter (wood)	5/10/15…	16,056 RWF

Table 16: Financial (private) benefits and costs of implementing tree belts on a 1 hectare tea plantation.

Due to the lack of quantitative evidence for the effect of tree belts on tea yield, a range of direct impacts on tea yield is tested (0% to 10%). This range is positive and conservative, reflecting the positive yield effect tree belts have on other crops whilst acknowledging that tea may not experience the same magnitude of yield benefits as other crops. Further direct private benefits result from the wood that is harvested during every 5-year pruning cycle. It is assumed that each tree produces 10kg of dry matter (wood) every 5 years, based on evidence for high yielding tree species (Chamberlain, 2001). At 36 RWF/kg of wood[16], the dry matter benefits are estimated to be 16,056 RWF/ha every 5 years. In addition to these direct benefits, tree belts also reduce the rate of soil erosion. A conservative reduction in the annual tea yield loss parameter by 10% after year 5 is applied in this study. This is less than the impact on soil erosion estimated for grass strips. Other benefits and costs associated with specific tree varieties are not assessed in this study because the species to be implemented have not yet been decided.

Sensitivity analysis: Tree belts (+10% direct tea yield)	**IRR**	**0% Discount Rate**		**13% Discount Rate**	
		BCR	**NPV**	**BCR**	**NPV**
Scenario 1: RCP2.6 / No climate change	70.69%	3.67	USD 16.04m	3.36	USD 2.30m
Scenario 2: RCP8.5 / Climate change	70.56%	3.43	USD 15.62m	3.25	USD 2.28m

Table 17: Cost-benefit analysis for tree belts on 3,120ha of smallholder tea plantations for high and low emissions scenarios.

If tree belts do not change tea yield, from Table 16 it is clear that the cost of pruning the trees every 5 years (50,000 RWF) outweighs the benefits received from the dry matter produced (16,056 RWF). In this instance, investing in tree belts is not worthwhile as the financial returns and economic net benefits are too low regardless of the future climate. However, if the tree belts increase tea yield by 10%, then the financial and economic returns are high enough to consider investing in tree belts (Table 17).

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[16] Estimated using 2013 prices for domestic wood in rural areas of Rwanda and adjusting for inflation (Source: Republic of Rwanda, 2013d)

This result holds for both Scenario 1 (no climate change) and 2 (climate change). Interestingly, the financial and economic returns to tree belts are lower in the high emissions scenario because the rate of tea yield and quality degradation exceeds the benefits provided by the tree belts. The investment from a private financial and economic net benefits perspective remains attractive even if the direct change tree belts have on tea yield is as low as 1-2%.

Tea low-regret strategy

To ensure smallholders implement grass strips and tree belts effectively, the project intends to invest in farmer field schools. These schools will be carried out at each of the five tea cooperatives, using the 75 existing trainers in the cooperatives educated in the PRICE project (IFAD, 2011). These trainers can teach approximately 30 farmers each year, meaning the annual training capacity is 2,250 tea smallholders. The project will fund one cohort of 2,250 tea smallholders, which is nearly 25% of the total membership of these cooperatives. The total financial cost of this training is RWF 31m or 38,638 USD. It should be noted that additional cohorts could be trained at a significant discount, as the lessons learned by the cooperative trainers can be transferred.

The costs and benefits from efficient implementation are implicitly assumed in the benefit-cost analysis of the two low-regret options above. This is a reasonable assumption for French Cameroon Grass, as WOCAT (2014) found high voluntary adoption rates of progressive terracing in Rwanda (100% of 207 families assessed). This assumption may not be applicable to tree belts; one stakeholder provided anecdotal evidence of trees being removed by tea smallholders in Rwanda[17]. The farmer field schools in this project will therefore need to focus on educating farmers about the long-term benefits of implemented these low-regret options in order to ensure the two options are implemented effectively.

To estimate the project outcome for the tea low-regret adaptation options as a whole, this study has combined all the benefits and costs from implemented French Cameroon Grass, tree belts and farmer field schools. The estimated outcome for this aggregated tea low-regret strategy is shown in Table 18.

Sensitivity analysis: Tea low-regret strategy	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
Scenario 1: RCP2.6 / No climate change	60.86%	3.88	USD 87.86m	3.18	USD 11.51m
Scenario 2: RCP8.5 / Climate change	60.92%	3.72	USD 86.70m	3.13	USD 11.52m

Table 18: Cost-benefit analysis of tea low-regret strategy in high and low emissions scenarios.

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[17] Evidence from interview with Director of Tea for Rwanda Agriculture Board (25.04.16).

Existing coffee plantations

Business as usual

The project plans to implement adaptation options that address current climate variability and the adaptation deficit in the coffee sector using two institutional approaches; working with smallholders through the Government's existing coffee consolidation programme and working with smallholders through a third-sector organisation. Under the coffee consolidation programme the Government of Rwanda is developing 6,000ha of smallholder coffee plantations (IFAD, 2011). Of this, 1,500ha has been identified for implementing the physical adaptation options of mulching and shade trees (Table 19). In addition, the third-sector project partner Sustainable Harvest plans to implement a combination of mulching and shade trees, and mulching and banana intercropping on its existing smallholder plantations (Table 19).

Existing Locations:	**Shade Trees (ha)**	**Banana Trees (ha)**	**Mulching (ha)**
Coffee consolidation programme	**1,500**	**0**	**1,500**
Gakenke (North)	300	0	300
Kirehe (East)	600	0	600
Nyamagabe (South)	200	0	200
Rulindo (North)	400	0	400
Sustainable Harvest	**4**	**2**	**6**
Tongere Umusaruro (East)	2	2	4
Nyampinga (South)	2	0	2
Total Area	**1,504**	**2**	**1,506**

Table 19: Existing coffee plantations established by public (IFAD, 2011) and third sector[18].

To assess the potential impact of climate change on these existing plantations, a 35-year business as usual plantation model has been developed and analysed in both Scenario 1 (no climate change) and 2 (climate change). This model covers the entire project area (1,506ha) and assumes all the coffee plantations are 2 years old[19]. The current yields for all the project locations are calibrated using evidence from the 2015 National Coffee Census (Republic of Rwanda, 2016b) and the map in Annex 3, which shows projected and actual Arabica yields in different agro-ecological zones across Rwanda (Nzeyimana et al., 2014). The price received for coffee cherries is assumed to be 200 RWF/kg, which is line with current prices and within a 50% range of historic prices[20]. Future yields and prices are calibrated using the altitude of project locations (Annex 3), forecasting temperature at these locations and applying the coffee climate suitability functions. The results from the business as usual analysis are shown in Table 20.

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[18] Third sector project partner, Sustainable Harvest, plantation sizes confirmed in interview (22.04.16).

[19] In reality the planting scheme is phased, meaning there are some coffee trees that are planted and productive, some that are planted and not productive, and some that are not yet planted.

[20] Historic farm gate prices for coffee cherries (RWF/kg) provided by NAEB (28.04.16).

Sensitivity analysis: BAU existing coffee	IRR	0% Discount		13% Discount	
		BCR	NPV	BCR	NPV
Scenario 1: RCP2.6 / No climate change	24.61%	1.46	USD 26.30m	1.45	USD 5.48m
Scenario 2: RCP8.5 / Climate change	52.13%	1.58	USD 33.53m	1.52	USD 6.46m

Table 20: Financial and economic returns for 2-year-old coffee plantations (1,506ha) in both emission scenarios.

Unlike tea, the financial and economic returns for 1,506ha of existing coffee plantations are better in Scenario 2 (climate change). This is because increasing temperatures lead to an average yield increase of 9.62% across the project locations by year 35. The average price received for coffee cherries falls by 2.62% by year 35. Therefore, the increased yield that is expected in Scenario 2 dominates the fall in prices.

The difference in financial and economic returns shows the level of uncertainty about how future climate change might impact these existing plantations. The financial IRR in the Scenario 1 is almost double that in Scenario 1 (no climate change). Similarly, at a 13% social discount rate the economic net benefits are 18% higher (nearly USD 1m) in Scenario 2. It should be noted that these results are aggregated for all the specific project locations. Therefore some locations are expected to perform worse in Scenario 2, because their current temperatures are close to optimum for yield and price.

To improve the output of coffee in both climate scenarios, this study considers the following SWC investments for these plantations: mulching, shade trees and banana intercropping. These adaptation options will be implemented in combination with farmer field schools, to improve the efficiency of their implementation and educate farmers about additional SWC techniques.

Mulching / Cover crops

Mulching involves putting organic matter on the ground surrounding the coffee trees. This ground cover provides protection against surface soil erosion and also to conserve the soil by improving the nutrient content through the process of direct leaching or decomposition (Romero et al., 2002). This is particularly important for the Rwanda agricultural sector given the country’s hilly topography and high rates of soil erosion (Bizimana, 2015). Mulching rates for coffee in Rwanda have improved over the last decade, and now stand at around 59.7% in 2015 (Republic of Rwanda, 2016b). The Government of Rwanda has already invested in mulch as part of the coffee consolidation programme, giving precedence to its use as an intervention in the coffee sector in Rwanda (IFAD, 2011).

Cover crops are a substitute to mulch, providing ground cover by growing between coffee trees. Cover crops use less land than mulch as they can be grown alongside coffee, which reduces the pressure on land use[21]. This study compares the benefits and costs of mulching and cover crops for the 1,506ha of existing coffee plantations. The private financial benefits and costs are shown in Tables 21 and 22.

Table 21 shows the private benefits and costs (per hectare) of implementing mulch. The project considers buying mulch using existing markets, rather than implementing new plantations to grow mulch. This approach minimises the impact on scarce land and the benefits are quicker to materialise. Each hectare of coffee requires 2,500kg of mulch per year, which includes the need to reapply mulch every 3 to 4 months. This translates to 625 bunches of fodder at 250 RWF

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[21] Anecdotal evidence from interview with Rwanda Agriculture Board (18.03.16).

each[22]. Including labour for applying mulch, the cost of implementing mulch is approximately 211,250 RWF/ha (265 USD/ha) each year.

Inputs	**Year(s)**	**Private costs**
Buying mulch material	1+	156,250 RWF
Transporting mulch material	1+	25,000 RWF
Applying mulch to ground	1+	30,000 RWF
Outputs	**Year(s)**	**Private benefits**
Direct change in coffee cherry yield	2+	+14% to +50%
Direct change in coffee cherry price	2+	+3% to +20%
75% reduction in manual weeding	2+	273,000 RWF

Table 21: Financial (private) benefits and costs of implementing mulch on a 1 hectare coffee plantation.

Inputs	**Year(s)**	**Private costs**
Establishment Costs		
Land for seed multiplication	1	13,867 RWF
Scyths (5 year life)	1/5/10…	4,000 RWF
Operation and Maintenance		
Seed production	1+	530 RWF
Sowing seeds / cultivation	2+	15,000 RWF
Cover crop management	2+	7,500
Outputs	**Year(s)**	**Private benefits**
Direct change in coffee cherry yield	3+	0% to -25%
91% reduction in manual weeding	3+	331,240 RWF

Table 22*: Financial (private) benefits and costs of implementing cover crops on a 1 hectare coffee plantation.*

Evidence from the Rwanda Agriculture Board (RAB) suggests that mulch may increase coffee yield by 14% to 50%[23] and that quality, as a proxy for price, can increase by 3% to 20%[24] depending on the existing management practices that are in place. This study uses a conservative yield increase of 14% and price increase of 3%. In addition to the direct changes in coffee output, mulching also reduces weeds. This generates large indirect benefits from the tools that no longer need to be bought and the labour saved (273,000 RWF/ha each year)[25]. In addition to the benefits shown in Table 21, the ground cover provided by mulch will reduce the rate of soil erosion (Doring et al., 2005). Therefore, the annual yield loss parameter is assumed to decrease by 75% from year 2 onwards[25]. As a result of the additional smallholder profits generated from increased revenue and reduced costs, coffee smallholders will have enough extra income (462,000 RWF/year) to cover the cost of buying and transporting mulch material after 2 years of project financing. This should lead to a sustainable outcome, whereby farmers can continue to implement mulch after the project ends.

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[22] Estimates from interview with Sustainable Harvest agronomists (08.09.16).

[23] Unpublished research from a mulch and cover crop trial by the RAB. This trial does not have any control plots, so the change in coffee yield for mulching and cover crops is estimated using an assumed baseline coffee parchment yield between 0.75 and 1 tonnes/ha each year.

[24] Research due to be published in RAB's 2015-16 Annual Report. The price increase as a result of mulching is estimated using changes in quality characteristics relative to those observed when only fertiliser and weeding are implemented.

[25] Estimates from interview with RAB (22.06.2016) and review of unpublished RAB 2015-16 Annual Report; the ground cover observed by agronomists in RAB is around 75% for mulching and 91% for cover crops.

Table 22 shows the private benefits and costs (per hectare) of implementing cover crops. Cover crops are expected to have a similar impact on smallholder coffee production in terms of reduced soil erosion and saved weeding costs. However, they take longer to implement and research from the RAB shows cover crops may actually reduce coffee yields by 0% to 25%[23]. This may be because they actively compete with coffee trees for nutrients. There is no evidence on the impact of cover crops on coffee quality. Therefore, this study assumes cover crops do not affect coffee price and tests a 0% or -25% change in coffee yield. The ground cover provided by cover crops is better than mulching (91% vs. 75%)[25]. As a result, the weeding investment and labour saved is estimated to be higher than mulching (331,240 RWF/ha each year)[25]. Similarly, this ground cover is assumed to cause a higher reduction in the rate of soil erosion compared to mulching (91% after year 2)[25].

Sensitivity analysis: Mulch and cover crops	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
Mulching					
Scenario 1: RCP2.6 / No climate change	129.44 %	3.34	USD 21.97m	2.86	USD 3.87m
Scenario 2: RCP8.5 / Climate change	133.08 %	3.58	USD 23.82m	2.99	USD 4.09m
Cover crops (no direct coffee yield change)					
Scenario 1: RCP2.6 / No climate change	292.56 %	12.23	USD 18.12m	10.28	USD 3.02m
Scenario 2: RCP8.5 / Climate change	292.43 %	12.07	USD 18.20m	10.22	USD 3.02m
Cover crops (-25% direct coffee yield change)					
Scenario 1: RCP2.6 / No climate change	63.95%	(13.44)	USD (0.61m)	(9.83)	USD (0.32m)
Scenario 2: RCP8.5 / Climate change	39.18%	(12.29)	USD (2.40m)	(72.60)	USD (0.56m)

Table 23: Cost-benefit analysis for mulching and cover crops on 1,506ha of smallholder coffee plantations in high and low emissions scenarios.

The cost-benefit analysis results for mulching and cover crops are shown in Table 23. Three types of uncertainty are addressed in this analysis: the impact of cover crops on coffee yield, the future climate scenario and the social discount rate. It is clear that the economic net benefits of cover crops strongly depend on how they are expected to impact coffee yield; if coffee yield decreases by 25% then the economic net benefits are negative for both a 0% and 13% social discount rate. If there is no impact on coffee yield then the economic net benefits are positive for both discount rates.

The difference in financial and economic returns between climate scenarios is different for mulching and cover crops. Mulching has higher financial and economic returns in Scenario 2 (climate change) than Scenario 1. In most cases the opposite is true for cover crops.

Due to the large downside uncertainty associated with cover crops, the project will implement mulch instead of cover crops across all the existing coffee plantations identified for addressing current climate variability and reducing the adaptation deficit.

Shade trees

The project plans to implement shade trees on 1,504ha of existing coffee plantations in combination with mulch. Shade trees provide additional SWC benefits to coffee plantations; their canopy reduces the soil and air temperature, their litter prevents surface soil erosion and adds nutrients to the soil, and their roots stabilise deeper soil[26]. These effects may be attributed to the higher yield and quality observed for shaded coffee in Rwanda (van Asten, 2011; Beer et al., 1998; Gaie and Flemal , 1988; Muschler, 2001; Staver et al., 2001; Pinard et al., 2014; Vaast et al., 2005). Shade trees also provide off-farm benefits, including reducing the downhill impacts from soil erosion and contributing to climate change mitigation through carbon sequestration (Goodall et al., 2015; ICRAF, 2016). However, if the spacing between trees is too wide/narrow or the canopy is not properly managed they can also negatively impact coffee production (Pinard et al., 2014). Similarly, they may also increase the impact of pests and diseases by altering the habitat and climate in which coffee is grown (Mugo et al., 2013).

This study assess the benefits and costs of implementing shade trees on 1,504ha of existing coffee plantations. The private financial benefits and costs are shown in Table 24. The costs are based on investing in 123 trees per hectare, which provides tree spacing (9mx9m) recommended by RAB[27]. For the 1,504ha of existing coffee plantations around 220,000 shade trees will need to be cultivated and planted (including a 20% contingency for infilling). Evidence from Rwanda suggests that shaded coffee can yield 55% more coffee than unshaded coffee (Pinard et al., 2014). These results are in line other research (Machado, 1959; Vaast et al., 2007). Pinard et al. (2014) also say coffee berry quality is higher with shade trees, but no quantifiable evidence is given. This study tests an increase in coffee yield between 0% and 55% and assumes shade trees do not affect coffee cherry prices.

Inputs	**Year(s)**	**Private costs**
Establishment Costs		
Land for nursery	1	642 RWF
Tools and materials (1 - 5 year life)	1+	30,900 RWF
Nursery and seedling establishment	1	9,139 RWF
Transplanting seedlings	1	47,654 RWF
Operation and Maintenance		
Nursery maintenance and infilling	2	2,859 RWF
Pruning / canopy management	5/10/15…	138,889 RWF
Transporting tree biomass	5/10/15…	12,346 RWF
Outputs	**Year(s)**	**Private benefits**
Direct change in green leaf yield	5+	+0% to +55%
Revenue from tree dry matter (wood)	5/10/15…	44,601 RWF
10% reduction in manual weeding	5+	36,400 RWF

Table 24: Financial (private) benefits and costs of implementing shade trees on a 1 hectare coffee plantation.

Further private benefits result from the wood that is harvested during every 5-year pruning cycle. It is assumed that each tree produces 10kg of dry matter (wood) every 5 years, based on evidence for high yielding tree species (Chamberlain, 2001). At 36 RWF/kg of wood[16], the dry matter benefits are estimated to be 44,601 RWF/ha every 5 years. In addition to these direct benefits, shade trees reduce the rate of soil erosion. A conservative reduction in the annual tea yield loss parameter by 10% after year 5 is applied in this study. This is less than the impact on

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[26] Information gathered through interviews with Rwanda Agriculture Board coffee agronomists (2016).

[27] Implementation method used by Rwanda Agriculture board at Rubona shade tree trial (2002 - 2015).

soil erosion estimated for mulching. Finally, shaded coffee will require less weeding, which is assumed to result in annual investment and labour savings of 36,400 RWF[25]. Other benefits and costs associated with specific tree varieties are not assessed in this study because the species to be implemented have not yet been decided.

Sensitivity analysis: Shade trees	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
No direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	10%	1.51	USD 0.86m	1.04	USD 0.02m
Scenario 2: RCP8.5 / Climate change	9.75%	1.53	USD 0.89m	1.05	USD 0.02m
+55% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	100.98%	8.69	USD 38.69m	7.61	USD 5.71m
Scenario 2: RCP8.5 / Climate change	103.30%	8.83	USD 42.56m	7.78	USD 6.15m

Table 25: Cost-benefit analysis for shade trees on 1,506ha of smallholder coffee plantations in high and low emissions scenarios

The results from the shade tree benefit-cost analysis are shown in Table 25. The financial and economic returns are positive regardless of the climate scenario, social discount rate or the direct impact shade trees have on coffee yield. However, the financial returns when shade trees do not change coffee yield are relatively low. The difference in financial and economic returns between climate scenarios is relatively small when shade trees don't directly impact coffee yield. However, the difference in financial and economic returns between climate scenarios when shade trees directly increase coffee yield by 55% is more substantial; financial returns are 2.32pp higher and the economic net benefits are between USD 0.44m and USD 3.87m higher in Scenario 2 (climate change), depending on the social discount rate that is used.

Banana intercropping

The project intends to intercrop banana trees on 2ha of existing coffee plantations assisted by Sustainable Harvest. The small size of land chosen for banana intercropping in this project is a result of the Government of Rwanda's preference for protecting existing coffee trees, as they are a key export crop for Rwanda. There is no conclusive evidence published about the direct impact banana trees have on coffee yields in Rwanda (van Asten, 2011), which justifies this concern. However, preliminary results from a trial in Kirehe show banana intercropping (500 trees/ha) has no impact on coffee yield[28]. In addition, van Asten et al. (2015) show that coffee-banana intercropped plantations can almost double the annual yield value per hectare compared to coffee monocrop plantations. This is important for Rwanda given the increasing pressure on land use (Republic of Rwanda, 2012). The private financial benefits and costs of intercropping banana on 1ha of existing coffee are shown in Table 26.

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[28] The results from the Kirehe trial (Eastern Province, Rwanda) are due to be published by the Rwanda Agriculture Board in 2017. The preliminary results show no significant difference in banana or coffee yield when intercropping with 2,500 coffee trees/ha and 500 banana trees/ha, compared to banana and coffee monocrop systems.

Inputs	Year(s)	Private costs
Establishment Costs		
Land for nursery	1	2,080 RWF
Tools and materials (1 - 5 year life)	1+	35,900 RWF
Nursery and seedling establishment	1	47,640 RWF
Transplanting seedlings	1	154,400 RWF
Operation and Maintenance		
Nursery maintenance and infilling	2	13,248 RWF
Purchase and apply fungicide	2+	34,000 RWF
Pruning / management	2+	30,000 RWF
Harvesting & transporting bananas	3+	150,672 RWF
Outputs	**Year(s)**	**Private benefits**
Revenue from bananas	3+	1,732,728 RWF

Table 26: Financial (private) benefits and costs of implementing banana intercrop on a 1 hectare coffee plantation.

The costs and benefits in Table 26 are based on a banana planting density of 5m x 5m on existing coffee plantations. This means 400 banana trees are intercropped with every 2,500 coffee trees (per hectare). In total, the project will invest in 960 banana seedlings for the 2ha site (including a 20% contingency for infilling). The cost per hectare to intercrop banana trees is 240,020 RWF (300 USD), and the operation costs are 214,672 RWF (268 USD) from year 3 onwards. The only direct private benefits modelled are from the income smallholders can receive from harvested bananas. The results for this analysis are shown in Table 27.

Sensitivity analysis: Banana intercropping	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
Scenario 1: RCP2.6 / No climate change	96.61%	8.54	USD 0.13m	5.86	USD 0.02m
Scenario 2: RCP8.5 / Climate change	96.61%	8.54	USD 0.13m	5.86	USD 0.02m

Table 27: Cost-benefit analysis for banana intercropping on 2ha of smallholder coffee plantations in high and low emissions scenarios

The financial and economic return for banana intercropping doesn't vary between climate scenarios. This is because the model doesn't capture the impact of climate change on banana yield or price, and it assumes there are no direct or indirect effects of banana intercropping on coffee. In reality, the financial and economic returns may change if climate change is realised. Irrespective of this, investing in bananas intercropping provides strong returns with a BCR of 5.86 at a 13% social discount rate and IRR of 96.61%. The study found no other quantifiable evidence for either direct or indirect benefits of banana intercropping. However, it is likely that the banana canopy will provide protection from soil erosion and nutrients from the litter (van Asten, 2011). It may also generate the same benefits as shade trees, in terms of altering the agro-climatic variables below the canopy; reduced intertemporal range, higher humidity[29] (van Asten et al., 2011). This may be beneficial for the specific project location where they are being implemented because temperatures are approaching the limit of what is suitable for growing Arabica coffee (Nzeyimana et al., 2014).

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[29] Evidence from unpublished report provided by coffee agronomist, Peter Baker (August, 2016).

New coffee plantations

In addition to the SWC measures that will be implemented on existing coffee plantations, the project will establish new plantations with a drought and coffee leaf rust resistant variety of Arabica, called RABC15. The National Agricultural Export Board (NAEB) will implement 50ha of this new variety alone, and Sustainable Harvest will implement 4 x 5ha demonstration plots (Table 28). Each demonstration plot will have 1ha control (RABC15 alone), 2ha of RABC15 intercropped with banana and mulch, and 2ha of RABC15 combined with shade trees and mulch. The sites implemented by NAEB will be smallholder owned and operated. The sites implemented by Sustainable Harvest will be owned and operated by the charity for the duration of the project, and will provide farmer field schools to local cooperatives and research stations for evidence of the interaction between climate, RABC15 and the different SWC measures in various agro-ecological zones.

New Locations	RAB C15 (ha)	Shade Trees (ha)	Banana Trees (ha)	Mulch (ha)
Rulindo (smallholders)	50	0	0	0
Sustainable Harvest plots	20	8	8	16
Total Area	**70**	**8**	**8**	**16**

Table 28: Size of new coffee plantations to be established by the project.

The cost for implementing mulch, shade trees, banana intercropping are the same as that for existing plantations (Tables 21, 24 and 26). The cost of implementing RABC15 is the same as establishing a regular coffee plantation (Table 9), except the seeds will be provided from RAB's existing seed bank and no land investment costs will be incurred for the 50ha implemented by NAEB. The annual opportunity cost of land used for these plantations is assumed to be 400 USD per hectare for all 70ha, which is different to the opportunity cost for existing plantations (Table 10). Similarly, the operating costs are assumed to be the same as other coffee varieties, despite the reduced need for fungicide. This is a conservative estimate to account for other pests and diseases that may need controlling.

The benefits of the SWC measures are also assumed to be the same as before; the direct coffee yield and price benefits of mulch are assumed to be 14% and 3% respectively, and the direct coffee yield benefits of shade trees are tested between 0% and 55% as before. The benefits of RABC15 are more difficult to define. There is a lack of evidence on the probability and severity of coffee leaf rust on a given plantation in any particular year. Therefore it is difficult to quantify the yield and quality saved relative other coffee varieties. However, estimates from RAB indicate that coffee leaf rust may be responsible for an annual yield loss of 40% in Rwanda (Republic of Rwanda, 2016c). Research by Bigirimana (2012) suggests that this yield loss could be applicable to all coffee growing regions in Rwanda. This study therefore tests a range of direct coffee yield benefits for RABC15, from 0% to 40% higher than baseline yields associated with other varieties (Republic of Rwanda, 2016c).

The current yield for the new coffee plantations in Rulindo is calibrated using the map in Annex 3. The current yield for the Sustainable Harvest demonstration plots is assumed to be an average of the yield of existing Sustainable Harvest coffee plantations. The current price for all new sites is assumed to be 200 RWF, as the quality of RABC15 is similar to dominant coffee varieties in Rwanda (Republic of Rwanda, 2016c). The change in future yield and price is estimated by calibrating the current Rulindo plantation temperature relative to Kigali's temperature and altitude (15.9^{o}C), and the average demonstration plot temperature as the Kigali mean (19.8^{o}C) (WHO, 2015). The change of temperatures in the two climate scenarios generates the expected yield and price for all the new plantations.

Sensitivity analysis: SHR demo plots	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
+11% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	10.29%	1.61	USD 0.69m	0.99	USD (0.00m)
Scenario 2: RCP8.5 / Climate change	10.23%	1.60	USD 0.68m	0.98	USD (0.01m)
+33% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	13.00%	1.79	USD 0.91m	1.10	USD 0.03m
Scenario 2: RCP8.5 / Climate change	12.94%	1.78	USD 0.90m	1.10	USD 0.03m
+56% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	15.58%	1.96	USD 1.13m	1.22	USD 0.07m
Scenario 2: RCP8.5 / Climate change	15.52%	1.95	USD 1.12m	1.22	USD 0.07m
+86% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	18.92%	2.20	USD 1.44m	1.38	USD 0.13m
Scenario 2: RCP8.5 / Climate change	18.86%	2.19	USD 1.43m	1.37	USD 0.13m

Table 29: Cost-benefit anlaysis for Sustainable Harvest demonstration plots in high and low emission scenarios.

Sensitivity analysis: 50ha RABC15 (Rulindo)	IRR	0% Discount Rate		13% Discount Rate	
		BCR	NPV	BCR	NPV
No direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	0.12%	1.04	USD 0.11m	0.77	USD (0.14m)
Scenario 2: RCP8.5 / Climate change	6.69%	1.25	USD 0.66m	0.88	USD (0.07m)
+40% direct coffee yield change					
Scenario 1: RCP2.6 / No climate change	12.19%	1.41	USD 1.09m	1.05	USD 0.03m
Scenario 2: RCP8.5 / Climate change	16.86%	1.68	USD 1.85m	1.20	USD 0.13m

Table 30: Cost-benefit analysis for RABC15 smallholder coffee plantations in high and low emissions scenarios.

Coffee low-regret strategy

To ensure the low-regret options are implemented efficiently and to improve management of coffee plantations, farmer field schools will be used to provide extension services for good agricultural practice. For existing coffee plantations established under the coffee consolidation programme and the new RABC15 variety established in Rulindo, TechnoServe will provide training to smallholders. Sustainable Harvest will also provide education to smallholders at both their existing and new sites.

The farmer field schools will train a total of 6,264 farmers for a total financial cost of 294m RWF (367,000 USD). TechnoServe will train 5,000 farmers at a cost of 42,000 RWF/farmer (USD 53) and Sustainable Harvest will train the remaining 1,264 farmers at a cost of 66,000 RWF/farmer (83 USD). TechnoServe is already training 30,000 farmers over two years at a cost of 1 million USD in the PRICE project (IFAD, 2011). After accounting for inflation (CPI), this equates to roughly 41 USD per farmer. However, in this project TechnoServe will carry out additional activities, including shade trees implementation and demo plot monitoring. This has justified a higher unit cost of 53 USD per farmer. However, the difference between the cost per farmer for TechnoServe and Sustainable Harvest is due to economies of scale; TechnoServe is training almost 5 times as many farmers as Sustainable Harvest. The majority of the costs are capital inputs, including training materials and travel. Therefore, for the economic analysis tax is removed and capital inputs are multiplied by the appropriate conversion factor (Table 10).

In addition to the 5,000 farmers trained by TechnoServe, the project will finance the cultivation of shade tree seedlings to be implemented by TechnoServe. Each training plot contains 40 coffee trees (0.016ha) and is used to teach 40 farmers. Therefore, 125 shaded demo plots will need to be established to train the 5,000 farmers. Each demo plot will require 2 shade trees and in total 300 shade tree seedlings will be provided to TechnoServe, at a cost of 25,208 RWF (32 USD). This includes transport from nursery to plantation and a 20% contingency for infilling.

The benefits of farmer field schools are implicitly assumed in the previous benefit-cost analysis i.e. all the adaptation options are implemented efficiently[30]. For simplicity, this study estimates the outcome for the coffee low-regret adaptation options as a whole, combining all the benefits and costs from the SWC measures, the new plantations and the farmer field schools. The estimated outcome for this aggregated coffee low-regret strategy is shown in Table 31.

Sensitivity analysis: Coffee low-regret strategy	**IRR**	**0% Discount Rate**		**13% Discount Rate**	
		BCR	**NPV**	**BCR**	**NPV**
Minimum yield impact					
Scenario 1: RCP2.6 / No climate change	47.38 %	2.57	USD 23.50m	2.00	USD 3.56m
Scenario 2: RCP8.5 / Climate change	49.61 %	2.74	USD 25.92m	2.08	USD 3.85m
Maximum yield impact					
Scenario 1: RCP2.6 / No climate change	71.08 %	4.40	USD 63.07m	3.33	USD 9.56m
Scenario 2: RCP8.5 / Climate change	73.62 %	4.69	USD 69.54m	3.48	USD 10.32m

Table 31: Cost-benefit analysis of coffee low-regret strategy in high and low emissions scenarios.

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[30] In reality, only the sites where the farmer field schools take place are likely to benefit from efficient implementation.

3.2 Climate-smart planning: Portfolio Analysis

A form of portfolio analysis is used to appraise the investment into climate risk maps. Portfolio analysis is typically used to evaluate investments into different portfolios of options, in order to identify portfolios that yield the highest return for a given level of risk. However this study uses portfolio analysis to appraise the outcomes that could result from an investment into climate risk mapping. The options are different altitude bands in which new tea plantations can be established (geographical choice). Portfolios are the different combinations of these options (altitude bands) that investors can choose to form their "plantation portfolio". This study evaluates how the information gained from climate risk mapping could change the plantation portfolio chosen by the tea investors.

Altitude bands and climate scenarios

The facts that temperature falls by 0.65°C for every 100 masl climbed (ICAO, 1993), combined with the varying tea yield and price at different temperatures (Figures 4a and 4b), means that tea plantations in one altitude band may perform differently to tea plantations in another. Without climate change, the relative performance of tea plantations in different altitude bands is likely to remain the same because the yield and price outcomes for tea in different altitude bands are constant. However, with climate change the yield and price of a tea plantation in a given altitude band is likely to change (CIAT, 2011). The optimal altitude band for planting tea in a scenario without climate change may be suboptimal in a future scenario with climate change.

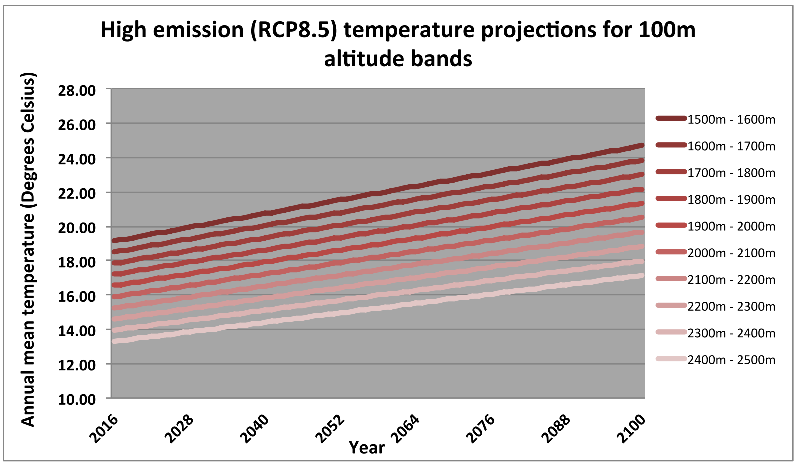

Figure 8: Altitude bands' current and projected future annual mean temperatures in high emissions scenario. Calibrated to annual mean temperature in Kigali (19.8°C at 1497 masl in 2016) using 90th percentile WHO Country Profile temperature projections for RCP8.5 (Source: WHO, 2015).

This study uses annual mean temperature in different altitude bands (Figure 8) to evaluate how tea plantations in these bands are expected to perform in different future climate scenarios. Altitude is divided into 10 x 100m bands between 1500 and 2500 masl. These bands are the individual options investors can choose to plant tea in to form their plantation portfolio. The temperature in these altitude bands is projected to remain the same in the low emissions scenario (Table 2). However, in the high emissions scenario temperature is projected to increase by 11.84% by 2050 and 28.95% by 2100 (Table 2). This study applies portfolio analysis to these altitude bands and climate scenarios.

Application

As with the low-regret adaptation options, this analysis uses the climate scenarios, climate suitability functions and 1ha financial and economic tea plantation model characterised in the methodology. The study considers one location, Kibeho and Munini in Nyaruguru District, where investors will decide at which altitude to plant 3,415ha of smallholder tea plantations (DfID, 2016). This study assumes the entire 3415ha will be planted in 2016. In reality, the smallholder tea plantations will be incrementally planted over a period of 12 years, from 2016 to 2028. The non-incremental approach used in this study is justified for following reasons:

1. It is light touch - There is only one decision point (2016), at which both the climate risk mapping and planting investment decisions are made;
2. The effects of climate change are likely to be small over a 12-year period and there is no guarantee that future climate uncertainty will diminish, so opportunities for learning and improved decisions in the phased planting scheme are limited;
3. The portfolio analysis results will be more clear, as timing and learning are removed from the problem;
4. The results should be the same as analysing a phased investment plan, because the relative timing of benefits and costs are the same.

Without climate risk mapping, the investors can only use the Government of Rwanda’s current tea expansion maps to decide where to plant tea at the Kibeho and Munini sites (Annex 1). This is the business as usual (BAU) case where the optimal plantation portfolio is chosen under the assumption of no climate change. With climate risk mapping, the investors may have more information about the suitability of planting tea in different altitude bands in different future climate scenarios. In addition, the BAU plantation portfolio may no longer appear to be optimal if climate change is realised. This study first assesses the BAU plantation portfolio in climate scenarios 1 and 2, before considering how the climate risk mapping investment may change the investors’ planting decision. Finally, the net financial and economic benefits of changing the planting decision are assessed and attributed to the investment in climate risk mapping.

The BAU plantation portfolio: Without climate risk mapping

Without the investment into climate risk mapping, only information about the current climate can be used to decide how to allocate the 3415ha between different altitude bands. Using the current tea expansion maps for Kibeho and Munini (Annex 1), this study has designed a BAU portfolio. The investors at these sites will establish new tea plantations in four sectors of the Nyaruguru District, in the Southern Province of Rwanda (DfID, 2016). The specific smallholder plantations will be established at different elevations, depending on the topography of the chosen locations. The altitudinal range for the four sectors are shown in Table 32.

Sector	Min altitude (metres)	Max atitude (metres)
Cyahinda	1,650	1,875
Kibeho	1,825	1,925
Mata	1,850	1,975
Munini	1,775	1,950

Table 32: Rwandan sectors where 3,415ha of new smallholder tea plantations will be planted (Source: DfID, 2016).

Altitude bands (masl)	BAU Investment Proportions
1600 – 1700	6%
1700 – 1800	15%
1800 – 1900	51%
1900 – 2000	28%

Table 33: Altitude band allocations for BAU plantation portfolio.

The proportions of tea plantations allocated to each these sectors are yet to be decided. Therefore, it is assumed that the BAU plantation portfolio is equally distributed between them (25% in each sector). In addition, the exact elevations at which to plant have not yet been decided. Therefore it is assumed that the plantations are distributed evenly within the altitudinal range of each sector. The BAU portfolio allocations from these assumptions are shown in Table 33. These percentages show how much of the 3,145ha smallholder tea plantations will be planted in each 100m altitude band without climate risk mapping. This is known as the BAU plantation portfolio.

The financial and economic performance of the BAU plantation portfolio in each climate scenario is shown below. Table 34 shows that the BAU plantation portfolio has a higher financial return in the Scenario 1 (2.93%) than in Scenario 2 (0.76%); it will take 10 years longer for the smallholder plantations to break-even in Scenario 2.

Sensitity analysis: BAU tea portfolio (3,415ha)	IRR	0% Discount Rate		13% Discount Rate	
		BCR	Max - Min NPV	BCR	Max - Min NPV
Scenario 1: RCP2.6 / No climate change	2.93%	1.24	USD 39.39m	0.58	USD 1.65m
Scenario 2: RCP8.5 / Climate change	0.76%	1.10		0.55	

Table 33: Cost-benefit analysis of the BAU plantation portfolio (3,415ha) in the high and low emissions scenarios.

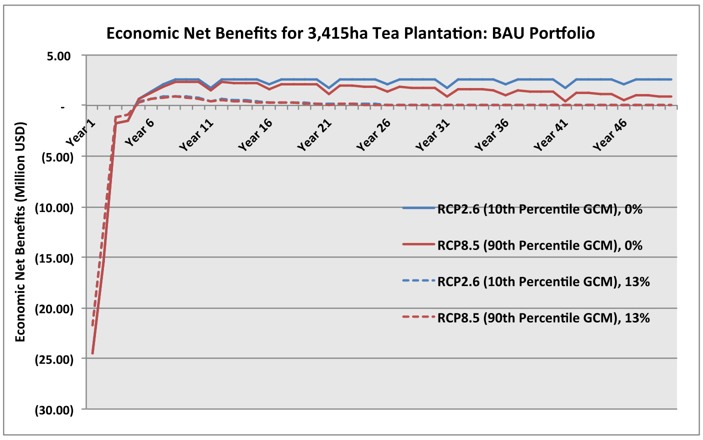

Figure 9: Economic returns of the BAU plantation portfolio (3,415ha) in the high and low emissions scenarios at a 0% and 13% social discount rate.

Table 33 also shows the economic BCRs to be higher in Scenario 1 compared to Scenario 2 at both the 0% and 13% social discount rate. At the 0% social discount rate, the economic net benefits are USD 39.39m higher than the economic net benefits in Scenario 1. At the 13% social discount rate this difference is USD 1.65m. Therefore, a higher social discount rate reduces the absolute variation in economic returns between different climate scenarios. The relative difference in economic returns is also higher with a lower social discount rate; the net present value in Scenario 1 is 138% higher than in Scenario 2 at the 0% social discount rate, but only 6% higher at the 13% social discount rate.

