Climate risk analysis for adaptation planning in Uganda's agricultural sector

An assessment of maize and coffee value chains

On behalf of

Potsdam Institute for Climate Impact Research

PIK

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Federal Ministry for Economic Cooperation and Development

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Authors' contributions

Christoph Gornott and Sophie von Loeben coordinated and edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Christoph Gornott, Lisa Murken and Sophie von Loeben designed the study approach with steering input from stakeholders. Sophie von Loeben and Eres Awori coordinated the stakeholder engagement process. Paula Romanovska and Albina Muzafarova performed the climate analysis in Chapter 2. Abel Chemura analysed climate impacts on maize yields and the risk mitigation potential of improved maize seeds using crop models in Chapter 3. David Abigaba analysed climate impacts on coffee suitability and the risk mitigation potential of agroforestry in Chapter 4 under the supervision of Abel Chemura. Sophie von Loeben and Eres Awori, with inputs from Sophia Weituschat, analysed climate impacts on maize and coffee processing, aggregation and marketing based on interviews that were conducted under the coordination of Eres Awori. Matti Cartsburg and Steffen Noleppa together with the support of Juliane Kaufmann and Lina Staubach conducted the cost-benefit analyses of adaptation strategies in Chapter 3 and 4. Antonia Zvolsky contributed to Chapter 1 and 3. Carla Cronauer contributed to Chapter 4. Naima Lipka and Julia Tomalka contributed the sections on Gender in Chapter 3 and 4. Lisa Murken and John Adriko contributed to the Box and sections on Land Tenure.

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Abstract

Climate change increasingly affects the productivity of Uganda's agricultural sector, with droughts and precipitation variability challenging livelihoods as well as the economic prospects of entire value chains. The country's national policies and plans on climate change and agriculture recognise that investing in effective adaptation is key to mitigating climate risks. Yet, limited information on current and projected climate impacts on the different steps of agricultural value chains is available on which sound adaptation decisions can be based. This study aims to address this gap by providing a comprehensive climate risk analysis for two selected agricultural value chains: maize, a major food crop, and coffee (Robusta and Arabica), a major export crop. Based on ten global climate models (GCMs), we project how temperature and precipitation is expected to change under two greenhouse gas (GHG) emissions scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario) and how these impacts might affect maize and coffee production. In addition, interviews with key actors involved in post-harvest activities (including aggregation, processing, marketing and distribution) have been conducted, to better understand how climate change affects later stages of the value chains. Based on the projected impact analysis as well as on a participatory process with various stakeholders in Uganda, four adaptation strategies were selected for our analysis: improved maize varieties, improved maize storage, agroforestry systems for coffee production and improved coffee storage. As part of our adaptation analysis, we consider aspects of risk mitigation potential, cost-effectiveness and gender. The results have been complemented and cross-checked by expert- and literature-based assessments and two stakeholder workshops.

The results of this climate risk analysis show that, in response to increasing GHG concentrations, temperatures in Uganda will increase by 1.1 °C under the low emissions scenario (SSP1-RCP2.6) and by 1.5 °C under the high emissions scenario (SSP3-RCP7.0) by 2050, compared to 2004. The number of hot days and hot nights are projected to steadily increase, with severe temperature extremes especially in the north of Uganda. The majority of models project slight future increases of annual precipitation, but precipitation projections are subjected to high model uncertainties.

Climatic conditions also substantially affect crop production in Uganda. The projected changes translate into modelled maize yield losses of up to 26.8 % by the end of the century, especially in high maize potential areas such as parts of the Central and Eastern regions, as well as in shifts and reductions in suitability of land to grow coffee. Arabica coffee is particularly affected with projected suitability losses of up to 20 % until 2050. Robusta suitability will only slightly, but progressively, reduce with time with higher losses expected under the high emissions scenario (SSP3-RCP7.0) of up to 5 %. Climate impacts are also felt at later stages of the value chain, significantly affecting post-harvest products, activities and finances, as well as the overall composition of the value chain. The analyses of the four adaptation strategies show that improved maize varieties and agroforestry for coffee production are examples of promising agricultural practices, both in terms of their potential to buffer projected losses due to climate change, but also in terms of cost efficiency. Beyond that, improved storage is a cost-efficient approach for both, maize and coffee, to reduce post-harvest losses and secure the products' quality. Implementation of these strategies should take farmer types and their local context into consideration and be seen as part of broader resilience-building strategies. Aspects of inequality, such as gender and land tenure, should feed into the design of adaptation strategies. Generally, taking dynamics of the broader value chain into consideration will help to ensure the feasibility and long-term successful uptake of adaptation strategies.