The difference in economic returns between the two climate scenarios at different social discount rates is demonstrated in Figure 9. The continuous blue and red lines show the annual economic net benefits at the 0% social discount rate for Scenario 1 (no climate change) and Scenario 2 (climate change) respectively. The dashed lines follow the same colour pattern at the 13% social discount rate. When visually comparing economic returns, the contrast between climate scenarios is much more stark for the lower social discount rate. In addition, the economic returns follow the same pattern as an infrastrucutre investment; large investment costs at the start, followed by long-lived benefits. This demonstrates the importance of getting the decision right about which altitude bands to plant tea in before the investment is actually made.

It is clear from both Table 33 and Figure 9 that the financial and economic returns for the BAU plantation portfolio are worse in Scenario 2 (with climate change) than in Scenario 1 (no climate change). However, without climate risk mapping the tea investors will not know the returns of different plantation portfolios in different climate scenarios. Therefore, they are likely to implement the BAU plantation portfolio based on the information they have about the current climate. This study now analyses the investment into climate risk mapping, and how the tea investors' decision may change as a result of seeing the returns for portfolios other than the BAU plantation portfolio in both climate scenarios.

Climate risk mapping

The financial cost of climate risk mapping is just under RWF 122m (USD 152,500), of which 30% is tax and can be deducted for the economic analysis. The inputs are estimated to be 11% capital (data and software) and 89% skilled labour. Therefore, using the shadow price conversion factors (Table 10) the undiscounted economic cost of climate risk mapping is estimated to be just over RWF 72m (USD 90,000), with 78% incurred in year 1, 4% in year 2 and 18% in year 3.

Therefore, the investment into climate risk mapping will be economically worthwhile if it is able to inform the tea investors about plantation portfolios that generate returns greater than RWF 72m relative to the BAU plantation portfolio. This study assumes the difference in NPV between climate scenarios that is "acceptable" for the tea investors is the same as that in the BAU portfolio i.e. USD 39.39m at the 0% discount rate and USD 1.65m at the 13% discount rate (Table 33). This represents the tea investors' uncertainty preference i.e. the acceptable difference in portfolio returns between climate scenarios.

Options analysis

Before defining alternative plantation portfolios, this study analyses the individual options i.e. altitude bands. The analysis assumes that 3,415ha of land is available for establishing new tea plantations in each altitude band. In reality this is unlikely, particularly at higher altitudes. The study compares and contrasts the results from investing 100% of the 3,415ha smallholder tea plantation in each altitude band i.e. the adaptation options. The financial IRR (Table 41), economic BCR and NPV, and the difference in NPV between climate scenarios for a 0% discount rate (Table 42) and 13% discount rate (Table 43) are shown in Annex 4.

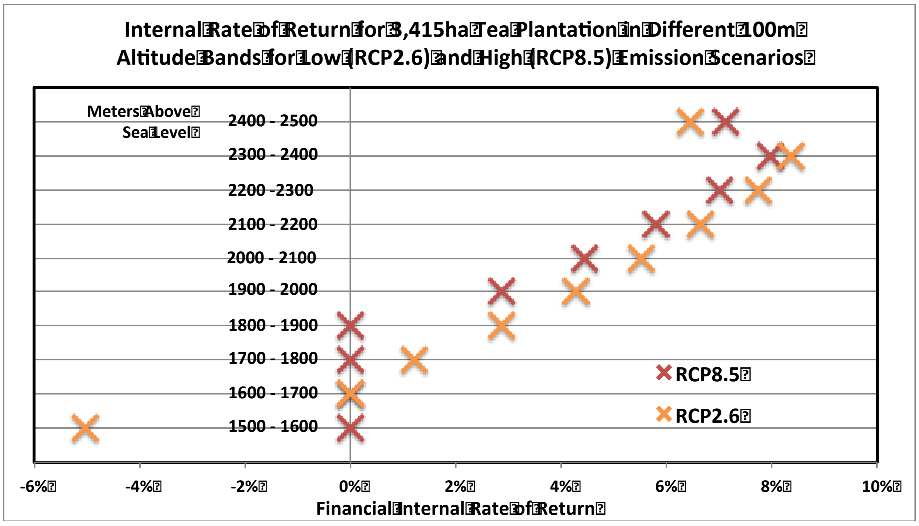

Figure 10: Financial internal rate of return (%) for a 3,415ha smallholder tea plantation in different 100m altitude bands in emissions scenarios RCP2.6 and RCP 8.5. Data points on the y-axis (0%) are non-calculable in Microsoft Excel.

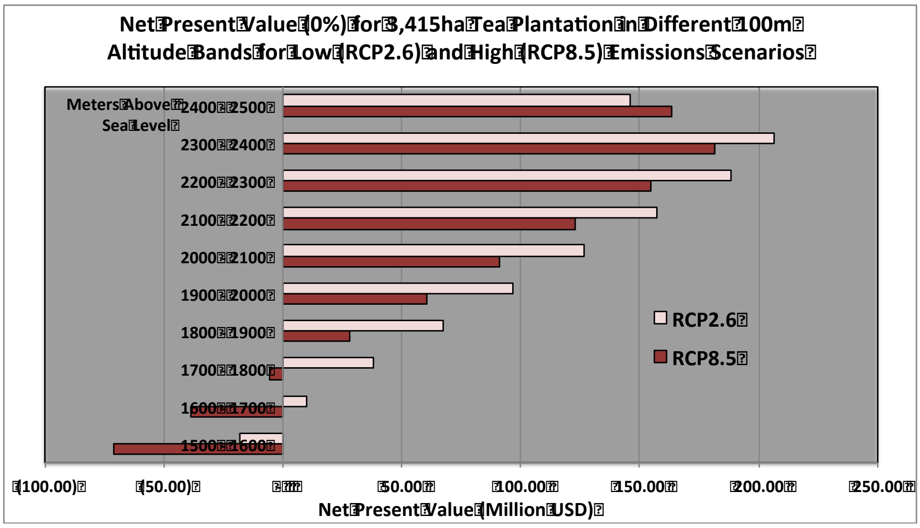

Figure 11: Economic net present value for a 3,415ha smallholder tea plantation in different 100m altitude bands in emissions scenarios RCP2.6 and RCP 8.5, at a 0% social discount rate.

From these tables, the expected and absolute difference in financial (Figure 10) and economic (Figure 11) returns can be represented graphically. The graphs show the absolute financial and economic returns in each climate scenario. Expected returns, whereby each climate scenario would be assigned a probability weight, are not calculated. This is to make sure that no assumptions are made about the likelihood of either climate scenario being realised i.e. there is full uncertainty about the future climate. This approach allows the tea investors to see the difference in returns between climate scenarios, rather than aggregating information into one "expected value", and is endorsed by HM Treasury (2015). The risk assessed in traditional portfolio analysis is represented by the difference in returns between the two climate scenarios, the outcome of which is fully uncertain.

Figures 10 and 11 show planting 3,415ha of tea between 2,300 and 2,400 masl is expected to produce the highest financial and undiscounted economic returns in both climate scenarios. In financial terms, planting tea between 2,300 and 2,400 masl also produces the lowest absolute difference in returns between the climate scenarios (0.67pp). However, at a 0% social discount rate planting tea between 2,400 and 2,500 masl produces a lower absolute difference in returns between the climate scenarios (USD 17.46m) compared to planting tea between 2,300 and

2,500 masl (USD 25.40m). This shows a trade-off between economic returns in each climate scenario and the absolute difference in economic returns between the two highest altitude bands; a higher difference in returns is rewarded with higher expected returns. This may indicate that these altitude bands are on the efficient frontier (Box 1).

In contrast, from 1,500 to 2,300 masl the returns (financial and economic) in each climate scenario increase, whilst the absolute difference in returns fall (figures 10 and 11). This means that tea investors can achieve higher returns for a lower absolute difference in returns between climate scenarios simply by planting tea at higher altitudes. Therefore altitude bands below 2,300 masl are not on the efficient frontier (Box 1).

In addition, the financial results show that planting below 1,900 masl is expected to yield zero (non-calculable) returns in the high emission scenario, and below 1,700 masl the financial returns are negative or zero (non-calculable) for both climate scenarios. With deep uncertainty between climate scenarios it is financially robust to plant tea above 1,900 masl. Therefore 1,900 masl represents the lower financial threshold.

Similarly, the undiscounted economic results show that planting below 1,800 masl is expected to yield negative returns in the high emission scenario, and below 1,600 masl is expected to yield negative returns in both scenarios. With deep uncertainty between climate scenarios 1,800 masl is the lower economic threshold when the social discount rate used is 0%.

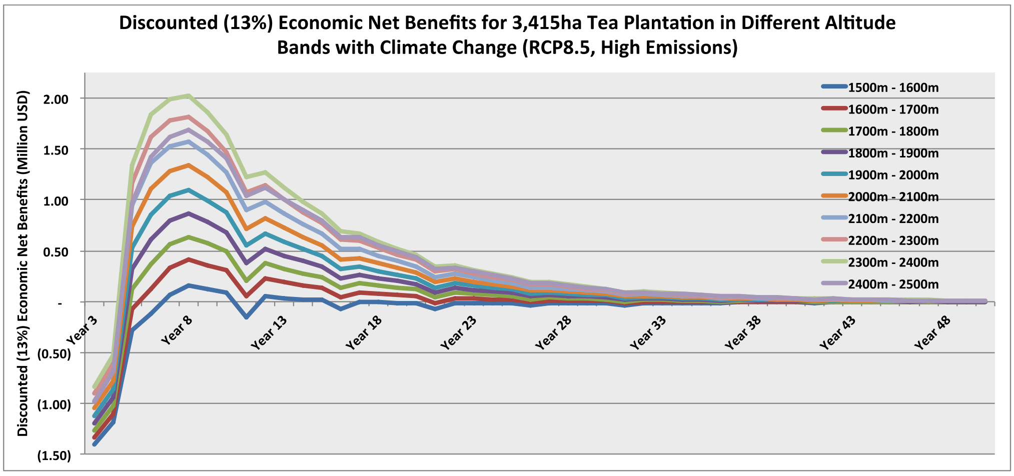

Figure 12: Economic net benefits at a 13% social discount rate for 3145ha tea plantation in different altitude bands for the high emissions scenario (RCP8.5, climate change).

However, when the economic returns are discounted by 13% all the altitude bands produce negative expected returns (Table 44). This is concerning because the Government of Rwanda uses a 13% social discount rate in its economic appraisal. Figure 12 clearly demonstrates the effect of discounting on the economic returns from Year 3 to Year 50 in the Scenario 2 (climate change); the economic net benefits for all altitude bands quickly tail off after peaking around Year 8. When including the large investment costs incurred in Years 1 and 2 (around USD 34m @ 13%), none of the altitude bands are estimated to be economically efficient at the 13% social discount rate. This study found that 9.08% is the highest discount rate at which the best performing altitude band (2,300 – 2,400 masl) achieved positive economic returns in both climate scenarios. Therefore, the economic performance of the individual altitude bands strongly depends on the social discount rate used.

Alternative plantation portfolios

The decision about whether or not to invest in 3,415ha of new smallholder tea plantations is not appraised in this study. Instead, the focus is on how climate risk mapping might better inform the decision about which altitudes bands to allocate the 3,415ha of smallholder tea plantations to, so that the financial and economic returns are robust across possible future climate scenarios. From Figures 10 and 11, it is clear that some of the higher altitude bands outperform the BAU plantation portfolio. Planting tea at higher altitudes between 1,900 and 2,500 masl will yield higher financial and economic returns with a lower difference in returns between climate scenarios.

This study uses these findings to construct alternative plantation portfolios to the BAU plantation portfolio. Standard portfolio analysis minimises the variance and co-variance of returns of the options in the portfolios (Markowitz, 1952). This ensures the individual risk associated with each option in the portfolio is cancelled out, leaving the portfolios exposed to market or systemic risk only (Markowitz, 1952). The portfolios that maximise expected return (minimise risk) for a given level of risk (expected return) are said to be on the efficient frontier i.e. these are the best performing portfolios investors can choose for their respective risk (expected return) category (Markowitz, 1952). This study does not use this approach for four reasons:

1. There is deep uncertainty about the future climate change, which means probabilities cannot be assigned to future climate scenarios. Therefore expected returns, which weight a scenario's outcome by the scenario's probability, cannot be calculated.
2. Only two climate scenarios are used. Therefore the absolute or relative difference of these returns in each climate scenario can be used as a measure of uncertainty.
3. The altitude band options in this case study have returns that are highly correlated with each other; the lowest correlation is 0.977 for undiscounted returns between altitude bands 1,500 - 1,600 masl and 2,400 - 2,500 masl. This is a feature of the model; any two neighbouring altitude bands have similar returns because the same climate suitability function is used to calculate returns in each altitude band.
4. It requires a certain level of statistical processing, and is therefore restrictive in IDA decision-making contexts.

The portfolio construction method employed in this study uses the options analysis, an understanding of the decision problem and heuristics (Table 34). From the options analysis it is clear that 2,300 and 2,400 masl is the "optimal" altitude band in both climate scenarios, so one of the plantation portfolios allocates 100% of the 3,415ha to this interval (P1). The second plantation portfolio (P2) equally allocates the 3,415ha plantation to the 7 altitude bands above the economic threshold defined in the options analysis (488ha each between 1,800 and 2,500 masl). The third plantation portfolio (P3) equally distributes the plantation across all 10 altitude bands from 1,500 to 2,500 masl (341.5ha each). These first three plantation portfolios are hypothetical and slightly unrealistic; it is unlikely that 3,415ha is available between 2,300 and 2,400 masl for P1 and equally distributing the tea plantations across many altitude bands may create logistical problems in reality for P2 and P3 e.g. prohibitively high transport costs for tea harvest to the factory.

This study also defines some more realistic plantation portfolios using the altitude bands from the BAU portfolio (Table 34). The fourth plantation portfolio (P4) allocates 100% of the 3,415ha plantation to the altitude band 1,900 and 2,000 masl. The fifth (P5) and sixth (P6) plantation portfolios test two reasonable allocations to the upper two altitude bands defined in BAU plantation portfolio, which are above the economic threshold (1,800 masl). The final plantation portfolio (P7) switches the 28% and 51% allocations above the economic threshold (1,800 masl) in the BAU portfolio, but keeps the allocations below this threshold unchanged. The 3,415ha smallholder tea plantation altitude band allocations for these portfolios are shown in Table 34.

Altitude band (masl)	P1	P2	P3	P4	P5	P6	P7
1500 - 1600	0%	0%	10%	0%	0%	0%	0%
1600 - 1700	0%	0%	10%	0%	0%	0%	6%
1700 - 1800	0%	0%	10%	0%	0%	0%	15%
1800 - 1900	0%	14.29%	10%	0%	25%	50%	28%
1900 - 2000	0%	14.29%	10%	100%	75%	50%	51%
2000 - 2100	0%	14.29%	10%	0%	0%	0%	0%
2100 - 2200	0%	14.29%	10%	0%	0%	0%	0%
2200 - 2300	0%	14.29%	10%	0%	0%	0%	0%
2300 - 2400	100%	14.29%	10%	0%	0%	0%	0%
2400 - 2500	0%	14.29%	10%	0%	0%	0%	0%

Table 34: Plantation portfolios for 3,415ha of smallholder tea plantations, showing the different altitude band allocations.

Returns to climate risk mapping

The plantation portfolios defined in Table 34 are the alternative planting decisions the tea investors might take as a result of the information they received from climate risk mapping. Therefore, the financial and economic returns to investing in climate risk mapping are estimated by subtracting the BAU plantation portfolio's benefits and costs from these alternative plantation portfolios' benefits and costs, and then subtracting the cost of climate risk mapping. This approach indirectly attributes the marginal benefits and costs of changing the planting decision to the climate risk mapping investment.

The results from the alternative portfolios are ranked by the absolute difference in returns between climate scenarios. These are called "uncertainty rankings" in this study. In financial terms, the uncertainty rankings are based on the percentage point difference in the IRR between the two climate scenarios. In economic terms the uncertainty rankings are based on the absolute difference in NPVs between the two climate scenarios. Figures 13 and 14 show the financial and economic results for the 7 portfolios. In both graphs, portfolios that are higher on the y-axis (vertical) have a greater financial or economic uncertainty ranking.

From Figure 13, it seems that the financial returns for portfolios increase in both climate scenarios as the financial uncertainty ranking increases i.e. percentage point difference in returns between climate scenarios increases. The correlation between the difference in portfolio returns and actual portfolio returns in each climate scenario is around 0.96. This represents a strong trade-off between financial uncertainty across climate scenarios and the absolute financial returns within each scenario i.e. portfolios with greater uncertainty are rewarded with higher returns. Traditional portfolio theory supports this finding, concluding that more risky portfolios are rewarded with higher expected returns along the efficient frontier (Markowitz, 1952).

However, not all the portfolios in Figure 13 support this finding. P4 is expected to yield higher returns in both climate scenarios whilst having a lower financial uncertainty ranking than P5, P6 and P7. This means that that P5, P6 and P7 are not on the financial efficient frontier, as they do not provide the highest possible returns for a given level of uncertainty. It can be argued that P4 is closer to the financial efficient frontier than these three alternatives. In contrast, P1, P2 and P3 provide the highest financial return in both climate scenarios for their respective uncertainty rankings. Out of the portfolios analysed in this study, P1, P2, P3 and P4 are the closest to the financial efficient frontier for their respective financial uncertainty rankings. It should be noted that the construction of the portfolios was more arbitrary than in standard portfolio analysis. Therefore, the actual financial efficient frontier may be found somewhere to the South-East of P1, P2, P3 and P4 in Figure 13.

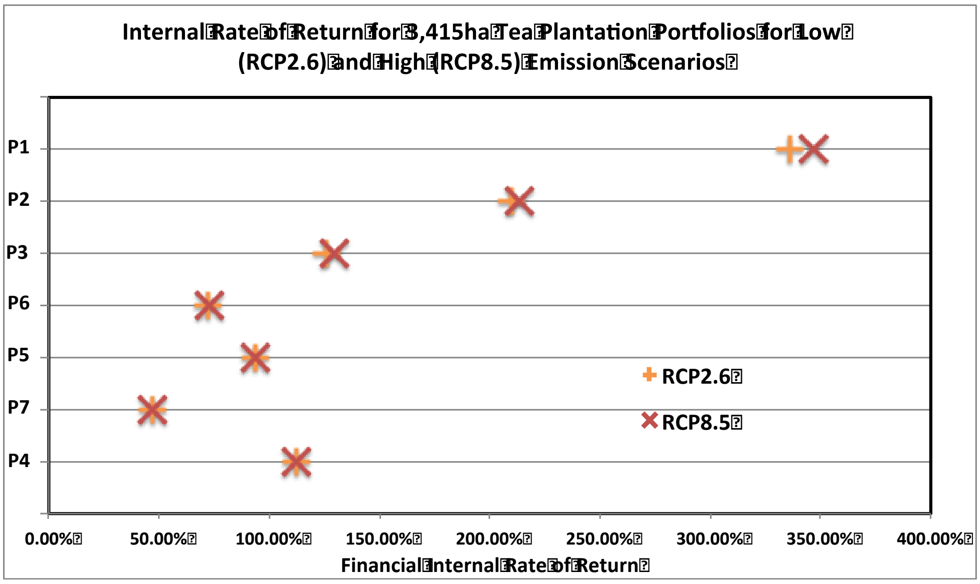

Figure 13: Financial internal rate of return for 3,415ha smallholder tea plantation portfolios in high (RCP8.5) and low (RCP2.6) emissions scenario, ranked by percentage point difference in returns between climate scenarios.

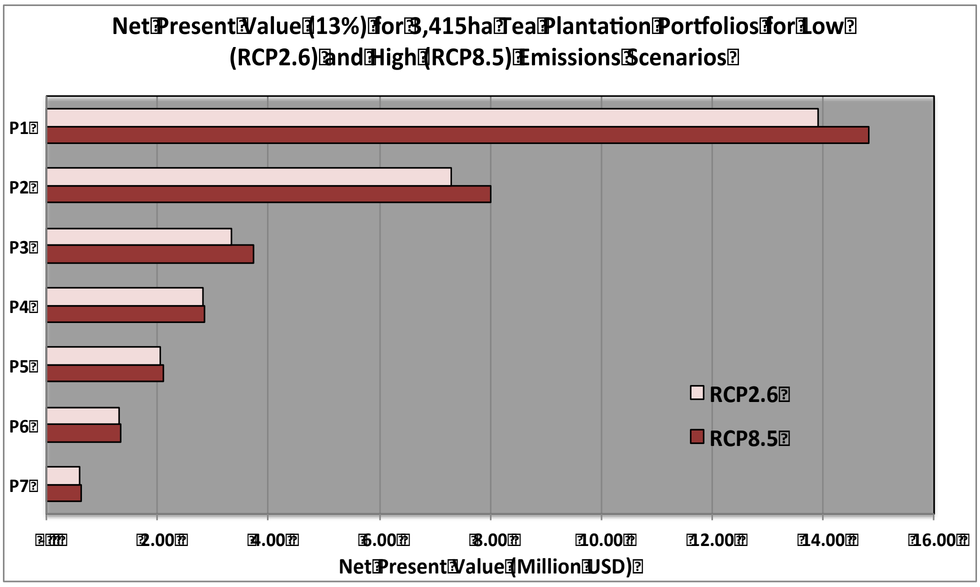

Figure 14: Economic returns (NPV) for 3,415ha smallholder tea plantation portfolios in high (RCP8.5) and low (RCP2.6) emissions scenario, ranked by absolute difference in returns between climate scenarios.

Figure 14 shows a similar pattern for the economic returns at a 13% social discount rate; portfolios with higher economic returns in both climate scenarios have a higher economic uncertainty ranking i.e. the absolute difference in NPV between climate scenarios increases. The correlation between the difference in portfolio returns and actual portfolio returns in Scenario 1 (no climate change) is 0.94 and the correlation between the difference in portfolio returns and actual portfolio returns in Scenario 2 (climate change) is 0.95. This represents a strong trade-off between economic uncertainty and absolute economic returns within each scenario. All of the portfolios analysed in this study support this finding. Therefore P1 to P7 represent the closest portfolios (in this analysis) to the economic efficient frontier for their respective economic uncertainty rankings.

It could be that P5, P6 and P7 are the closest portfolios to the economic efficient frontier, but not the financial efficient frontier, because of the portfolio construction method used in this analysis. These portfolios where constructed using the economic altitude threshold (1,800 masl) and not the financial economic threshold (1,900 masl). Therefore between 21% and 50% of the tea planted in these portfolios is below the financial threshold. However, all of these portfolios outperform the BAU portfolio in both climate scenarios because they shift the tea planting decision to higher altitudes. As a result the financial and economic returns of these portfolios are positive in both climate scenarios, but the allocations are not sufficient enough to make these portfolios financially efficient (compared to P4).

This study has captured a range of outcomes for different plantation portfolios that could result from investing in climate risk mapping and different climate scenarios. The widest range of these results is shown numerically for the best (P1) and worst (P7) alternative plantation portfolios evaluated in this study in Table 35.

Sensitivity analysis: Climate risk mapping	IRR	0% Discount Rate		13% Discount Rate	
		BCR	Max - Min NPV	BCR	Max - Min NPV
Portfolio 1					
Scenario 1: RCP2.6 / No climate change	336.28%	7.00	USD 13.99m	7.21	USD 0.92m
Scenario 2: RCP8.5 / Climate change	346.80%	8.12		7.93	
Portfolio 7					
Scenario 1: RCP2.6 / No climate change	47.29%	8.74	USD 0.62m	58.54	USD 0.01m
Scenario 2: RCP8.5 / Climate change	47.35%	11.73		51.09	

Table 35: Financial and economic returns for P1 and P7 in high and low emissions scenarios.

Table 35 shows a wide range of financial and economic outcomes that could be attained following the investment into climate risk mapping. It shows a significant trade-off between financial returns and the financial uncertainty ranking in both climate scenarios; using the information from climate risk mapping, investing in P1 is expected to generate financial returns just over 7 times greater than investing in P2, and the percentage point difference in returns is also 175 times higher. However the economic BCRs seem to contradict the above findings. The BCR is higher in both scenarios for P7 (compared to P1), whilst the economic uncertainty ranking is lower for the 0% (23 times lower) and 13% (92 times lower) social discount rate. Yet for the same level of investment, the undiscounted NPVs are just under 20 times higher and the discounted (13%) NPVs are just over 20 times higher in both scenarios for P1 compared to P7. This supports the idea that higher levels of risk are rewarded with higher absolute returns in both climate scenarios.

Uncertainty preferences

Table 35 also shows that the returns to climate risk mapping are more dependent on the portfolio that is chosen by the tea investors than the climate scenario. The most likely portfolio to be chosen following the investment into risk mapping can be inferred from the tea investors' "uncertainty preferences". This study uses the difference in returns for the BAU plantation portfolio to elicit the tea investors' uncertainty preferences. This method of elicitation is slightly flawed because it assumes the tea investors chose the BAU plantation portfolio on the basis of its financial and economic returns in both climate change scenarios. In practice, the working assumption throughout this analysis is that the tea investors do not know the impact climate change will have on the BAU plantation portfolio until the investment into climate risk mapping has taken place. Without means of directly eliciting the level of acceptable uncertainty, this study continues to use the BAU plantation portfolio as a basis defining the tea investors' uncertainty preferences.

From the BAU portfolio, the acceptable difference in financial returns between climate scenarios is 2.17pp (2.93% minus 0.76%), the acceptable difference in undiscounted economic returns is USD 39.39m (USD 68.01m minus USD 28.63m) and the acceptable difference in discounted (13%) economic returns is USD 1.65m (USD -25.94m minus USD -27.59m). These values represent the level of uncertainty the tea investors' are willing to accept i.e. their uncertainty preferences. Plantation portfolios that provide higher financial and economic returns for a lower or equal level of uncertainty should therefore be chosen over the BAU plantation portfolio once the tea investors receive information from climate risk mapping.

All of the alternative plantation portfolios (P1 to P7) have higher financial and economic returns than the BAU plantation portfolio. This is because they shift the tea plantations to more favourable climatic conditions (altitude bands) for growing tea in both climate scenarios. However, the financial uncertainty rankings of P1, P2 and P3 exceed the financial uncertainty preferences shown in the BAU plantation portfolio (>2.17pp). The portfolio with the highest financial returns for the acceptable level of uncertainty is P4. Assuming P4 is chosen, the potential financial returns to climate risk mapping are in the region of 112%, with little variance between climate scenarios. In contrast, all of the of alternative plantation portfolios have a lower economic uncertainty ranking than the BAU plantation portfolio. Assuming rationality, the tea investors would choose the alternative plantation portfolio that yields the highest return across both climate scenarios i.e. P1. The potential economic returns are therefore in the region of USD 13.90m to USD 152.52m, depending on the social discount rate and the climate scenario.

In reality, the plantation portfolio that is chosen will probably not differ significantly from the BAU portfolio. This is because the preliminary boundaries drawn up by current tea expansion maps[31] and the cost of altering the planting strategy provide barriers to change. In addition, the investment and operating costs may vary between altitude bands and locations, making it difficult to establish tea plantations in some altitude bands e.g. infrastructure and transport. On this basis, it is more realistic that the tea investors will choose a plantation portfolio similar to P4/P5/P6/P7 following the information received from climate risk mapping. This means the undiscounted economic returns to climate risk mapping are likely to be in the region of USD 0.61m to USD 31.59m, depending on the social discount rate and climate scenario.

Other uncertainties

1. Altitude band cost heterogeneity

The actual financial and economic benefits of climate risk mapping will depend on a number of factors. One of the main factors not quantified above is heterogeneous costs between the different altitude bands. The plantation model used in this study assumes that the fixed costs of and the unit value of variable costs are the same for all altitude bands. In reality this assumption may not hold; higher altitudes are probably more difficult to access, requiring greater infrastructure investments and greater costs for transporting harvested tea. This study chose to focus on the climatic suitability for planting tea in different altitude bands and for high and low emissions scenarios. This reductive approach is more light touch and produces results that are easier to interpret.

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[31] Elicited from an interview with Director of Tea at the National Agricultural Export Board (21.06.16). The Government of Rwanda is open to redrawing boundaries on the tea expansion maps.

2. Costs of changing the plantation portfolio (ex-ante)

Following the recommendations from climate risk mapping, there will be costs associated with switching from the BAU plantation portfolio to one that is more robust across both climate scenarios. These costs include redrawing boundaries (thresholds), farmer engagement and resettlement costs[31]. These costs were not determined in this study, and were therefore only included qualitatively.

3. Public good value

This study focuses on the potential benefits (and costs) of climate risk mapping for one expansion site in Kibeho and Munini (3,415ha). In reality the Government of Rwanda's target is to plant 18,000ha of tea between 2013 and 2018 (Republic of Rwanda, 2013a). The exact amount planted to date (2013 - 2016) is not known, but the total unplanted area is estimated to be 3 to 5 times greater than the Kibeho and Munini site i.e. 10,000ha to 18,000ha. Given that climate risk mapping is predominantly a fixed cost and that the findings could easily be transferred to other tea expansion sites, the returns to climate risk mapping could therefore be 3 to 5 times higher than in the analysis above.

The project will also carry out climate risk mapping for the coffee sector in Rwanda. This study has not estimated the marginal benefits and costs of climate risk mapping for the coffee sector, but a similar method could be applied in future studies. The coffee climate suitability function defined in this study is reasonably similar to the tea climate suitability function. So it is plausible that applying the approach used in this study could find a similar range of financial and economic benefits for the coffee sector in Rwanda.

Summary

The returns to climate risk mapping depend on a number of uncertain factors, including the future climate, the plantation portfolio that is ultimately chosen by tea investors, and the indirect benefits and costs associated with disseminating and implementing the findings. This study shows positive returns to climate risk mapping across a wide range of these uncertainties; the worst-case scenario is no climate change and the tea investors choosing a plantation portfolio that is similar to the BAU portfolio (P7). However, even this scenario has positive financial returns (47.29%) and economic returns (USD 6.70m at 0% and USD 0.61m at 13%). In the best-case scenario, with climate change and P1 being chosen, the returns to climate risk mapping are just over 20 times greater.

The indirect benefits and costs are not captured in these figures. Given the scale of tea and coffee expansion in Rwanda, the magnitude of indirect "public good" benefits from climate risk mapping will probably outweigh the costs of disseminating and implementing the findings. As a result, the investment into climate risk mapping is estimated to generate even greater positive financial and economic outcomes when accounting for the wider indirect benefits and costs.

The investment into climate risk mapping will allow the findings of this study to be validated, by recalibrating the climate suitability functions, incorporating suitability factors other than temperature and producing maps that show the specific suitability of locations for expanding tea production. Once this information is available, the actual benefits and costs of climate risk mapping can be represented more accurately. This will allow the returns to climate risk mapping to be re-examined and updated. Using the information made available by the climate risk mapping investment, an ex-post project appraisal is recommended to validate the findings of this study.

3.3 Qualitative analysis: Socio-economic and other uncertainties

Long-term uncertainties

A quantitative analysis of socio-economic scenarios is not carried out in this case study. Instead, the focus is on quantifying the effect climate change uncertainty might have on the project's outcome. However, future social welfare and perceptions about climate change will play a significant role in the rate of climate change adaptation, which adds another layer of uncertainty about the future vulnerability of the tea and coffee sectors to climate change. Therefore, a qualitative analysis of socio-economic factors is presented here, to highlight their level of uncertainty and the impact they might have on the economic outcome of the project.

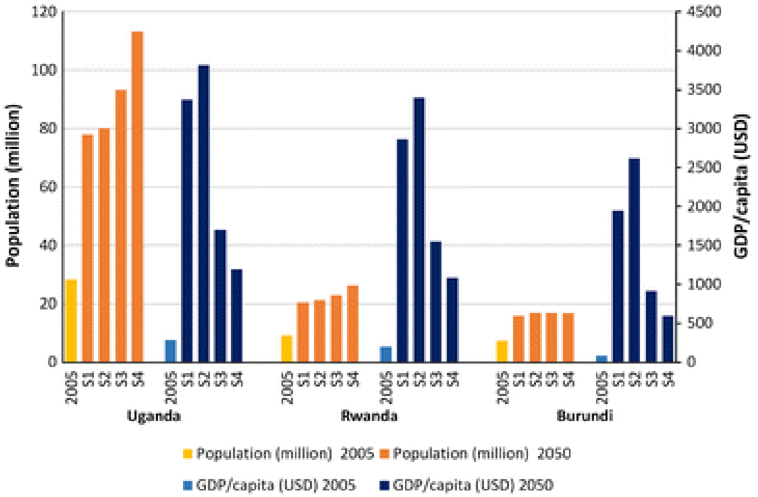


Figure 15: Projected changes in population and GDP for four socio-economic scenarios for Uganda, Rwanda and Burundi (2005–2050) (Source: van Soesbergen et al., 2016)

Rwanda is a relatively small landlocked country with a high population growth rate 1.155pp higher than the global average (World Bank, 2015); both high and low estimates project a doubling of Rwanda's population by 2032 (NISR and MINECOFIN, 2012) and more than doubling by 2050 (van Soesbergen et al., 2016). This is likely to lead to an increasing demand for the countries limited resources: land, water, food and energy. It may also lead to an increasing strain on public resources and infrastructure. As a result, the price of inputs and opportunity cost for using land to produce tea and coffee could increase.

When accounting for economic incentives, i.e. responses to changes price and output, Nelson et al. (2014) argue that autonomous adaptation of farmers in Rwanda will significantly counteract the agricultural damages that might result from climate change. Despite this, tea and coffee farmers will face increasingly difficult trade-offs about how they should use their land, and they will need to increase the productivity of tea and coffee to ensure it remains a viable source of income. The cost of adaptation for tea and coffee farmers will probably increase under these circumstances. Therefore, population growth is one of the greatest socio-economic risk factor for the project's long-term outcome.

However, van Soesbergen et al. (2016) also project GDP per capita in Rwanda to increase substantially across a wide range of future socio-economic and climate scenarios. Reasons for this may include improved governance, better technology and future benefits as a result of investment today. This will benefit the project, as higher GDP per capita should lead to an increase in adaptation investments the tea and coffee sectors ensuring the project's legacy is maintained. In addition, the high rate of population growth could improve Rwanda's comparative advantage in labour intensive sectors, such as agriculture. This is because the increasing supply of labour might suppress future wages and keep the cost of production low, resulting in comparatively cheap exports from sectors such as agriculture. This might positively impact the project's outcome, but it should be noted that the beneficiaries of cheap labour would be exporters and not necessarily smallholders.

Van Soesbergen et al. (2016) project a loss of biodiversity across 24 – 30% of the total land area in Rwanda by 2050 (baseline 2005). This loss is likely to occur as a consequence of increasing urbanization, and agricultural expansion and intensification. Existing forests are unlikely to face increasing rates of deforestation due to the strong conservation laws in Rwanda. On the whole, the project's low regret options should counteract the loss of biodiversity relative to monocrop tea and coffee plantations. However, the aggregate trend for biodiversity in Rwanda will probably have a negative impact on the project's outcome.

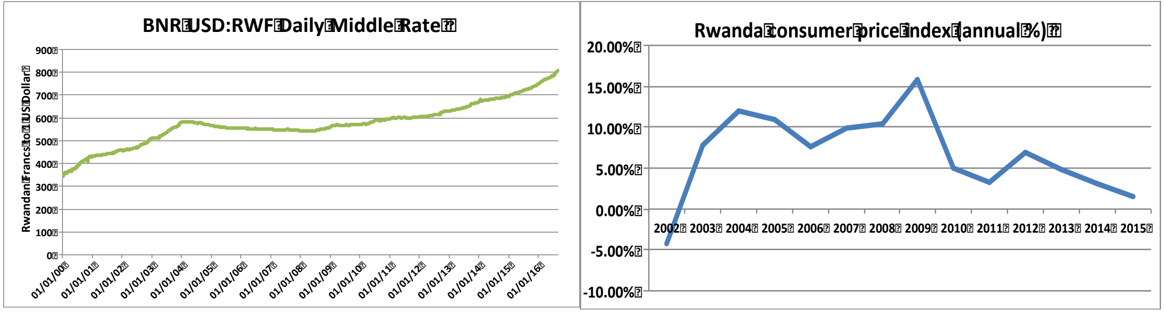
Factor	Projections by 2050	Uncertainty	Impact on Project
Population	+100 - 150%	Low	Negative
Economy	+600 - 1800%	Medium low	Positive
Land scarcity	Higher	Low	Negative
Water scarcity	Same/Higher	High	Negative
Food scarcity	Higher/Lower	High	Pos /Neg
Energy scarcity	Higher/Lower	High	Pos / Neg
Biodiversity	Lower	Low	Negative
Carbon sequestration	Higher	Low	Positive
Off-farm soil erosion	Lower	Low	Pos / Neg
Aggregate impact on the project			**Negative**

Table 36: Socio-economic factors' uncertainty and their impact on the project (Source: IPCC, 1998).

The impact of the uncertain socio-economic factors and externalities on the long-term outcome of the project are qualitatively assessed in Table 36. Overall it is estimated that population growth will play the biggest role in the project's long-term success, as it will increase natural resource scarcity and consequently the cost of adaptation.

Short-term risks

Figure 16: Macro-economic indicators for Rwanda (Source: NISR, 2016).



4. Guidance

Uncertainty categories	Recommendations
Climate scenarios	
Data sources: • **Which data source(s)?**	• Use long enough baseline period (>30 years) • Use latest projection data available (CMIP5)
Emissions scenarios: • **Which emissions scenarios?** • **How to capture uncertainty in light touch way?**	• Use most recent emissions scenarios (RCPs) • Choose two scenarios with widest range of outcomes (e.g. with RCP2.6 and RCP8.5)
Circulation models: • **Which models are suitable for the local context?** • **How to tackle intra-model (projection) and inter-model uncertainty?**	• Use an ensemble of most granular / reliable models possible e.g. regional over global models • Use models that are dynamically bias corrected using local data where possible, otherwise use statistically bias corrected models • Exclude outliers e.g. percentile approach
Climate variables: • **Which climatic variables?**	• Use the most relevant and accessible climatic variables • Exclude variables that lack clear evidence or trends
Crop-climate suitability functions	
Crop models: • **How to translate climate into crop outcomes?**	• Use existing models or define light touch models using literature and expert quality assurance e.g. agronomists • Calibrate using local data if possible, avoid spatial transfers of evidence • Qualitatively assessment of the outcome where quantitative is not possible
Market values	
Financial costs and benefits: • **Which data to use?** • **How to transform this data?**	• Use reliable market sources where possible e.g. Mombasa tea auction • Use conservative estimates when sources unreliable or conflicting e.g. take the mean or use the highest value • Adjust for inflation
Economic conversion factors	
Opportunity costs and shadow prices	• For existing plantations, assume opportunity cost is BAU • For new plantations, estimate opportunity cost from next best sources of farmer income e.g. other crops • Use local government / donor appraisal conversion factors to adjust market value of inputs to shadow prices
Externalities	• Quantify specific externalities where possible, otherwise include positive income externalities in a conservative multiplier • Qualitatively assess if not quantified
Social discount rate	• Use local government / donor social discount rate
Impact of intervention	
Crop yield and/or price impact	• Only make assumptions based on (scientific) evidence • Avoid transferring evidence between countries / regions • When evidence is conflicting, test a wide range of impacts
Socio-economic scenarios	
Impact on project outcome	• Consider a number of socio-economic variables • Assess direction and magnitude of impact on project outcome

Table 38: Recommendations for treating uncertainty, including climate change, in IDA project appraisal.

4.1 Treatment of uncertainty

The methodology used in this case study can be applied to other project appraisals. Table 38 summarises the main categories of uncertainty handled in this case study and provides recommendations on how they should be treated.