KEYWORDS

agriculture

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climate change adaptation

climate impacts

climate risk

coffee

cost benefit analysis

maize

Uganda

value chains

Foreword

Climate change is one of the greatest challenges of our time, affecting every aspect of our lives and posing risks to people's livelihoods, whole ecosystems, and ultimately the national economic development efforts. Adapting to the impacts of climate change is a top priority for our country and for the National Agricultural Research Organization (NARO). The National Agricultural Research Organization (NARO), was established as a body corporate by the National Agricultural Research Act of 2005 with the mandate to coordinate and oversee all aspects of agricultural research in Uganda in the areas of crops, livestock, fisheries, forestry, agro-machinery, natural resources, and socio-economics. Climate action and responsiveness are some of the core research drivers for NARO. However, to achieve an inclusive, climate-resilient transformation, stakeholders need comprehensive knowledge of current and projected climate risks and their impacts to back up their adaptation decisions. This applies especially to highly climate-vulnerable sectors, like agriculture, as climate change presents a major challenge to the vitality of entire agricultural value chains. Climate-resilient agriculture is therefore a prerequisite to improving rural livelihoods, ensuring food security, as well as product quality in Uganda, which is competitive in international markets.

With Uganda's National Climate Change Policy in 2015 and the third National Development Plan (NDP III) guiding efforts toward achieving our Vision 2040, our country has developed a sound policy framework to tackle the challenges which climate change entails. Furthermore, the National Climate Change Act 2021 provides a framework governing the national response to climate change. On an international level, Uganda is committed to the implementation of the Paris Agreement and has adopted various national policies, including our Nationally Determined Contribution (NDC), as well as a National Adaptation Plan for the Agricultural Sector (NAP-Ag), which emphasizes the importance of investing in effective adaptation strategies as key to tackling climate risks. The National Agricultural Research Organisation contributes to the National Adaptation Plan for the Agriculture Sector (NAP-Ag) by promoting climate-resilient food systems and value chains.

The conception of the present study addresses this need by providing a comprehensive climate risk analysis focusing on two selected agricultural value chains (maize, as a fundamental food crop – and coffee, a major export crop). These examples shall encourage policymakers and practitioners to incorporate and adopt these findings into national and subnational adaptation planning and implementation. The study highlights the link between agriculture and the environment and will support Uganda in implementing science-based climate change adaptation action. This requires the consideration of whole value chains to entire food systems. Now, more than ever, it is important for various actors to work together for inclusive and climate-resilient economies.

Dr. Yona Baguma
Director General, National Agricultural Research Organization

NARO

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List of abbreviations

AEZ	Agro-Ecological Zone
ASSP	Agriculture Sector Strategic Plan
AUC	area under the curve
BCR	Benefit-Cost Ratio
BRT	Boosted regression trees
CBA	Cost Benefit Analysis
CIAT	Centre for Tropical Agriculture
CMIP	Coupled Model Intercomparison Project
CWD	Coffee Wilt Disease
DRC	Democratic Republic of the Congo
DSSAT	Decision Support System for Agrotechnology Transfer
FAO	Food and Agriculture Organization of the United Nations
FAQ	Fair Average Quality
FGD	Focus Group Discussions
GBIF	Global Biodiversity Facility
GCM	Global Climate Model
GHG	Greenhouse Gas Emissions
HST	Hermetic Storage Technologies
IDRC	International Development Research Centre
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LMIC	Low- and Middle-Income Countries
m ASL	meters Above Sea Level
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MWE	Ministry of Water and Environment
NAP	National Adaptation Plan
NAPA	National Adaptation Programmes of Action
NAP-Ag	National Adaptation Plan for the Agriculture Sector
NARO	National Agricultural Research Organization
NDC	Nationally Determined Contribution
NPV	Net Present Value
OPV	Open-Pollinated Varieties
PRUDEV	Promoting Rural Development in Uganda
RELAPU	Responsible Land Policy in Uganda
REDD+	Reducing emissions from Deforestation and forest degradation in developing countries
RF	Random Forest
SACCO	Savings and Credit Cooperative Organisations
SPAM	Spatial Production Allocation Model
SSP	Shared Socioeconomic Pathway
SVM	Support Vector Machine
UBOS	Uganda Bureau of Statistics
UCDA	Uganda Coffee Development Authority
VAT	Value-Added Tax
VSLA	Village Savings and Loan Association
WEMA	Water Efficient Maize for Africa
WFP	World Food Programme