General rules:

- If no quantifiable evidence:
    - Do not make any assumptions
    - Qualitatively assess the impact
- If wide range of evidence for a particular variable:
    - Quality assure evidence, exclude unreliable sources
    - Conduct sensitivity analysis with range of plausible values
- Use local data where possible:
    - Avoid transferring evidence between countries and regions
- Do not take expectations if there is uncertainty – show absolute values for outcomes in widest plausible range of scenarios

4.2 Applying portfolio analysis to IDA project appraisal

General Methodology

- Incorporate uncertainties in Table 38
- Use widest plausible range of chosen independent variables to capture full range of outcomes
- Do not take expected values, show absolute values and difference between scenarios
- Analyse individual options (100% investment) first - certain options may outrank others in both scenarios, which saves time defining and analysing portfolios
- Construct simple portfolio based on the option analysis (if possible)
- Rank portfolios based on “uncertainty ranking” i.e. difference in NPV between scenarios
- Assess trade-off between “uncertainty ranking” and return in both climate scenarios
- No explicit identification of the efficient frontier, but you can identify portfolios that have the highest returns for a given uncertainty ranking

Specific methodology

- PA crop model – assess different altitudinal options for crops
- Altitude as proxy for temperature when local climate data unavailable for crop project appraisal

Transferability

- Use in following contexts:
    - No probabilities for climate scenarios
    - IDA context with time constraints / limited capacity
    - Lack of ground-level climate data
- PA crop model has already been used for another tea project in Rwanda (Green Climate Fund)
- Agriculture Technical Assistance Fund (AgriTAF) can use PA crop mode for other Rwandan crops
- Can be transferred to other East African countries, especially tea

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Annex 1: Tea expansion maps

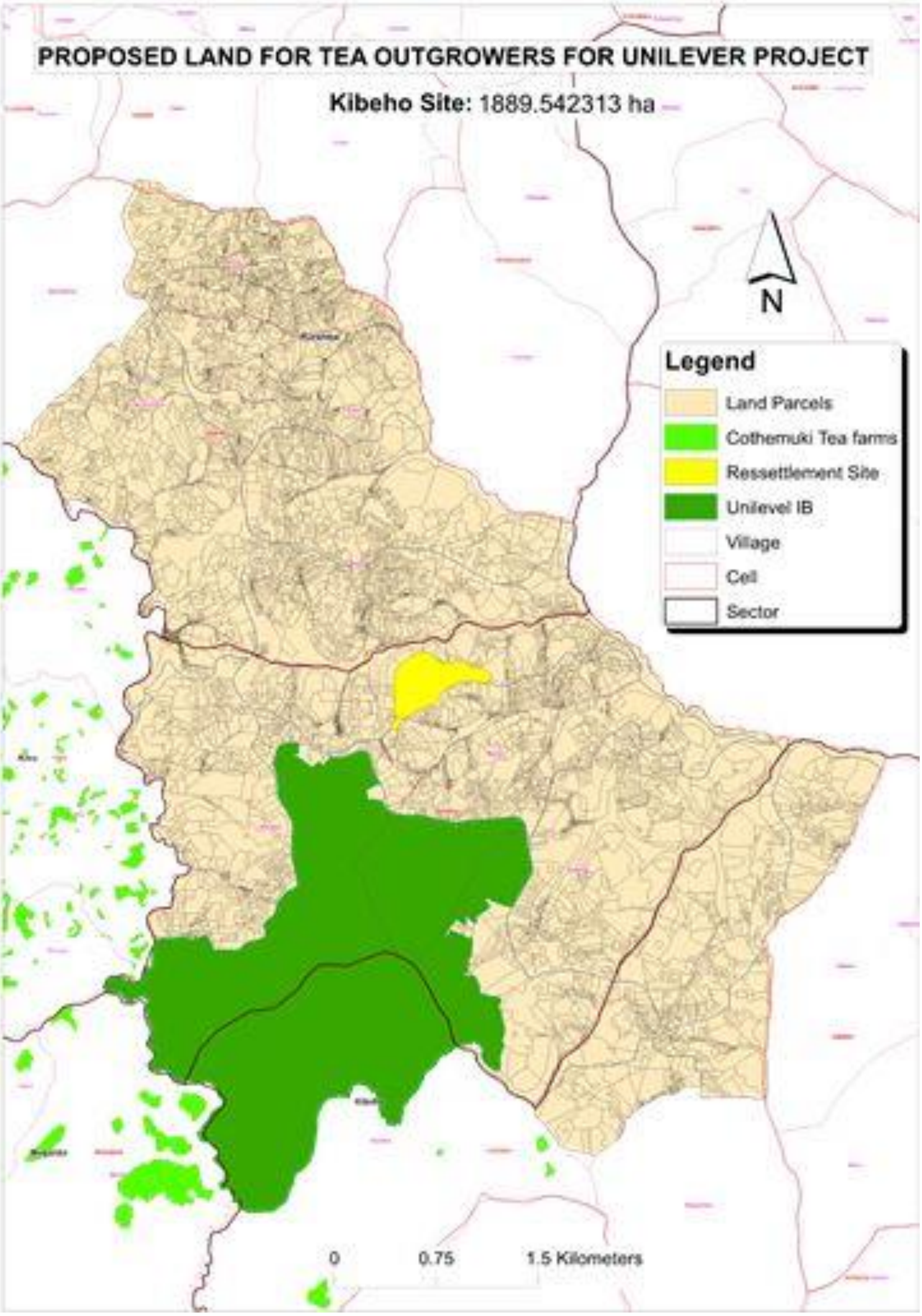


Figure 17: Kibeho tea expansion map (Source: Republic of Rwanda).

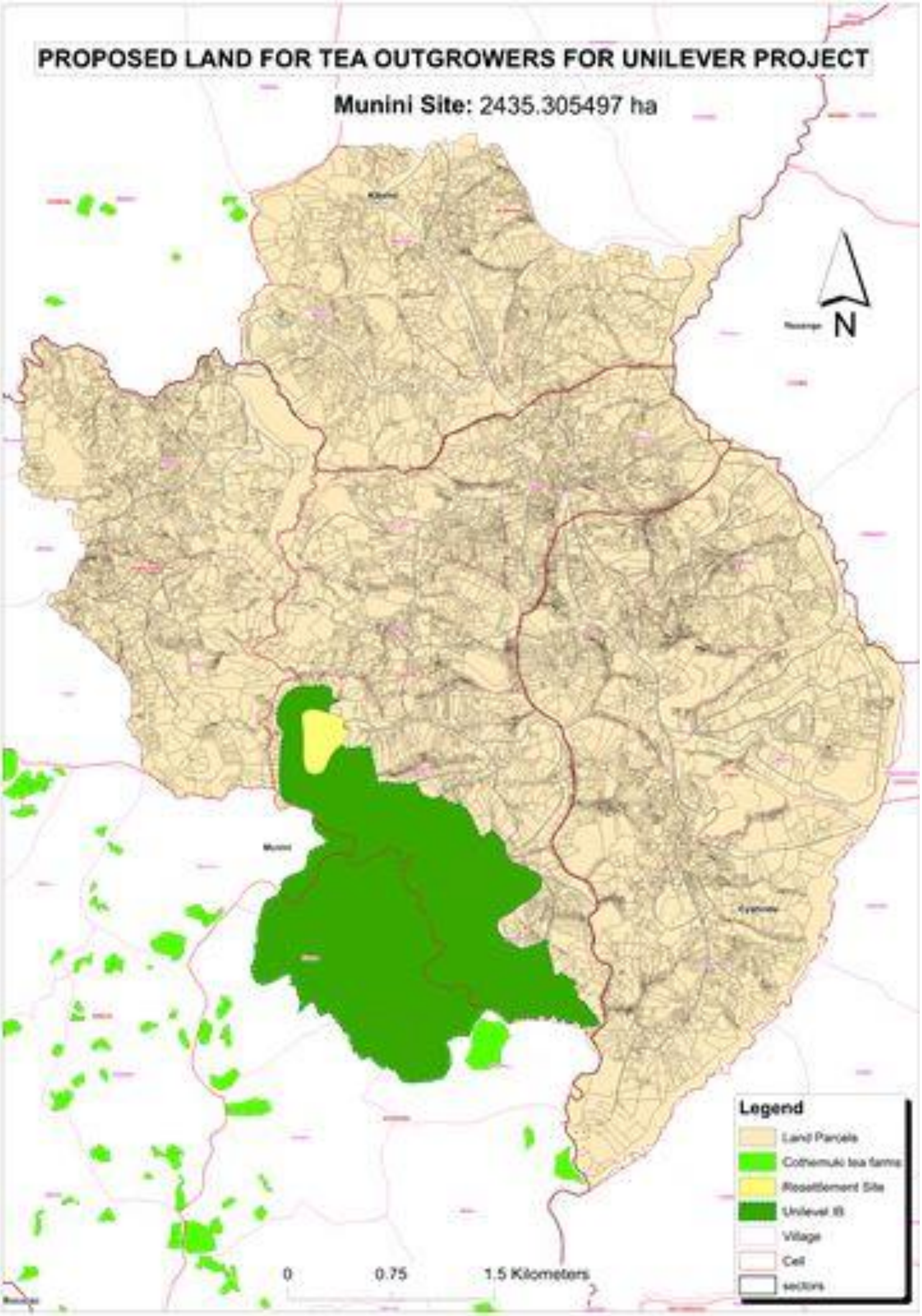


Figure 18: Munini tea expansion map (Source: Republic of Rwanda).

Annex 2: Model calibration

Figure 19: Tea factory coordinates used to calibrate financial and economic models (Source: Republic of Rwanda, 2013).

Coffee project location coordinates		
Project location	Latitudinal Coordinates	Longitudinal Coordinates
Gakenke	-1.6908586	29.835230300000035
Kirehe	-2.2168302	30.757983400000057
Nyamagabe	-2.4538548	29.46435900000006
Nyampinga	-2.662764300000001	29.46435900000006
Rulindo	-1.7555339	30.020296400000007
Twongere Umusaruro	-1.9138576	30.619989499999974

Table 39: Tea project locations coordinates used to calibrate financial and economic models, defined using Internet search (Source: elevationmap.met).

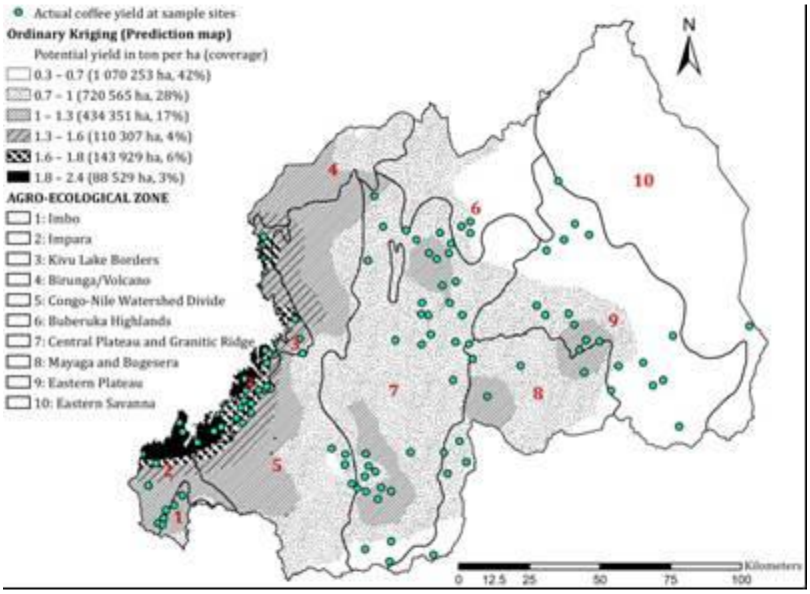
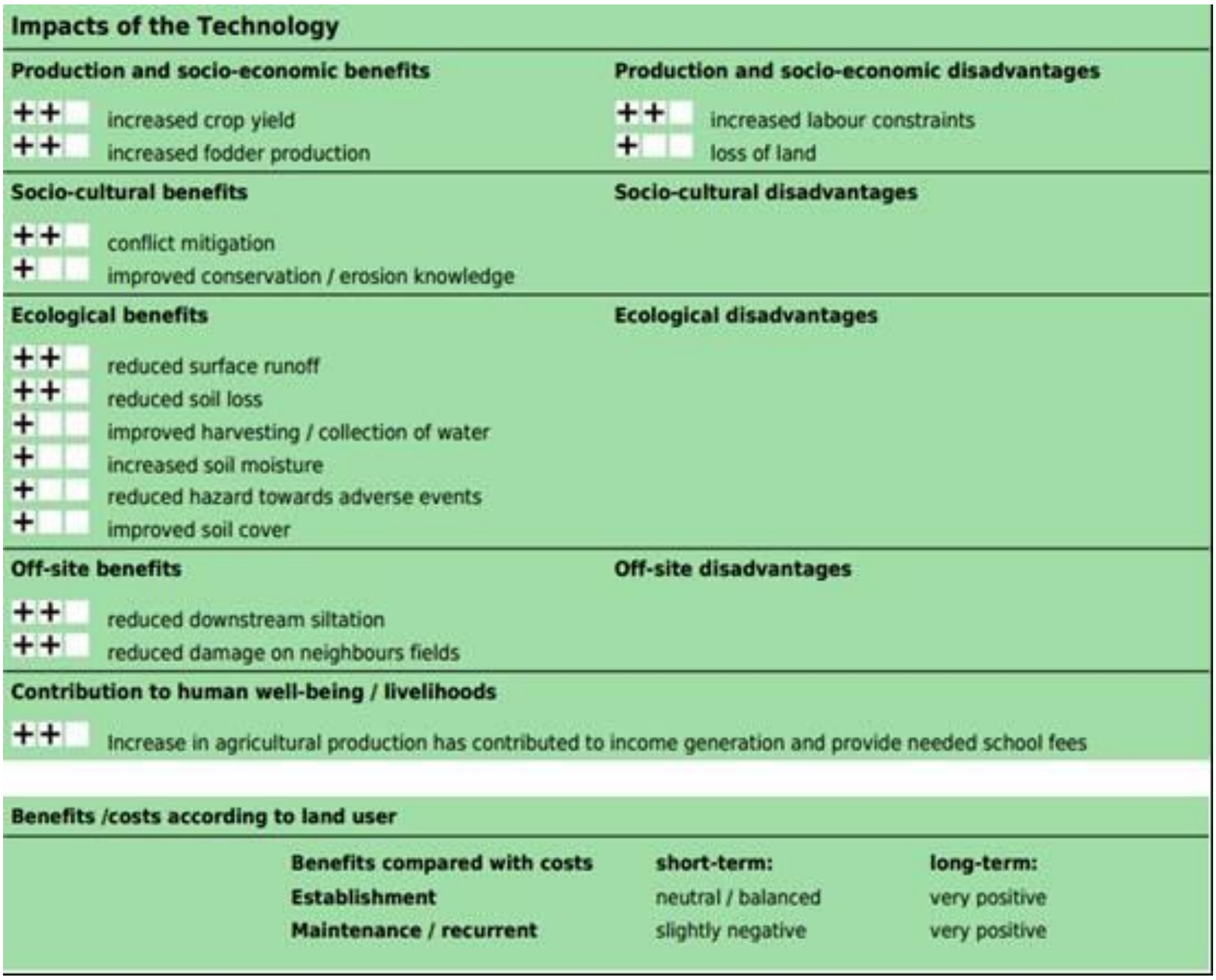


Figure 20: Potential Arabica coffee yield (t ha^{-1}) predicted using ordinary kriging in the ten agro-ecological zones based on actual yields (t ha^{-1}) measured at sample sites (Source: Nzeyimana et al., 2014).

Annex 3: Progressive terracing



Impacts of the Technology

Production and socio-economic benefits		**Production and socio-economic disadvantages**	
++	increased crop yield	++	increased labour constraints
++	increased fodder production	+	loss of land
Socio-cultural benefits		**Socio-cultural disadvantages**	
++	conflict mitigation		
+	improved conservation / erosion knowledge		
Ecological benefits		**Ecological disadvantages**	
++	reduced surface runoff		
++	reduced soil loss		
+	improved harvesting / collection of water		
+	increased soil moisture		
+	reduced hazard towards adverse events		
+	improved soil cover		
Off-site benefits		**Off-site disadvantages**	
++	reduced downstream siltation		
++	reduced damage on neighbours fields		
Contribution to human well-being / livelihoods			
++	Increase in agricultural production has contributed to income generation and provide needed school fees		

Benefits /costs according to land user

Benefits compared with costs	**short-term:**	**long-term:**
Establishment	neutral / balanced	very positive
Maintenance / recurrent	slightly negative	very positive

Table 40: Qualitative cost-benefit analysis of progressive terracing (Source: World Overview of Conservation Approaches and Technologies (2014), available from: http://www.fao.org/3/a-au297e.pdf)

Annex 4: Tea altitude options analysis

Altitude band (masl)	RCP2.6 / No Climate Change	RCP8.5 / Climate Change	Percentage Point Difference
1500 - 1600	- 5.04%	N/C	N/C
1600 - 1700	N/C	N/C	N/C
1700 - 1800	1.23%	N/C	N/C
1800 - 1900	2.88%	N/C	N/C
1900 - 2000	4.27%	2.87%	1.40pp
2000 - 2100	5.51%	4.45%	1.06pp
2100 - 2200	6.66%	5.81%	0.85pp
2200 - 2300	7.73%	7.02%	0.72pp
2300 - 2400	8.35%	7.95%	0.39pp
2400 - 2500	6.45%	7.11%	0.67pp

Table 41: Financial returns for 3,415ha tea plantation in 100m altitude bands, where N/C stands for "not calculable".

Altitude band (masl)	RCP2.6 / No Climate Change		RCP8.5 / Climate Change		Max – Min NPV (USDm)
	BCR	NPV (USDm)	BCR	NPV (USDm)	
1500 - 1600	0.94	(18.08)	0.76	(70.78)	52.70
1600 - 1700	1.03	9.71	0.87	(38.52)	48.23
1700 - 1800	1.13	38.10	0.98	(5.30)	43.40
1800 - 1900	1.23	67.07	1.10	28.07	39.00
1900 - 2000	1.34	96.61	1.21	60.31	36.30
2000 - 2100	1.45	126.70	1.32	91.28	35.42
2100 - 2200	1.57	157.34	1.44	122.78	34.56
2200 - 2300	1.69	188.53	1.56	154.74	33.79
2300 - 2400	1.77	206.64	1.67	181.23	25.40
2400 - 2500	1.58	145.77	1.63	163.22	17.46

Table 42: Economic returns for 3,415ha tea plantation in 100m altitude bands at 0% social discount rate.

Altitude band (masl)	RCP2.6 / No Climate Change		RCP8.5 / Climate Change		Max – Min NPV (USDm)
	BCR	NPV (USDm)	BCR	NPV (USDm)	
1500 - 1600	0.45	(34.62)	0.41	(37.03)	2.41
1600 - 1700	0.49	(31.82)	0.46	(33.73)	1.91
1700 - 1800	0.53	(28.96)	0.51	(30.67)	1.71
1800 - 1900	0.58	(26.04)	0.55	(27.67)	1.63
1900 - 2000	0.62	(23.06)	0.60	(24.66)	1.60
2000 - 2100	0.67	(20.03)	0.65	(21.59)	1.57
2100 - 2200	0.72	(16.94)	0.70	(18.47)	1.54
2200 - 2300	0.77	(13.79)	0.75	(15.33)	1.53
2300 - 2400	0.80	(11.97)	0.79	(12.70)	0.73
2400 - 2500	0.69	(18.11)	0.73	(16.09)	2.01

Table 43: Economic returns for 3,415ha tea plantation in 100m altitude bands at 13% social discount rate.

ECONADAPT
The Economics of Adaptation

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Chapter 2: Adaptation decision-making in Zanzibar’s clove plantations: a cost benefit analysis extended to “light touch” uncertainty treatment

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For further information on the ECONADAPT project, please contact Alistair Hunt at: ecsasph@bath.ac.uk

Abbreviations

BCR	Benefit to Cost Ratio
CBA	Cost Benefit Analysis
DR	Discount Rates
DFID	Department For International Development
GDP	Gross Domestic Product
GMP	Good Management Practice
GHG	Green House Gas
IRR	Internal Rate of Return
LULC	Land Use and Land Cover
MANR	Ministry of Agriculture, Forestry and Natural Resources, Zanzibar
NPV	Net Present Value
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
ROA	Real option analysis
RGZ	Revolutionary Government of Zanzibar
URT	United Republic of Tanzania
USD	United States Dollar
ZCCS	Zanzibar Climate Change Strategy
ZSTC	Zanzibar State Trade Corporation
ZWBS	Zanzibar Woody Biomass Survey

Summary

Recently, flexibility and robustness have been repeatedly mentioned to be important characteristics for sound decision making in the realm of climate change adaptation. This is because traditional methodologies for project appraisal do not match well with uncertain circumstances in the real world. These include uncertainties about climate change projection and modelling as well as classical socio-economic uncertainties that usually make investments risky. Real option analysis (ROA) derived from financial markets as well as robust decision making (RDM) have attracted much interest to adaptation economists for their potential to generate additional information into project evaluation processes where the most widespread standard cost benefit analysis is usually performed.

Generally however, all these methodologies require high computational expertise and most ROA and RDM practice to date are found in sectors with high infrastructural components or sectors where complex data is available for methodological processing. Their application is therefore limited to a restricted expert community which hinders wider replicability and provides few space for generalization in project appraisal. In this study we aim at testing these new methodologies and their pertinence to adaptation in international development cooperation by adopting “light touch” approaches that capture intrinsic concepts of formal applications without losing their economic rationale.

To do so, we use the ongoing National Adaptation Action Plan process of the Revolutionary Government of Zanzibar within the United Republic of Tanzania (URT) where stakeholders identified clove plantations as one of the key priorities to be addressed. From the perspective of project finance application we first develop a cost benefit analysis of a simplified clove agroforestry systems focusing on Pemba Island. We assess the profitability of different adaptation options that aim at resilient clove plantations in Zanzibar both with and without climate change. We then extend the analysis to ROA and RDM light touch uncertainty treatments to verify their relevance for the adaptation practitioner community in the field.

Results of our case study show “light touch” applications of uncertainty treatment can provide the analyst with additional information that can be valuable to decision makers in three in four ways: by better disclosing and framing the variety of uncertainties the decision is subject to (i), providing complementary results as to how outcomes change with varying uncertainties or challenging traditional cost benefit results (ii), providing opportunities for iterative adaptation management through stakeholder engagement (iii) and forcing the analyst to consider alternative “in project”, flexible and robust adaptation options that avoid locking in present decisions.

Keywords: Adaptation, international development, agroforestry, cost benefit analysis (CBA), light touch uncertainty treatment, robust decision making (RDM), real option analysis (ROA), Zanzibar (Tanzania)

1. Introduction

1.1 Study and data collection

The methodology of this study has been developed within the ECONADAPT FP7 Project of the European Union in support of the International Development Working Package. This work builds on the Zanzibar Climate Change Strategy and enabled us to participate in the local stakeholder process put in place for the development of the UK-funded Climate Change Action Plan of Zanzibar. Data collection has been carried out in close collaboration with the Department of Forestry of the Ministry of Agriculture, Forestry and Natural Resources (MANR) of Zanzibar during two missions, in January and June 2016. It is a product of regional workshops held in Zanzibar aiming to narrow down strategic priority actions identified in the Strategy on the one hand, and a series of semi structured interviews with main stakeholders of interest to the clove sector on the other hand. More information on the stakeholders met and the list of questions used are to be found in Annex 1 and 2.

1.2 The clove sector

The Zanzibar archipelago lies in the western Indian Ocean, close off the coast of the United Republic of Tanzania (URT) of which it is an autonomous region (Figure 1). At the crossroads of trade routes that have linked South Asia to the East African coast and Europe, Zanzibar's history has been closely related to the rise and fall of clove plantations. Clove trees were introduced into Unguja Island in form of extensive monoculture under Omani rule, at the beginning of the 19th century. The clove sector was a particularly attractive business to the Sultanate given the dominant trading position of Zanzibar combined with a low input sector linked to free slave labour and high demand for clove in the world market. Ever since, and despite socioeconomic changes in the region, clove forests have been a strategic sector to changing Governments in terms of the foreign income it could attract and the national economic performance it could sustain. The initial success and high price of cloves might be one of the most important reasons the clove sector in Zanzibar has been a monopoly of State, nowadays managed by the Zanzibar State Trade Corporation (ZSTC). ZSTC is mandated to buy the totality of clove production at the farm gate price it sets.

Figure 1: Topographic map of Zanzibar, showing both Unguja and Pemba islands

Source: **Zanzibar Climate Change Strategy, Final Draft, 2014**

Today, clove trees are mainly grown on Pemba Island in complex agroforestry systems in which many species of cash, food crops and trees are grown together in subsistence farming systems (Indufor, 2013a). In 2010, clove exports in value shared 62% of total exports of Zanzibar (OCGS, 2011) and represent the most important source of foreign exchange. The clove industry also catches the attention as it sustains the livelihood of about 8,139 households or about 6% of the crop growing households in Zanzibar (RGZ, 2012). This is of importance, as Zanzibar is one of the least developed regions of the world both as part of the URT and as a Small Island Developing State. Despite a high average growth rate of 6.4%, 44% of its population lives under the basic needs poverty line set at about 1 USD/day[32] (OCGS, 2012). Zanzibar's total Gross Domestic Product (GDP) amounted to USD 679 Million[33], the agricultural sector accounting for 33% of the GDP, out of which 66% is generated by crop production. Per capita GDP was reported to be about 561 USD/capita in 2010 (OCGS, 2011).

The sector has yet experienced variations and cascading difficulties, especially since the 1960's (Figure 2). While up to 20,000 tonnes of cloves could be harvested at the end of the 50's, production oscillates between around 5 000 tonnes since 2006 (OCGS, 2011)[34]. There are several explanations to this downward trend: firstly, clove trees have been observed to be characterised by a high production variability, featuring one to two low crop years after a bumper harvest (Martin et al., 1988, 1987). This is found to be due to exogenous and endogenous factors linked to climate in combination with the agronomy of the plant (Razakaratrimo, 2014). Secondly, there has been increasing competition in the clove market with the rise of competitors such as Madagascar and Brazil. Indonesia plays a particular role in the clove market since it became the first producer and consumer worldwide, strongly driven by the success of and the consumers' taste for clove cigarettes in Indonesia[35] (Indufor, 2013a). Thirdly, declining hectarage and neglected management has usually been observed in low clove price contexts precipitating the sector in a spiral of ageing trees, the presence of pests and diseases, decreasing tree population, declining plantation area, scarce replanting as well as neglected husbandry and plantation management (Martin, 1991; RGZ, 2004; R.S. Troup, 1932). Finally, historical features specific to Zanzibar such as the inherited land tenure systems and land fragmentation as well as the transition from a slavery to a free labour driven systems did not encourage farmers to grow clove trees at a high scale. As a result, the crop has remained dominant as farmers usually believe prices will recover if policies change (Juma, 2010) and most plantations feature booms and busts depending on the prevailing clove market price and interests of individual owners (Martin, 1991a).

In the past few years there has also been increased concern about the impacts of climate change on clove plantations of Zanzibar (RGZ, 2014). The Zanzibar Climate Change Strategy (ZCCS) mentions the clove sector as vulnerable to climate change in its sectoral priorities. This reflects the opinion of stakeholders from the MANR who rank cloves as a priority sector and the farmers that experience erratic rainfalls and dry spells more frequently[36].

Indeed, the revival of the clove sector has recurrently been on top of the political agenda in Zanzibar. If there is legitimate concern about an overestimation of the sector's potential to

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[32] Exchange rate used is USD 1=TZS 1,465 as provided for 2009/2010 by OCGS (2012)

[33] Exchange rate used is USD 1=TZS 1,396 as provided for 2010 by OCGS (2011).

[34] There are important discrepancies between data for clove production in Zanzibar provided by FAO and those given by the Office of Chief Government Statistician (OCGS). See also the Clove advocacy report (Juma, 2010).

[35] Indonesian clove cigarettes are commonly referred to as "kretek" cigarettes. The kretek industry drives the clove market in Indonesia which has important consequences on the dynamics of the world market of cloves.

[36] Stakeholder consultation workshops hold in Unguja and Pemba during the January 2016 mission and semi-structured interviews with farmers on both islands during January and June mission 2016.

Zanzibar's economy[37], there is consensus about the importance of replantation and sound farm husbandry to sustain clove plantations and the livelihoods of farmers that depend on them. The Zanzibar cash crop farming system project of 1995 already recognised the vital ecological role that clove trees have played in maintaining soil fertility and avoiding soil erosion (Salim et al., 1995). The latest clove development strategy has reintroduced the free distribution of clove seedlings to farmers (RGZ, 2004) and the most recent Agricultural Sector Review plans a rehabilitation of the sector with production objectives of 10 000 t/year by 2020 (RGZ, 2015).

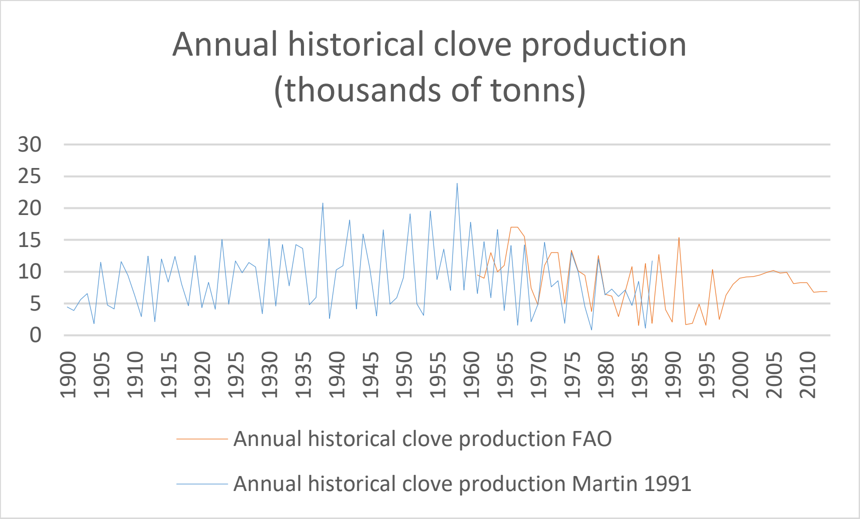

Figure 2: Annual historical clove production in Zanzibar, 1900 – 2012.

Source: Own compilation with data from FAOStat and digitalised graphic from Martin (1991).

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[37] Meeting at Department of Environment, June 2016

1.3 Uncertainties

Uncertainties hamper decision making in general and climate change uncertainties pose additional challenges to anticipatory adaptation more specifically. In this study uncertainty factors are present under different forms. They stem from the lack of knowledge (the climate change, its impact and the response of clove trees and other crops to climate and soil variables), conflicting datasets (production figures provided by FAO and the OCGS), measurement errors and subjectivity of opinions (in data collection and methodological choices). Uncertainties do also originate from more classical socio economic circumstances that make investments risky such as volatility of crop prices in international markets, usual climate variability, farmers' preferences and perception of risk or local political instabilities (Figure 8).

With a recognised need for action, we look into uncertainties related to the clove sector in two main ways: we design an adaptation framework that aims at building resilience by jointly addressing immediate vulnerability to present day and future more erratic climate in 2050-2100. We then look into decision making methodologies alternative to the cost benefit analysis (CBA) that have been recently mentioned to introduce more flexibility and robustness in decision making processes.

1.4 Adaptation with and without climate change

For the definition of adaptation options in the clove sector of Zanzibar we take the development perspective of Burton (2004) arguing that both climate variability and change need to be considered as the one and only continuous process of adaptation. We think this makes sense given the adaptation deficit and potential future climate risks in clove plantations of Zanzibar, the clove revival policies the country has been planning and the development country context in which adaptation is one of a plethora of other development priorities to address. In his study, Burton suggests two types of adaptations (Adaptation I and II) distinguished by the perspective adopted (adaptation as occurred since humankind and adaptation as developed under the United Nation Framework Convention for Climate Change), the magnitude and type of climate they respond to (current and future climate) and their source of funding (sustainable development and climate change funding). The author strongly recommends both types to be part of the same continuous adaptation process. More recently, this has been referred to as adaptation pathways as depicted in Figure 3 (Downing et al., 2011) and iterative risk management (Margulis et al., 2010; Fisher et al., 2007) and this is more deeply rooted in four different aspects of adaptation: adaptation as a range of practices on the development to vulnerability spectrum (McGray et al., 2007), the recognition of deep uncertainties in climate projections (Hallegatte, 2009) and the lack of detail needed in project application (Burton and van Aalst, 2004) as well as the shift away from impact assessments towards user oriented studies (Downing, 2012; Watkiss, 2015).

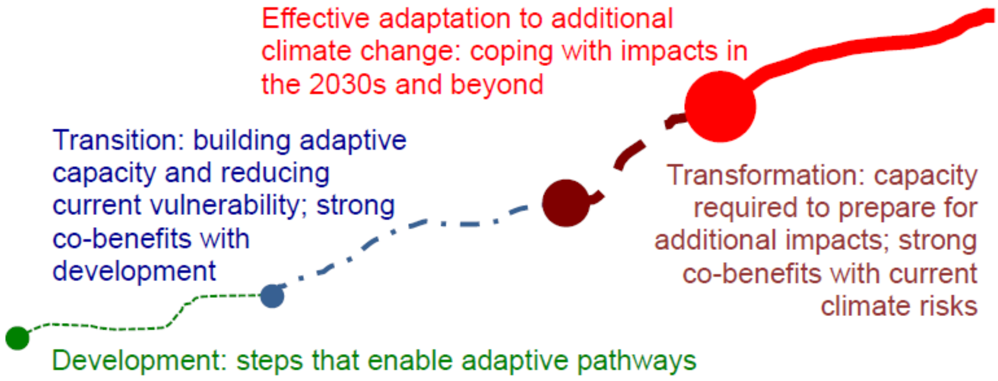

Figure 3: Adaptation as a pathway from development to climate protection.

Source: (Downing et al., 2011)

We adopt the same precautionary principle as Burton (2004) and suggest there is more of both adaptation to current and future climate to be done in clove plantations of Zanzibar, in order to fully untap their real potential. Indeed, as a result of our work in Zanzibar we take the view that clove trees are inherently resilient tree species. We believe this to be so for two main reasons: firstly, because of the range of climates it adapted to out of its native space. Although producing cloves of different qualities, trees thrive from Brazil to China and have been coping with recurrent cyclone stress especially on the east coasts of Madagascar (Danthu et al., 2014). Secondly, because in Zanzibar clove trees are reported to conserve soil fertility despite the deforestation of native species(Salim et al., 1995). In line with a study on climate change in Tanzania (OECD, 2003), this implies that adaptation in Zanzibar may capitalize on opportunities in addition to attenuating adverse impacts.

In this paper we analyse the profitability of different adaptation options in clove plantations of Zanzibar under both current and projected climates for the future. In a first step, we develop a CBA on a simplified agroforestry model including a baseline and four alternative agricultural practices and analyse their viability under present climate (Section 2). Subsequently, we analyse results from introducing future climate impacts in the form of rainfall projections (Section 3) and extreme events in form of a cyclone hitting at three different timings (Section 4). We then look into economic outcomes resulting under current, future climate and cyclone events (Section 5). In a second step, we look into conceptual aspects of real option analysis (ROA) and robust decision making (RDM) that we apply in light touch treatments to our agroforestry model (Section 6). Finally, we compare results from the CBA, ROA and RDM and conclude about the relevance of these methodologies to development project applications (Section 7).

2. CBA under present climate

2.1 The agroforestry model

According to the Zanzibar Woody Biomass Survey (ZWBS) (Indufor, 2013b) and its Special Report on Cloves (Indufor, 2013a) 93% of clove trees of Zanzibar are presently grown on Pemba island. Clove trees mainly thrive on the western side of the island in Wete district, mostly in complex agroforestry systems, intercropped with banana stands, cassava, grapefruit, cinnamon and a multitude of other trees and crop species. In Zanzibar this diversity is remarkable, as each farmer designs its farm according to inherited land use patterns and practices, own farm management and risk reduction strategies. The ZWBS defines three Land Use and Land Cover (LULC) categories of agroforestry in Zanzibar. The share of clove trees planted in agroforestry systems is 96% out of which 91% are concentrated in clove "plantations". These are equally agroforestry systems implying highest clove tree densities (Indufor, 2013a) (Figure 4).

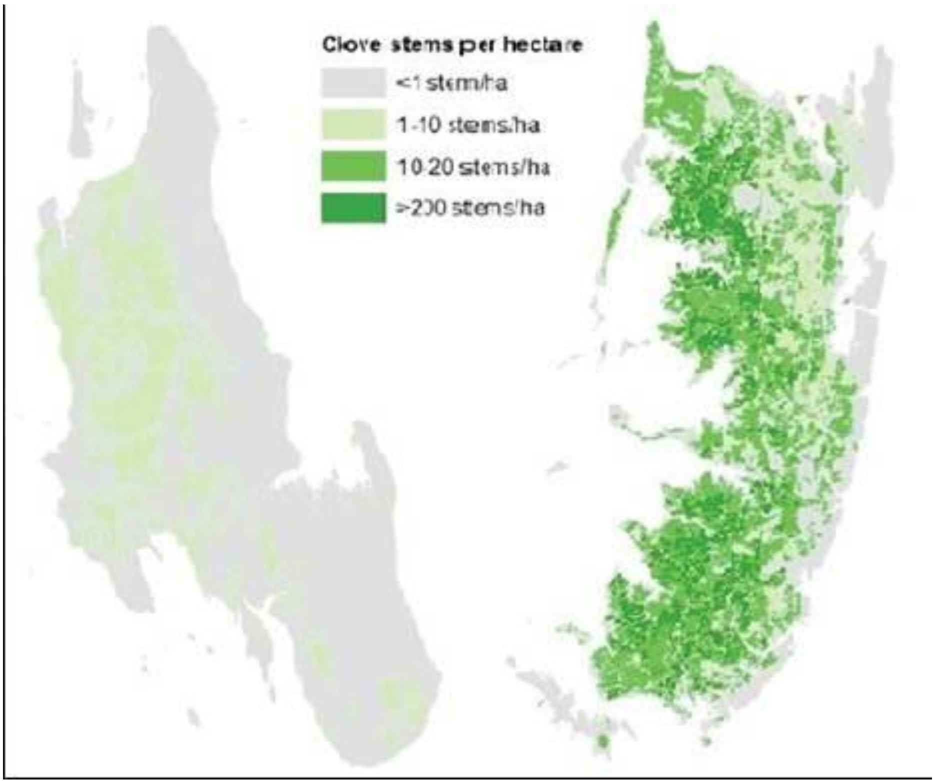

Figure 4: Distribution of clove trees on Unguja and Pemba

Source: (Indufor, 2013a)

Breaking off the dichotomy between forests and agriculture, agroforestry is an interface between the two. According to Nair (1993) it refers to old land use systems, mixed technologies and practices in which woody perennial crops such as trees and palms are deliberately grown together with agricultural crops and/or animals on the same unit of land. This is done in some form of spacial arrangement (intercrop) or temporal sequence (fallow and shifting cultivation). In agroforestry systems there are both ecological and economical interactions between the different components and systems range between simple rotations and more complex hedgerow intercropping. These include systems with various tree densities, systems in which trees play a predominant service role (e.g., windbreaks) to those in which they provide the main commercial product (e.g., intercropping with plantation crops) (Nair, 1993).

For our study we construct a simplified agroforestry model in which we only account for limited intercrop species to capture its rationale and avoid a high degree of complexity in the analysis. We first develop the baseline without adaptation to account for the average situation in Pemba today. Then we account for good management practices (GMPs), alternative intercrops and a windbreak, in order to compare economic results under current climate conditions.

2.2 Baseline (no adaptation)

We look into a farmer’s investment in a new, one hectare clove plantation and its viability. We assume therefore bare land is bought, and clove seedlings together with intercrops are all planted at once at the onset of the project in year zero. We assume the clove plantation has a lifespan of 80 years, which is considered to be the productive lifetime of the clove trees in Zanzibar (Indufor, 2013a).

While during field missions clove trees were reported to be resistant and requiring minimum maintenance, this conclusion needs to be put in perspective. Specifically, because the seedling stage and the three years after transplantation into the field is the period clove trees are most sensitive, and this is especially so in case of dry soil conditions and direct sunlight (R.S. Troup, 1932; Thankamani et al., 1994). While transplantation timing depends on the age, appearance of embryonic leaves and the height of the seedlings (Thankamani et al., 1994), this is likely to also depend on local ecological and climatologic specificities. In Zanzibar, transplantation is argued to be enabled only after a period of 18 up to 24 months. Usually, clove seedlings are produced and kept in nurseries during this time of their lifetime. Afterwards, they are either sold or distributed to farmers who plant them in their farms (Martin, 1991; Thankamani et al., 1994). As Martin (1991) states in his study, “The success of replanting will depend upon the availability of good quality seedlings and the adoption of methods of tree establishment which are appropriate for the Zanzibar climate and farming systems.” (page 458).