1. Introduction

The agricultural sector is particularly vulnerable to climate change due to its high dependency on climatic factors. Extreme weather events, such as droughts or floods, and slow-onset hazards, such as temperature rise or season shifts, increasingly threaten agricultural production and thereby pose a serious threat to rural livelihoods with cascading economic losses along the entire value chain. Climate change may reduce yields, shrink areas suitable to grow certain crops and increase the risk of pest and diseases. At later stages of the value chain, reduced availability of crops may threaten business operations. Furthermore, changes in climatic factors can significantly impact a product's quality during aggregation and processing.

> The present study provides an in-depth analysis of climate risks for selected agricultural value chains in Uganda together with an assessment of the feasibility, costs and benefits of selected adaptation strategies, as well as policy recommendations.

increasing risks, including Uganda's National Climate Change Policy (2015) or the third National Development Plan (NDP III). The National Climate Change Act (2021) provides a framework governing the national response to climate change. As part of Uganda's commitments to the Paris Agreement, it has adopted various national policies, including the Nationally Determined Contribution (NDC), as well as a National Adaptation Plan for the Agricultural Sector (NAP-Ag). Priorities for climate change adaptation in the agricultural sector outlined in these policies and plans include climate-smart agriculture, as well as expanding value addition, post-harvest handling and storage and access to markets. Maize, a major staple food in Uganda and coffee, the most important export commodity, are two crops that have a significant impact on Uganda's food security and export earnings. To ensure that both crops can be produced within resilient agricultural systems will be key to help Uganda achieve an inclusive, productive, and climate-resilient transformation of its agricultural sector.

However, limited information on current and projected climate risks and their impacts on the different steps of the agricultural value chain hinder science-based and forward-looking planning. A better understanding of projected climate impacts on the whole value chains, together with sound information on the performance of adaptation strategies, is important to guide, incentivise and accelerate public and private sector investments for climate-resilient agricultural development. This study aims to address this gap by providing a comprehensive climate risk analysis for the maize and coffee value chains in Uganda. Driven by ten global climate models (GCMs) under two climate change scenarios, the SSP1-RCP2.6 low emissions scenario and the SSP3-RCP7.0 high emissions scenario, we used impact models to analyse future trends in temperature, precipitation, climatic extremes, crop yields and crop suitability. In addition, we conducted key informant interviews with actors involved in post-harvest steps of the selected value chains, including in aggregation, processing and marketing and distribution, to better understand how climate change impacts are felt at later stages of the value chains. Based on the climate change impact results as well as on a participatory process with various local stakeholders, we selected four adaptation strategies for the assessment of their overall feasibility and suitability for Uganda. Using climate change impact and economic models, we analysed the potential of the selected strategies to cost-effectively mitigate climate risks, which was complemented by expert- and literature-based assessments regarding aspects of inequality, such as gender and land tenure, and which was informed by semi-structured key informant interviews and two stakeholder workshops.