In the baseline we account for intercropping that serves as shading while maintaining soil moisture on the one hand, as well as for appropriate survival rates of clove trees on the other hand. As for intercropping, we allow for cloves to be grown together with cassava and banana trees during the first 3 years of the plantation's lifetime. We denominate as survival rate the percentage of seedlings remaining on the plot one year after transplantation on the farm. Survival rates are reported by farmers to be between 40% and 80%. To insure high survival of clove seedlings regular and good management practices of plantations are essential (Martin, 1991; Thankamani et al., 1994). We use a weighted average of survival rate of 55% reflecting the generalized tendency of plantation neglect in the past years as cited earlier. If the seedlings survive one year after transplantation, we assume they will survive the complete cycle and therefore we do not directly account for pests and diseases throughout the lifetime of the tree. We also assume farmers are aware of the survival rate, so that they plant additional seedlings necessary to obtain a plantation with the desired density. Lower survival rates therefore reflect higher costs to farmers via higher seedling, transportation, digging and plantation expenses in the initial investment phase.

Clove trees start producing in year 6 at an increasing pace, reaching production maturity at 40 years, which is then sustained till 70 years. Afterwards, production falls back to low levels, before being considered null starting year 80 (Indufor, 2013a). On recommendation of stakeholders in Pemba we apply an average tree density of 100 trees/ha. For consistency, we also use the annual average production of 390kg/ha/year. This was obtained by computing the average of digitalised production figures from Martin (1991) downscaling them to the area of interest. Production figures serve to derive harvesting and drying costs as well as the revenues from clove production.

Detailed cost and revenue items, their monetary values and respective timings used for the baseline are provided in Annex 3. All assumptions for the construction of the baseline are to be found in Annex 4. The main investment costs that farmers bear in the first year include land acquisition and preparation, costs of seedlings and their transportation to the farm as well as the digging and planting. Recurrent costs encompass weeding, seasonal harvesting, drying of cloves, felling of unproductive trees and replantation, harvesting being the most important recurrent cost.

According to Crofts Report (1959) and Troup (1932), harvesting is the main recurrent expense and absorbs on average half of the value of cloves. In line with historical reports, data obtained in the field this year indicate harvesting amounts to about 62% of total annual expenses. All recurrent costs start together with production in year 6. Weeding is practiced every year and to account for scarce management practice and low survival rates in the baseline, we assume weeding is implemented at 50%, thereby reducing the costs by the same amount. Felling of unproductive clove trees and replantation are assumed to start in year 70 and are repeated every 5 years at 20% and 40% of trees respectively. For replantation we assume the same survival rate as for initial plantation and do not account for further shading, production and harvesting needs resulting from replanted crops. Regarding replantation, earlier renewal is likely to be needed to insure clove forests' sustainability. Because there does not seem to be an optimised replantation strategy in the region and consistent with low levels of plot management, we keep renewal of trees in late years of the plantation's lifetime.

2.3 Adaptation under current climate

Meeting with actors from different institutions that have the clove sector under their mandate and with farmers throughout both islands, we gathered information about existing best practices in clove plantations. Our intention was twofold: to look out for how farmers already successfully adapt to current climate variability and analyse to what extent it makes economic sense to expand these practices at larger scales. In the following paragraph, we refer to these agricultural techniques as adaptation options and compute each of them into the CBA, in addition to the baseline. These include good management practices (GMPs), intercrop with vanilla, intercrop with cinnamon and a windbreak, and exhibit different timelines in terms of rationale for intervention and the benefits they grasp (Table 1). A complete overview of assumptions and data used for the cost benefit analysis is detailed in Annex 4 for both baseline and alternative agricultural practices.

During our missions, GMPs stood out as the most important characteristic for healthy and sustainable clove plantations. GMPs have a broad scope and in our agroforestry model we represent this option through an adaptation package including organic compost, right timing of transplantation from nursery to the field, mini drip irrigation, lemon grass mulching reported to be the only solution to prevent termite nests, removal of parasites from trees and pruning of damaged branches after harvesting. These techniques enable to obtain higher survival rates of up to 80% and an increase in clove bud production of 20%. These options are already partly practiced throughout the region, the most expanded being mini drip irrigation. Mini drip is a low cost technique farmers apply by making use of the top of a closed, funnel-shaped plastic bottle in which cap wholes are drilled to release water drops. It is then filled with water and fixed into the soil at root level of the young tree to enable constant moisture of the tree’s root area.

Intercrop with vanilla is less frequent practice in Zanzibar which is likely to be caused by high maintenance and manual pollination costs. However, some farmers do intercrop clove with vanilla. Vanilla is a climbing plant that grows up trees and is usually planted on support trees with a distance of 4m x 4m. Given our field investigation, it seems therefore reasonable to assume in our model three vanilla subplots of 20 x 20m^2 with a distance between vanilla supporting trees of 4m x 4m and 25 vanilla plants on each subplot. As clove trees are usually interspaced at 10m x 10m, vanilla subplots imply the reduction of four mature clove trees per subplot or 12 clove trees for the entire farm. As compared to the baseline, this is expected to reduce total clove plantation costs and revenues to 88% and additional costs specific to vanilla plantation are added. These include additional land preparation costs for maintenance of vanilla support trees every five years and considerable annual costs from additional weeding and manual pollination. Vanilla production is assumed to start in the first year of the plantation and to be constant throughout the considered time frame of 80 years.

Cinnamon intercropping reflects one of the farmers' diversification strategies we most observed throughout the islands. To integrate cinnamon intercropping in the agroforestry model we assume 50% cinnamon and clove tree distribution with an identic density for both species, equal to baseline. Costs and revenues from clove production will therefore be reduced by 50% while additional costs and revenues from cinnamon are accounted for including for weeding, where applied. In our 80 year timeframe cinnamon trees are assumed to start production in year 10 and produce at 50% of their productive potential till year 30. Afterwards, and till the end of their lifecycle they produce at maximum potential of annual 875t/ha.

A windbreak is designed to protect the plantation from strong winds and cyclones (Thankamani et al., 1994). On all its sides the land plot is supposed to be fenced off by two lines of teak trees, a specie much valued for its hard wood. Assuming the same density is required for both clove and teak species and land area available remains identical, clove plantation reduces to 36 clove trees, the remaining being replaced with 64 teak trees. This reduces clove trees related costs arising throughout the lifecycle to 36% of initial amounts. Cost of plantation and felling are the same for both tree species therefore we keep our model identical for most items. Weeding at 50% of application and survival rates of 55% are kept identical to the baseline. Clove revenues are drastically shortened to 36% while the teak trees only provide benefits in latest years: either from the commercialization of its hard wood when trees are replaced or from avoided damage costs that only potentially materialize in case of a cyclone events. To that extent it is also different from the classical intercropping as the vanilla and cinnamon diversification mentioned above. Under intercropping, we do not assume any increase in production of cloves nor higher clove tree survival rates.

Table 1: Framework for an adaptation pathway in clove plantations of Zanzibar

Nr.	Adaptation option	Description	Intervention	Timeline	Benefits
1	GMPs (adaptation package)	*100 clove trees/ha and* *Shading with banana stalks* *Weeding (100%)* *Replantation starting year 60* *Organic compost* *Timing of transplantation* *Mini-drip irrigation* *Cover crop: lemon grass* *Removal of parasites* *Pruning after harvest*	Good development/addressing climate vulnerability	Short term	Short term
2	Intercropping with Vanilla	*3 subplots of 20m*20m planted with vanilla and* *70 clove trees/ha*	Resilience for the future	Mid-term	Short and mid term
3	Intercropping with Cinnamon	*50 % clove trees and 50% cinnamon trees/ha*	Resilience for the future	Mid-term	Short and mid term
4	Windbreak (with Teak)	*The clove plantation is fenced with 2 lines of teak trees: 64 teak and 36 clove trees/ha*	Capacity for the future	Long term	Long term

Source: Adapted from Watkiss (2015)

2.4 Results

We run a CBA that highlights the monetary profitability from a one hectare clove plantation (Table 2). In our analysis we do not account for potential economic costs that could arise from harvest injuries and deaths or environmental benefits of forest covers that channel through carbon sequestration or avoided soil erosion. We however believe these are likely to be substantial (Mbow et al., 2014a, 2014b). We first apply this methodology to the baseline and subsequently to the four alternative agricultural practices: GMPs, vanilla intercrop, cinnamon intercrop and the windbreak.

For each, we compute three profitability indicators that provide different and complementary economic information to our investment plans: net present values (NVP), benefit to cost ratios (BCR) and the internal rate of returns (IRR). Because future monetary expenses and incomes are valued differently depending on the source and purpose of the funding institution, we apply three discount rates (DR): a low DR of 3.5% that represents public discounts used in OECD countries for long term projects as it is for example the case for Her Majesty Treasury (UK), a medium discount of 10% that is used by the Department for International Development (DFID) for development projects in Tanzania and a high DR of 13% that represents private investments largely emphasising on short term investment. These are used in the sensitivity analysis.

When prices are high, as expected, results from our baseline model with banana and cassava shading indicate the clove sector is profitable in Pemba. NPVs are positive though they reflect high discrepancies depending on the DR applied: NPVs range from USD 3,380 to USD 35,251 for high and low discounts respectively. This is also the case when observing BCRs, though they exceed one in all cases, meaning that under all discounts considered clove plantation generate higher benefits for each USD invested. An IRR of 19% indicates the return of clove plantations is higher than the desired returns reflected by the discount rates. Usually these represent the cost of capital which decreases with longer time horizons considered.

Alternatively, and in line with other literature sources (Crofts, 1959; Martin, 1991; R.S. Troup, 1932), results suggest that clove production is not profitable when clove prices are low (Annex

5). As mentioned above, clove prices are volatile and depend on a multitude of factors: the varying crop cycles and climate conditions, the trade position of Indonesia as the driving clove producing and consuming country, the demand of Zanzibar cloves that Indian importers seem to enjoy most as well as the position of the Zanzibar State Trade Corporation which, as a Monopoly of State, is able to regulate the country specific price of cloves in Zanzibar[38] (Indufor, 2013a; Martin, 1991).

Table 2: Results for baseline and best agricultural practices without climate change

	No adaptation with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	62,611	21,775	16,704	73.316	24.762	18.714	152.313	55.982	43.203	52,356	17,191	13,333	31,488	12,248	10,276
PV Costs (USD 2016)	27,360	14,921	13,323	29.934	15.913	14.099	42.062	20.943	18.142	20,518	13,091	12,126	17,344	12,126	11,443
NPVs (USD 2016)	35,251	6,854	3,380	43.382	8.849	4.615	110.250	35.038	25.061	31,838	4,100	1,208	14,144	122	-1,167
BCRs (%)	2.29	1.46	1.25	2,45	1,56	1,33	3,62	2,67	2,38	2.55	1.31	1.10	1.82	1.01	0.90
IRR			19%			20%			59%			15%			10%

Note 1: Results are expressed in 2016 USD at USD 1 = TZS 2186.32. Exchange rate, checked on 28 August 2016.

Note 2: Clove prices assumed are high (USD 6.17/kg); Results with low prices are to be found in Annex 5.

Results from alternative practices show all are profitable in absolute terms. GMPs and vanilla intercrop perform better than the baseline, all indicators being higher. In the case of GMPs this is so because the increasing revenues from good management in terms of higher survival rates and 20% additional production outweigh the additional costs incurred. This is especially so for vanilla intercrop which exhibits an IRR of 59%, NPVs between three and seven times higher and BCRs about twice those of the baseline. There are two explanations to such results: on the one hand, vanilla starts production in the first year of the cycle. On the other hand, it is sold at USD 57/kg which generates high annual cash flows throughout the lifetime of the plantation[39].

Results from cinnamon intercropping are not straightforward. While the option is profitable in absolute terms, it is relatively less interesting than the baseline with lower NPVs, lower BCRs and a lower IRR. An exception however is the case of low discount rates in which the BCR exhibits a relatively more interesting outcome than the baseline. This is mainly driven by the current relatively low price of cinnamon assumed.

The windbreak exhibits an IRR of 10% which turns positive NPV to negative and BCRs to lower values as DRs increase. A 13% discount rate does not allow the internal rate of return to reach the expected return from the project. The explanation of such result is tied to the windbreak being designed for potential future benefits that do not materialize in this case. These include avoided damages from wind storms on the one hand and additional revenues from teak wood sold and triggered by the residual damages caused to the windbreak on the other hand.

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[38] It is not sure how the price setting mechanism works in Zanzibar and to what extent the ZSTC regulates the clove price and the farm gate production compensation. Unfortunately few information could be gathered on this topic during our field missions.

[39] In the first step of the analysis we assume a high vanilla price, which we will be able to relax in the second part of the analysis. See the uncertainty treatment section for modelling of low vanilla price.

From the point of view of the economic profitability our results suggest that implementing vanilla intercrop and GMPs are the most viable solutions, in decreased order of preference, with cinnamon intercrop and the windbreak.

Our results are illustrative of the role that the economic analysis can play when deciding upon agricultural practices. Nevertheless, the conclusions should be taken with care for several reasons: firstly, less tangible benefits are likely to generate more positive results: these are likely tied to benefits grasped from the diversification of cultivations and improved food security (Mbow et al., 2014b) and for environmental purposes such as the cultivation of forests for reduced GHG emissions and erosion control (Mbow et al., 2014a; Salim et al., 1995). Secondly, because our results are based on advantageous clove and vanilla prices (as well as currently low cinnamon prices), while consideration of low clove prices would dramatically change the outcomes. More generally, results are strongly driven by assumptions made. Although these are coherent with information gathered in the field, circumstances are dynamic and assumptions will need to be put in perspective and challenged.

3. CBA under future climate: dry spell impacts

3.1 Climate impacts on clove plantations

So far, there is little in the literature helping to understand the sensitivity to and magnitude of climate impacts on the growth of clove trees, triggering losses that plantations could suffer in consequence. Two previous studies investigate the reasons of the clove tree's production variability (Martin et al., 1988), and the weather impact on clove production (Miraji, 2013). The first study finds a positive, statistically significant correlation between clove harvest data and rainfall from October to February, two years before harvest for Pemba Island. Nevertheless, the analysis is limited by the lack of consideration of economic factors that strongly affect clove harvest, making it difficult to extrapolate to a causal relationship between rainfall and tree production. Miraji (2013) finds contradictory results with a statistically significant negative relationship between the two variables. As a product of our field missions and intensive discussions with local stakeholders, lower future rainfall in Zanzibar is likely to have a significant impact on clove production.

Firstly, farmers met during our missions reported dry soil conditions and direct sunlight to put a strain on clove production. Farmers in the field also reported present rainfall has become more unpredictable. The Zanzibar Climate Change Strategy reports no observational records for this and an absence of a simple precipitation trend across the archipelago (RGZ, 2014). However, there is a trend in increasing rainfall during the rainy season (Massika) from March to May and a decreasing trend during the dry season (Vuli) from June to October for the future (Figure 5). This strengthens existing precipitation trends and is likely to be to the disadvantage of rain fed agriculture (RGZ, 2014).

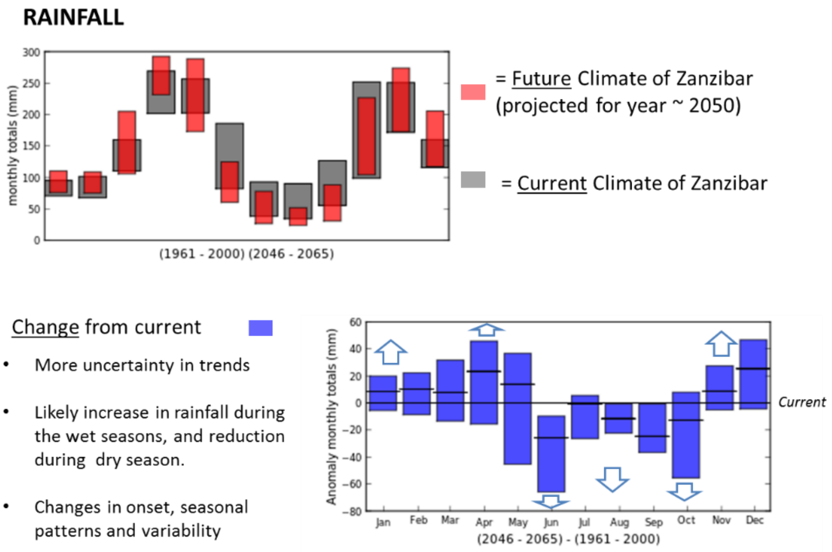

Figure 5. Simulated future monthly rainfall for 2040- 2060, Zanzibar.
Absolute future rainfall (top panel) and rainfall change compared to historical (bottom panel).
Source: Zanzibar Climate Change Strategy with data from Climate Systems Analysis Group (CSAG), University of Cape Town, South Africa.

Secondly, clove trees are reported to thrive in humid climates, with 1500mm-2000mm precipitation per year and 20-30 average temperature, suited for deep red loam, sandy and black soil and deep subsoils that enable a good water drainage, waterlogged conditions being undesirable (Thankamani et al., 1994). The Molucca islands, where the clove tree is native from, enjoy a sub-equatorial wet climate with heavy rainfall throughout the year and an average monthly and annual precipitation of 170mm/month and 2600mm/year respectively. There is no dry season, but low rainfall periods of 100mm/month. In comparison, Zanzibar enjoys a tropical climate with two rainy and two dry seasons that regulate the clove harvesting periods. Main rains fall between March and May (Massika) followed by the first clove harvesting in July/August and shorter rains fall from November to December (Vuli) followed by the second clove harvesting during December/January (Martin et al., 1988). Zanzibar receives an average of 115mm/month and has two dry seasons that are suggested to provide a stimulus for flower bud differentiation in/appearance of cloves. Such differentiation is thought to occur about one year before the cloves are picked and rainfall in these periods is found to be negatively correlated with yield in the following year (Martin et al., 1987). The drought stimulus is also suggested to primarily depend on the balance between rainfall and evaporation and be influenced by the water retention properties of the soil on which trees are grown.

3.2 Modelling climate impacts and climate data: rainfall

Limited by the complexity of biophysical interactions and the lack of knowledge on the climate response of clove trees, we use sensitivities reported by farmers during our field missions for scarce rainfall. We use a mean annual rainfall of 1800mm/year that clove trees require to grow and apply a minimum annual rainfall of 1000mm below which production is reduced by 70% reduction[40]. We use this for illustrative purposes as in reality, climate impact may depend on distributions rather than rainfall averages and biophysical, ecological and socio/economic interactions are likely to be more complex that rainfall considered in isolation.

High uncertainties persist as regarding future climate projections in Zanzibar (RGZ, 2014). To model our climate impacts, we look into downscaled climate projections for Zanzibar based on CMIP 5 models for two Representative Concentration Pathways, RCP 4.5 and RCP 8.5. RCPs have been used to illustrate uncertainty in future emissions of greenhouse gases (GHG) triggering different climate projections in the future. We use both RCP 4.5 and 8.5 to investigate possible future GHG emission and climate scenarios ranging from middle of the road to worst case scenario: RCP 4.5 represents a stabilization of GHG emissions at a moderate rate during the 21st century and RCP 8.5 the absence of severe mitigation policies. Uncertainties are also captured by the use of 11 different models under each RCP suggesting different climate realisations might occur in the future. All data is provided by the Climate Systems Analysis Group (CSAG), University of Cape Town, South Africa and available at http://www.csag.uct.ac.za/unitar-cie/.

We use total monthly rainfall simulations for 1960 to 2099 considering the historical and future projection simulations stretch from 1960 to 2015 and 2016 to 2099 respectively. We aggregate monthly rainfall under both RCPs for the period 1960 to 2099 to obtain annual rainfalls for each of the 11 models. To compare model projections, we compute annual rainfall averages and standard deviations for each model for both RCPs (Annex 8)[41].

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[40] Farmer interview, Pemba, June 2016

[41] Firstly, we observe that under Model 4 (FGOALS-s2) the drought impact is strongest for both RCPs. We confirm this by applying the threshold of 1000mm annual rainfall under which clove is impacted and observe the number of dry spell occurrencies under each model and each RCP. Model 4 stands out as the strongest dry impact with 24 occurrencies throughout the future 80 years under consideration both in RCP 4.5 and 8.5. In comparison, 16 and 18 occurrencies of dry spells for the future 80 years are observed under Models 11 and Model 13 for RCP 4.5. For RCP 8.5 we identify 10, 13 and 17 occurrencies under Model 2, Model 5 and Model 3. According to the dry spell

Considering the worst case scenario, we pursue with the rainfall impact only using Model 4 which features lowest projected annual rainfall. Figure 6 shows the historical and projected annual rainfall simulated for both RCPs. Linear trends of projections exhibit a minimal decrease of annual rainfall of RCP 4.5 and a slight increase for RCP 8.5. From this figure we suggest rainfall follows similar patterns though some divergences and time lags can be observed during some periods. Annex 9 illustrates annual rainfall as compared to the threshold that triggers impact on clove production and annual rainfall distributions by rainfall abundance for both RCPs. Occurrences of dry spells can be identified in these graphs for Model 4 (frequency of rainfall <=1000 mm/year).

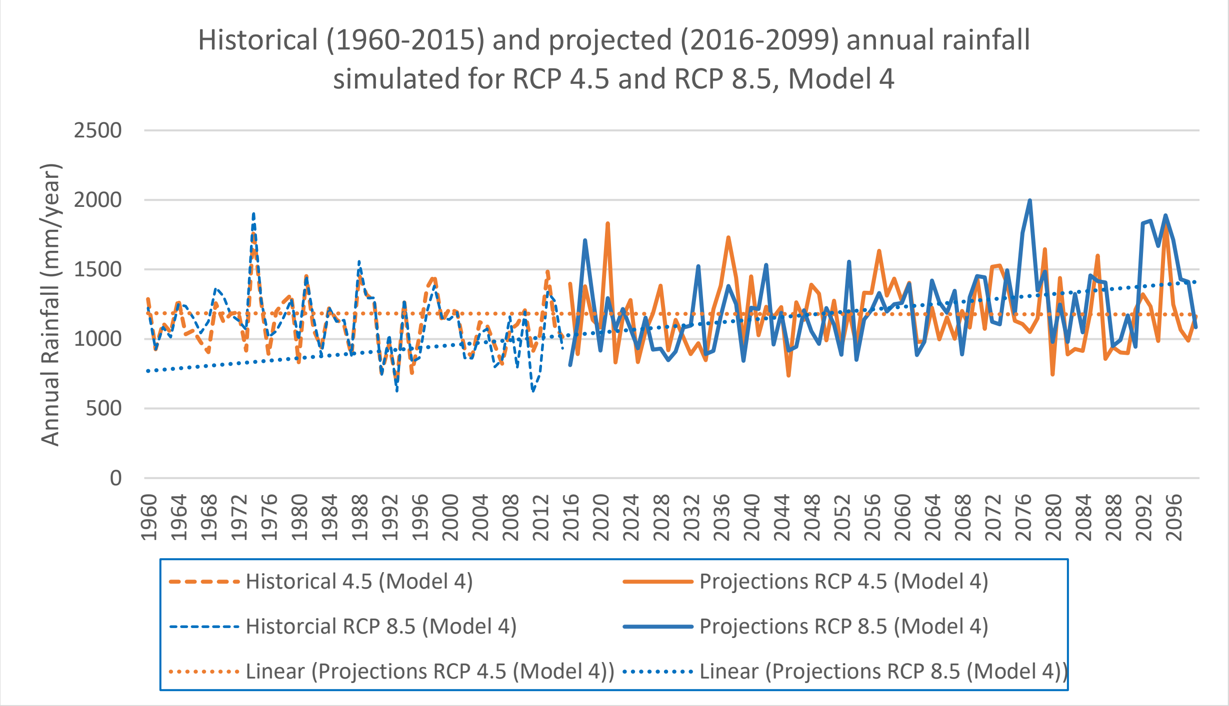

Figure 6: Historical (1960-2015) and projected (2016-2099) annual rainfall simulated for RCP 4.5 and RCP 8.5, Model 4

Source: Own compilation with original monthly rainfall simulation data taken from the Climate System Analysis Group / University of Cape Town (http://www.csag.uct.ac.za/unitar-cie/)
Note: Observed historical data is too fragmented and for availability reasons could not be compiled in annual rainfall data.

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threshold set, no impacts are featured by Model 7, 9 and 10 in RCP 4.5 and by Model 10 in RCP 8.5. In our analysis this will therefore take us back to baseline results under no climate change realisations. Secondly, in line with conclusions from the ZCCS, data interpretation allows us to confirm there is no unique trend standing out, rainfall increasing or decreasing depending on model and RCP used. Thirdly, data does not feature substantial difference between RCPs and models, both in terms of annual rainfall averages and standard deviations. Finally, data also suggests rainfall will not make drastic shifts away from historical simulations. However, the latter is to be taken with care: on the one hand, historical projections are tied to model specifications and are not bias corrected. On the other hand, there is little and fragmented observed data which makes it difficult to compare how well models perform in reproducing historical data.

3.3 Adaptation to dry spells: good management practices and crop diversification

Three adaptation options are considered under scarce rainfall projections: GMPs, vanilla and cinnamon intercrop. In addition to the benefits they harness under recurrent climate conditions, GMPs are assumed to reduce drought impacts on clove plantations from 70% to 50%. Note that for more simplicity we do not model additional impacts or benefits for vanilla and cinnamon intercrop in the case of rainfall[42].

3.4 Results

Results under the rainfall impact are provided in Table 3 for RCP 4.5 and RCP 8.5 under high clove prices.

Table 3: Results for adaptation with rainfall impacts (RCP 4.5 and RCP 8.5 Model 4)

		No adaptation, with shading			GMPs			Vanilla intercropping			Cinnamon intercropping		
RCP 4.5 – Model 4	Discount rates	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
	PV Revenues (USD 2016)	50,899	18,081	14,121	64.951	22.124	16.869	142.006	52.732	40.930	46,500	15,344	12,042
	PV Costs (USD 2016)	27,360	14,921	13,323	29.934	15.913	14.099	42.062	20.943	18.142	20,518	13,091	12,126
	NPV (USD 2016)	23,539	3,161	797	35.016	6.210	2.770	99.944	31.788	22.788	25,982	2,253	-84
	B/C ratio (%)	1.86	1.21	1.06	2,17	1,39	1,20	3,38	2,52	2,26	2.27	1.17	0.99
	IRR			15%			18%			58%			13%
RCP 8.5 – Model 4	PV Revenues (USD 2016)	49,337	17,667	13,976	63.835	21.828	16.765	140.631	52.367	40.802	45,719	15,137	11,969
	PV Costs (USD 2016)	27,360	14,921	13,323	29.934	15.913	14.099	42.062	20.943	18.142	20,518	13,091	12,126
	NPV (USD 2016)	21,976	2,746	652	33.900	5.914	2.666	98.569	31.423	22.661	25,201	2,046	-156
	B/C ratio (%)	1.80	1.18	1.05	2,13	1,37	1,19	3,34	2,50	2,25	2.23	1.16	0.99
	IRR			14%			18%			59%			13%

Note 1: Results are expressed in 2016 USD at USD 1 = TZS 2186.32 exchange rate, checked on 28 August 2016.
Note 2: Clove prices assumed are high (USD 6.17/kg); Results with low prices are to be found in Annex 6.

Under dry spells our baseline remains profitable according to all financial indicators considered with a NPV of about USD 23 Thousands and a BCR of 1.86 under the low DR. Due to an IRR of 15%, its BCR is however close to the unit with high discount rates. This is the case for both RCPs though previous result are slightly strengthened under RCP 8.5, the IRR reaching 14%. As previously, results are driven by high clove prices and low prices changes the outcomes dramatically (Annex 6).

However, vanilla intercropping and GMPs are better options all indicators featuring higher financial performance. Results from the cinnamon intercrop are not straightforward: results suggest profitability of cinnamon is less attractive than the baseline except in case low discount rates are applied in which case the analysis shows slightly higher NPVs and BCRs. The economic indicators under no adaptation are the ones that are most reduced by the modelled rainfall reduction and therefore the baseline is the most sensitive to rainfall predictions. Results under the RCP 8.5 are less positive though very similar: NPVs vary by an amount as low as USD 781 in the case of the cinnamon intercrop to a maximum of USD 1,563 in the case of the baseline.

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[42] See the uncertainty treatment section for modelling of a drought impact on vanilla.

4. Extreme events: cyclones

In complement to the previously analysed rainfall impact in RCP 4.5 and RCP 8.5 we now look into cyclone impacts in perspective of worst case scenarios. Zanzibar lies just off the cyclone pathways in the South-West Indian Ocean and the hurricane that hit land in 1872 is mostly believed to remain exceptional. Previous work citing the Tanzania Meteorological Agency (RGZ, 2014) reports observed changes in wind speeds for the Zanzibar station on Unguja between 1988-1997 and 1998-2007. Evidence is provided on increasing wind speeds on the region and three recorded cyclones that have made landfall on the Tanzanian coast (Mahongo et al., 2012). Contradicting those results, an assessment made for the IPCC AR5 of past observed and future projected changes in frequency and intensity of tropical cyclones concludes that confidence remains low in tropical cyclone activity and region specific projections (Christensen et al., 2013). Nonetheless, low probabilities of occurrence do not justify inaction (Nature Climate Change Editorial, 2016) and delaying implementation is coming at a higher cost (Lemoine and Traeger, 2016). We thereby take the perspective that decision makers need to be informed and anticipate possible impacts from extreme events including from low probability cyclones.

4.1 Modelling cyclone impacts

So far, there is no existing data on cyclone occurrence and impacts in Zanzibar. During our missions farmers could report little on the sensitivity of clove trees to strong wind impacts, none of them experiencing those. However, farmers informed us about the extensive but superficial structure of clove tree roots and reports from Madagascar confirm clove trees suffer consequences of cyclones in that region (Danthu et al., 2014; Levasseur, 2012). For illustration purposes we use a potential cyclone occurring at different timings in year 7, 15 and 30 and reduces production by 80% in the first six years after the event. This is because clove trees are replanted after the event but need 6 years to start production at an increasing rate. We apply impacts of cyclones of 60% till year 10, 40% till year 20, 20% till year 30 and reduces to zero afterwards.

4.2 Adaptation to cyclones: windbreaks

A windbreak is designed with the specific purpose of reducing cyclone impacts on clove plantations. We assume the windbreak reduces cyclone impacts from 80% to 30% in the first six years, while they are reduced to 10% in subsequent four years and cancel out afterwards.

4.3 Results

Economic outcomes are presented in Tables 4 to 6. As expected, results show that the windbreak is financially more interesting as compared to the baseline. Although this may be considered as counterintuitive, this is due to the damages the windbreak is able to avoid, as well as to revenues grasped from selling wood of the damaged trees. Indeed, we observe that results increase for the same reasons even in the baseline and under low prices if the cyclone hits in year 7 (Annex 7).

Table 4: Results for adaptation with cyclone impacts in year 7

	No adaptation, with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	58.415	23.901	19.444	45.885	21.845	18.282
PV Costs (USD 2016)	27.615	15.077	13.450	17.599	12.282	11.569
NPV (USD 2016)	30.799	8.824	5.994	28.286	9.563	6.713
BCR (%)	2,12	1,59	1,45	2,61	1,78	1,58
IRR			27%			28%

Note 1: Results are expressed in 2016 USD at USD 1 = TZS 2186.32 exchange rate, checked on 28 August 2016.

Note 2: Cyclone costs include replantation. Benefits include revenues from selling wood from damaged trees. Not including these result in more negative outcomes.

Table 5: Results for adaptation with cyclone impacts in year 15

	No adaptation, with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	59.424	22.767	17.734	42.421	16.725	13.287
PV Costs (USD 2016)	27.554	14.994	13.371	17.537	12.199	11.490
NPV (USD 2016)	31.870	7.773	4.364	24.884	4.526	1.797
BCR (%)	2,16	1,52	1,33	2,42	1,37	1,16
IRR			20%			16%

Table 6: Results for adaptation with cyclone impacts in year 31

	No adaptation, with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	60.773	21.991	16.850	37.793	13.222	10.702
PV Costs (USD 2016)	27.472	14.937	13.330	17.455	12.141	11.449
NPV (USD 2016)	33.301	7.054	3.519	20.338	1.081	-747
B/C ratio (%)	2,21	1,47	1,26	2,17	1,09	0,93
IRR			19%			12%

5. Comparing results with and without climate change and extreme events

From comparing results with and without climate change of GMPs, vanilla and cinnamon intercrop specifically designed for drought resistance and diversification, we conclude that all economic indicators decrease under scarce rainfall impacts but that options remain profitable in absolute terms: NPVs are positive and BCRs are higher than the unit except for cinnamon intercrop which exhibits an IRR of 13% in case of dry spell impacts.

As compared to the baseline, vanilla intercrop is the most profitable option with and without drought impacts, which results are always higher than the baselines, even compared to the baseline under current climate conditions. This indicates it is always more profitable to practice vanilla intercropping. Results also suggest an interesting particularity of vanilla intercrop that seems relatively insensitive to assumptions it is subject to. Limitations of this result is however tied to the absence of drought impact on vanilla plants in our model and the assumption that vanilla prices will remain high in the international market.

GMPs exhibit higher NPVs, BCRs and IRRs than respective baselines under current and projected climate. Contrary to the vanilla intercrop, GMPs do not feature higher BCRs under drought impacts as compared to the baseline under no climate change which means there is always a risk a decreasing profitability. However, the comparative advantage of GMPs as compared to baselines increases under scarce rainfall impact.

Results from cinnamon intercrop are more ambiguous: although profitable in absolute terms, it features lowest IRR of 15% under no climate and 13% under scarce rainfall impact so that NPVs become negative and BCR below unit with higher discount rates. An exception to this is the low discount rate, under which cinnamon intercrop performs better than the baselines both under climate change and no climate change.

Similar to cinnamon, windbreaks result profitable under current climate only with low expected returns from the project. With an IRR of 10% it is the less attractive option under current climate. This perspective changes however with consideration of cyclones: indeed, despite the drastic production reduction on the clove plantation, the windbreak reduces damages and enables grasping additional revenues from selling damaged wood. Although NPVs are generally lower than the baseline under cyclone impact, BCRs are higher ranging between 2.61 with consideration of low discounts to 1.58 of high discount rates and in case the cyclone hits in year 7. This is also the case for low discount rates when cyclone hit in year 15. Profitability decreases however as cyclone impact is delayed in the future.
As a final remark, it is likely that other cyclone or socio economic patterns could realise. Specifically, it results could account for a slower recovery after the cyclone and or the inability to sell the damaged wood at high market prices, due to its reduced quality.

6. Dealing with uncertainty

A cost benefit analysis of adaptation options provides useful information to decision makers as they need to allocate scarce public funding. Reporting on costs and benefits of adaptation is recommended in any study where this is possible (UNFCCC, 2009).

However, traditional cost benefit analysis needs to account for sources of uncertainty as a positively evaluated investment today might not remain so in the future dependently of market evolutions, prices, demands or policies. Yet, circumstances that permit an investment to be profitable today might not fit to states of the future. As regarding climate change, it is for example not clear if precipitation will increase or decrease in some cases. Therefore, early adaptation responses to address long term risks might misallocate resources by over investing in risks that do not emerge. Analogically, they can “mal-adapt” by renouncing to implement measures that would cope with extreme events or implementing adaptation measures that increase vulnerabilities of the system instead of reducing them (Barnett and O’Neill, 2010; Macintosh, 2013).

Uncertainties in economic analysis had been recognised and identified as a limitation of traditional project evaluation methodologies in the past (Arrow and Fisher, 1974; Dixit and Pindyck, 1994; Pindyck, 2007). More recent calls to explore alternative approaches to project evaluation came to surface in the domain of climate change adaptation which investment decision are challenged by uncertainties (Dittrich et al., 2016; Hallegatte, 2009; Hallegatte et al., 2012; HM Treasury, 2009; Li et al., 2014; Watkiss et al., 2014).

Adaptation research identifies risk management and uncertainty assessments as key policy inputs (UNFCCC, 2009). Kunreuther et al. (2013) asserts that “Uncertainty in future climates is most often represented as the range of outcomes generated by different climate models run for a range of scenarios. There are, however, numerous physical grounds and some observational ones for suspecting that such ensembles of opportunity may not account for all sources of uncertainty. Some of the open issues relate to the ways the models are calibrated. Others reflect incomplete understanding of important feedbacks, like those involving the carbon cycle.”, (page 447).

The typical accumulation of uncertainties in the process of adaption to climate change is illustrated in the simplified scheme below Figure 7. The climate model provides uncertainty due to our lack of understanding of the full complexity of the Earth system. Uncertain climate projections, modelling results and possibly conflicting data provide inputs to biophysical models. In turn, biophysical models use uncertain inputs and generate outcomes for an economic model. Ultimately this assesses the economic impacts of climate under specific socio-economic assumptions and a fixed set of pre-defined adaptation options. There is also a feedback from economics in terms of GHG emissions whose impact on the climate is uncertain as well, for example due to policies.

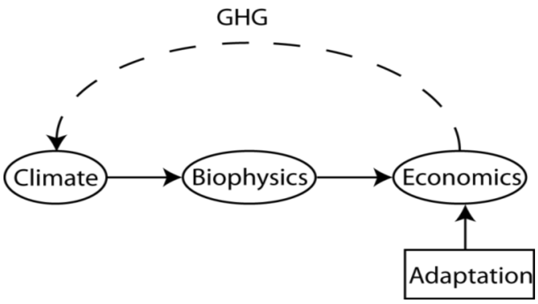
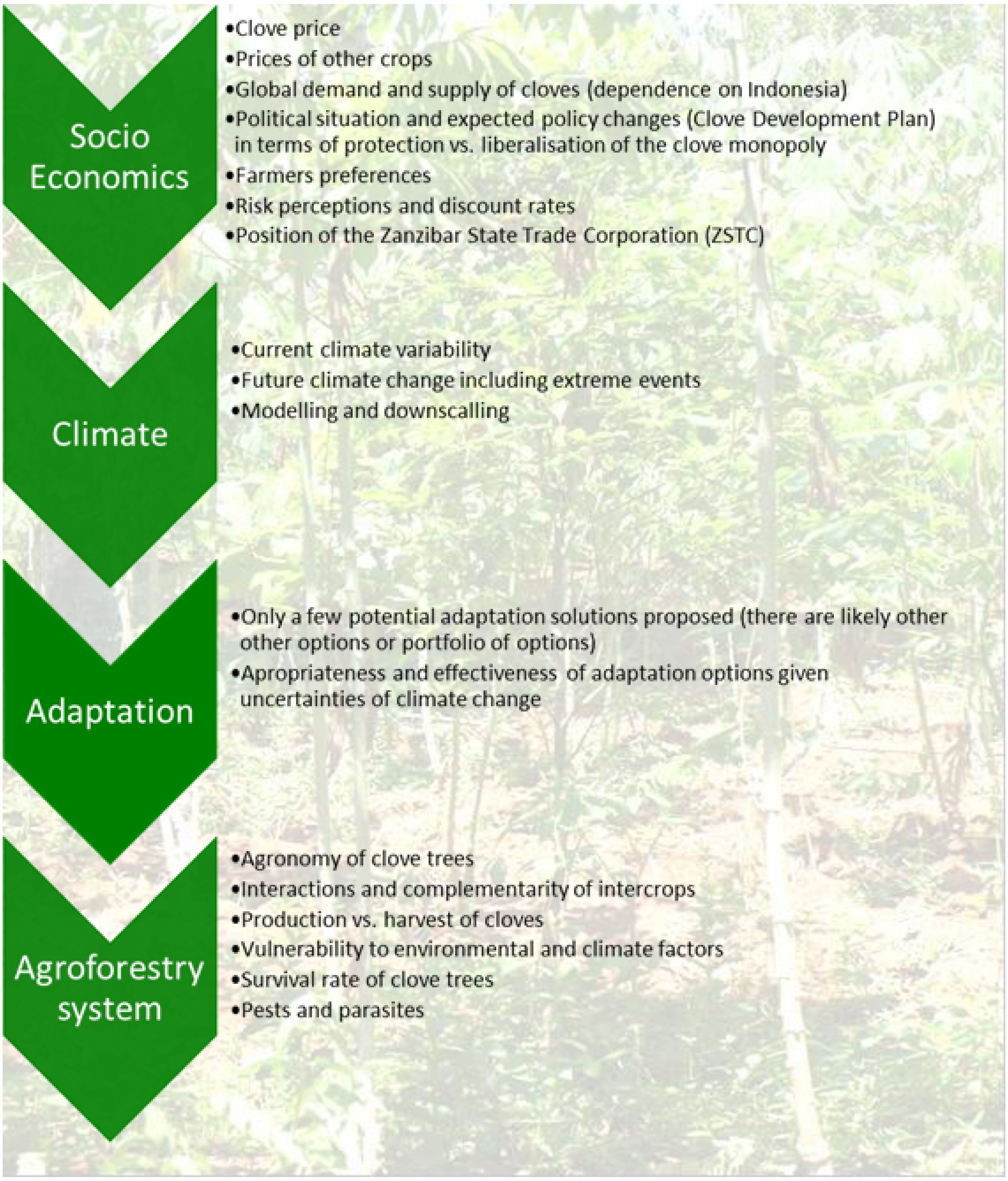


Figure 7: Conceptual scheme of uncertainties accumulation

***Source:* Econadapt, Deliverable 4.1**

The cascading uncertainties applied to our case study from the macro socio-economic to the farm level are illustrated below (Figure 8).