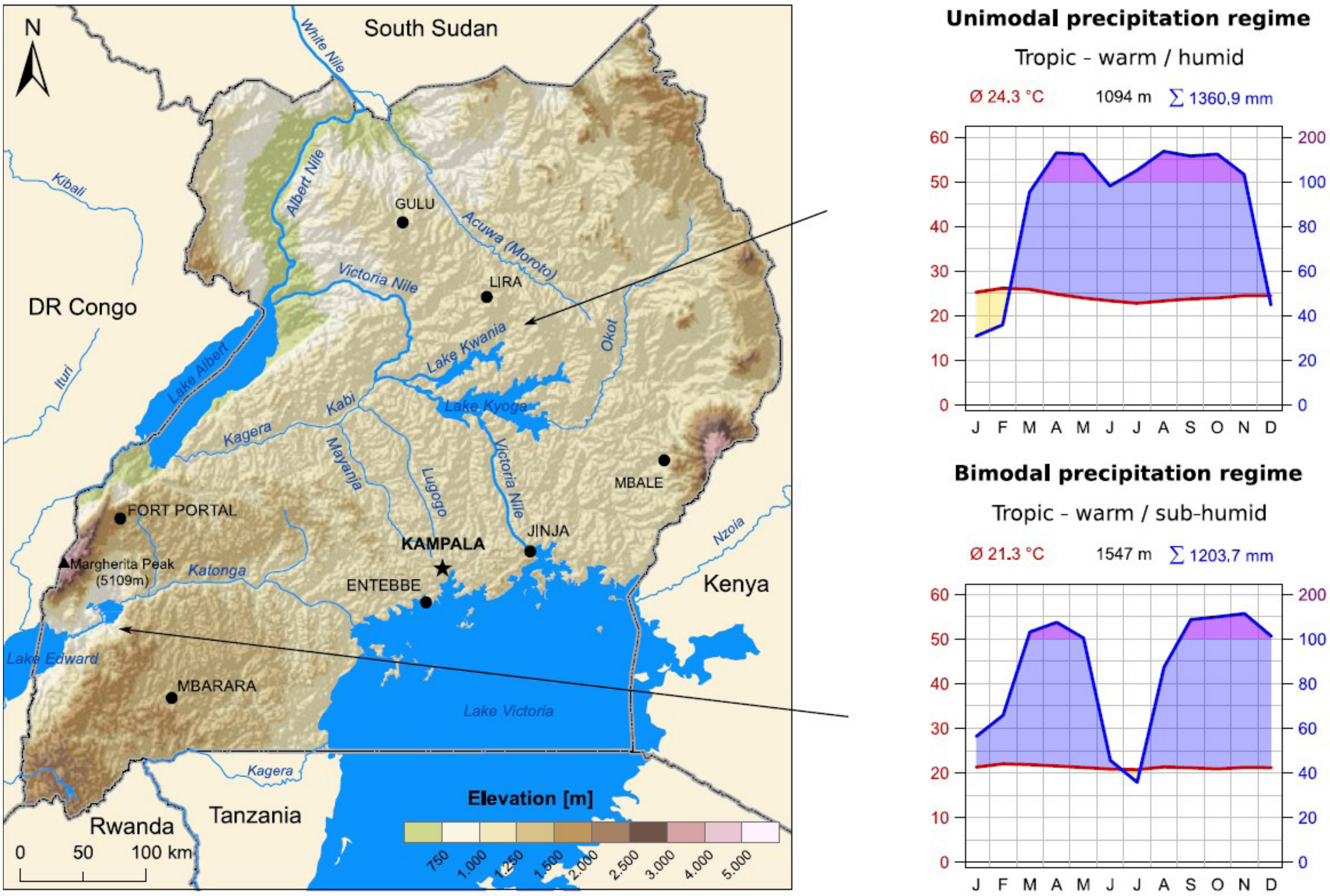


Figure 1: Topographical map of Uganda with existing precipitation regimes.