Figure 8: Cascading uncertainties in clove plantations of Zanzibar.



Source: Own source. Photography: typical clove seedlings intercropped and shaded by cassava.

Traditional “predict-then-decide” approaches also lack focus on flexibility to adjust to new contexts and fail to account for possible irreversibility of decisions (Dixit and Pindyck, 1994; Pindyck, 2007). There is therefore a growing focus on innovative decision support tools for adaptation. Recently, robustness and flexibility have been repeatedly identified as adequate criterion for adaptation choice (HM Treasury, 2009; Markandya, 2014; OECD, 2015; Watkiss et al., 2014). Robustness is characterised by low sensitivity of investment value to different states of the world. Flexibility provides investments with room for adjustments as new information becomes available and turns adaptations resilient to a wide range of possible futures (Jones et al., 2014).

Real Option Analysis and Robust Decision Making (RDM) are methodologies that are proposed for application to adaptation decision making (Dittrich et al., 2016; Hallegatte, 2009; Hallegatte et al., 2012; Mediation, 2013; MEDIATION, 2013; Watkiss et al., 2014). Generally however, most ROA and RDM applications to date are found in sectors with high infrastructural components or sectors where exhaustive data is available for methodological processing such as water management, coastal protection or the energy and fossil fuel sector (Lempert et al., 2003; Linquiti and Vonortas, 2012; Martínez Ceseña et al., 2013; Woodward et al., 2011). A few ROA applications have also been identified in the agricultural sector (Hertzler, 2007; Hertzler et al., 2006; Sanderson et al., 2016). In addition, these methodologies require computational knowledge and managers do not always have this expertise. There is a need therefore to explore which and how valuation frameworks of the academics can become more pragmatic and readily available to more widely employ them in practice (Lander and Pinches, 1998; OECD, 2015).

In this study we aim at testing these new methodologies and their pertinence to adaptation in international development cooperation by adopting “light touch” approaches that capture intrinsic concepts of formal applications without losing their economic rationale. In the next sections we develop such approaches for the real option illustrated by decision trees and the robust decision making methodology in complement of our cost benefit analysis.

6.1 Real options and decision trees: key concepts

Inherited from orthodox economic theory, positive net present value is the most widely used investment rule in benefit cost and optimisation based decision analysis. Its calculation is illustrated in Equation 1 below. Applied to our case study, *B* and *C* respectively represent per hectare benefits and costs of the clove plantation and *d* the discount rate, under a time horizon *t* of 80 years. The NPV states to invest in a project if the present value of expected flow of benefits exceeds the present value of its expected flow of costs (NPV>0).

$$NPV = \sum_{t=0}^{80} \frac{B_t - C_t}{(1+d)^t} \rightarrow NPV > 0 \qquad \textit{Eq. 1}$$

According to Dixit and Pindyck (1994) however, the NPV criterion is based on some important assumptions that do only apply in the real world in few exceptional cases: it assumes the investment is either recoverable and there are no sunk costs, or it is irreversible in which case the investment is a “take it or leave it” decision for ever. According to the authors, in reality, most investment decisions are characterised by irreversibility, uncertainty and timing, and these can play an important role on the investment decision one would make. In fact, before an investment is realised a decision maker has always the opportunity or the “option” to invest or not, or to invest now or at a later point in time, depending on market circumstances and expected new information. The real option is commonly defined as a right to invest which needs not necessarily be exercised. Once the investor realises the investment, she destroys the investment opportunity she was holding and gives up the possibility to wait for new information that was potentially valuable to her decision choice and timing. The investment therefore includes an opportunity cost, the forgone cost of holding the option providing the investor with flexibility about its investment timing. As a consequence, the NPV rule requiring present value of the stream of benefits to exceed the corresponding cost as in Equation 1 is incomplete. The real option approach suggests that the benefits from investment need to exceed the costs by the value of keeping the investment option. Put it differently, one should invest if the net benefits of investment exceed the benefits from keeping the option of investing later.

$$\sum_{t=0}^{80} \frac{B_t - C_t}{(1+d)^t} - Option\ Value\ \rightarrow NPV > Option\ Value \qquad \text{Eq. 2}$$

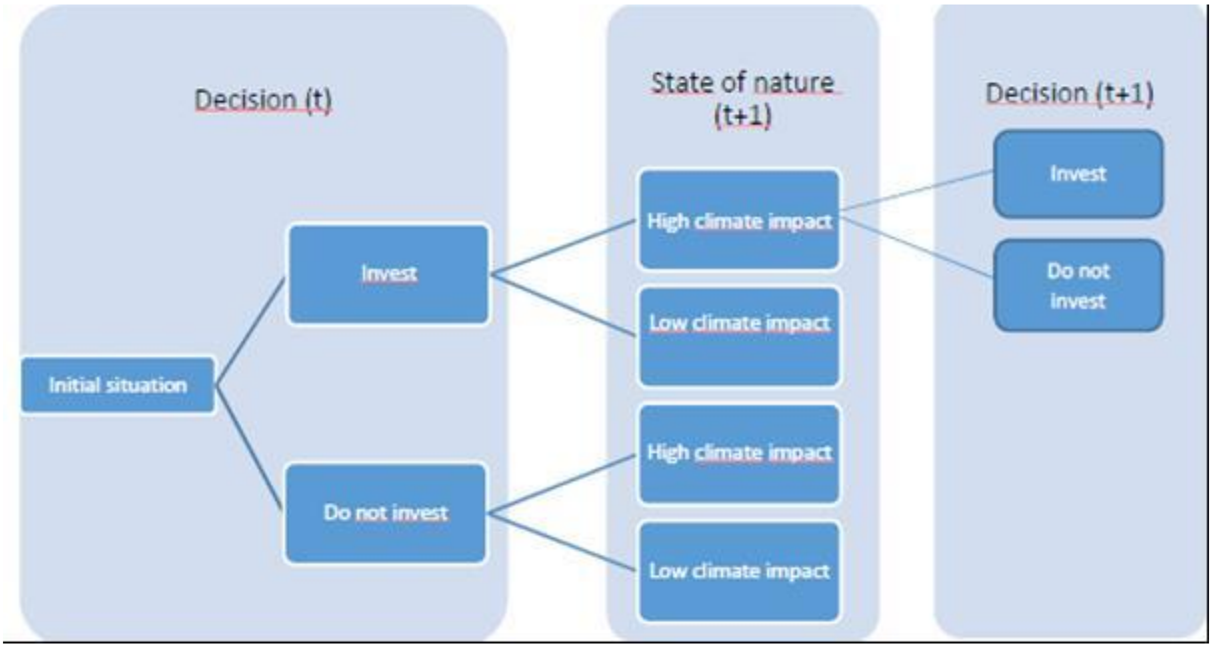
Alternatively, we can also express the extended NPV including the net benefit form options created and destroyed (Scandizzo, 2012).

$$Extended\ NPV = \sum_{t=0}^{80} \frac{B_t - C_t}{(1+d)^t} + Options\ created - Options\ distroyed \qquad \text{Eq. 3}$$

In practice this implies that results from cost benefit analysis can differ from those of the real option approach. Two different types of results can emerge: a simple NPV can either indicate to immediately invest where real options conclude it is worth waiting for better information or, on the opposite, it can indicate an investment is not cost-efficient where real options indicate it might make more sense to invest now (Mediation, 2013; Pindyck, 2007).

Real option analysis is also based on the assumption that uncertainty is not constant but changes over time. Information is supposed to be gained as time goes by and decisions to be taken accordingly if enough flexibility in investment options permit to do so. Decision making is a sequence of decisions over time and this is classically illustrated by decision trees which relates decision to states of nature or tree branches. Figure 9 illustrates a simplified decision tree with only one decision point and one state of nature.

Figure 9: Simplified scheme of a decision tree



Source: Own source

In the literature, two sources of flexibility are usually referred to, either separately or in conjunction: the flexibility of the timing and the flexibility “in” project design (Hallegatte et al., 2012; Wang, 2005). While the first is an option which could have different values depending on the timing of their exercise, the second is a technical and involves different types of options which intrinsically entail flexibility in their design. The most often cited example is the comparison on investing in a traditional dam designed to expected climate in a subsequent future to investing in an upgradable dam today with effective upgrade in the future if climate conditions require to do so (HM Treasury, 2009; Markandya, 2014).

Real option analysis has been identified as a method well suited for the evaluation of environmental policy for the same reasons it has been adopted in the adaptation domain: it permits to account for flexibility, where irreversibility and uncertainties related to long timeframes are dominant characteristics of investment (Arrow and Fisher, 1974).

6.1.1 Application to the case study

To illustrate possible applications of this methodology, we develop a decision tree together with potentially "in-project" flexible adaptation options to compare results with the traditional cost benefit analysis. We look especially into good management practices which the cost benefit analysis suggest are profitable even under no climate change. We also look more closely at the windbreak which is according to the cost benefit analysis, the less profitable option under no climate change impact but profitable under cyclone impact.

6.1.1.1 Good Management Practices (GMPs)

In our decision tree (Figure 10) we suggest two sources of uncertainty: (i) the clove price (low/high) and (ii) the prevailing climate change regime (no Climate change/RCP4.5 or 8.5). To simplify the analysis we here consider a unique discount rate of 10%.

In this case we would like to test adaptation investments that might create flexibility during the timeline of our investment. The idea is that investing an amount somewhere half way between nothing and 100% of good management practices would avoid either to overinvest or to underinvest. For this purpose we divide our timeline of 80 years into two distinct periods: period 1 stretching from 2016 to 2049 and period 2 from 2050 to the end of the century. This way, we are able to propose gradual stage decision making instead of a now or never investment. We propose an investment of 50% of initial GMPs in the first period with two possibilities in the second one: either continue investing the remaining 50% or renounce to that investment.

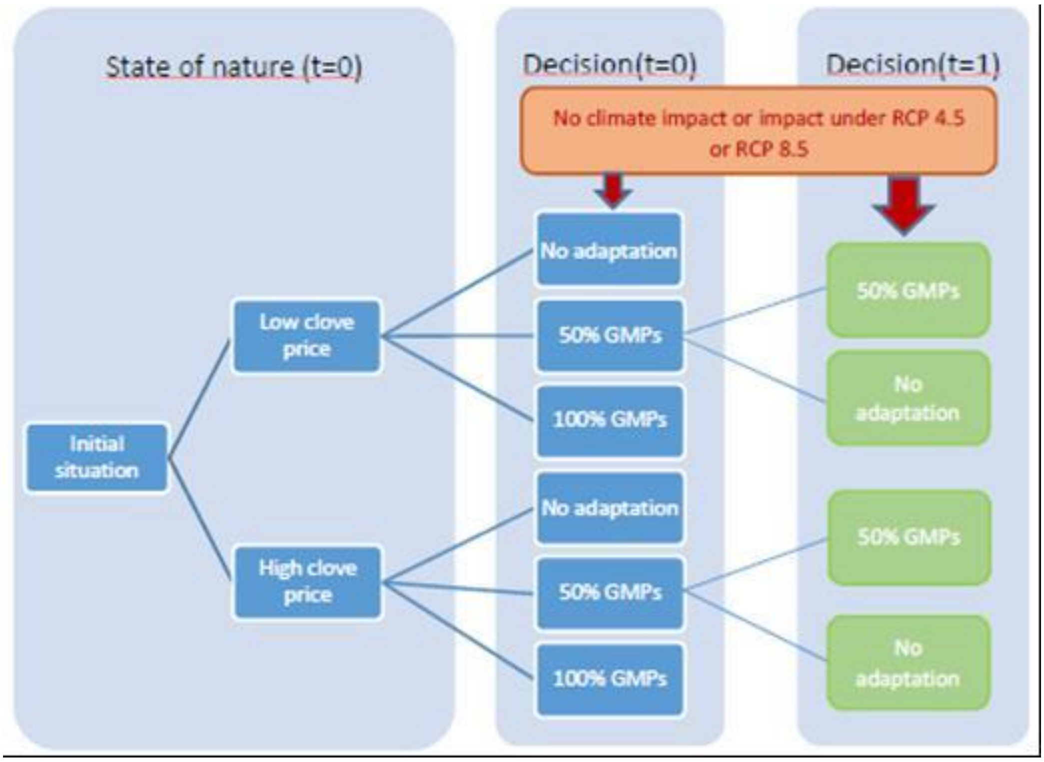


Figure 10: Decision tree for good management practices (GMPs). To keep the decision tree understandable, prices are assumed to remain on their initial path of t=0 in the next period 1.

Source: Own source

NPVs per period both for high and low prices are calculated[43]. A matrix is then constructed with NPVs of both periods for low and high prices to which we add four types of probabilities: probabilities of low or high prices, probabilities of no climate impact and probabilities of RCP 4.5 and RCP 8.5. We then calculate expected NPVs for high and low prices separately before considering the total expected value given uncertainties about high and low prices altogether. In the first step of our analysis we assume a 40% probability for clove prices being low and 60% for the high price case. In addition, the probabilities of no climate change occurring is assumed to be 45% for illustrative purposes. RCP 4.5 and RCP 8.5 probabilities of occurrence are set at 25% and 30% respectively. Note that all climate probabilities sum to the unit and so do the price probabilities, these being the only possibilities considered (Table 7).

In a second step we conduct a sensitivity analysis: In a first case, we vary RCP probabilities while keeping price and no climate change probabilities fixed[44]. In a second case, we look into 50% probability of either high or low prices and no changes in climate probabilities. In a third case, we analyse the situation when only the probability of no climate impact varies. To keep the analysis comprehensive, all sensitivity analysis are done separately.

6.1.1.1.1 Results

The first summary of results with fixed probabilities of price and no climate change is given in table 7 below.

Table 7: Summary results with fixed price and no CC probabilities

0 Investment	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
Low P	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,25	0,30	-4769	911
High P	6137	2685	2192	717	476	554	0,60	0,45	0,25	0,30	4698	

50% Investment	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
Low P	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,25	0,30	-4798	1683
High P	7052	4093	3670	799	592	660	0,60	0,45	0,25	0,30	6003	

Period 1: 50% Investment	NPV P1			NPV P2			Probabilities				Expected values	Expected values
Period 2: 0 Investment	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
Low P	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,25	0,30	-4808	1620
High P	7052	4093	3670	717	476	554	0,60	0,45	0,25	0,30	5906	

100% Investment	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
Low P	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,25	0,30	-4828	2454
High P	7967	5501	5149	882	709	765	0,60	0,45	0,25	0,30	7309	

Note: The first column of expected values look into low and high prices separately, so no price probability are applied. Price probabilities are applied in the last column only.

Equivalent to the CBA results, ROA indicates that investment in clove plantations is not profitable under low prices. And so do investments in good management practices. If the

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[43] Calculation of the net present values of our new adaptation options is simplified by considering half of the net benefits gauged for the good management practices. This is done by adding half of the difference between NPVs under GMPs and no adaptation to the no adaptation net present value[43]. This is a strong assumption, as half of the costs might not necessarily generate half of the benefits, especially for this strategy which practices is composed of are important to coordinate and provide benefits by their interaction all together. However, we believe this is useful to proceed with the analysis for illustrative purposes.

[44] In this case while both RCP probabilities summing up to 55%, one is decreased while the other is increased.

farmer knew the price would remain low forever she would neither invest in clove plantations as a whole nor in good management practices. However, in reality, a farmer might be tempted to invest today even if the price is low because she would expect an increase in the future that might be worth waiting for. This is reflected in the expected NPV when both price probabilities are taken into account, with a 60% probability of high prices.

Interestingly, a second result shows that, although not an optimal strategy because it does not grasp the maximum profit, when investing 50% in the first period it is better to continue investing in the second period than stopping the investment in period two. This is so both in the case under low and high prices. Although the CBA gives an intuition about the profitability of GMPs, ROA provides more information by suggesting how decisions and outcomes might look like after an investment is realised.

When accounting for both high and low prices together (last column), as before, investing in GMPs at 100% is most profitable, while not investing at all is the least optimal choice. If investing in the first period 50% it is better to continue in the second period.

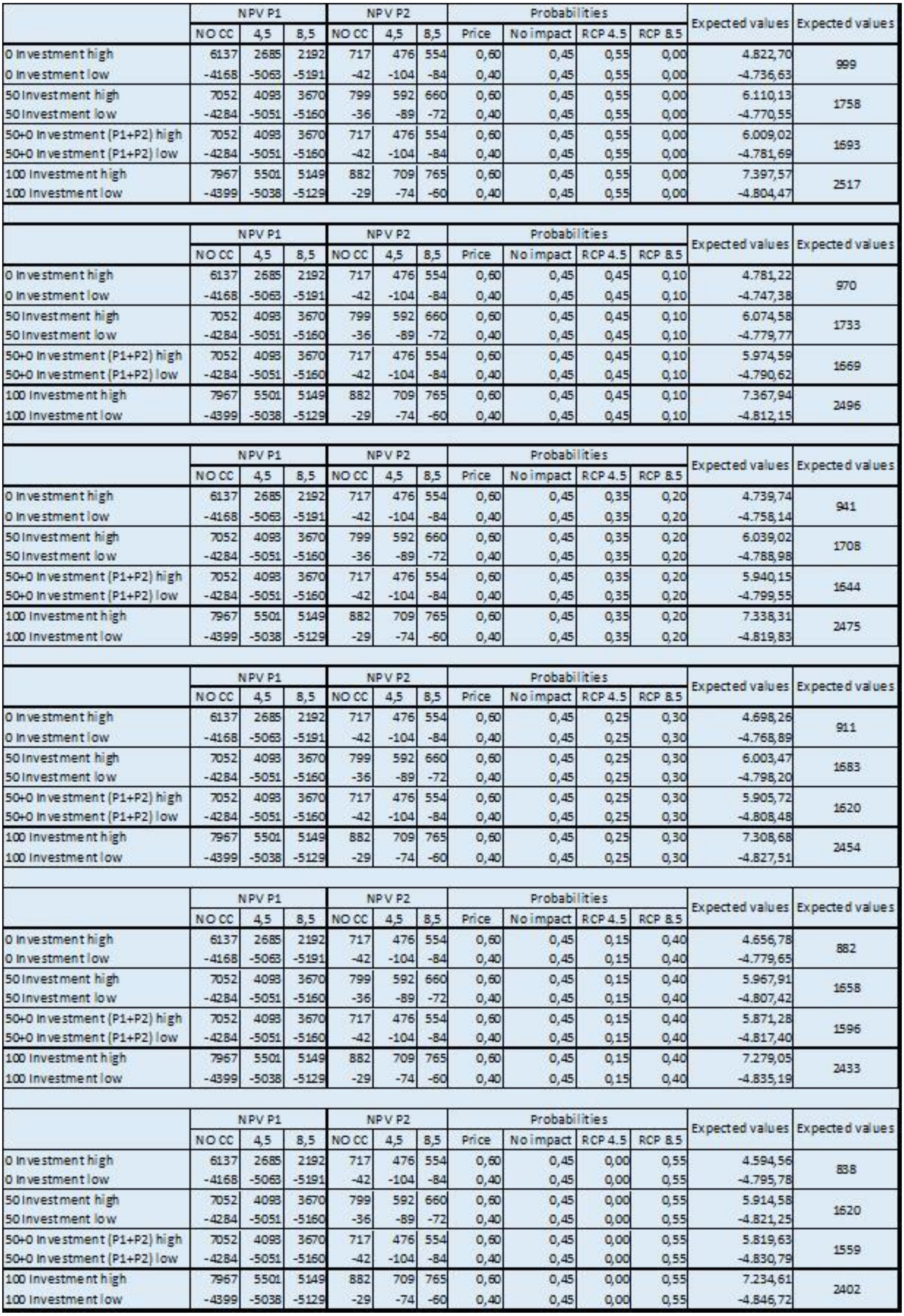
6.1.1.1.2 Sensitivity analysis

Case 1: varying climate change probabilities (RCP 4.5 and RC P8.5) with high price probability of 60%
Results from the sensitivity analysis varying RCP probabilities are shown in table 8 below. From only varying RCP probabilities we observe that with increasing RCP 8.5 probabilities, all values decrease, be they positive or negative: impacts of climate change reduce all net present values. Similar to above, it is better not to invest in GMPs when the price is low. Yet GMPs are profitable under high prices. In addition and as before, if a farmer first invests in GMPs at 50% then he is always better off continuing its investment in the second period. This is the case even if prices are low, in which case the NPV becomes less negative.

Case 2: varying climate change probabilities (RCP 4.5 and RC P8.5) with price probabilities of 50%
When applying probabilities of 50% jointly, we obtain similar results. However, the decision tree provides additional insight about a probability threshold above which NPVs would results negative. Not investing in GMPs provides negative NPVs with RCP 8.5 probabilities between 10% and 20% (Annex 10). Under price uncertainty, farmers are always better off investing. The lower the probability of high prices, the lower the NPV we expect.

Case 3: varying no climate change and climate change probabilities with high price probability of 60%
We also vary the probability of no climate impact, in which case we suppose a low probability no impacts occur goes together with a high RCP 8.5 probability. In this case we obtain intuitive results as before (Annex 11): higher impact probabilities lowering our NPVs and expected NPV are negative for no adaptation investment under very high climate probability confirming GMPs are useful to hedge plantations against climate impacts.

Table 8: Results with fixed price and no impact probabilities and varying RCP probabilities.



	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,55	0,00	4.822,70	999
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,55	0,00	-4.736,63	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,55	0,00	6.110,13	1758
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,55	0,00	-4.770,55	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,55	0,00	6.009,02	1693
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,55	0,00	-4.781,69	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,55	0,00	7.397,57	2517
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,55	0,00	-4.804,47	
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,45	0,10	4.781,22	970
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,45	0,10	-4.747,38	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,45	0,10	6.074,58	1733
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,45	0,10	-4.779,77	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,45	0,10	5.974,59	1669
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,45	0,10	-4.790,62	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,45	0,10	7.367,94	2496
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,45	0,10	-4.812,15	
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,35	0,20	4.739,74	941
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,35	0,20	-4.758,14	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,35	0,20	6.039,02	1708
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,35	0,20	-4.788,98	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,35	0,20	5.940,15	1644
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,35	0,20	-4.799,55	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,35	0,20	7.338,31	2475
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,35	0,20	-4.819,83	
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,25	0,30	4.698,26	911
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,25	0,30	-4.768,89	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,25	0,30	6.003,47	1683
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,25	0,30	-4.798,20	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,25	0,30	5.905,72	1620
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,25	0,30	-4.808,48	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,25	0,30	7.308,68	2454
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,25	0,30	-4.827,51	
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,15	0,40	4.656,78	882
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,15	0,40	-4.779,65	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,15	0,40	5.967,91	1658
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,15	0,40	-4.807,42	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,15	0,40	5.871,28	1596
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,15	0,40	-4.817,40	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,15	0,40	7.279,05	2433
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,15	0,40	-4.835,19	
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 investment high	6137	2685	2192	717	476	554	0,60	0,45	0,00	0,55	4.594,56	838
0 investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,45	0,00	0,55	-4.795,78	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,45	0,00	0,55	5.914,58	1620
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,45	0,00	0,55	-4.821,25	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,45	0,00	0,55	5.819,63	1559
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,45	0,00	0,55	-4.830,79	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,45	0,00	0,55	7.234,61	2402
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,45	0,00	0,55	-4.846,72	

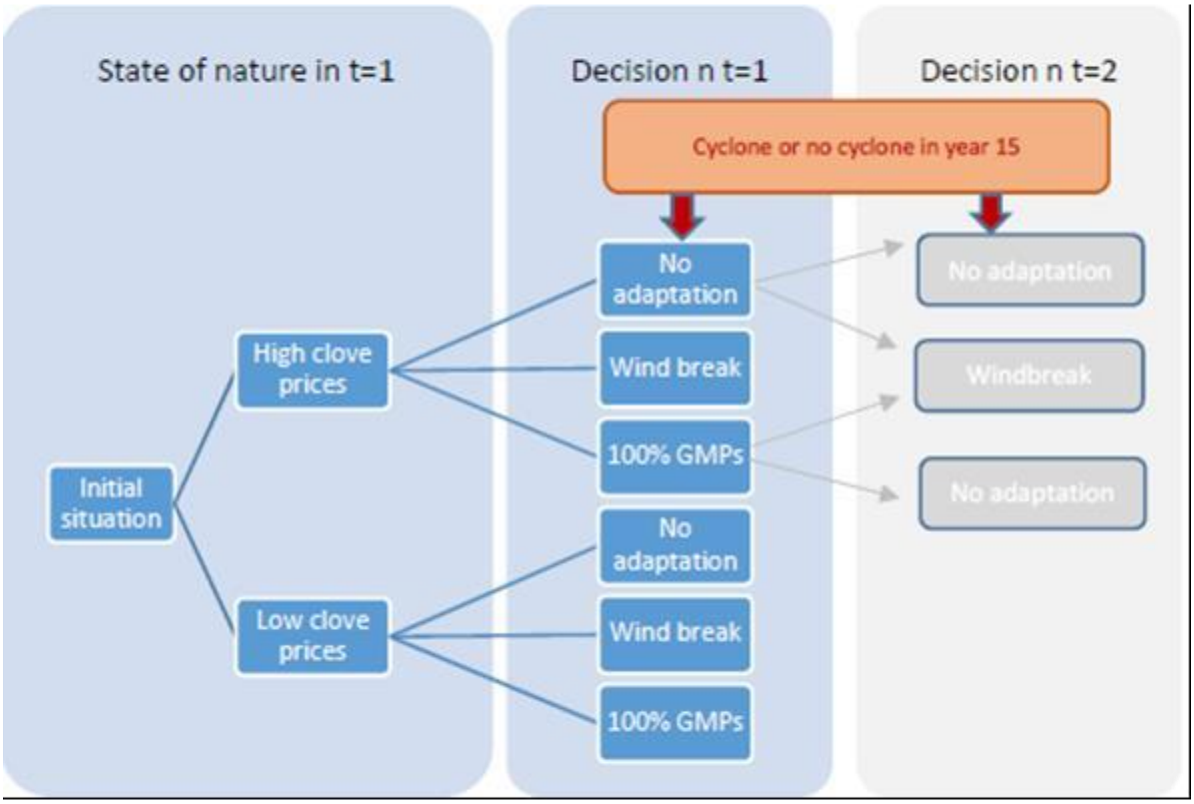
6.1.1.2 Windbreak

As previously, in our decision tree (Figure 11) uncertain variables and states of nature relate to high and low clove prices on the one hand and prevailing climate on the other hand. Under the climate evolutions we consider realisation of cyclones in year 15 of our time horizon. The discount rate is kept at 10%.

In this example we look at different adaptation strategies including the windbreak and their profitability depending on clove price and realisation of cyclone in year 15 or not. We use the same discount rate of 10% as above.

Figure 11: Decision tree for windbreak.

Source: Own source

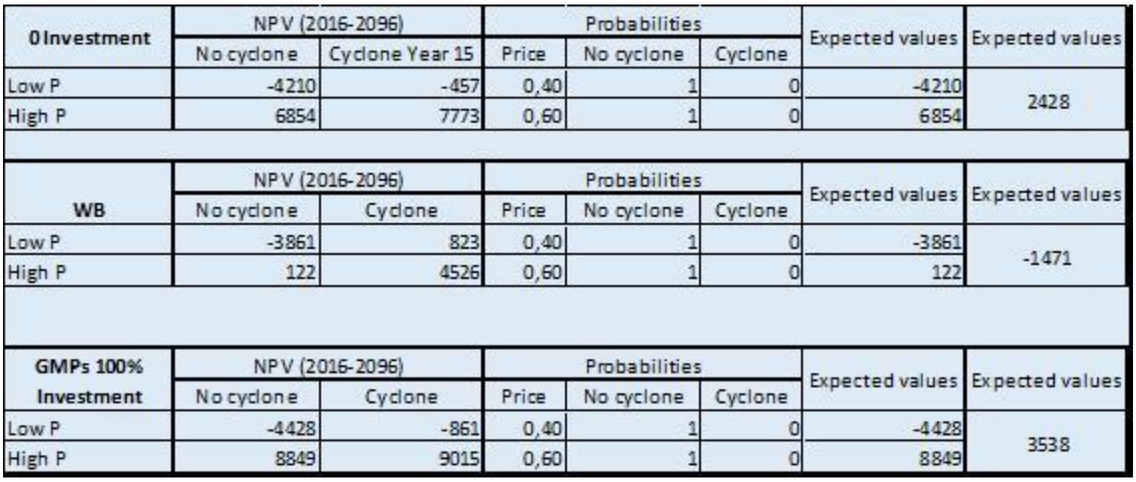


Note 1: The second period is included for illustrative purposes, it is not taken into consideration in the analysis.
Note 2: To keep the decision tree understandable, prices are assumed to remain on their initial path of year zero in subsequent periods.

6.1.1.2.1 Results

The first summary of results is given in table 9 below. As before, clove plantations under simple shading result to be unprofitable under low prices such as GMPs. Contrary, high prices turn clove plantations profitable and so do good management practices. This is when farmers observe low or high prices and believe this will be so for the perpetuity. In reality, this will not be the case as expect values indicate: clove plantations and good management practices are profitable without cyclone impacts and when looking at expected NPVs with a probability of low prices of 40%. Under GMPs, low clove prices effect exacerbates NPVs rendering them more negative while the high price improves NPVs. All in all considering a high price probability of 60% GMPs improve expected net present benefits.

Table 9: Results for the windbreak compared to no investment and GMPs with cyclone impact



0 Investment	NPV (2016-2096)		Probabilities			Expected values	Expected values
	No cyclone	Cyclone Year 15	Price	No cyclone	Cyclone		
Low P	-4210	-457	0,40	1	0	-4210	2428
High P	6854	7773	0,60	1	0	6854	
	NPV (2016-2096)		Probabilities			Expected values	Expected values
WB	No cyclone	Cyclone	Price	No cyclone	Cyclone		
Low P	-3861	823	0,40	1	0	-3861	-1471
High P	122	4526	0,60	1	0	122	
GMPs 100%	NPV (2016-2096)		Probabilities			Expected values	Expected values
Investment	No cyclone	Cyclone	Price	No cyclone	Cyclone		
Low P	-4428	-861	0,40	1	0	-4428	3538
High P	8849	9015	0,60	1	0	8849	

However, the expected value of the windbreak is negative when the cyclone probability is null. This is due to the assumptions made: the planted teak trees do not generate income unless a cyclone hits the plantation and by substituting clove trees, the number of these is drastically reduced. In reality, teak trees can be replanted and taken advantage from in a regular manner without waiting for a cyclone to occur. Our results however change as the probability of cyclone increases (Table 10) and a probability of cyclone occurrence of between 20 and 40% is needed to turn the windbreak profitable. Nevertheless, according to this analysis, as compared to the other options the windbreak will always be the least interesting in economic terms. Note that the windbreak hedges also against low clove prices under 100% cyclone impact probability. This is because of the diversification of the plantation and the realization of the cyclone which enables taking fully advantage of it.

Table 10: Results for the windbreak as compared to no investment and GMPs with increasing cyclone probability in year 15.

Option	NPV (2016-2096)		Probabilities			Expected values	Expected values
	No cyclone	Cyclone Year 15	Price	No cyclone	Cyclone		
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	1,00	0,00	6.854,00 USD	1.322,00 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	1,00	0,00	-4.210,00 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	1,00	0,00	122,00 USD	-1.869,50 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	1,00	0,00	-3.861,00 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	1,00	0,00	8.849,00 USD	2.210,50 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	1,00	0,00	-4.428,00 USD	
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	0,80	0,20	7.037,80 USD	1.789,20 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	0,80	0,20	-3.459,40 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	0,80	0,20	1.002,80 USD	-960,70 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	0,80	0,20	-2.924,20 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	0,80	0,20	8.882,20 USD	2.583,80 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	0,80	0,20	-3.714,60 USD	
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	0,60	0,40	7.221,60 USD	2.256,40 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	0,60	0,40	-2.708,80 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	0,60	0,40	1.883,60 USD	-51,90 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	0,60	0,40	-1.987,40 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	0,60	0,40	8.915,40 USD	2.957,10 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	0,60	0,40	-3.001,20 USD	
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	0,40	0,60	7.405,40 USD	2.723,60 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	0,40	0,60	-1.958,20 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	0,40	0,60	2.764,40 USD	856,90 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	0,40	0,60	-1.050,60 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	0,40	0,60	8.948,60 USD	3.330,40 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	0,40	0,60	-2.287,80 USD	
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	0,20	0,80	7.589,20 USD	3.190,80 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	0,20	0,80	-1.207,60 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	0,20	0,80	3.645,20 USD	1.765,70 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	0,20	0,80	-113,80 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	0,20	0,80	8.981,80 USD	3.703,70 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	0,20	0,80	-1.574,40 USD	
0 Investment high price	6.854,00 USD	7.773,00 USD	0,50	0,00	1,00	7.773,00 USD	3.658,00 USD
0 Investment low price	-4.210,00 USD	-457,00 USD	0,50	0,00	1,00	-457,00 USD	
WB high price	122,00 USD	4.526,00 USD	0,50	0,00	1,00	4.526,00 USD	2.674,50 USD
WB low price	-3.861,00 USD	823,00 USD	0,50	0,00	1,00	823,00 USD	
GMPs 100% Investment high price	8.849,00 USD	9.015,00 USD	0,50	0,00	1,00	9.015,00 USD	4.077,00 USD
GMPs 100% Investment low price	-4.428,00 USD	-861,00 USD	0,50	0,00	1,00	-861,00 USD	

6.2 Robust decision making and key concepts

Robust analysis has gained prominence as probabilistic analysis became ambiguous to policy makers in need for practical and context specific applications (Dessai and Hulme, 2004) and while adaptation policy moved from the "predict-first" to "policy-first" approaches (Ranger and Garbett-Shiels, 2011; Watkiss et al., 2014). Despite controversies from those who believe all uncertainties can be captured by probabilistic modelling, it has indeed been recognised that highly complex and uncertain systems where "deep uncertainty" prevails cannot be measured by probability and statistical decision theory as differences in behaviour from best modelled predictions (Bankes, 2002). As opposed to real option analysis, robust decision making is a decision support methodology that does assume uncertainties cannot be quantified using probability distributions and that minimises regret.

In the context of climate adaptation policy, robustness has been one of the most important criterion for adaptation decision making under uncertainties. The concept has been widely used in the literature and refers to different types of decisions (Hallegatte et al., 2012). These range from good development (Ranger and Garbett-Shiels, 2011) to "no-" or "low-regret" options as deviations from optimality (IPCC, 2012; Lempert and Groves, 2010) and flexibility by keeping options open (Lempert and Collins, 2007; Markandya, 2014).

Nonetheless, all approaches to robustness are commonly characterised by good performance under a wide range of possible futures even if they do not perform optimally in specific scenarios. As robust strategies are considered under both expected and surprise changes, they are likely to be decided upon even if decision makers do not agree on their visions of the world and be successful even if probabilistic assessments about the future states of the world fail (Groves and Lempert, 2007; IPCC, 2012). Therefore they will imply a certain trade-off between optimality performance and lower degrees of sensitivity to changing assumptions (Lempert and Collins, 2007).

Formal applications are computational and follow a series of steps that aim at defining both policy scenarios that can capture the largest uncertainty spectrum and robust adaptation strategies that perform well across these uncertain world visions. The methodology begins with structuring the problem, proposing candidate adaptation strategies and evaluating these by means of previously identified performance indicators (Groves and Lempert, 2007), (Figure 12). Within this process and depending on applications, RDM uses computer simulation models or stakeholder consultations to generate large ensembles of up to millions of possible future states of the world. Adaptation strategies' performances are systematically assessed against these scenarios, and "stress-tested" to identify model specifications and inputs under which the options do not perform well. New adaptation strategies are then proposed to verify if they perform better and which trade-offs exists among these alternative options.

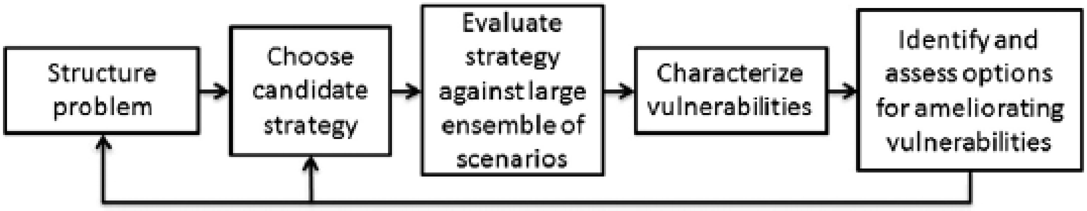


Figure 12: Steps in a Robust Decision Making analysis (Lempert and Groves, 2010)

RDM can use expected utility as performance indicators. However, it works in inverted order to an optimal utility method such as the CBA: firstly, adaptation options are defined before identifying their vulnerabilities. Secondly, RDM looks into insensitiveness of options to changes in future states of the world in contrast of traditional sensitivity analysis that compare changing ranks of option under different assumptions (Groves and Lempert, 2007).

The concept of robustness is not new (Matalas and Fiering, 1977) and robust decision making is similar decision making tool to decision scaling (Brown and Wilby, 2012), Info-Gap analysis (Ben-Haim, 2009) or Many Objective Robust Decision Making (Kasprzyk et al., 2013).

RDM has been historically tied to water management systems and has been recently explored at the RAND Corporation[45] (Lempert et al., 2003). In the literature, some examples of application exist and formal applications often support tools to real processes of national or regional development plans. Groves and Sharon (2013) developed coastal risk reduction and land loss restoration projects in Louisiana (USA) given a budget constraint and other objectives of Louisiana's master plan for a sustainable coast. Applications exist in support regional water resource management plans. In the Western US, Groves and Lempert (2007; Lempert and Groves, 2010) addressed climate change and uncertainties about future water management conditions in the long term and Mortazavi-Naeini et al (2015) developed a RDM for urban bulk water systems in New South Wales, Australia. An example was also developed for integrated flood risk management in Ho Chi Minh City's Nhieu Loc-Thi Nghe canal catchment area (Lempert et al., 2013).

A set of other studies made the attempt of simplified versions of RDM by capturing its key concepts. For example, a study evaluated flood management measures in North York Shire (UK) by looking into a reduced number (20) of climate change scenarios (Frontier Economics, 2013). A further study incorporated the rational of RDM applying it to a cost benefit analysis performed on an electricity generation project in Turkey (Bonzanigo and Kalra, 2014).

6.2.1 Application to the case study

In the adaptation analysis of clove plantations in Zanzibar, we apply a similar approach as Bonzanigo and Kalra (2014) by incorporating or analysing cost benefit result through the lens of the robust decision making main concept: the property of an option or decision to exhibit a low degree of sensitivity to changing assumptions it might be subject to (Dessai and Sluijs, 2007).

Various stakeholders in Zanzibar had already identified vanilla intercrop as being an option worthwhile analysing. Indeed, while computing economic results of the cost benefit analysis, the vanilla intercrop option caught our eye by the high performance in its results, even under cyclone impacts. As we model high vanilla prices and as we first omit to include drought impacts on vanilla stands, results remain considerably high, which is partly due to the hedging of price uncertainties of the diversification strategy. In this part, we look into further potential sensitivities of the vanilla intercrop. We "stress-test" the adaptation options to additional scenarios that vanilla is potentially vulnerable to and observe economic performance of the vanilla intercrop. The additional scenarios are the introduction of drought impact on vanilla stands on the one hand and low vanilla price on the other hand. Results are then compared to the alternative adaptation strategies considered.

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[45] "The RAND Corporation is a research organization that develops solutions to public policy challenges to help make communities throughout the world safer and more secure, healthier and more prosperous. RAND is a non-profit, nonpartisan, and committed to public interest." Source: http://www.rand.org/about.html (Visited on Sept 30)

6.2.3 Results

As an extension of our CBA, we observe that vanilla intercropping is both an optimal and robust strategy across the scenarios considered as observed in table 11 below. This is the case even when considering drought impacts for vanilla and low vanilla prices. This suggests that vanilla might be thought of as a resilient strategy to diversify clove plantations with. However, as stated before, there are potential barriers of implementation such as economic cost of investment or the high care of vanilla especially for manual pollination. These could be discussed and analysed together with local stakeholders.