1.1 Study area

Uganda is a landlocked country in East Africa, belonging to the Great Lakes region. Uganda is located on a plateau with altitudes ranging mostly between 1,000 m and 1,500 m. Elevation gradually decreases towards Lake Albert in the north-west, which is the lowest point of the country at 614 m (CIA World Factbook, 2020). The highest point is Margherita Peak at 5,109 m, which is located in the Western region of the country. Each of these topographies is characterized by different agro-ecological conditions with specific temperature and moisture regimes, and consequently, specific patterns of crop production and pastoral activities. Uganda is mostly dominated by a tropical climate with a single rainy season in the north and two rainy seasons in the south (Figure 1). The country has ample water resources, with 15 % of its total land surface covered by open water and 13 % by wetlands. The most important water source is Lake Victoria, followed by Lake Albert and Lake Edward on the border to DR Congo, Lake Kyoga in the central part of the country and the White Nile, which originates in Lake Victoria and flows north-west through Uganda to South Sudan (Rugumayo et al., 2015).

Uganda's agricultural sector is the backbone for both the economy and for securing food and income at the subsistence household level. The sector is among the key targets for achieving Uganda's Vision 2040 and the National Development Plan III (2020).

The agricultural sector also employs the highest share (68.1 %) of the country's working population, with the majority being women. Despite the wide range of crops grown, **maize**, banana (cooked), cassava and beans account for the largest share of grown food crops (UBOS, 2022). **Coffee**, on the other hand, is a strategic crop for Uganda, placing the country in the second position of African coffee production after Ethiopia (UCDA, 2019b, 2019a).

Agricultural productivity in Uganda is mainly influenced by weather conditions, crop management, crop varieties and soil fertility. However, weather is a significant driver since Ugandan agriculture is primarily rain-fed with only 0.5 % of the national crop land suitable for irrigation (3.03 million hectares) actually being irrigated (MAAIF & MWE, 2017). In addition, post-harvest value addition is also often exposed to weather, through e.g. crops that need to be sun-dried or that have specific environmental requirements for processing. Therefore, changes in the intensity, distribution and timing of weather variables due to climate change will significantly affect the agricultural sector, causing concerns over food security and economic stability.

1.2 Rationale

National priorities for climate change and agriculture show a strong focus on adaptation, while continuing to expand productivity and value creation. The different climate change policies that guide Uganda's climate action put the agricultural sector at the centre of their adaptation efforts. In alignment, the agricultural policies and plans also integrate climate smart-agriculture as key priorities for this sector. The Agriculture Sector Strategic Plan (ASSP), for instance, focuses on the entire agricultural value chain and climate change is identified as a cross-cutting issue with climate action to be mainstreamed across all activities. The plan aims to increase agricultural production and productivity, as well as access to critical farm inputs. In addition, the improvement of agricultural markets and value addition along with service delivery by strengthening the institutional capacity of the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) and its agencies are strategic priorities. Uganda's NAP-Ag entails short-, medium- and long-term climate change adaptation actions for the transformation of the agricultural sector towards more resilience to climate change.

In alignment with political priorities, a number of value chain assessments and climate risks analyses have already been conducted in Uganda. There are three broad categories that most publications fit into: First, there are multi-sectoral climate risk analyses that do not specifically assess agri-food value chains, as well as sector-specific assessments that analyse sectors other than agriculture (see e.g. MWE (2015) and World Bank Group (2021)). Second, there is literature on agri-food value chains that look into poverty and food security without systematically assessing the effects of climate change (see e.g. Daly et al. (2017) and Kilimo Trust and Heifer International (2018) for maize and FAO (2020b) for coffee). Third, a large body of studies looks at agriculture in the light of climate change vulnerability and adaptation, yet only focusing on the production link of the value chain while leaving out post-harvest actors and processes (see e.g. Bunn et al. (2019), UNDP & BCRP (2013)).

Overall, only few studies analyse the entire value chain, e.g. Dazé and Dekens (2016), Dekens and Bagamba (2014) and USAID (2013). However, no study systematically assesses both, the impact dimension of climate change on the agricultural sector and the action dimension assessing specific adaptation options and policy recommendations. Thus, there is a major gap in the existing literature to take the entire value chain into consideration when it comes to the assessment of climate adaptation strategies for the agricultural sector (K. F. Davis et al., 2021).

In line with the country's political priorities and building on existing studies in the country, this climate risk analysis therefore focuses on the entire agricultural value chain from production to consumption. This is necessary to identify adaptation strategies that show both a high climate risk mitigation potential as well as a high economic potential helping to support the country with increasing agricultural production and productivity in the face of climate change.

1.3 Study approach

A better understanding of projected climate impacts and of possible adaptation benefits is important to guide, incentivise and accelerate public and private sector investments. Consequently, this study combines **model-based climate impact assessments** with **economic and qualitative analyses** to evaluate adaptation strategies under two different greenhouse gas emissions (GHG) scenarios. The study thereby models the whole chain from the impact dimension of climate change for the coffee and maize value chains to an action dimension which is assessing specific adaptation options and policy recommendations, as well as a discussion on the uncertainty of the results (Figure 2). Maize and coffee value chains and the herein selected adaptation strategies are assessed as an example of projected climate change impacts on the agricultural sector and the potential of adaptation

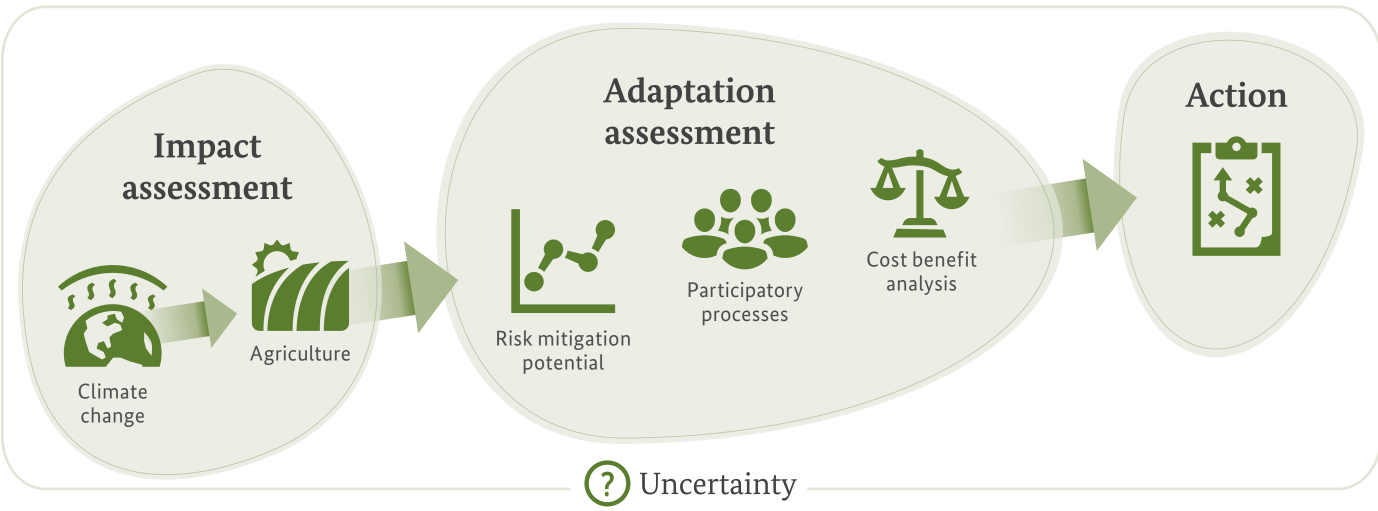


Figure 2: The impact-action chain of the climate risk analysis.

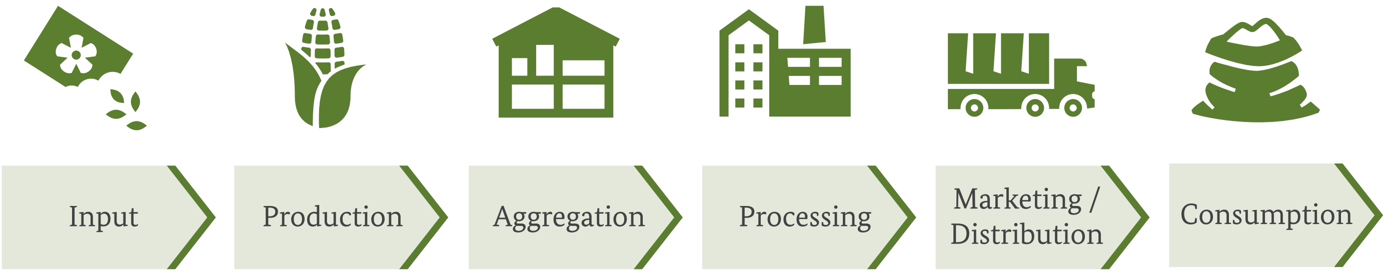


Figure 3: Simplified depiction of an agricultural value chain.

strategies to buffer climate change in Uganda. The results of this study are not meant to provide silver-bullet solutions, but should be interpreted within the wider context of building climate-resilient agri-food systems.