Table 11: RDM lens applied to CBA results indicate robustness of vanilla intercrop under various scenarios

	No adaptation (with shading)			GMPs			Vanilla intercropping			Cinnamon intercropping			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
High clove prices															
NPV baseline	35,251	6,854	3,380	43.382	8.849	4.615	110.250	35.038	25.061	31,838	4,100	1,208	14,144	122	-1,167
NPV RCP 4.5	23,539	3,161	797	35.016	6.210	2.770	99.944	31.788	22.788	25,982	2,253	-84	9,928	-1,207	-2,096
NPV RCP 8.5	21,976	2,746	652	33.900	5.914	2.666	98.569	31.423	22.661	25,201	2,046	-156	9,366	-1,357	-2,149
NPV Cyclone Year 7	30.799	8.824	5.994	34.973	9.206	6.088	76.295	24.442	18.612	33.142	8.757	5.807	28.286	9.563	6.713
NPV Cyclone Year 15	31.870	7.773	4.364	36.996	9.015	5.169	84.464	30.095	22.635	31.441	5.888	2.704	24.884	4.526	1.797
NPV Cyclone Year 31	33.301	7.054	3.519	29.419	8.555	4.609	95.383	33.964	24.719	29.900	4.301	1.347	20.338	1.081	-747
Low clove prices															
NPV baseline	-4.398	-4.210	-4.064	-4.196	-4.428	-4.319	75.359	25.302	18.510	12.014	-1.432	-2.515	-129	-3.861	-3.847
NPV RCP 4.5	-7.434	-5.168	-4.734	-6.365	-5.112	-4.797	72.687	24.459	17.921	10.496	-1.911	-2.849	-1.222	-4.206	-4.088
NPV RCP 8.5	-7.839	-5.275	-4.771	-6.655	-5.189	-4.824	72.331	24.365	17.888	10.293	-1.965	-2.868	-1.368	-4.244	-4.101
NPV Cyclone Year 7	5.976	3.835	2.856	5.185	3.219	2.323	54.450	20.051	15.851	20.730	6.262	4.238	15.156	6.180	4.488
NPV Cyclone Year 15	3.480	-457	-1.461	2.928	-861	-1.821	59.481	22.853	17.510	17.246	1.773	-208	11.479	823	-711
NPV Cyclone Year 31	146	-3.393	-3.696	-3.853	-3.749	-3.989	66.206	24.770	18.369	13.322	-923	-2.261	6.565	-2.841	-3.403
With sensitivity of vanilla to drought impact + high clove prices															
NPV RCP 4.5	23,539	3,161	797	35.016	6.210	2.770	79.984	23.970	16.692	25,982	2,253	-84	9,928	-1,207	-2,096
NPV RCP 8.5	21,976	2,746	652	33.900	5.914	2.666	76.510	23.555	17.033	25,201	2,046	-156	9,366	-1,357	-2,149
With sensitivity of vanilla to drought impact + low clove prices															
NPV RCP 4.5	-7.434	-5.168	-4.734	-6.365	-5.112	-4.797	52.728	16.641	11.825	10.496	-1.911	-2.849	-1.222	-4.206	-4.088
NPV RCP 8.5	-7.839	-5.275	-4.771	-6.655	-5.189	-4.824	50.272	16.496	12.260	10.293	-1.965	-2.868	-1.368	-4.244	-4.101
Low vanilla prices and high clove prices															
NPV baseline	**35,251**	**6,854**	**3,380**	**43.382**	**8.849**	**4.615**	**110.250**	**35.038**	**25.061**	**31,838**	**4,100**	**1,208**	**14,144**	**122**	**-1,167**
NPV RCP 4.5	23,539	3,161	797	35.016	6.210	2.770	41.790	9.878	5.887	25,982	2,253	-84	9,928	-1,207	-2,096
NPV RCP 8.5	21,976	2,746	652	33.900	5.914	2.666	39.366	9.488	5.994	25,201	2,046	-156	9,366	-1,357	-2,149
NPV Cyclone Year 7	30.799	8.824	5.994	34.973	9.206	6.088	43.094	12.576	9.109	33.142	8.757	5.807	28.286	9.563	6.713
NPV Cyclone Year 15	31.870	7.773	4.364	36.996	9.015	5.169	47.661	14.956	10.419	31.441	5.888	2.704	24.884	4.526	1.797
NPV Cyclone Year 31	33.301	7.054	3.519	29.419	8.555	4.609	53.766	16.586	11.097	29.900	4.301	1.347	20.338	1.081	-747
Low vanilla prices and low clove prices															
NPV baseline	**-4.398**	**-4.210**	**-4.064**	**-4.196**	**-4.428**	**-4.319**	**75.359**	**25.302**	**18.510**	**12.014**	**-1.432**	**-2.515**	**-129**	**-3.861**	**-3.847**
NPV RCP 4.5	-7.434	-5.168	-4.734	-6.365	-5.112	-4.797	14.534	2.550	1.020	10.496	-1.911	-2.849	-1.222	-4.206	-4.088
NPV RCP 8.5	-7.839	-5.275	-4.771	-6.655	-5.189	-4.824	13.128	2.430	1.221	10.293	-1.965	-2.868	-1.368	-4.244	-4.101
NPV Cyclone Year 7	5.976	3.835	2.856	5.185	3.219	2.323	21.249	8.186	6.348	20.730	6.262	4.238	15.156	6.180	4.488
NPV Cyclone Year 15	3.480	-457	-1.461	2.928	-861	-1.821	22.678	7.714	5.293	17.246	1.773	-208	11.479	823	-711
NPV Cyclone Year 31	146	-3.393	-3.696	-3.853	-3.749	-3.989	24.589	7.392	4.748	13.322	-923	-2.261	6.565	-2.841	-3.403

7. Discussion and policy implications

Uncertainties, be they climate or non-climate related, have been significantly challenging economic evaluation and project appraisal of adaptation intervention. Real option analysis and robust decision making have been developed to address these difficulties. This is often reported to occur at the cost of a higher degree of technicity that might only be accessible to a few. In our case study we find that the application of traditional cost benefit analysis through the lens of real option analysis and robust decision making, or alternatively, the integration of these methodological concepts, can provide the analyst with additional information that might be valuable to decision makers. Firstly, this kind of integration enables to disclose and frame the variety of uncertainties impacting any intervention and providing an analysis of results from alternative perspectives. Secondly, it challenges the analyst to think about potential "in-project" options that might be more flexible or robust options that are not necessarily captured in initial choices of adaptation options. It therefore opens the whole decision process to potentially consider alternative more flexible and robust intervention options. Thirdly, the uncertainty treatment provides more detailed information about how results can change with different probabilities in the case of ROA or with different world visions in the case of RDM. More specifically, we find in our case study that both CBA and ROA conclude with similar results as to the preference of good management practices over no intervention and that it will always be more profitable to invest even if the starting investment is only partly realised. Most interesting is the result we find in the decision tree of the windbreak by identifying threshold values of probabilities and specific circumstances under which the windbreak becomes profitable.

As regarding the comparison of the CBA and RDM, we extend the intuition about the robustness of the vanilla intercrop that results from the CBA. We do this by forcing the vanilla intercrop to undergo what we consider further vulnerable conditions for vanilla growth. We conclude they verify our initial results hold up under these extreme scenarios.
All in all, while the cost benefit analysis provides a sound basis for juggling with a variety of possibilities of outcomes and possibilities, the uncertainty treatment pushes the traditional sensitivity analysis to a more complete understanding of uncertainties and how these influences economic outcomes. It provides a variety of possibilities to approach the uncertainty analysis, each alternative providing information of different facets and from different perspectives.

Importantly, uncertainty treatment also provides a valuable opportunity for iterative decision making: light touch uncertainty analysis would also largely benefit from the integration of stakeholder engagement by confronting different visions and risk perceptions within an iterative decision process. This means that after evaluation, initial adaptation options can be jointly monitored, discussed upon, stress tested and iteratively adjusted in order to disclose interventions that prevent locking-in our existing natural resources and financial capital in erroneous adaptation visions. This is important as adaptation is one of many other priorities especially in developing countries. To that extent, stakeholder consultation enables to better disclose, frame, and find common grounds to their potential conflicting interests. This also includes adaptation considerations and economic impacts at larger scales than limited to the farm level.

While we conclude the light touch uncertainty treatment is a promising area for adaptation intervention, there are also limitations to the cost benefit analysis that provides its basis. These are closely tied to assumptions of the cost benefit model, especially the linear price and discount rate assumptions as well as the use of annual rainfall as main dry spell impact on clove plantations where rainfall variability is likely to play a more decisive role. These need to be challenged by building up on existing results which we conclude can be equally extended in further research by relaxing most important assumptions.

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Annex 1: List of stakeholders met, Zanzibar missions, January and June 2016

Institution	Location
First Vice President's Office, Department for Environment	Stone Town, Unguja
Ministry of Agriculture, Forestry and Natural Resources (MANR), Department of Agriculture, Department of Forestry (cash crop and tree crop divisions)	Stone Town, Unguja
Ministry of Agriculture, Forestry and Natural Resources (MANR), Department of Agriculture, Department of Forestry	Wete, Pemba
Ministry of Trade and Industry	Stone Town, Unguja
Zanzibar State Trade Corporation (ZSTC)	Stone Town, Unguja
Zanzibar Clove Producers' Association (ZACPO)	Chake-Chake, Pemba
United Nations Development Programme (UNDP)	Stone Town, Unguja
Matangatuani Agricultural Research Centre	Wete, Pemba
Kizimbani Agricultural Research Centre	Stone Town, Unguja
Various private and Government clove farms as well as private and public nurseries	Unguja and Pemba

Annex 2: Example of questions used in semi-structured interviews

Example of questions used during the semi-structured interviews, Zanzibar missions, January and June 2016

1. What is the area of clove plantation you owe?
2. How many trees do you grow on this land?
3. What is the survival rate of seedlings?
4. What does the survival rate depend on?
5. What is the average annual production of cloves per hectare?
6. What is the average annual production of clove trees per age class?
7. What are main investment items and costs?
8. What are main management needs and their costs?
9. What are main diseases, what are they related to?
10. How much are farmers paid for clove production?
11. Are clove trees sensitive to weather and climate or environmental indicators?
12. In there any issue of environmental degradation, weather and climate impacts on clove production?
13. Has any increase in these impacts been observed in the past 10 years?
14. Did you notice any link between production and weather/climate/rains dry conditions/soils/?
15. Do you believe strong winds have potential impacts on clove plantations?
16. How do farmers respond to environmental, weather and climate difficulties? What techniques are used to alleviate plantations from these effects?
17. To what extent do these measures reduce the impacts on the plantation? By how much would the effect be reduced?
18. Is there ongoing research on the agronomy of cloves on the islands?
19. Is there available time series for production per regions and prices?
20. Do you have any perspectives of expanding your clove plantation?
21. What is the investment incentive to grow clove trees?
22. What is the frequency of low/high production cycles?
23. What are the main crops you intercrop with cloves? Why?
24. What are the most important ones in terms of revenue?
25. What is the production of those intercrops/ha?
26. What is the value of your plantation/land without clove trees?
27. What is the cost of these measures?
28. To what extent would these reduce the impact on plantations?

Note: The list is not exhaustive and the questions were adapted to the stakeholders visited.

Annex 3: Costs and benefit items of clove plantations in the baseline

	Option / Item	Investment	Timing
Economic Costs	Land purchase	TZS 18,000,000/ha	Year 0
	Land preparation	TZS 400,000/ha	Year 0
	Seedlings	TZS 2,000/unit	Year 0
	Transportation of seedlings to field	TZS 450/unit	Year 0
	Digging and planting	TZS 400/unit	Year 0
	Drying mats	TZS 4,000/unit	Year 0 and every 5 years
	Weeding 50%	TZS 100,000/ha	Every year
	Harvesting	TZS 2,000/pishi[46]	Year 6 to 80
	Drying	TZS 1,000/pishi	Year 6 to 80
	Felling	TZS 10,000/tree	Year 70,75,80
	Replantation	TZS 6,400/tree	Year 70,75,80
	Intercrop with cassava		
	• Seedlings	TZS 20/seedling	Year 0,1,2
	• Dig and plant	TZS 100,000/ha	Year 0,1,2
	• Weeding	TZS 100,000/ha	Year 0,1,2
	• Harvesting	TZS 30,000/ha	Year 0,1,2
	Intercrop with banana		
	• Seedlings	TZS 750/stem	Year 0,1,2
	• Dig and plant	TZS 2,000/stem	Year 0,1,2
	• Thinning/uprooting	TZS 700/stand	Year 0,1,2
	• Harvesting	TZS 500/stand	Year 0,1,2
Economic Revenues	Clove production	389,88 kg/ha* TZS 13,500/kg	Year 6 to 80
	Clove timber	20 (40 and 40) * TZS 550,000/tree	Years 70 (75 and 80 respectively)
	Cassava production	2,900kg/ha * TZS 500/kg	Year 0,1,2
	Banana production	2,000kg/ha* TZS 2,000/kg	Year 0,1,2

Note: Exchange rate used: USD 1 = TZS 2186.32, checked on 28 August 2016.

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[46] Pishi is the local basket that serves for clove harvesting and its measure. It is also used to remunerate seasonal workers based on the number of pishis harvested. 1pishi is equivalent to about 2.3 kg of green cloves, 1/3 of which is dried cloves. A pishi thereby is about 0.76 kg of dry cloves.

Annex 4: Assumptions for baseline and alternative agricultural practices

No adaptation	
Clove tree density	100 trees/ha
Survival rate of clove trees	55%. During the field trip we were given a range of 40%-80% and we chose a survival rate slightly lower than the average to account for the damaged conditions of the average plantation
Seedling plantation	182 seedlings/ha (density/survival rate)
Weeding	Weeding is supposed to be practiced at 50% so costs are considered accordingly to be TZS 100,000/ha.
Mean annual production (Pemba)	389.88 kg dry or 513 pishis of cloves/ha/year
Harvest	513 pishi/ha. The harvest is calculated in pishi as the remuneration of seasonal clove pickers is effectively done in TZS/pishi. We use following measure equivalents: 1 pishi=2.3 kg fresh cloves and 1 kg fresh cloves=1/3 kg dry cloves. Si 1 pishi is equivalent to 0.76 kg of dried cloves.
Felling	20 trees are felled in year 70 and 40 both in years 75 and 80.
Replantation	As for the seedling plantation we replant in each year 70, 75 and 80 the number of tree felled accounting for the survival rate (trees felled/survival rate)
Cassava seedlings	5,000 seedlings/ha
Banana seedlings	160 stems/ha
Revenues	Revenues arise from clove buds (390kg/ha/year at a price of TZS 13,500 –high– and TZS 3,000 – low), from clove timber in years 70,75 and 80 and each tree will generate a revenue of TZS 550,000 in each of those years.
GMPs	Package of good management practices
Weeding of the clove plantation	Weeding is done at 100% and so the total cost is TZS 200,000/ha.
Organic compost	TZS 50,000/ha
Timing of transplantation	Zero cost
Mini drip irrigation	TZS 20,000/ha. Low cost technique using of the top of a closed, funnel-shaped plastic bottle in which cap wholes are drilled to release water drops. It is then filled with water and fixed into the soil at root level of the young tree.
Mulching	TZS 10,000/ha. Lemon grass mulching is reported by farmers in the field to be the only to prevent termite nests.
Removal of parasites	We consider 3% of trees are affected by parasites and each treatment costs TZS 1 500.
Pruning of damaged branches after harvest	We assume 50% of the plantation (50 clove trees) need to be pruned after harvest at the cost of TZS 1,000/tree.
Additional revenues	We assume 10% additional production resulting from GMPs together with a higher survival rate of 80%.

Vanilla intercropping	We assume 3 subplots of $400m^2$ are planted with 75 vanilla stands reducing the total number of clove trees by 12 and total clove plantation costs and revenues by 88%.
Land clearing	Vanilla intercropping is assumed to necessitate additional land clearing at the cost of TZS 494200/ha every 10 years, when the vanilla supporting trees are replanted.
Vanilla seedlings	We plant 75 vanilla seedlings at the cost of TZS 1,000 each.
Support trees	Vanilla support trees cost TZS 15,000/ha.
Digging and planting	TZS 250/vanilla seedling
Usual clove weeding	Clove weeding is kept at 50% as in the baseline but additional weeding is necessary for the vanilla plantation.
Additional weeding	TZS 741,000/ha
Harvesting	TZS 216,000/ha
Pollination	TZS 150,000/ha
Processing	TZS 114,000/ha
Vanilla Revenues	We assume a vanilla production of 62.5 kg/ha and a price of TZS 126,000/kg
Cinnamon intercropping	For intercropping with cinnamon trees, we assume 50% cinnamon and 50% clove tree distribution. As both type of trees imply similar costs, most of the costs remain the same when they do not need to be adapted (see below)
Seedlings	We assume the same number of seedlings are planted (182 seedlings/ha) implicating cinnamon trees have the same survival rate as clove trees
Clove weeding	It is kept at 50% as in the baseline
Additional weeding	Additional weeding costs of TZS 62,500/ha need to be applied.
Harvesting	We assume a cost of TZS 22,500/ha
Cinnamon revenues	Cinnamon production is assumed to be TZS 437.5 ton/ha/year between years 10 and 30 and the double afterwards and till year 80 when trees are felled.
Windbreak	We assume the same density is required for both species and land area available remains identic: the clove plantation is reduced and replaced by 64 teak trees. We assume teak trees have the same 80 year lifecycle as clove trees. Clove production decreases to 36% of initial amounts. Cost of plantation and felling are the same for both species therefore we keep our model identic for most items.
Clove weeding	It is kept at 50% as in the baseline
Teak seedlings	We use the same amount of seedlings as in the baseline implicating the survival rate is the same for teak and clove trees.
Revenues from teak	Revenues from teak only arises in year 70, 75 and 80 when trees are felled. Indeed trees are kept for the protection for the clove plantation. Revenues per teak tree are TZS 2,000,000.

Annex 5: Results for the baseline and best agricultural practices without climate change – low clove prices

	No adaptation, with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	22.962	10.711	9.259	25.738	11.485	9.780	117.422	46.246	36.652	32.531	11.659	9.611	17.214	8.265	7.596
PV Costs (USD 2016)	27.360	14.921	13.323	29.934	15.913	14.099	42.062	20.943	18.142	20.518	13.091	12.126	17.344	12.126	11.443
NPV (USD 2016)	-4.398	-4.210	-4.064	-4.196	-4.428	-4.319	75.359	25.302	18.510	12.014	-1.432	-2.515	-129	-3.861	-3.847
B/C ratio (%)	0,84	0,72	0,69	0,86	0,72	0,69	2,79	2,21	2,02	1,59	0,89	0,79	0,99	0,68	0,66
IRR			1%			1%			57%			8%			3%

Note 1: Results are expressed in 2016 USD at USD 1 = TZS 2186.32. Exchange rate, checked on 28 August 2016.
Note 2: Clove prices assumed are low (USD 1.60/kg)

Annex 6: Results for adaptation with rainfall impacts (RCP 4.5 and RCP 8.5 Model 4) – low clove prices

		No adaptation, with shading			GMPs			Vanilla intercropping			Cinnamon intercropping		
RCP 4.5 – Model 4	Discount rates	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
	PV Revenues (USD 2016)	19.926	9.753	8.590	23.569	10.801	9.302	114.750	45.403	36.063	31.013	11.180	9.276
	PV Costs (USD 2016)	27.360	14.921	13.323	29.934	15.913	14.099	42.062	20.943	18.142	20.518	13.091	12.126
	NPV (USD 2016)	-7.434	-5.168	-4.734	-6.365	-5.112	-4.797	72.687	24.459	17.921	10.496	-1.911	-2.849
	B/C ratio (%)	0,73	0,65	0,64	0,79	0,68	0,66	2,73	2,17	1,99	1,51	0,85	0,77
	IRR			0%			1%			56%			7%
RCP 8.5 – Model 4	PV Revenues (USD 2016)	19.521	9.646	8.552	23.280	10.724	9.275	114.393	45.308	36.029	30.811	11.126	9.257
	PV Costs (USD 2016)	27.360	14.921	13.323	29.934	15.913	14.099	42.062	20.943	18.142	20.518	13.091	12.126
	NPV (USD 2016)	-7.839	-5.275	-4.771	-6.655	-5.189	-4.824	72.331	24.365	17.888	10.293	-1.965	-2.868
	B/C ratio (%)	0,71	0,65	0,64	0,78	0,67	0,66	2,72	2,16	1,99	1,50	0,85	0,76
	IRR			0%			1%			57%			7%

Note: Results are expressed in 2016 USD at USD 1 = TZS 2186.32 exchange rate, checked on 28 August 2016.

Annex 7: Results with and without adaptation with cyclone impacts in year 7 – low clove prices

Results with and without adaptation with cyclone impacts in year 7

	Baseline with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	33.592	18.912	16.306	32.755	18.462	16.057
PV Costs (USD 2016)	27.615	15.077	13.450	17.599	12.282	11.569
NPV (USD 2016)	5.976	3.835	2.856	15.156	6.180	4.488
B/C ratio (%)	1,22	1,25	1,21	1,86	1,50	1,39
IRR			23%			25%

Note 1: Results are expressed in 2016 USD at USD 1 = TZS 2186.32 exchange rate, checked on 28 August 2016.
Note 2: Cyclone costs include replantation. Benefits include revenues from selling wood from damaged trees. Not including these result in more negative results.

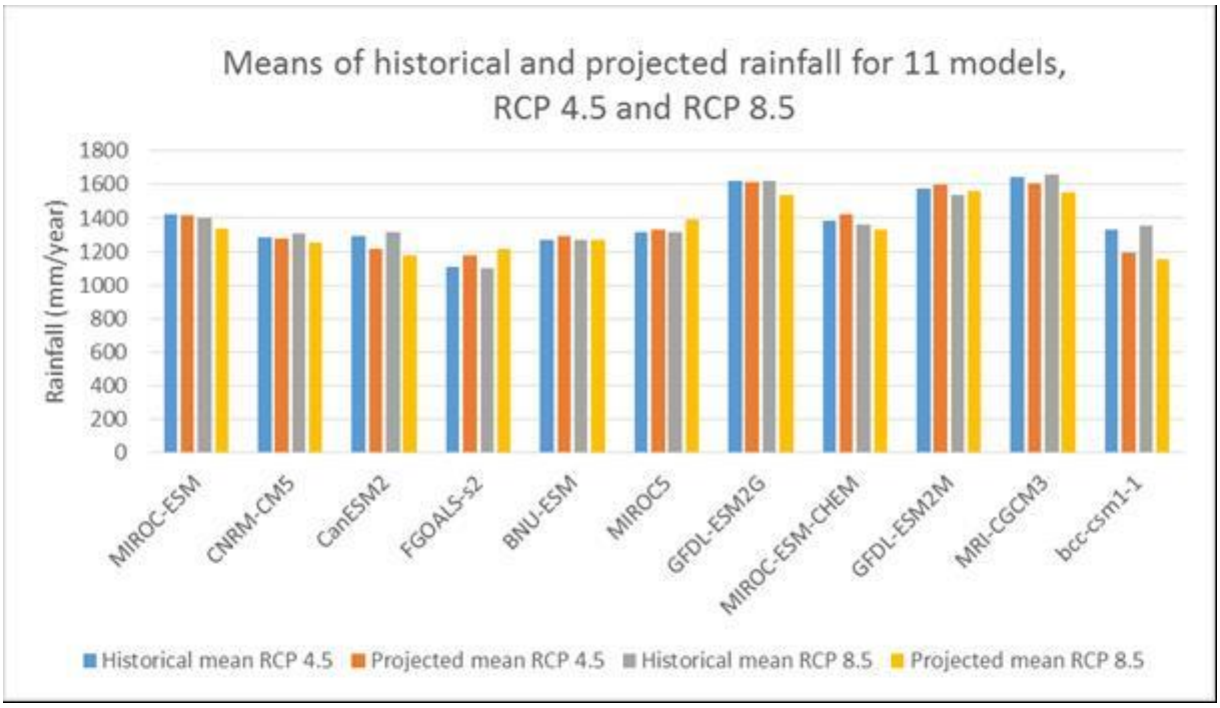
Results with and without adaptation with cyclone impacts in year 15

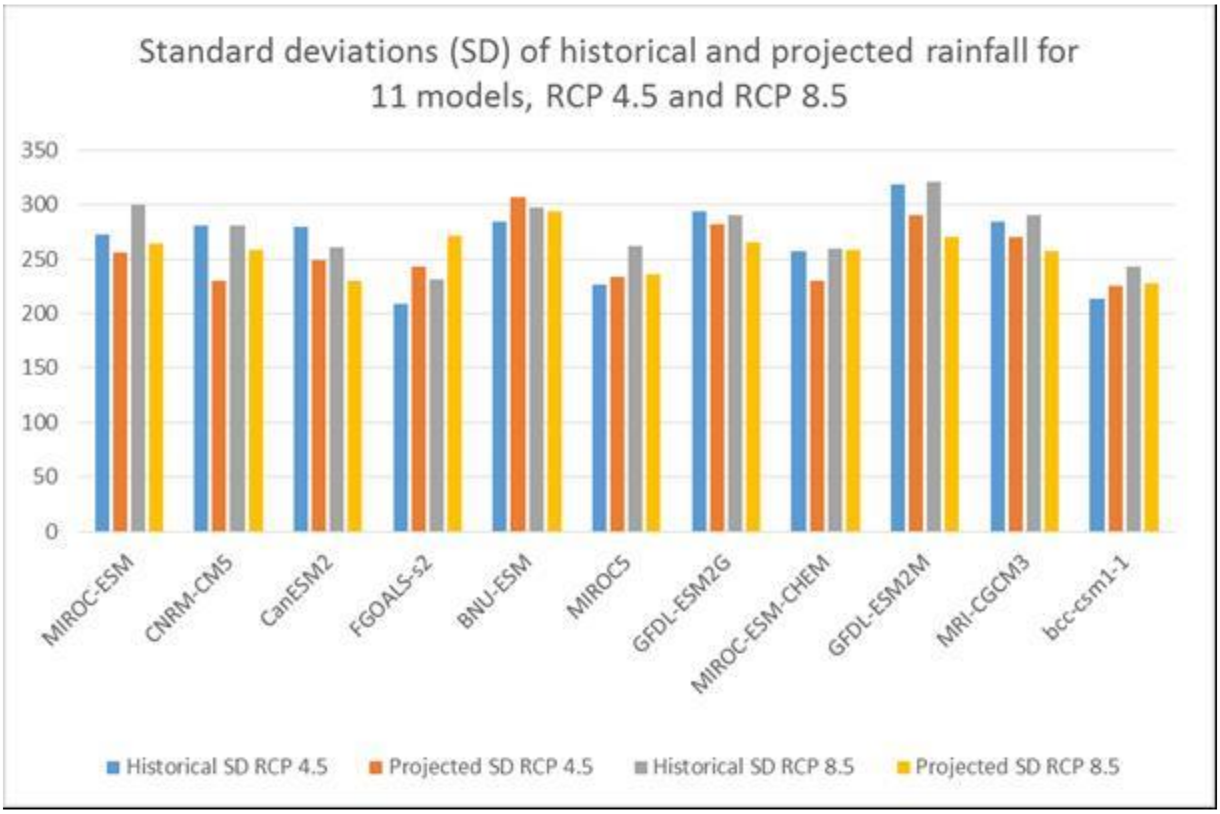
	Baseline with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	31.034	14.537	11.910	29.016	13.022	10.779
PV Costs (USD 2016)	27.554	14.994	13.371	17.537	12.199	11.490
NPV (USD 2016)	3.480	-457	-1.461	11.479	823	-711
B/C ratio (%)	1,13	0,97	0,89	1,65	1,07	0,94
IRR			9%			11%

Results with and without adaptation with cyclone impacts in year 31

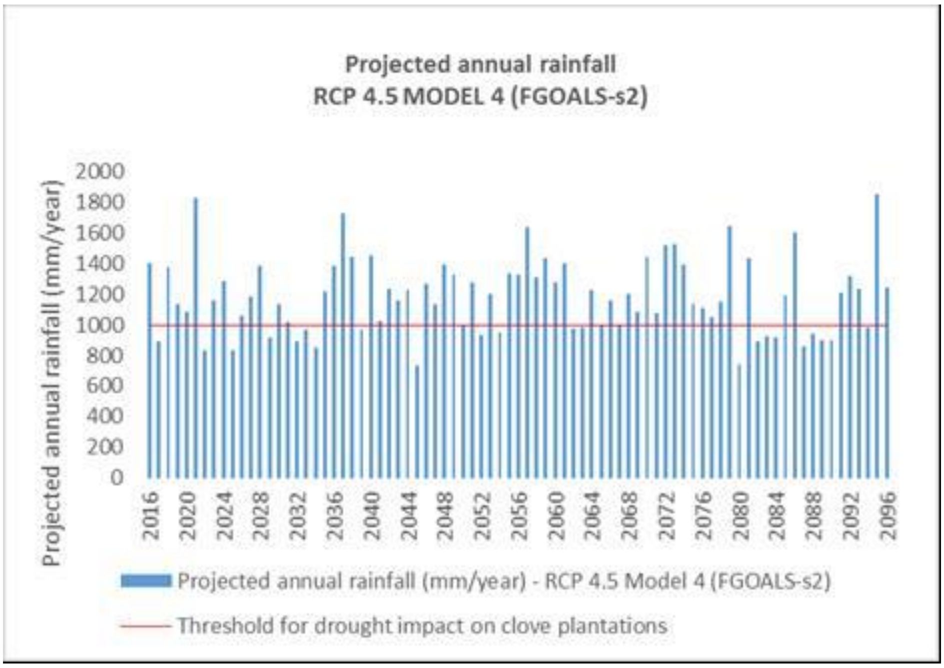
	Baseline with shading			Windbreak (with Teak)		
Discount rates	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	27.618	11.543	9.634	24.020	9.300	8.046
PV Costs (USD 2016)	27.472	14.937	13.330	17.455	12.141	11.449
NPV (USD 2016)	146	-3.393	-3.696	6.565	-2.841	-3.403
B/C ratio (%)	1,01	0,77	0,72	1,38	0,77	0,70
IRR			4%			6%

Annex 8: Comparing average and standard deviation of annual rainfall for eleven model for RCP 4.5 and RCP 8.5

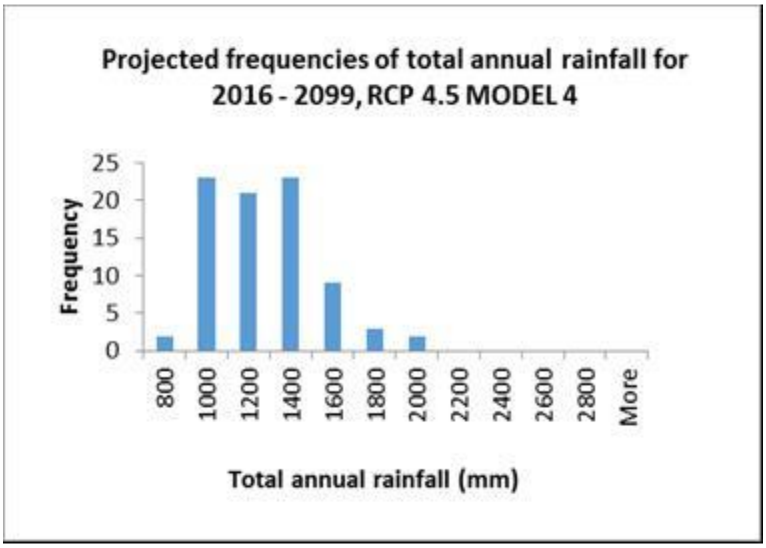




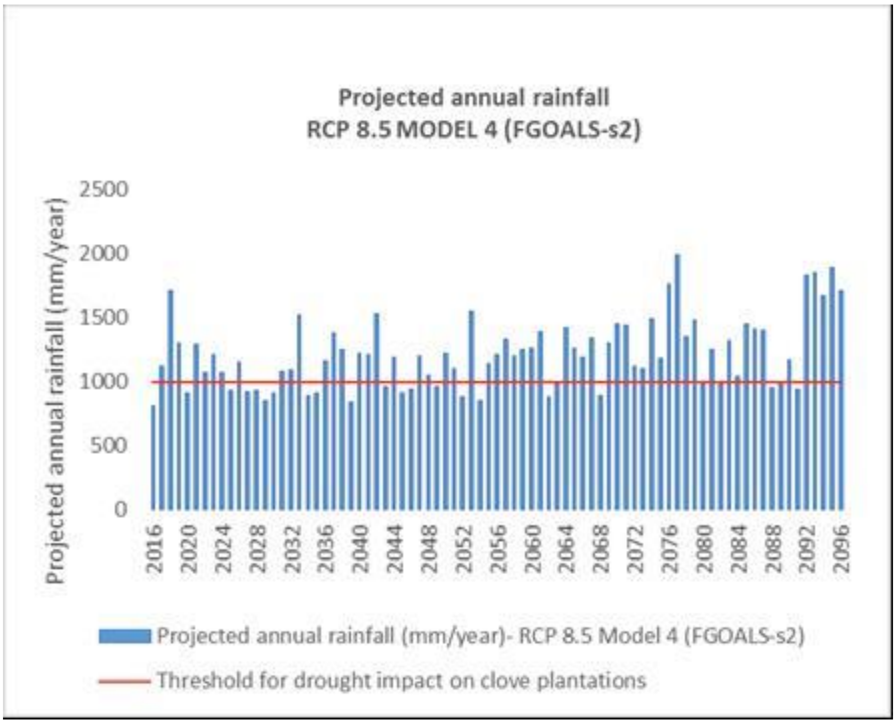
Annex 9: Projected annual rainfall as compared to the dry spell threshold and frequencies of occurrence during the lifecycle of the clove plantation



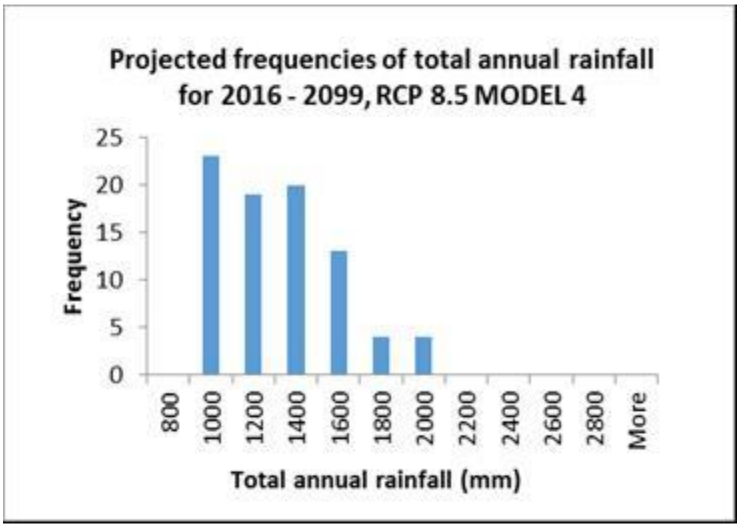
Projected annual rainfall as compared to the rainfall threshold under which clove production is reduced, RCP 4.5 Model 4 (FGOALS-s2)



Frequency of total annual rainfall by annual rainfall category and occurrence of dry spells (frequency of rainfall <=1000 mm/year), RCP 4.5 Model 4 (FGOALS-s2)

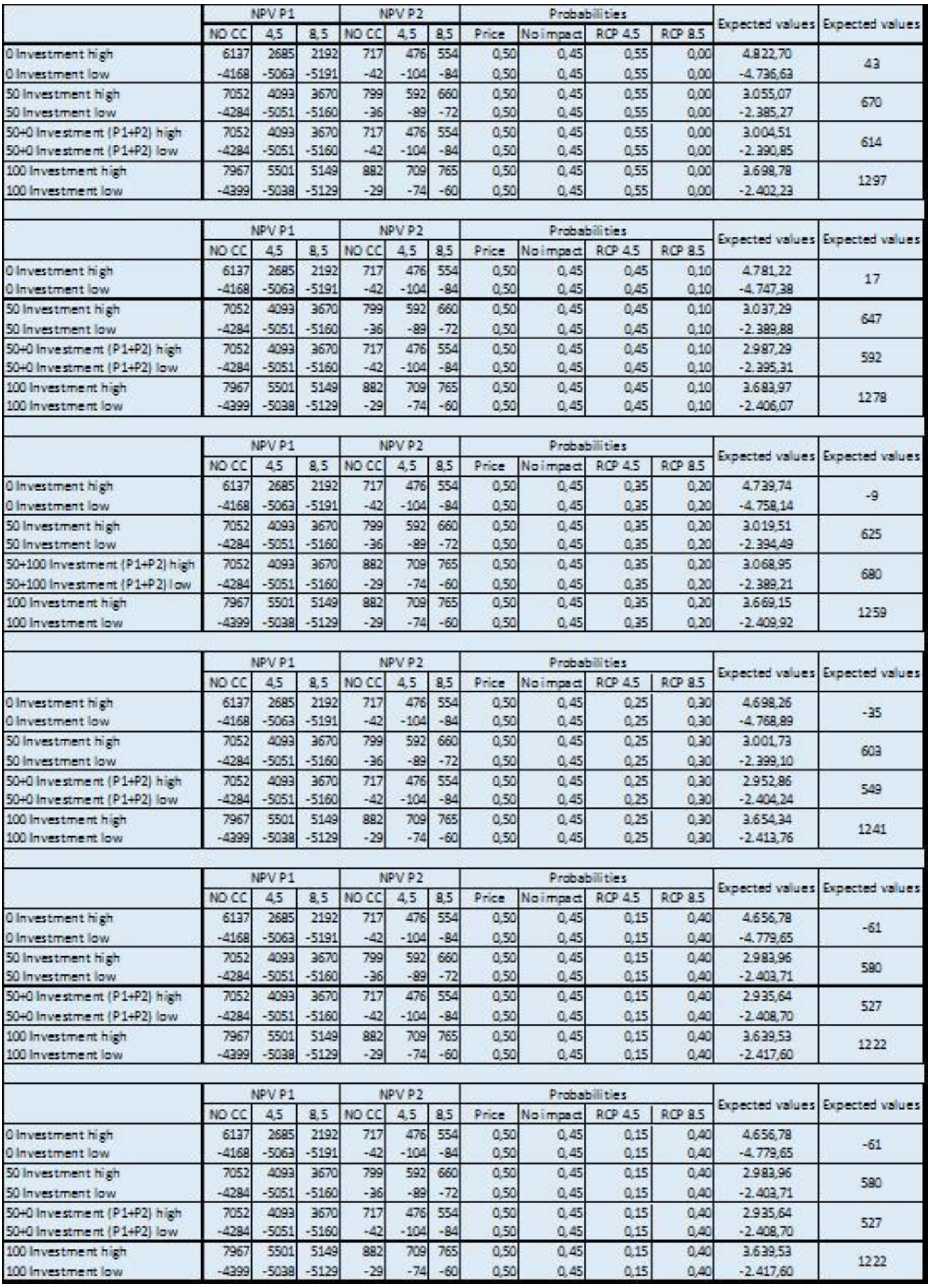


Projected annual rainfall as compared to the rainfall threshold under which clove production is reduced, RCP 8.5 Model 4 (FGOALS-s2)



Frequency of total annual rainfall by annual rainfall category and occurrence of dry spells (frequency of rainfall <=1000 mm/year), RCP 4.5 Model 4 (FGOALS-s2)

Annex 10: Sensitivity analysis of ROA with 50% price probabilities



	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,55	0,00	4.822,70	43
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,55	0,00	-4.736,63	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,55	0,00	3.055,07	670
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,55	0,00	-2.385,27	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,45	0,55	0,00	3.004,51	614
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,45	0,55	0,00	-2.390,85	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,55	0,00	3.698,78	1297
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,55	0,00	-2.402,23	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,45	0,10	4.781,22	17
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,45	0,10	-4.747,38	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,45	0,10	3.037,29	647
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,45	0,10	-2.389,88	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,45	0,45	0,10	2.987,29	592
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,45	0,45	0,10	-2.395,31	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,45	0,10	3.683,97	1278
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,45	0,10	-2.406,07	

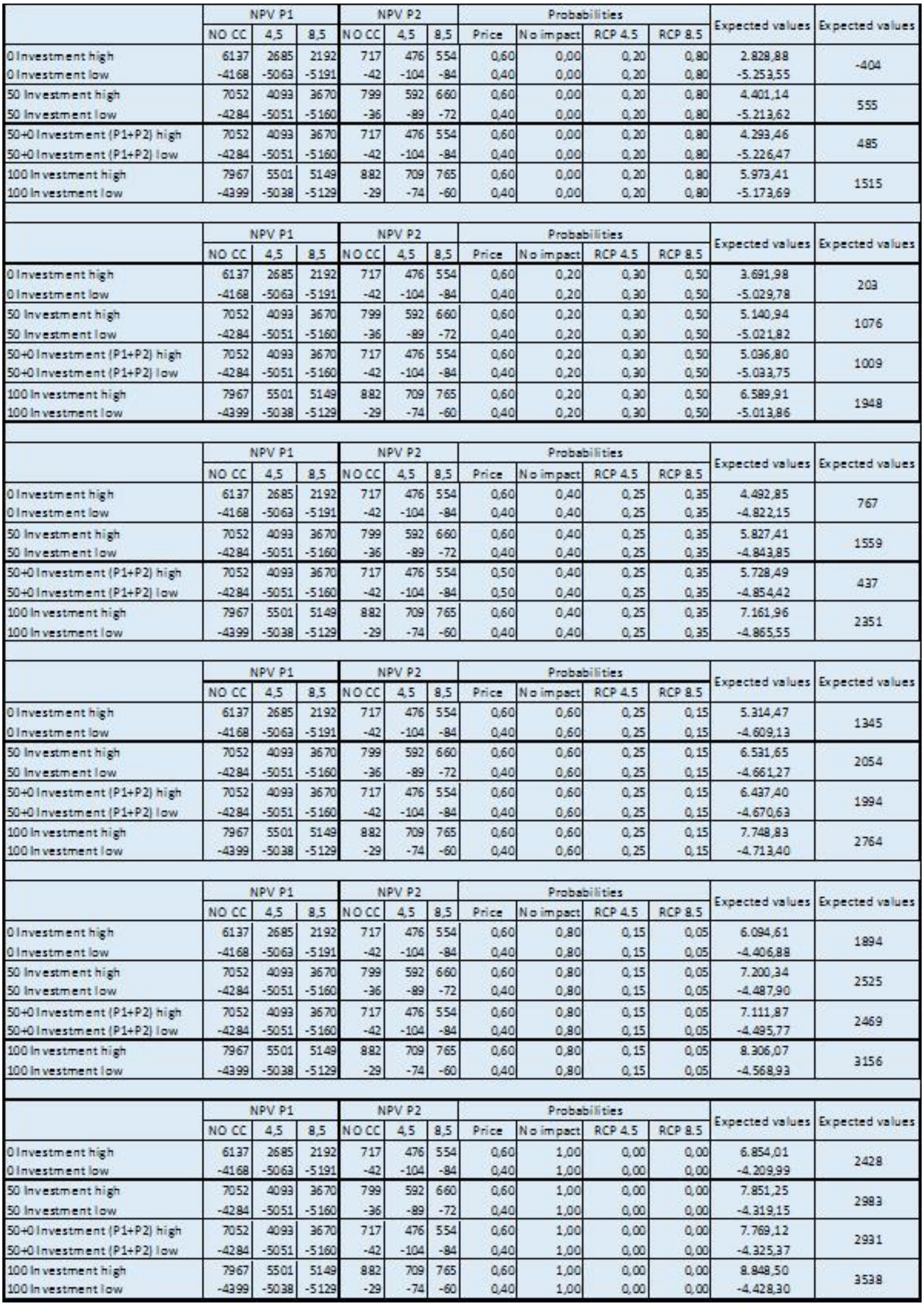
	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,35	0,20	4.739,74	-9
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,35	0,20	-4.758,14	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,35	0,20	3.019,51	625
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,35	0,20	-2.394,49	
50+100 Investment (P1+P2) high	7052	4093	3670	882	709	765	0,50	0,45	0,35	0,20	3.068,95	680
50+100 Investment (P1+P2) low	-4284	-5051	-5160	-29	-74	-60	0,50	0,45	0,35	0,20	-2.389,21	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,35	0,20	3.669,15	1259
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,35	0,20	-2.409,92	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,25	0,30	4.698,26	-35
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,25	0,30	-4.768,89	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,25	0,30	3.001,73	603
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,25	0,30	-2.399,10	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,45	0,25	0,30	2.952,86	549
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,45	0,25	0,30	-2.404,24	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,25	0,30	3.654,34	1241
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,25	0,30	-2.413,76	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,15	0,40	4.656,78	-61
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,15	0,40	-4.779,65	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,15	0,40	2.983,96	580
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,15	0,40	-2.403,71	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,45	0,15	0,40	2.935,64	527
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,45	0,15	0,40	-2.408,70	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,15	0,40	3.639,53	1222
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,15	0,40	-2.417,60	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,50	0,45	0,15	0,40	4.656,78	-61
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,50	0,45	0,15	0,40	-4.779,65	
50 Investment high	7052	4093	3670	799	592	660	0,50	0,45	0,15	0,40	2.983,96	580
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,50	0,45	0,15	0,40	-2.403,71	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,45	0,15	0,40	2.935,64	527
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,45	0,15	0,40	-2.408,70	
100 Investment high	7967	5501	5149	882	709	765	0,50	0,45	0,15	0,40	3.639,53	1222
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,50	0,45	0,15	0,40	-2.417,60	

Annex 11: Sensitivity analysis of ROA including variation of “no impact” probabilities



	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	0,00	0,20	0,80	2.828,88	-404
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,00	0,20	0,80	-5.253,55	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,00	0,20	0,80	4.401,14	555
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,00	0,20	0,80	-5.213,62	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,00	0,20	0,80	4.293,46	485
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,00	0,20	0,80	-5.226,47	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,00	0,20	0,80	5.973,41	1515
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,00	0,20	0,80	-5.173,69	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	0,20	0,30	0,50	3.691,98	203
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,20	0,30	0,50	-5.029,78	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,20	0,30	0,50	5.140,94	1076
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,20	0,30	0,50	-5.021,82	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,20	0,30	0,50	5.036,80	1009
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,20	0,30	0,50	-5.033,75	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,20	0,30	0,50	6.589,91	1948
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,20	0,30	0,50	-5.013,86	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	0,40	0,25	0,35	4.492,85	767
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,40	0,25	0,35	-4.822,15	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,40	0,25	0,35	5.827,41	1559
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,40	0,25	0,35	-4.843,85	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,50	0,40	0,25	0,35	5.728,49	437
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,50	0,40	0,25	0,35	-4.854,42	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,40	0,25	0,35	7.161,96	2351
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,40	0,25	0,35	-4.865,55	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	0,60	0,25	0,15	5.314,47	1345
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,60	0,25	0,15	-4.609,13	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,60	0,25	0,15	6.531,65	2054
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,60	0,25	0,15	-4.661,27	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,60	0,25	0,15	6.437,40	1994
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,60	0,25	0,15	-4.670,63	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,60	0,25	0,15	7.748,83	2764
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,60	0,25	0,15	-4.713,40	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	0,80	0,15	0,05	6.094,61	1894
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	0,80	0,15	0,05	-4.406,88	
50 Investment high	7052	4093	3670	799	592	660	0,60	0,80	0,15	0,05	7.200,34	2525
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	0,80	0,15	0,05	-4.487,90	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	0,80	0,15	0,05	7.111,87	2469
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	0,80	0,15	0,05	-4.495,77	
100 Investment high	7967	5501	5149	882	709	765	0,60	0,80	0,15	0,05	8.306,07	3156
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	0,80	0,15	0,05	-4.568,93	

	NPV P1			NPV P2			Probabilities				Expected values	Expected values
	NO CC	4,5	8,5	NO CC	4,5	8,5	Price	No impact	RCP 4.5	RCP 8.5		
0 Investment high	6137	2685	2192	717	476	554	0,60	1,00	0,00	0,00	6.854,01	2428
0 Investment low	-4168	-5063	-5191	-42	-104	-84	0,40	1,00	0,00	0,00	-4.209,99	
50 Investment high	7052	4093	3670	799	592	660	0,60	1,00	0,00	0,00	7.851,25	2983
50 Investment low	-4284	-5051	-5160	-36	-89	-72	0,40	1,00	0,00	0,00	-4.319,15	
50+0 Investment (P1+P2) high	7052	4093	3670	717	476	554	0,60	1,00	0,00	0,00	7.769,12	2931
50+0 Investment (P1+P2) low	-4284	-5051	-5160	-42	-104	-84	0,40	1,00	0,00	0,00	-4.325,37	
100 Investment high	7967	5501	5149	882	709	765	0,60	1,00	0,00	0,00	8.848,50	3538
100 Investment low	-4399	-5038	-5129	-29	-74	-60	0,40	1,00	0,00	0,00	-4.428,30	

ECONADAPT

The Economics of Adaptation

Funded by
the European Union

Chapter Three: Adapting to Climate Change in Zanzibar's Seaweed Farming Sector

Author: Jacob Wellman

Deliverable number	
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1. Introduction

This document is a companion to quantitative analysis conducted in the “Zanzibar Seaweed Economics” spreadsheet containing cost benefit analysis data on all options presented in this report. While representative figures are included in this document along with conclusions from the quantitative analysis, both should be viewed together for complete understanding of the project appraisal carried out in this deliverable.

1.1 Objectives of case study

This case study is designed to examine the treatment of risk and uncertainty in economic appraisals of climate adaptation projects in the context of international development funded by European countries. Specifically, this case study examines adaptation options for the seaweed farming industry in the Zanzibar islands located in the United Republic of Tanzania. The project appraisals are conducted in support of a UK-funded climate change strategy for the region. The findings in this report are informed by desk-based research as well as onsite interviews with stakeholders and officials.

This case presents strategies to aid decision-makers where data around prices, costs and future impacts from climate change are uncertain. Impacts from climate change have already caused disruption in the sector and policy decisions on future investments in seaweed farming require relevant and immediate consideration of future climate change. Ambiguity between different climate futures introduces uncertainty about the long-term returns of investments in the sector, given that the viability of seaweed crops is sensitive to changes in temperature that may result from climate change. The combination of short-term interventions and long-term threats from climate change enable this case study to highlight the need for flexible decision tools in climate adaptation.

The development of adaptation options in this case required the engagement of several important stakeholders across the community including various government departments, actors in the seaweed value chain, researchers in the coastal economy and communities reliant on seaweed farming for income and employment. Methods utilised and findings gathered from this case study are presented as demonstrative practices for future efforts to fund climate adaptation projects.

Seaweed farming in Zanzibar represents an economically important sector that has already begun to suffer from the effects of climate change. By taking steps to adapt to these climate impacts, the industry can preserve economic opportunities for vulnerable populations in a Least Developed Country with growing pressures from population growth and resource degradation.

1.2 Country Context

Zanzibar is comprised of two islands, Unguja and Pemba, off the East coast of the United Republic of Tanzania. As a part of Tanzania, it is listed by the United Nations as a Least Developed Country. Details of Zanzibar’s demographics, geography and economy are included in Deliverable 9.1 for the ECONADAPT project. The Zanzibar Climate Change Strategy is under development, which will outline main sources of climate risk and top priorities to mitigate and adapt to these risks.

2. Methods

This deliverable specifically deals with the treatment of uncertainty in project appraisals of interventions into the seaweed farming sector in Zanzibar. Seaweed farming was chosen as a high-priority adaptation area due to its heightened vulnerability to impacts from climate change—some of which have already begun to affect the industry. Seaweed exports contribute more than any other tradable marine product to the Zanzibar economy and seaweed farming represents one of the only income sources for women in coastal villages (Msuya, 2013).

2.1 Policy context for climate risk

Seaweed farming around Zanzibar has developed over the last 20 years into an important revenue source for coastal communities. Local villagers farm seaweed containing carrageenan in shallow salt water, which is collected after harvest by exporting businesses and sent around the world for carrageenan extraction. Seaweed farming activities in Zanzibar supply 3-5% of the global market for carrageenan-producing seaweed, making the region the third largest supplier in the world after Philippines and Indonesia.[47]

Two types of seaweed have been farmed historically around Zanzibar, *spinosum* and *cottonii*. The former (scientific name *Eucheuma denticulatum*) is a resilient species of seaweed but has weaker carrageenan content than *cottonii* and is therefore less valuable to export markets, yielding a lower price for farmers selling this species. From a production peak in 2001, *cottonii* seaweed (scientific name *Kappaphycus alvarezii)* production has declined to nearly non-existent levels. Despite prices that are nearly twice that of *spinosum*, farmers have been unable to harvest healthy *cottonii* seaweed due to an increase in disease thought to be linked to rising sea surface temperatures (Msuya, 2013).

Both species of seaweed have historically been grown in an off-bottom method, in which farmers stake lines in shallow, knee-deep waters and tie seaweed seedlings to the lines, allowing seedlings to grow over a 45-day harvest cycle. This method requires substantial labour inputs, especially during low tides, when farmers scrub lines and seaweed of algae and debris that can cause disease in the seaweed. A majority of seaweed farmers (57%) are women, who do not have access to many alternative occupations in rural coastal villages.[48]

Due to its role in poverty reduction, seaweed farmers are the primary stakeholder population of interest in the industry. A recent government census estimates over 20,000 farmers currently active in Zanzibar, though this number fluctuates with market trends.[1] A draft mariculture strategy prepared by the FAO in support of the RGZ identifies a goal to increase the number of seaweed farmers by 50% to 30,000 by 2020 (RGZ, 2015). Farmers are loosely organised through government-facilitated seaweed committees in coastal villages as well as more informal networks coordinated through the Zanzibar Seaweed Cluster Initiative. Seaweed committees are active on both islands whereas the Seaweed Cluster Initiative is currently active on Unguja island with plans to expand to Pemba. Each holds annual meetings with training and stakeholder engagement built in to gather feedback.[1,2] Key decisions made by farmers include whether to farm or exit the industry, how to work with seaweed buyers and whether to cooperate to share capital-intensive technology or participate in value addition activities.

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[47] Conversation with Mahmoud Soud at the RGZ Ministry of Fisheries, 7 June 2016

[48] Conversation with Dr Flower Msuya at the Institute for Marine Sciences in Zanzibar Town, 6 June 2016

The gender composition of seaweed farmers differs greatly between the two islands that comprise Zanzibar: Unguja and Pemba. In Unguja, the more populated island with a large urban centre, over 90% of farmers are women while in Pemba men are much more involved in growing seaweed.[2] The majority of seaweed (70-80%) in Zanzibar is grown on Pemba, while the remainder is grown on Unguja island.

A growing population, poor conditions for inland agriculture and commercial development along Zanzibar's coasts all contribute pressure on areas traditionally used for seaweed farming. Government officials have expressed concern that growing interest in seaweed has pushed farmers further out from the coast in search for open areas to stake lines.[49] The growing footprint of off-bottom seaweed farms brings environmental impacts on seagrass beds that serve an important ecological function in marine systems (Ibid.).

While farmers provide labour and space for the seaweed industry, exporting companies play an important collaborative role, setting prices for seaweed harvest, negotiating markets for harvested product and providing capital to farmers to defray start-up costs for farms. Seaweed buyers may provide lines, seedlings and harvesting barges to farmers to encourage entry into the market. These companies offer a reduced price for harvested seaweed in order to recover the costs of capital provided. Because of loose regulation around the farmer-buyer relationship, farmers may accept capital from one buyer and sell their harvest to another offering higher prices, reducing incentives for buyers to invest in farms.[50] Seaweed buyers decide what prices to offer to farmers and whether to invest in capital for farmers growing seaweed. Even large exporters are dependent on demand from foreign buyers, which may be intermittent and unreliable.

Global seaweed prices differ across species of seaweed, but are dependent on the export market for each type of seaweed. While the market for *cottonii* remains high (around 1000TZS/dry kg), very few farmers in Zanzibar are able to produce any of this species without losing the entire harvest to disease. Instead, *spinosum* is primarily grown and faces a much more volatile market. Current prices for *spinosum* are amongst the lowest in five years, at 300-400TZS/dry kg. These low prices have caused some farmers to exit the industry, but as many do not have alternative income sources, they continue to grow seaweed at minimal profit.[51] Prices over the past 10 years have risen since 2009, but remain volatile, as shown in Figure 1.

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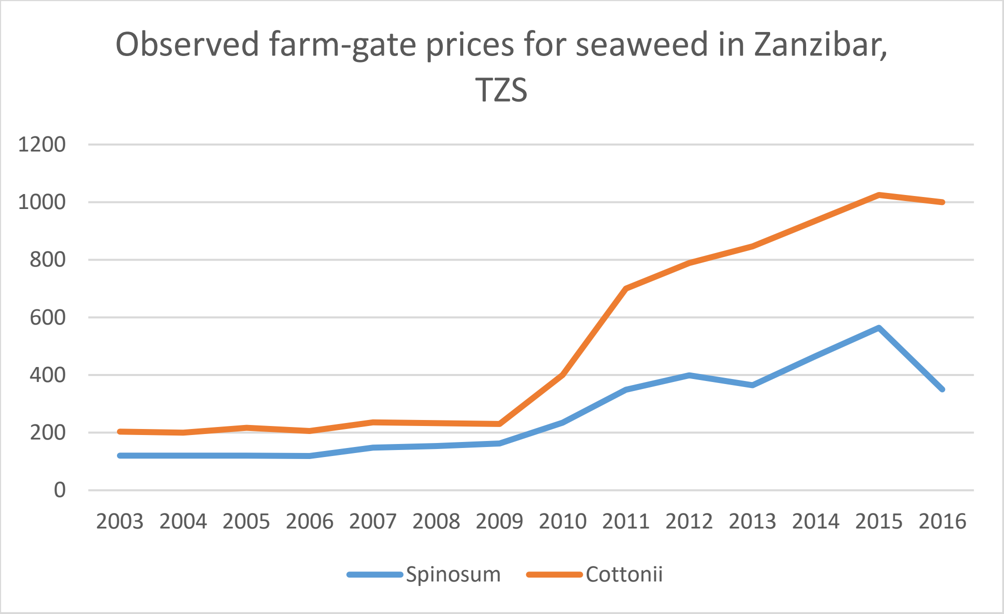
[49] Conversation with Dr Aboud Jumbe at the RGZ Department of the Environment, 6 June 2016

[50] Conversation with Makame Nassor at the C-Weed Corporation in Zanzibar Town, 8 June 2016

[51] Conversation with Ali Hamad on Pemba Island, 3 June 2016

Figure 1. Zanzibar seaweed prices, farm-gate



Source: RGZ Ministry of Fisheries, Msuya personal observation

Government regulators play a lesser role in the seaweed industry than in other markets, but do have an important role to play in regulating exporters. In order to buy seaweed from farmers and sell it internationally, a buyer must obtain a license from the Ministry of Trade and permission from either the Zanzibar Investment Promotion Authority or the Ministry of Agriculture. These permissions require proof of capital (30 million TZS) and include a two-month waiting period before traders are allowed to buy seaweed from farmers.[1] Concerns amongst long-term exporters include a lack of enforcement of this cooling period, introducing a high level of volatility in the market that discourages investment in farming techniques and equipment.[4]

Recent declines in the export price of *spinosum* combined with increased environmental, economic and social pressures on existing seaweed farming communities to form a pressing need for intervention in the industry. Several adaptation options identified in this study respond to this need.

2.2 Climate change risk analysis

As a large portion of Zanzibar's GDP is tied to agriculture and tourism activities, climate change poses a significant disruptive risk to the island economy. Regular variability due to El Niño and La Niña storms pose significant threats to the island's ecosystems, including seaweed farming from increased variability in SSTs during storm years (Manyilizu, et al, 2014). Recently, strong temperature increases have been observed in both terrestrial and marine environments. In the surrounding waters, wave and wind strength has picked up in recent years, threatening increasing damage on coastal resources (Hunt & Watkiss, 2015).

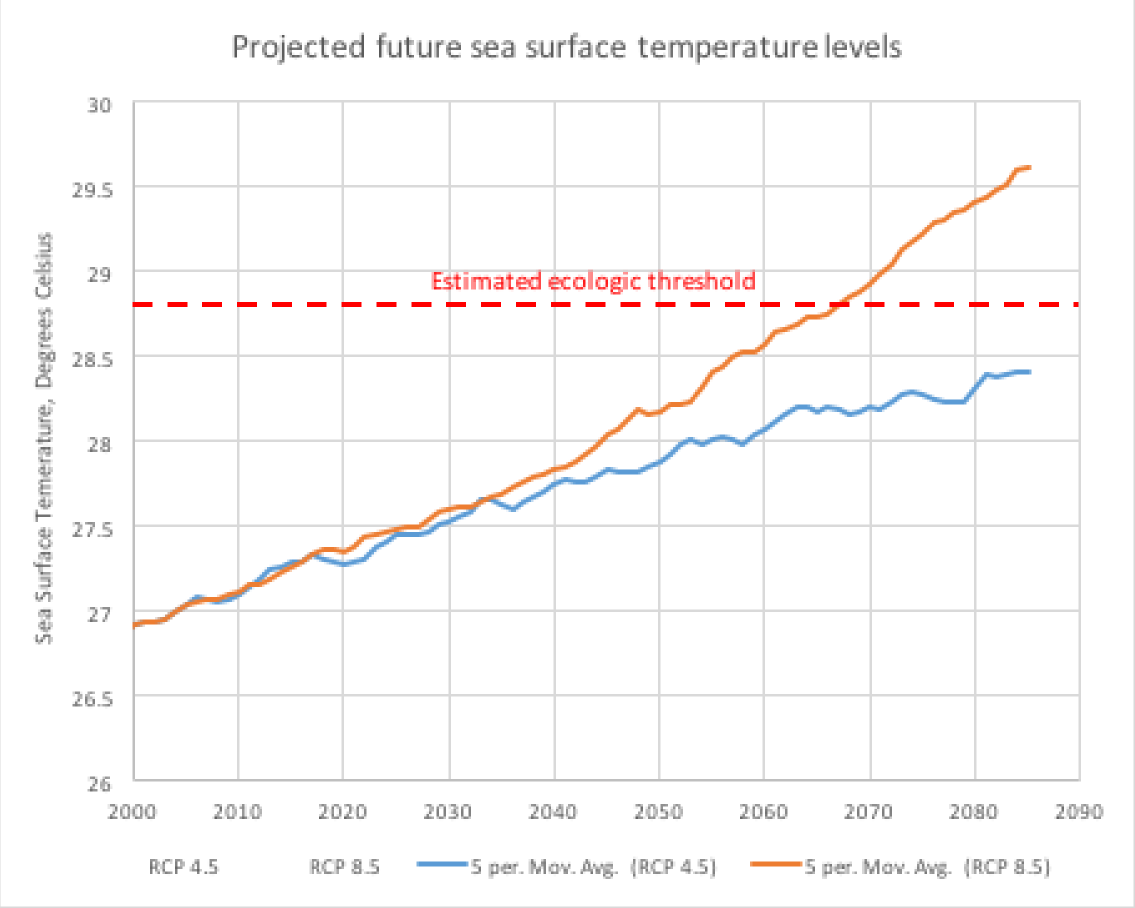
Seaweed farming is particularly vulnerable to higher sea surface temperatures (SSTs), which correspond with a significant increase in the so-called *ice ice* disease, killing viable seaweed plants before they can be harvested.[5] Measurements of SSTs from the mid-1990s recorded temperatures in waters where seaweed was grown around 31°C. These same areas now experience maximum temperatures of 38°C. Researchers at the Institute of Marine Sciences (IMS) estimate that *cottonii* can grow without high risk of disease in waters below 33°C, while *spinosum* has begun to reach its ecological threshold at current temperatures. High SSTs of

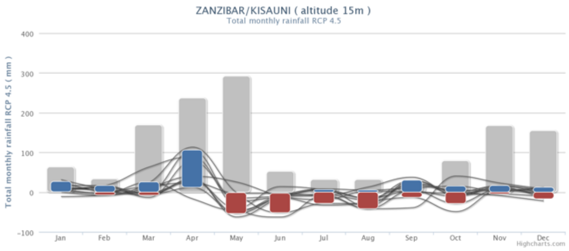
40°C are expected to eliminate the entire seaweed industry. Strong winds and waves are estimated to break off up to 50% of a seaweed crop in stormy seasons, while longer rainy seasons prevent drying of seaweed, requiring farmers to forego a full 45-day cycle of seaweed growth.[2] Climate impacts including higher SSTs and stormy seasons that are more violent and wet threaten to reduce seaweed yields in Zanzibar.

Future climate projections suggest increases in SSTs of 1.3-2.7°C by the end of the century, depending on the greenhouse gas concentration pathway followed (see figure 2). These temperature levels shown in Figure 2 were derived from the mean results over nine regional climate model representing different combinations of inputs from global climate models. The lower distribution assumes a concentration pathway following Representative Concentration Pathway 4.5, as presented by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report (IPCC, 2013A). The upper distribution assumes a higher concentration corresponding to RCP 8.5. An increase of 2°C, which is projected to occur under the higher concentration pathway, but not the lower, would push observed SSTs to the temperature threshold for growing *spinosum* seaweed in shallow waters.

Climate projections also show an increase in extremes for precipitation—with rainy months expected to become increasingly so. This will create further complications for drying seaweed harvests during these periods.

Figure 2. Future climate change projections for Zanzibar





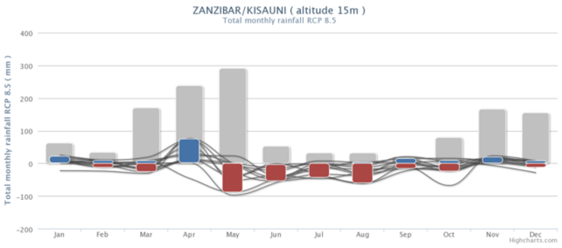


Table 1. Predicted relative sea surface temperature changes from climate models *(relative change from 2015)*

Scenarios	2050	2085
RCP 4.5	+0.5 C	+1.2 C
RCP 8.5	+0.7 C	+2.1 C

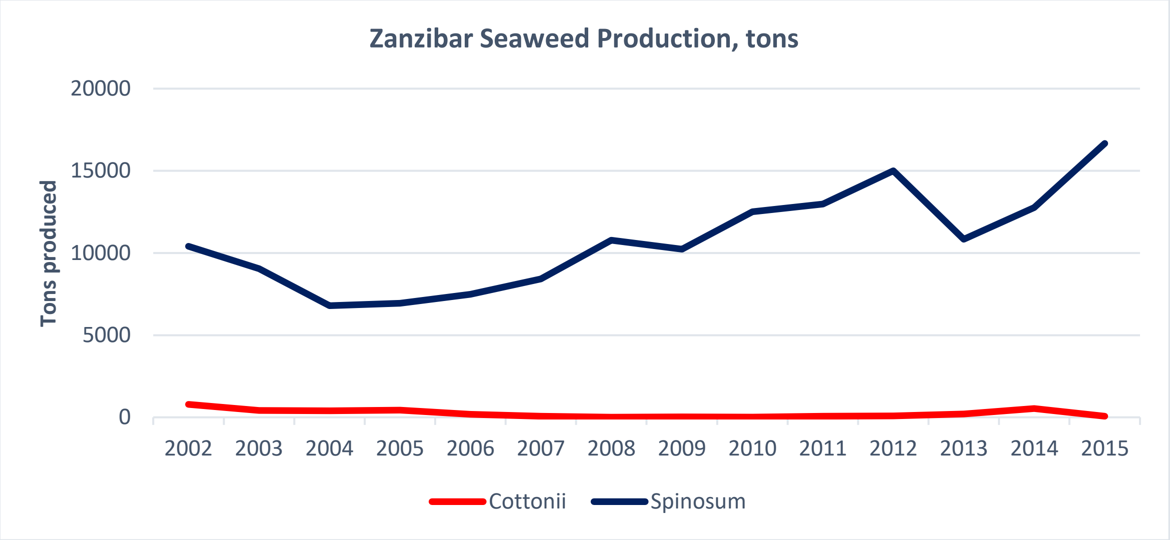
Source: Ole Bøssing Christensen, Danish Meteorological Institute

Some level of uncertainty remains around these projections, given the difficulty of producing projection data at a resolution as specific as the area occupied by Zanzibar. Climate models are structured to generate data from 50 km grids, which cover both land and sea surface around Zanzibar. Temperature changes can be applied from these projections to actual observed temperatures to construct models with higher confidence. For this study, temperature changes from regional climate models are applied to observed SSTs collected from a temperature logger installed at 3 meters off the coast of Zanzibar's Unguja island. Data is provided from the Institute of Marine Sciences dating back to 1997.

Current impacts from climate change include increased SSTs beyond the threshold for growing *cottonii* varieties of seaweed in shallow waters where off-bottom seaweed is currently farmed. Volumes of *cottonii* have declined over the past 15 years as shown in figure 3. Higher water temperatures combine with floating sediment to cause higher rates of *ice ice* disease and algal die-back in seaweed crops. Currently, *cottonii* is only grown in a few remote areas off satellite islands, such as Fundo Island.[5] The floating line method proposed in this project appraisal suggests moving seaweed crops to deeper waters where temperatures are lower and more stable and sediment is less present at the level of the seaweed plants.

This intervention improves conditions for *cottonii* in the short-term, but also offers benefits for *spinosum* farmers facing future climate impacts. Maximum water temperatures observed in shallow waters are currently approaching threshold levels for spinosum seaweed as well, posing a challenge in the near future to all off-bottom seaweed farmers (nearly 100% of current farmers). The high GHG concentration pathway projections from regional climate models show SSTs increasing beyond the maximum temperature for *spinosum* seaweed, rendering off-bottom seaweed farming no longer viable by around 2070. Lower concentration pathways do not exceed this maximum threshold for *spinosum*, but project continued warming, which is expected to increase the rates of disease amongst seaweed crops. Deeper-water temperatures are expected to increase as well, though temperature data is sparse for the levels planned for the deep water seaweed farms. New temperature monitoring efforts can provide data for long-term policy decisions as climate impacts and their effect on deep water seaweed farms are better understood.

Figure 3. Zanzibar-based seaweed production, in volume



Source: RGZ Ministry of Fisheries, 2016

Separate from climate impacts, seaweed farmers face socioeconomic pressures that will likely impact the sector's ability to continue supporting vulnerable populations. Declining productivity from agricultural activities and a high population growth rate both exert pressure on coastal populations and in turn increase interest in seaweed farming.[52] Coastal villages manage tidal lands collectively, but increasing pressure on farmable shallow waters has already produced a noticeable threat to seagrass beds—an ecologically rich habitat—close to shore.[3] International demand for seaweed continues to be uncertain without a formal marketing system for seaweed, contributing to an unstable price regime for farmers.[4]

2. 3 Identification of Adaptation actions

Adaptation options proposed in the analysis below were drawn from findings produced from research projects conducted on Zanzibar with the particular problems faced by communities engaged in seaweed farming. Floating line rafts were the subject of a pilot study of the Sustainable Coastal Communities an Ecosystems programme, funded by USAID (Msuya et al, 2007). Tubular net rafts adopted from Brazil were re-designed and tested under the MARG I project, funded by the Western Indian Ocean Marine Science Association (Msuya, 2015). These options were further investigated with field visits to Zanzibar in June 2016. Seaweed exporters, government ministries and development organisations were consulted on possible interventions in the seaweed sector.

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[52] Conversation with Hamoud Salim Abdullah on Pemba Island, 4 June 2016

2.4 Economic analysis of Adaptation

The baseline scenario for the seaweed sector is the current practice of growing *spinosum*, using an off-bottom method in low tidal areas. This method consists of farming seaweed seedlings on rope suspended between wooden stakes driven into the seabed (see figure 4). Farmers tend to seaweed lines during low-tide periods (two one-week periods each month) and harvest seaweed after 45 days. In the baseline scenario, farmers—often women—typically farm 50 lines of seaweed, occupying an area of 2000 m^2. Table 2 presents an overview of costs borne by the average off-bottom seaweed farmer. These costs represent capital required to set up, maintain and harvest a seaweed farm plot. Capital costs vary from one to ten years. Labour costs represent hired labour to assist with harvesting,

Figure 4. Off-bottom seaweed farm lines near Fundo Island

Photo by: Alina Tepes

Table 2. Annual costs to farmers for off-bottom seaweed farm

Item	Cost (TZS)
Farming system (ropes, floaters)	19490
Boat construction (shared across a group of farmers)	741
Boat maintenance	86
Diving masks	5000
Knife	500
Machete	1000
Drying rack frame	1400
Palm fronds	1500
Tarps	2500
Labour costs	31913
Total annual costs	63680 TZS

Source: Msuya et al, 2007

Export prices for *spinosum* remain unstable, with great variability within and between years (see figure 1). At these low prices, farmers are experiencing reduced profits from harvesting seaweed, but few have alternative income sources on which to rely.[2] The average annual yield for a seaweed farm is 0.66 tonnes of dried seaweed. Annual cost benefit analyses of current practices yield a positive net cash flow with current prices. Prices for *spinosum* are dynamic and depend on the world market, set by the prices individual foreign buyers are willing to pay exporters for seaweed. In the baseline model, an average price of 500TZS/kg dry is used as the amount paid to farmers for dried *spinosum* harvest. In addition to temporal variability, prices may vary amongst exporters based on initial investments in ropes, boats and other supplies necessary for setting up seaweed farms. This difference is typically equivalent to 40TZS/kg (Msuya et al, 2007). When natural disasters destroy seaweed farms in competitor countries such as Indonesia or the Philippines, demand for *spinosum* sharply increases, driving up the price for seaweed in Zanzibar and generating increased interest amongst farmers in producing seaweed.

Community-based efforts to create value-added products from seaweed, such as creams, soaps and food products generate some annual income in addition to seaweed sales. There is no Zanzibar-wide accounting of these sales, but they are believed to be small in comparison to the sales of dried seaweed crop. An estimate of 1,000,000TZS is included over all farms as an additional annual revenue source (Msuya, 2010).

Rising sea surface temperatures have corresponded with an increase in disease and dieback amongst seaweed crops, especially the more profitable cottonii. Higher disease rates have led farmers to abandon growing this more sensitive variety in favour of low but more certain prices for spinosum. Seaweed experts predict that spinosum can remain a viable crop up to 40 degrees Celsius.[2] The loss of *cottonii* as a viable off-bottom crop and the potential future loss of *spinosum* in warmer waters pose a strong economic threat to the region, with many coastal villagers dependent on the seaweed industry for income. In the baseline scenario for this project appraisal, no *cottonii* is included in production and damage from disease and dieback in the off-bottom method is represented by removing one production cycle from the revenues generated by a seaweed farm (Msuya et al, 2007). Benefits for the baseline scenario are derived from the revenue generated by seven 45-day cycles of *spinosum* farming, valued at 330,920TZS per farm, added to a representative share of income from value-added activities. Msuya (2012) estimated that 200,000TZS in value-added seaweed product such as soaps, flours and juices were produced over a two-year study period. Split over the total farmer population, this amounts to 67TZS per farm. This estimate is probably low, but without a more comprehensive accounting of value-added sales it serves to represent a second income stream for seaweed farmers.

The project appraisal is broken out into financial and economic analyses. The financial analysis compares costs in Table 1 to benefits identified above. The economic analysis also includes non-market costs and benefits. Non-market values for the baseline scenario include 1) economic benefits from the additional revenue generated by export sales after farm-gate prices are accounted for and 2) distributional benefits from the creation of income for rural women. Methods used to calculate distributional weights are described below. In the baseline case, farmer income is multiplied by distributional weights and the share of rural women amongst the farmer population (57% in the baseline). Other values present in the baseline include impacts to farmer health and environmental degradation resulting from the off-bottom farming method. These values are not included as costs in the baseline appraisal, but rather as counterfactual benefits for valuations of adaptation options.

Farmers and some buyers of seaweed have sought to implement new technologies and practices to rejuvenate the sector, with little sustained success. These efforts have included introducing new species of seaweed into the area and growing seaweed off of floating rafts. The floating rafts initiative did not last due to the dissolution of the sponsoring export company.[5] The adaptation options identified below seek to preserve seaweed farming as a poverty mitigation strategy in the face of climate impacts.

Adaptation Option 1. Farm *spinosum* off of deep-water floating rafts.
Continuing work piloted in the 2009 Marine and Coastal Environmental Management Project, this adaptation option assumes that farmers abandon current off-bottom farming practices in favour of growing seaweed on floating rafts in 2-3 meters of seawater. This method has been shown to be more productive in seaweed harvested, as compared to off-bottom growing methods (Msuya et al, 2007).

In comparison to the baseline scenario, this option requires higher costs for both capital and labour expenditures, but also yields additional revenue as the adaptation option allows for full production of eight cycles of seaweed harvest. Costs of constructing, maintaining and harvesting from a floating line farm are outlined in Table 3. Assumptions made in these costs estimates include costs of a family-sized boat (1000000TZS) and sharing amongst farmers (a group of 10 farmers). While smaller and cheaper boats may be sufficient to reach floating lines, larger boats are important to allow for participation from female farmers, who may be displaced by a move to deeper waters and women are less likely to be able to swim. Financial benefits for this adaptation option are similar to revenues in the baseline scenario, though a larger yield is assumed for floating-line farms based on higher productivity observed in early pilot farms. A floating line farm is assumed to produce 0.81 tonnes of dry seaweed, compared to 0.66 tonnes in an off-bottom farm.

Table 3. Annual costs to farmers for floating line seaweed farm

Item	Cost (TZS)
Frame line	3700
Anchor line	2800
Anchor bag ties	8000
Seaweed lines	7500
Tie-tie	3025
Anchors	800
Floaters	1500
Frame construction	640
Boat construction (assumes 1000000TZS boat shared amongst 10 farmers, lasts for 10 years)	10000
Boat maintenance	500
Diving masks	5000
Knife	500
Machete	1000
Drying rack frame	1400
Palm fronds	1500
Tarps	2500
Storage containers	1500
Labour costs	36472
Total annual costs	88337TZS

Source: Msuya et al, 2007

Non-market values accounted for in this adaptation option include economic benefits from marginal income generated by exporter sales of seaweed above the farm-gate price, distributional benefits of income for rural women, health costs from off-bottom farming avoided, deforestation impacts and seagrass destruction avoided from off-bottom farming and the value of fish bycatch attracted to the floating line farms. Additional income from export sales is calculated via the same method as in the baseline scenario, as is the value of distributional weighted income for women, though the share of income received by women is reduced to 50% of the total seaweed farmer population. This lower expected share of female participation is due to the need for men and boys to participate in the water-based installation and maintenance of floating line farms as deeper waters require swimming and diving. A female share of 50% assumes that male farmers will include women in boat- and shore-based activities around farm management and share farm income equitably.[2]

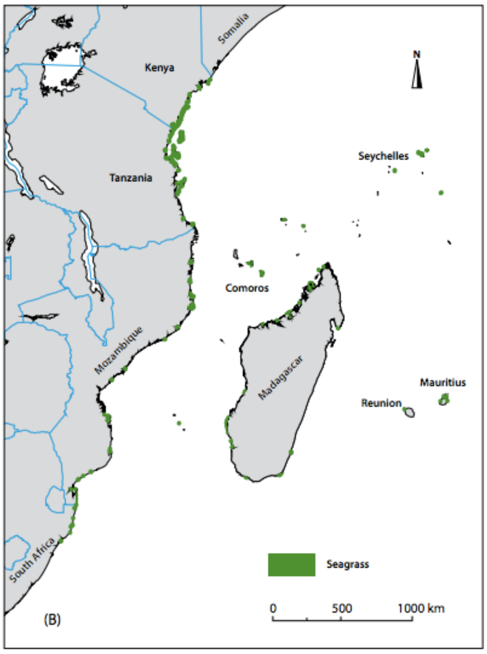
Non-market values for environmental and health-related co-benefits from floating-line farms are calculated in reference to the baseline scenario of off-bottom farming. Health impacts facing off-bottom farmers include fatigue, saltwater rashes and stings from sea urchins, stonefish and rayfish. As medicinal treatments are rare, values for these ailments are calculated by income lost from time spent away from the farm, typically ranging from one week to two months, depending on severity of the sting.[2] Sea urchins commonly live under seaweed lines (see figure 5).