A simple **value chain** constitutes the full range of activities which are required to bring the product from conception through the different phases of production, delivery to final consumers, and final disposal after use (Kaplinsky & Morris, 2012). Recognizing the complexity of agricultural value chains, this study works with a simplified version of an agricultural value chain. The value chains are broken down into the following steps: (a) input, (b) production including all agricultural management and harvest (c) aggregation, (d) the different steps of processing leading to the final product, (d) marketing and distribution and (e) consumption (Figure 3), based on an extended version of the sustainable food value chains framework developed by FAO (2014). These steps, especially the post-harvest steps, are not necessarily linear but can occur in different configurations. The concept of value addition is key in this definition. Value can be added not only by processing products, but also by storing them (value increasing over time) and transporting them (value increasing over space) (FAO, 2014).

In order to ensure alignment of the study focus with national goals and priorities, a wide range of **local experts and stakeholders** have been involved throughout the study process via workshops, farmer interviews and expert discussions, ranging from national ministries, non-governmental organizations, academia and the private sector. Close collaboration with our local partner institute, the National Agricultural Research Organization (NARO), allowed the continuous validation of our study focus and results.

This study is organized as follows: after this introduction (**Chapter 1**), **Chapter 2** provides an overview of past and projected future climatic changes in Uganda focusing on changing temperature and precipitation regimes in the country. All future projected climate impacts are assessed using two future climate scenarios, a low emissions scenario (SSP1-RCP2.6) and a high emissions scenario (SSP3-RCP7.0). In **Chapter 3**, we analyse how climate change impacts the maize value chain by looking at both, projected climate impacts on maize yields, as well as perceived climate impacts on the aggregation, processing, marketing and distribution stages of the maize value chain. This is followed by an assessment of the risk mitigation potential and economic feasibility of improved maize varieties and improved post-harvest storage as adaptation strategies. **Chapter 4** assesses climate change impacts on the coffee value chain. We assess how the suitability to grow Arabica and Robusta coffee as part of coffee-banana intercropping systems is impacted by climate change and how climate risks are already experienced at the aggregation, processing, marketing and distribution stages of the value chain. Agroforestry and improved post-harvest storage are analysed in terms of their risk mitigation potential and economic feasibility to adapt to the projected and experienced impacts. In addition, the assessments in **Chapter 3 and 4** consider opportunities and barriers of adaptation strategies for different farmer types. The two-value chain-specific climate risk assessments are synthesized in a conclusion followed by policy recommendations (**Chapter 5**). The results are meant to inform and support local and national government authorities, non-profit, and private sector stakeholders in prioritizing and designing their adaptation investments to achieve an inclusive, climate-resilient transformation of agri-food systems.

2. Changing climatic conditions

To identify changes in future climatic conditions in Uganda, this chapter analyses several indicators concerning temperature and precipitation under two global greenhouse gas (GHG) emissions scenarios (SSP1-RCP2.6 and SSP3-RCP7.0) which constitute a low and a high GHG concentration pathway covered in the Intergovernmental Panel on Climate Change (IPCC) reports. SSP1-RCP2.6 low emissions scenario represents a scenario that remains globally below 2 °C above pre-industrial temperatures and is thereby in line with the upper end goal of the Paris Agreement. The SSP3-RCP7.0 high emissions scenario refers to the "without climate policy" scenario. Projected climate data was analysed to show the range of possible future climate conditions by 2030, 2050 and 2090.