Figure 5. Sea urchins in proximity to seaweed lines off Fundo Island

Photo by: Alina Tepes

Environmental impacts from off-bottom farming include clearing ocean floor for seaweed lines, disrupting marine ecosystems with frequent movement across shallow seabeds and foraging coastal mangrove forests for wood to use as stakes for seaweed lines. In the floating-line scenario, these avoided costs are counted as co-benefits. Ocean floor used for off-bottom lines is assumed to be covered in seagrass before conversion for farming. The waters around Zanzibar support one of the densest seagrass habitats in the Western Indian Ocean (see figure 6). Seagrass beds are an ecologically rich habitat, providing ecosystem services valued annually by an Indonesian study at $2287/ha (Dirhamsyah, 2007). Across the average farm size of 50 lines of seaweed, the value of seagrass saved by the floating lines method amounts to nearly one million TZS. Seagrass has been shown to be a resilient plant, a study of grasses in the Caribbean Sea shows substantial grow-back rates within five years of damage (Farrer, 2010).

Figure 6. Seagrass habitat map in the Western Indian Ocean



Source: (Lugendo, 2015)

Mangrove forests also represent key coastal ecosystem services. A meta-analysis of economic valuations for mangroves estimates an average annual value for mangroves of $28,662/ha (Salem & Mercer, 2012). The appraisal assumes that a 10 m^2 section of mangrove forest is used to source a year's supply of wooden stakes for an average off-bottom seaweed farm.

The final non-market value included in this appraisal is the value of fish bycatch resulting from floating-line seaweed farms. In pilot farms, 2-4 kg of fish were caught in baskets underneath the farms every two days.[2] At an estimated farm-gate price of 4000TZS/kg of fish, this co-benefit amounts to 160,000TZS annually.

Adaptation Option 1.1. Farm *cottonii* off of deep-water floating rafts.
This option assumes the same switch from off-bottom to deep-water floating rafts as the previous option, but substitutes the more valuable *cottonii* species for *spinosum*. Because of lower SSTs in deeper waters, floating-line farms are able to support *cottonii*, even in areas where it is not possible to grow the species using the off-bottom farm method. Before the current fall in prices, *cottonii* was valued at 1,000,000TZS per dry tonne, compared to 500,000TZS for *spinosum*.[53] Costs and yield are assumed to be the same as in Adaptation Option 1. Economic costs and benefits are also similar to those discussed above, adjusted to match the higher income from *cottonii*.

Adaptation Option 1.2. Farm *cottonii* off of deep-water floating rafts with net enhancement.
This option is responsive to the observed loss of up to 50% of seaweed grown on floating rafts during storm periods, in which heavy winds, rains and waves destroy the crop growing on raft farms (Msuya, 2015). An enhanced raft design using PVC pipes and fishing nets has been tested and shown to reduce storm loss to 10% of normal crop levels. The construction of nets replaces the rope inputs for a normal raft, changing the costs for floating rafts slightly, as accounted for in Table 4.

Table 4. Annual costs to farmers for floating line seaweed farm with protective nets

Item	Cost (TZS)
Frame line	0
Anchor line	0
Anchor bag ties	8000
Seaweed lines	0
Tie-tie	3025
Anchors	800
Floaters	1500
Frame construction	640
Boat construction (assumes 1000000TZS boat shared amongst 10 farmers, lasts for 10 years)	10000
Boat maintenance	500
Diving masks	5000
Knife	500
Machete	1000
Drying rack frame	1400
Palm fronds	1500
Tarps	2500
Storage containers	1500
Tubular nets	83666
Labour costs	36472
Total annual costs	158003TZS

Source: *Msuya et al, 2007; Msuya, 2010*

Revenue in this scenario is reduced by 10% to account for loss from storms with tubular nets. Economic costs and benefits remain similar to Options 1 and 1.1, adjusted for revenue.

Adaptation Option 1.3. Farm *cottonii* off of deep-water floating rafts with greenhouse drying facility enhancement.

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[53] Prices based on personal observation of 2015 farm-gate price provided by Dr Flower Msuya

This option responds to losses in seaweed harvest during rainy seasons. Farmers report leaving seaweed on lines in the water when rains come during stormy seasons, as the standard drying process requires sunshine to dry harvested seaweed on beaches. Observed losses to date amount to an entire farm cycle, or one-eighth of annual income.[5] Seaweed exporters also report contaminated harvests that result in lower prices for farmers.[4] The use of sheltered greenhouses to dry seaweed would allow for harvest during rainy seasons and reduce contamination in farmed product. Local estimates for the costs of a simple greenhouse include plastic sheeting and labour, totalling 95,000TZS.[54] If this cost is shared amongst 20 farmers, costs per farm total 4750TZS, which has been added to the costs for this scenario. Revenues for this scenario are reduced by one-eighth to represent the crop lost during rainy seasons. Other parameters remain unchanged, though adjusted for revised revenues.

Adaptation Option 2. Invest in climate information infrastructure to inform future decision points.
Separate from farming method options, this investment presents the costs of gathering data on sea surface temperature around the Unguja and Pemba islands. At present, one temperature logger is operated off Chumbe island near Unguja by the University of Dar es Salaam Institute of Marine Sciences. This option explores the cost of expanding monitoring activities to Pemba island. Temperature loggers cost $600 for a set of 4 that can be rotated for cleaning in four-month intervals. These loggers last for five years, with an amortised cost of $120 for a set. Two sets of loggers are proposed to be installed and maintained, offering a detailed picture of temperature trends for both islands.[55] Labour for monitoring and replacing these monitors is estimated to cost $1,180 annually. Table 5 provides a schedule of these costs.

Benefits from detailed local climate data include information for future decisions on whether to continue to support seaweed farming or to transition to an alternative revenue-generating activity if sea temperatures appear to remain on track to exceed thresholds for farming seaweed. The value of these benefits is difficult to estimate, but can be seem as the value of the seaweed sector past 2040, as this time frame appears to be the point at which climate scenarios substantially differentiate and thus require a decision about the future of the industry.

Table 5. Capital and labour costs to operate long-term sea-surface temperature loggers

Item	Cost (USD)	Lifespan	Annual cost
Loggers, 4 required per site, 2 sites (8)	1200	5 years	240
Transportation to sites	580	1 year	580
Per Diem for installation and cleaning	600	1 year	600
Staff cost for writing monitoring reports	2220	5 years	444
		Total annual costs	1,864

Source: Communication from Dr Christopher Muhando (09/2016)

2.5 Accounting for uncertainty in project appraisals

Uncertainty in this appraisal is present in two forms: cost uncertainty in the short-term and climate risk uncertainty in the long term. Short-term cost uncertainty exists primarily around the upfront investment necessary to construct boats for farmers to use to access floating line seaweed farms. Sturdy boats are especially important for women farmers, who are largely do not know how to swim. A trustworthy boat can allow families and groups of families to access floating farms and perform the planting, harvesting and maintenance necessary to yield the revenues projected in the CBA. Cost estimates for sturdy boats range from 1 million to 3

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[54] Estimate provided by Leonard Mlowe of the Balton company

[55] Budget estimates provided by Dr Christopher Muhando with the Institute of Marine Sciences

million TZS per boat, depending on material used and price negotiated with the manufacturer of the boat. Exact specifications of farming boats are not known—this is one area of the project analysis that would benefit from a local pilot study. High quality boats come with the risk that male villagers will use them primarily for fishing, which can have a higher return for effort. Low quality boats may not be viewed as safe for women to use in deeper waters.

To account for the cost uncertainty around floating farm boats, a sensitivity analysis was conducted in the CBA framework, allowing for the high end of boat costs (3 million TZS). The results from this sensitivity analysis are included in results section below.

Longer term uncertainty in the seaweed farming sector stems from ambiguous climate futures past 2040. Climate projections past this point suggest temperature increases of varying magnitudes, depending on the emissions pathway employed in modelling. The low emissions scenario—RCP 4.5 on Figure 2—projects temperature increases that remain in the range of at least one species of seaweed grown in Zanzibar. However, a higher emissions scenario (RCP 8.5) expect temperatures to exceed the threshold for both *spinosum* and *cottonii* seaweed varieties by 2075. In the case of a high-emissions future, returns from investments in seaweed farming may fall to zero if sea temperatures exceed the threshold for all varieties. In this situation, diversification and exit strategies for communities reliant on seaweed farm income are more appropriate adaptation options than those proposed in the CBA for short and medium-term time frames. Due to uncertainty around climate sensitivity represented by different concentration pathways, policymakers cannot reliably project the viability of seaweed farming past mid-century. A more appropriate use of resources would be to plan for alternative outcomes using a flexible decision-making tools such as Real Options Analysis or decision trees.

Box 1. Real Options Analysis in the seaweed sector
For ambiguous or uncertain situations where information is subject to change in the future, flexible decision-making tools such as Real Options Analysis (ROA) and decision trees allow policymakers to prepare for multiple outcomes while preserving actions that are appropriate across a number of scenarios. In the case of adapting to future climate change, ROA allows policymakers to consider actions given different emissions levels and climate impacts.

For seaweed, the range of possible climate impacts includes high sea surface temperatures that may eliminate any habitat appropriate for farming seaweed in the waters around Zanzibar. If water temperatures surpass the threshold for *spinosum* seaweed to grow, donor and government interventions should focus on developing alternative livelihoods for seaweed farmers. However, before this threshold is reached, significant income can be generated amongst a vulnerable population in coastal villages. Higher incomes from seaweed farming may aid families in diversifying skills ahead of a need to exit the seaweed industry. As both market and climate conditions change, the optimal mix of species of seaweed grown may change in order to minimize disease and meet global demand for various seaweed products.

Short-term actions that increase flexibility across potential climate scenarios include investing in climate information infrastructure, such as sea surface temperature loggers. These loggers allow for careful monitoring of temperatures in the water around Zanzibar, which can be compared to climate projections to identify emissions corresponding climate impacts.

Figure 7 illustrates the phases of a real options analysis using climate monitoring techniques to design flexible adaptation pathways. This technique requires action from policymakers in several phases around decision points, presented here at the years 2020, 2040 and 2080, though these decision points may occur more regularly if adequate information is available to decision makers. Pre-2020 actions include investing in information to generate accurate trends of local climate change. This information is important for the seaweed sector as it can indicate whether the high-concentration or low-concentration climate change projections shown in Figure 2 are more applicable based on observed water temperatures. General temperature trends as well as specific dynamics for water temperatures between and around the two islands should indicate where seaweed can continue to be grown in light of climate change and which areas will require diversification strategies.

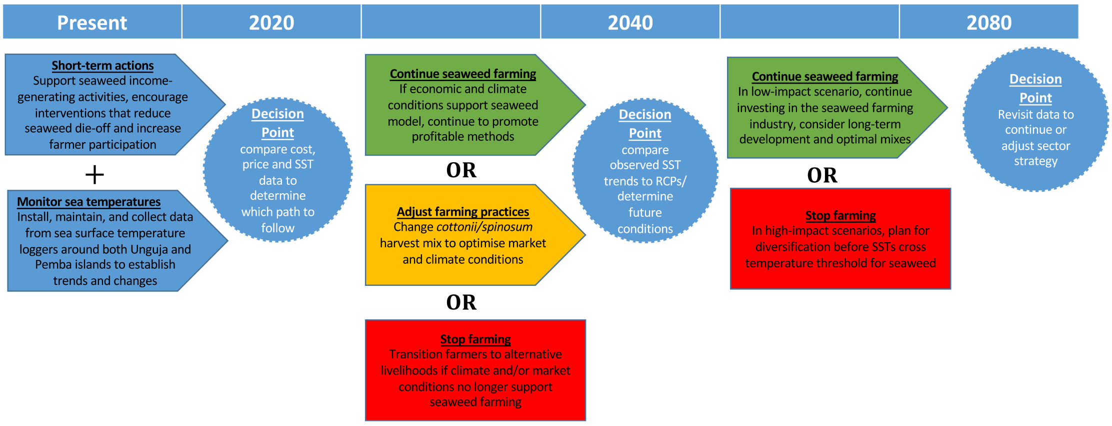

Figure 7. Real Options Analysis framework for seaweed farming in Zanzibar

Given variations in global prices for both *spinosum* and *cottonii* and conditions in other areas of the global seaweed market, strategic adjustments to the mix of seaweed grown on floating rafts can maximise the income generated by seaweed farming in Zanzibar. The development of robust analytical capabilities within the sector and the trade ministry could leverage marketing information for markets around the world to determine optimal species mixes in the Zanzibar seaweed farming sector. A commitment to evaluating the sector's progress regular against the latest available climate and economic data is key for the proper management of seaweed farming in the region.

Short-term investments in information include the installation and maintenance of sea surface temperature loggers around Pemba and Unguja. The Institute of Marine Sciences in Zanzibar currently maintains one such logger, but additional data is needed to understand how different areas around the islands respond to climate change. Three to five additional loggers placed around both islands will provide monthly water temperature meetings at 3 meters of depth. Over several years, temperature data can be compared to projections, which are likely to become more specific as time passes. The additional value that local temperature loggers can provide is in understanding whether and how different areas around Zanzibar respond to climate change.

If temperature increases appear to be following a high-emissions scenario, it may be more beneficial in the long term to consider exit and diversification strategies for seaweed farmers in certain areas. However, where temperatures appear to remain below the survival threshold, seaweed can continue to serve as an important income source for coastal villagers. High-cost, long-term investments such as value-added processing facilities stand to benefit from improved information on future climate patterns. Government ministries are also developing plans for a seaweed research facility which may be used to develop climate-resilient varieties of seaweed in a diversification strategy.[1]

2.6 Considering distributional impacts of interventions

Financial analysis and non-market valuation capture monetised costs and benefits of particular actions, but the impacts of a given action can have other implications, such as the distribution of benefits across the population. This is a particular concern amongst officials in Zanzibar.[3] Seaweed farming has been celebrated as an important industry for women in Zanzibar, as women in rural coastal villages have no other revenue-generating activity to rely upon for additional resources, while men—especially on Unguja—have opportunities to find employment in construction, harvesting and other labour-intensive sectors around the island. Income from seaweed farming is used to purchase clothing, food and make house improvements (Msuya, 2013). Off-bottom farming methods included in the baseline scenario allow for broad participation from women. Across Zanzibar, 57% of seaweed farmers are women. On Unguja island, 93% of all seaweed farmers are women.[2]

The practice of floating line farms risks reducing the benefits women gain from the sector, as the seaweed is grown in deeper waters than are currently used. Women are rarely taught how to swim in the communities currently involved in seaweed farming. To preserve gender benefits in a switch from off-bottom to floating line farming methods, precautions must be taken to enable women to participate without having to enter deep waters. The use of family-sized boats in floating-line seaweed farms can preserve female participation by allowing women to remain on boats to tie seedlings and assemble floating line frames while male farmers install anchors and carry out in-water maintenance. With complete compliance, the family boat model would reduce female participation to 50% of the farmer workforce. Family-sized boats are included in the cost-benefit analyses carried out in this appraisal, but must be implemented with proper education and awareness-raising measures in order to preserve gender benefits from seaweed farming.

In order to capture the benefits of providing an income stream to women in particular, the project appraisals apply distributional weights as discussed in ECONADAPT Deliverable 2.3 (Rouillard et al, 2016). In order to illustrate the value of benefits accrued by a group with no access to regular income—women in coastal villages—distributional weights are calculated by comparing average rural male income in Zanzibar to average female income in Zanzibar:

$$Distributional\ Weight = \frac{Average\ rural\ male\ income}{Average\ rural\ female\ income}$$

Using 2009/2010 data, the ratio of male to female income in rural areas is 3.02, representing a preference for female income due to disparate wages between genders in rural areas (RGZ, 2012). Total benefits are calculated in the economic valuation of the appraisal by substituting weighted income equal to the proportion of farm workforce that women comprise (I.E. in the baseline scenario, 57% of seaweed income would be multiplied by the distributional weight).

In addition to demographic distributional concerns, geographic disparities between Unguja and Pemba should be considered where present. At present, 70-80% of all seaweed farming in Zanzibar is carried out on Pemba island. Little information is available as to differences in climate risks faced by each of the two islands. Investments in climate monitoring technology for both Pemba and Unguja islands could help policymakers track where risk to seaweed farming is greatest and respond appropriately. As the islands have different geographical features, they may experience climate change at different rates and a tailored adaptation plan may be appropriate for each island. Assessing the distribution of climate impacts across the two islands will only be possible with improved climate information.

3. Results

The results of the cost benefit analyses conducted under each of the scenarios discussed above are presented in this section. For the baseline scenario and each adaptation option, the net cash flow is given for a low (3.5%), intermediate (10%) and high (16%) discount rate. These different levels are presented in order to demonstrate results across a number of costing possibilities. While public sector discount rates for long-term projects may be low, private sector rates in developing countries are often much higher than those used in government projects in developed countries. For example, while the United Kingdom advises a 3.5% discount rate be applied in all projects funded by central government and even lower rates be used in long-term projects (UK Government, 2011). This rate does not apply to international development projects and in practice the UK Department for International Development employs a 10% discount rate for Tanzania. This mid-level rate corresponds to the World Bank’s typical practice of calculating 10-12% discount rates in project appraisals. Further, the private sector interest rate for Tanzania was reported as 16.1% in 2015 (World Bank, 2016). This commercial lending rate can also serve as a measure for the opportunity cost of capital in Tanzania, as investors would expect a return equal to this rate if they invested in local banks. As this project appraisal is not specific to a particular funding source, three levels of discount rate are presented.

The results below also present Financial Net Present Values (FNPVs) next to Economic Net Present Values (ENPVs) calculated over a 35-year period. These two classifications are separated out in order to show returns for private market investments (FNPV) as well as returns that include non-market social values that cannot be directly monetised but result from any particular intervention (ENPV). The latter should be of interest to donors with a focus on improving social welfare in addition to generating financial returns. Social, environmental and economic goods that are not directly accrued by farmers are included in the economic net present value calculation but not the financial NPV.

Finally, financial and economic Internal Rates of Return (IRR) are generated for the baseline scenario and each adaptation option. This number represents the return on resources invested into the project (costs), presented as a comparison to returns on the same resources if they were invested elsewhere. For seaweed farming, most IRRs are high as the capital required for a successful farm cycle is relatively low.

3.1 Baseline Scenario

The baseline scenario, farming *spinosum* seaweed using the off-bottom method, is presented here with positive NPVs and a high IRR. It should be noted that negative non-market costs for this scenario are not counted against the financial returns as they are included as benefits in alternative options that avoid these costs. Cash flows also assume that the current price for *spinosum* will hold steady. While it is at a relative low point, there are no indicators that it will substantially rise, though extreme weather events in the South Indian and Pacific Oceans have spurred price increases in the Zanzibar market in the past.

Baseline Scenario (TZS)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	5,321,193	17,532,313	2,552,273	8,440,377	1,633,092	5,427,779
Zanzibar Total	122,387,449,632	403,243,204,627	58,702,286,605	194,128,687,593	37,561,128,814	124,838,919,806

Baseline Scenario (USD)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	2436	8027	1168	3864	747	2485
Zanzibar Total	56,038,209	184,635,166	26,878,336	88,886,761	17,198,319	57,160,677

Baseline Scenario	FNPV	ENPV
IRR[56]	353%	1036%

Baseline Scenario	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Benefit/Cost Ratio	5.12	14.55	5.09	14.48	5.07	14.43

3.2 Adaptation Options

Adaptation Option 1 Farm *spinosum* off of deep-water floating rafts

The first adaptation option—growing *spinosum* on floating rafts—has much higher ENPV values than the baseline in part because benefits for this option include avoiding non-market economic, environmental and social costs associated with off-bottom farms, including the value of marine ecosystem destruction avoided by floating line methods and health impacts in farmers that appear only in off-bottom farming.

Option 1 (TZS)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	6,226,022	43,971,172	2,945,511	21,145,920	1,853,306	13,582,862
Zanzibar Total	143,198,527,988	1,011,336,971,899,67	67,746,756,522	486,356,177,648	42,626,042,721	312,405,829,364

Option 1 (USD)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	2,850	20,133	1,348	9,682	848	6219
Zanzibar Total	65,567,091	463,066,379	31,019,577	222,690,557	19,517,418	143,042,962

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[56] N.B. Rates of return in this analysis are reflective of costs to farmers to deliver seaweed product to exporters for farm-gate payment. Exporting companies face additional costs in capital, labour and transaction costs to export seaweed. These costs are not included in the farm-level analysis.

Option 1	FNPV	ENPV
IRR	166%	988%

Option 1	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Benefit/Cost Ratio	4.42	25.09	4.33	24.60	4.27	24.23

Adaptation Option 1.1 Farm *cottonii* off of deep-water floating rafts.

Option 1.1 (TZS)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	14,293,889	47,627,257	6,835,772	22,908,856	4,360,449	14,719,015
Zanzibar Total	328,759,461,461	1,095,426,919,112	157,222,755,989	526,903,678,306	100,290,335,084	338,537,338,891

Option 1.1 (USD)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	6,545	21,807	3,130	10,489	1,997	6,739
Zanzibar Total	150,530,889	501,569,102	71,988,441	241,256,262	45,920,483	155,007,939

Option 1.1	FNPV	ENPV
IRR	347%%	1078%

Option 1.1	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Benefit/Cost Ratio	8.84	27.09	8.67	26.56	8.54	26.17

Adaptation Option 1.2 Farm *cottonii* off of deep-water floating rafts with net enhancement

Option 1.2 (TZS)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	16,369,676	55,455,376	7,841,536	26,688,348	5,009,906	17,156,048
Zanzibar Total	376,502,553,613	1,275,473,648,627	180,355,335,414	613,832,014,545	115,227,855,708	394,589,093,437

Option 1.2 (USD)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	7,495	25,392	3,590	12,220	2,293	7,855
Zanzibar Total	172,391,279	584,008,081	82,580,281	281,058,615	52,760,007	180,672,662

Option 1.2	FNPV	ENPV
IRR	348%	1072%

Option 1.2	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Benefit/Cost Ratio	6.10	18.26	6.05	18.10	6.00	17.97

Adaptation Option 1.3 Farm *cottonii* off of deep-water floating rafts with greenhouse drying facility enhancement.

Option 1.3 (TZS)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	12,181,714	44,500,867	5,816,943	21,401,116	3,703,471	13,747,093
Zanzibar Total	280,179,425,561	1,023,519,949,940	133,789,696,594	492,225,661,676	85,179,838,834	316,183,144,182

Option 1.3 (USD)	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Per farm	5,577	20,376	2,663	9,799	1,695	6,294
Zanzibar Total	128,287,282	468,644,666	61,259,018	225,378,050	39,001,757	144,772,502

Option 1.3	FNPV	ENPV
IRR	295%	998%

Option 1.3	FNPV (3.5%)	ENPV (3.5%)	FNPV (10%)	ENPV (10%)	FNPV (16%)	ENPV (16%)
Benefit/Cost Ratio	7.35	24.62	7.21	24.15	7.11	23.80

3.3 Sensitivity Analyses

Cost Sensitivities

Internal rates of return are listed below for the baseline and adaptation option scenarios under higher cost assumptions for boat costs. These values assume family-sized boat construction would cost 3,000,000TZS instead of 1,000,000TZS as assumed in the above analyses, and that boat maintenance costs 15,000TZS annually rather than 5,000TZS as in the main analysis. The model maintains the assumption that 10 farmers would share a boat and related maintenance expenses. As the baseline scenario does not require family-sized boats, there is no change from high boat costs observed in the cost benefit analysis for the off-bottom farming. For comparison, IRRs from the primary analysis described above are included in parentheses next to the high-cost IRRS in the table below.

High-cost boat scenario	FNPV IRR	ENPV IRR
Baseline	353% *(353%)*	1036% *(1036%)*
Option 1	85% *(165%)*	532% *(998%)*
Option 1.1	182% *(346%)*	575% *(1078%)*
Option 1.2	197% *(348%)*	616% *(1072%)*
Option 1.3	156% *(295%)*	535% *(998%)*

High-cost boat scenario	FNPV BCR @ 3.5% discount	ENPV BCR @ 3.5% discount	FNPV BCR @ 10% discount	ENPV BCR @ 10% discount	FNPV BCR @ 16% discount	ENPV BCR @ 16% discount
Baseline	2.66	10.32	2.65	10.27	2.64	10.23
Option 1	3.46	19.81	3.34	19.13	3.25	18.62
Option 1.1	6.92	21.40	6.68	20.66	6.51	20.11
Option 1.2	5.27	15.78	5.16	15.47	5.08	15.22
Option 1.3	5.82	19.57	5.63	18.91	5.48	18.42

The high-cost IRRs show a significant reduction in returns on investment, around 40% lower than the values found in primary analysis. However, specific values for IRRs may not be more important in this analysis than general trends. All IRRs are positive, at rates higher than the opportunity cost for capital in the region. This is indicative that, at an annual return rate, seaweed farming is a good investment due to its short (45-day) return on investment. The highest cost for any of the adaptation options is the construction of a family-sized boat. In a high-cost boat scenario, the lowest IRR remains at 85%, still well above the commercial lending rate.

Price Sensitivities

Prices paid for both *spinosum* and *cottonii* can have significant impacts on participation in seaweed farming. It is expected that males will exit the sector and seek alternative income when prices for *spinosum* fall below 600TZS/kg, while females will continue farming due to a lack of alterative incomes available to them.[2] *Spinosum* prices are currently amongst the lowest levels in recent history, at 300TZS/kg, and are highly sensitive to global demand, with disruptions in supply from competitors leading to an increase in prices offered for seaweed in Zanzibar. *Cottonii* prices appear to be relatively stable around 1000TZS/kg. In the following price sensitivity scenarios, both lower and higher prices for *spinosum* are modelled and *cottonii* prices are assumed to remain constant.

The high-price scenario assumes that prices will continue to grow along a similar trend to the past ten years. In order to model this trend, historical prices were regressed over time to derive an annual average change in price. This yielded 32TZS/kg annually for *spinosum* and 76TZS/kg annually for *cottonii*. Calculate out over 10 years, this trend provides a high farm-gate price of 821TZS/kg and 1763TZS/kg in 2025 for *spinosum* and *cottonii*, respectively. If export prices are assumed to change proportionately to farm-gate prices, then export prices would be $424/tonne and $832/tonne for *spinosum* and *cottonii* in 2025, respectively, in a high-price scenario.

The low-price scenario assumes that historical prices will provide a picture of the future market. A weighted average was calculated for farm-gate prices over the past 10 years, with recent prices weighted highest and distant prices lowest. This exercise yielded a weighted average price of 380TZS/kg for *spinosum* and 798TZS/kg for *cottonii*. Adjusting export prices proportionately provides $196/tonne for *spinosum* and $376/tonne for *cottonii* in the low-price scenario.

Neither scenario accounts for farmer response to price levels, so the IRR and BCR values should be viewed as a per-farm rather than an aggregate evaluation. Increased competition of both farmers and exporters within Zanzibar in a high-price scenario may reduce the benefits realised, while in a low-price scenario, many farmers may exit the market and exporters may struggle to meet demand from foreign buyers. These effects are not modelled in the following sensitivity analysis. As with the high-cost sensitivity analysis, IRR values from the adaptation option analysis in section 3.2 are included next to model outputs for reference.

High-price scenario	FNPV IRR *(primary value)*	ENPV IRR *(primary value)*
Baseline	592% *(353%)*	1708% *(1036%)*
Option 1	282% *(166%)*	1299% *(998%)*
Option 1.1	618% *(346%)*	1496% *(1078%)*
Option 1.2	627% *(348%)*	1553% *(1072%)*
Option 1.3	528% *(295%)*	1360% *(998%)*

High-price scenario	FNPV BCR @ 3.5% discount	ENPV BCR @ 3.5% discount	FNPV BCR @ 10% discount	ENPV BCR @ 10% discount	FNPV BCR @ 16% discount	ENPV BCR @ 16% discount
Baseline	8.40	23.91	8.36	23.80	8.33	23.71
Option 1	7.11	32.61	7.01	31.98	7.26	31.50
Option 1.1	15.58	37.55	15.28	36.82	15.05	36.27
Option 1.2	10.75	26.40	10.66	26.16	10.58	25.98
Option 1.3	12.96	33.51	12.72	32.88	12.54	32.40

Low-price scenario	FNPV IRR *(primary value)*	ENPV IRR *(primary value)*
Baseline	260% *(353%)*	783% *(1036%)*
Option 1	121% *(166%)*	885% *(998%)*
Option 1.1	273% *(346%)*	967% *(1078%)*
Option 1.2	273% *(348%)*	944% *(1072%)*
Option 1.3	232% *(295%)*	902% *(998%)*

Low-price scenario	FNPV BCR @ 3.5% discount	ENPV BCR @ 3.5% discount	FNPV BCR @ 10% discount	ENPV BCR @ 10% discount	FNPV BCR @ 16% discount	ENPV BCR @ 16% discount
Baseline	3.88	11.03	3.86	10.98	3.85	10.94
Option 1	3.35	22.26	3.28	21.83	3.24	21.51
Option 1.1	7.05	24.31	6.91	23.83	6.81	23.48
Option 1.2	4.87	16.10	4.82	15.96	4.79	15.84
Option 1.3	5.86	22.25	5.75	21.83	5.67	21.51

Price sensitivities in *spinosum* seaweed only affects the baseline and Option 1 analyses above, as the others model a *cottonii*-only seaweed farm. BCRs and IRRs indicate a substantial strengthening of returns from higher prices and marginal lowering of returns from a price drop.

Across all scenarios, appraisals including non-market costs and benefits present much higher returns than financial cash flows alone. This indicates that there is significant social value in the adaptation options. Economic, environmental and social benefits of all interventions indicate ample opportunity for public investment in the sector.

In terms of implementation of any of these options, a financial mechanism to fund the up-front costs of boats is likely necessary, as seaweed farmers have limited access to capital and seaweed buyers lack confidence in their own ability to recover long-term investments in specific farms. Community-based savings and credit cooperatives (SACOs) may provide a demonstrative model for community investment at the level required by these interventions. One such organisation has been successful in receiving a private bank loan for community investments in Kiyuli village on Pemba island.[57] Community-based financial institutions may require high returns. A micro-lending facility in Mlingotini lends money at a 48% interest rate (Msuya et al, 2007). All of the adaptation options maintain positive NPVs at this rate.

The summative numbers presented above do not include finite valuation of future climate change risks, as information around specific impacts of climate change are ambiguous at the time of publication and the primary relevance of future climate impacts—whether crucial temperature thresholds are reached—are not discernible from current information. The adaptation options presented are responsive to observed impacts of climate change by relocating farms to deeper waters that are less affected by increasing SSTs. Future climate change impacts are addressed by the recommendation to invest in temperature monitoring equipment around both Unguja and Pemba islands, but these costs are not reflected in scenario-specific cost-benefit analyses as the benefits of access to climate information in 2040 are not calculable at this time.

These results indicate positive value in the form of both financial returns and social welfare generated from all adaptation interventions included in the analysis. The baseline scenario should be viewed as an indicative estimate given that it assumes that 1) temperature increases will remain below 2°C from current maximums, 2) that prices for *spinosum* will not drop below current lows and 3) that non-market costs will not impact financial cash flows over the course of the analysis. With these assumptions, the baseline scenario has higher IRRs and benefit-cost ratios (BCRs) than some the adaptation options counting financial benefits alone, but when non-market benefits are included, all adaptation options have higher BCRs. These options should be implemented as soon as feasible in order to maximise social welfare in the seaweed sector.

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[57] Conversation with Ali Hamad of the Food and Agricultural Organisation in Zanzibar Town, 7 June 2016

4. Discussion

4.1 Potential barriers to interventions

Potential barriers to implementation of the adaptation options presented in this analysis include a reticence to convert to floating line farms for both financial and cultural reasons. Financial barriers to floating raft farms concern the capital investments required to provide family-sized boats to groups of farmers. These boats, at 1,000,000-3,000,000TZS a piece, require investments larger than farmers alone are likely to be able to make to acquire new boats specifically for the purpose of seaweed farming. A community loan scheme or donor-supported financing mechanism may aid in providing boats to farmers, but a delay in complete uptake is to be expected. The current population of seaweed farmers would require at least 2300 family-sized boats to service a similar number of floating raft farms. Existing family-sized boats are mainly used for fishing. Using boats for the best economic use for respective communities may require decision-making processes to be developed by groups that share family-size boats that can be used for both fishing and farming.

A cultural barrier is present in growing concern amongst villagers for the safety of women farmers in deeper waters. Government departments noted existing concerns over women engaging in off-bottom seaweed at growing distances from shore, particularly in shallow waters where coral reefs create a shelf of shallow sea floor far into the ocean.[3] The use of family-sized boats in floating-line farms trust amongst villagers in the safety of the boats for women to take them to deeper waters to aid men in the installation and maintenance of floating line farms. Education campaigns, such as those currently provided by the Food and Agriculture Organization and the Zanzibar Seaweed Cluster Initiative may be effective in educating farmers about safety practices and building trust in floating rafts farming methods.

Spatial constraints could test coastal governance structures as demand for participation in seaweed farming increases. Though participation in seaweed farming is reduced during times of low market prices for the crop, pressure from inland farmers transitioning to coastal agricultural practices and continued development from the hospitality industry along Zanzibar's coasts have begun identify challenges to the open-access model that villages have relied up on to govern seaweed farm plots. In the past, a community-governed allocation system has been in place in which village residents have access to coastal property and outsiders are required to seek permission to use nearby ocean floor for seaweed farming. A shift to floating raft farming removes some pressure on the distribution of sea floor, as there is greater area available at further distances from the shore. However, deeper waters also serve as access routes for fishing boats, transport vessels and other seagoing activities. Proper identification of seaweed farms and steps to ensure access for other users of the marine environment are necessary to sustain farming in deeper waters. In addition to these challenges, the Zanzibar government is discussing a goal to increase the number of seaweed farmers by 50% in the next five years.

The analysis carried out in this deliverable assumes a static population of farmers, though the tools used in the exercise can easily be adjusted for a larger farm population, as both financial and non-market values are calculated on a per-farm basis. Any increase in farmer population, though, is likely to complicate governance issues discussed in the previous paragraph. Further, changes in farmer population may have spillover effects on non-market values represented in the economic analyses.

4.2 Market trends in seaweed farming

Though the third largest supplier of carrageenan seaweed in the world, Zanzibar is dwarfed by the first and second largest suppliers—Indonesia and the Philippines. Compared to 2.3% of the global seaweed market produced in all of Tanzania in 2010, Indonesia produced 61% of global supply and the Philippines produced 32% of the market that same year (Cai et al, 2015). In Tanzania, 95% of the seaweed produced in the country is farmed in Zanzibar. Because of the market share controlled by Indonesia and the Philippines, any disruption in seaweed farming in either country can have a substantial effect on global demand for seaweed, raising prices offered for seaweed crop in Zanzibar, with a corresponding interest in farming on the islands. Spikes in prices paid to Zanzibar farmers can be matched with damaging typhoons in the two competitor countries.

Climate change is already credited with playing a role in an increased rate of damaging storms in the South Pacific and future climate change is expected to bring more frequent and intense weather events, most concentrated in the areas that currently experience extreme weather events (IPCC, 2013B). With an increased occurrence of extreme events in the first and second producers of seaweed, frequency of high demand for seaweed in Zanzibar could also increase in the future. As long as the ocean temperatures around Zanzibar are able to support seaweed farming, the industry may benefit from a competitive advantage over competitors situated in areas prone to destructive extreme weather events.

4.3 Analytical considerations

Distributional effects of seaweed farming as well as discount rates applied in analysis both have important implications for interpreting the findings of this analysis. Distributional impacts of any intervention are of high interest to policymakers as seaweed farming represents a unique source of income for women in coastal villages. With no alternative, adverse impacts on women farmers should be avoided wherever possible. Introducing floating raft farms may bring a reduction in female farmer participation as a proportion of all farmers, shifting from the *status quo* female farmer share of 57% to 50%. In Unguja, this switch would be more pronounced; currently over 90% of seaweed farmers in Unguja are female. Though the share of female farmers drops in the adaptation options, non-market values of distribution-weighted income to females increases in all of the adaptation options over the baseline scenario, due to higher total incomes. Over the long-term, the seaweed farming growth strategy could target equal growth across genders in order to preserve maximum distributional benefits from the sector.

Deciding which discount rate to apply in cost benefit analysis spanning a multi-year investment project such as seaweed farming can have significant impacts on the economic findings of analyses. In the interventions proposed above, the longest return period is a 10-year payback on family-sized boats. Over 10 years, a high discount rate can still have a much larger impact on these costs than a lower rate. The advantages and contexts of the different rates presented in this project appraisal are discussed briefly at the start of the Section 3. Ultimately, different audiences may employ different discount rates. The country-specific discount rate for Tanzania as set by the UK Department for International Development is 10%, while the national rate for commercial lending (the opportunity cost of capital) is over 16%. Across all rates, returns on adaptation options are positive, with IRRs higher than the commercial lending rate and BCRs over 1.0. This indicates that any option presented in this study would be a worthy investment in both financial and economic terms.

A crucial point to make in this analysis is the need for continued monitoring and follow-up on long-term plans for the seaweed sector once local temperature data is available to plot against future climate change projections. An immediate switch to floating farms with no further attention to potential climate impacts could have disastrous impacts for communities reliant on seaweed crop production if sea surface temperatures exceed viable thresholds for *spinosum*. Alternatively, a managed transition to alternative livelihoods could have minimal adverse impacts on farm-reliant villages.

5. Conclusions

This case study presented a sector with important social and economic benefits that is already suffering the impacts of climate change in the seaweed farming industry on the islands of Zanzibar off of Africa's East coast. Over 20,000 farmers depend on seaweed sales for income but warming shallow waters over the past fifteen years have eliminated the more valuable *cottonii* species from the market. Without intervention, the more resilient *spinosum* species could also be threatened by warming waters. Future climate change impacts are expected to continue warming the waters that seaweed is grown in, though the extent to which these temperatures will increase is uncertain, based on the two alternative greenhouse gas concentration pathways presented in section 2.

Interventions recommended included a variety of deep-water floating raft farm methods to replace the current off-bottom shallow water method as well as a long-term real options analysis programme to gather information on temperature changes around the islands for use in long-term strategic decisions based on likely climate scenarios. In appraising the floating raft farm options, 35-year cost benefit analyses were calculated under a number of discount rates, ranging from official rates to higher commercial lending rates. Financial cash flow analysis yields high internal rates of return for these options above the social opportunity cost of capital. Economic appraisals include non-market values for economic benefits, environmental services provided by mangrove forests and seagrass beds spared by the floating rafts, social benefits from health costs avoided and the value of distribution-weighted income to rural women. Economic value calculations boast IRRs five to ten times the financial values, suggesting large values in social welfare generated by the adaptation options presented.

The Real Options Analysis included in this project appraisal is designed to build flexibility into long-term decision-making for the seaweed sector by investing in the short-term in information that will be used to inform long-term strategic planning in the sector. Despite uncertainty between climate scenarios that cover the threshold temperature for seaweed farming, investments in information can provide the data necessary for Zanzibar decision makers to chart a path for the sector from 2020 onwards.

The importance of non-market values and the flexibility of two-stage decision making are two key takeaways from this case study. While global damage assessments have long recognised inequities in climate impacts across regions in the world and between national income groups, this case study highlighted an important dimension of climate impacts by focusing on gender impacts in a particular sector. With distributional weights included in economic valuation, the appraisal demonstrates how a political obstacle can be considered quantitatively alongside other costs and benefits. This case also provides an example of a situation where the different climate projections will have very different realities for the seaweed sector. A Real Options Analysis approach demonstrates how investments in improving local information unavailable from climate models can improve a future decision. By identifying a future decision point, investments can be made in the short- and medium-term time frames while preparing information to aid in a later decision. This two-stage process can be adopted in many adaptation contexts that are reliant on evidence of future climate change that is not available in the present time.

Many of the interventions proposed herein are based off of one-time experiments or ideas that remain untested in the realities of coastal villages. Floating line farms have been successfully operated and are widespread in major seaweed-producing countries like Indonesia and the Philippines, but have not yet been taken up by farmers in Zanzibar outside of a project intended to study their effectiveness. Tubular nets have only been used in an experimental sense in Zanzibar, despite being the method of choice in Brazil and India, and drying greenhouses have not been tried in the form suggested in Option 1.3. Close collaboration with researchers and careful documentation of each of the options implemented is necessary to build an empirical stock of evidence for each method. Outside the seaweed context, this case study can serve as an example for designing climate adaptation options in sectors where many stakeholders are active and issues of uncertainty exist as impediments to investment. Successful implementation will require learning between stakeholders in order to deliver interventions that work for the communities they are intended to assist.

Future research in improving the resolution of climate models, understanding the sensitivity of seaweed species and understanding how coastal communities are responding to increased environmental and social pressure on their community resources are all applicable to this project. Accounting for the value of climate information in an economic context is another field of research that extends the work of this case study.

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