> We analyse two emissions scenarios which cover the range of possible CO_2 emissions pathways: one scenario which assumes that global temperature increases remain below 2 °C (SSP1-RCP2.6 low emissions scenario), the other scenario represents a world without climate policy (SSP3-RCP7.0 high emissions scenario).

First, an outline of the current climate conditions is given hereafter, followed by the presentation of past and future climate trends of mean annual temperature and precipitation as well as extreme weather events.

2.1 Present climate conditions

Uganda currently experiences a mean annual temperature between 19–25 °C, with higher values in the north of the country. The interseasonal temperature differences are low (Figure 4). The mean annual precipitation sum is between 500 and 1500 mm/year, with the lowest values in the most north-eastern part of the country. Precipitation amounts over Lake Victoria can reach values up to 1800 mm/year. Figure 4 illustrates that the country experiences different rainfall regimes, with two rainy seasons in the south and one in the north. In the south, the first rains occur from March to May and the second rainy season spans from September to December. Towards the north, the second season tends to peak earlier causing the first and second rainy seasons to merge and leading to a modal rainfall regime. The timing of the rainy seasons and their length vary considerably from year to year.

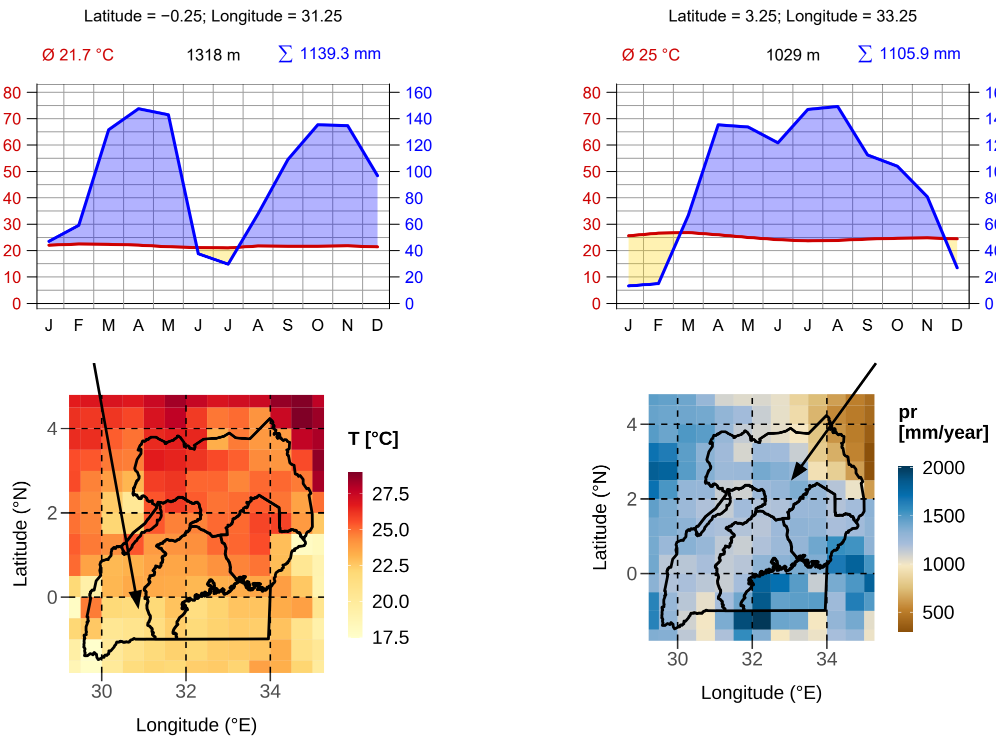


Figure 4: Top: Two climate diagrams displaying the annual distribution of precipitation and temperature in the south [0.25 °S; 31.25 °E] (left) and in the north [3.25 °N; 33.25 °E] (right). Bottom: Mean annual temperature in °C (left) and mean annual precipitation in mm (right) over Uganda 1995–2014.

2.2 Climate change and variability in the past and the future

2.2.1 Temperature

During the last four decades, mean temperatures showed a rise of 0.29 °C on average per decade. Slightly higher increases were observed in the north and lower increases over Lake Victoria (Figure 4). The minimum daily temperatures have increased stronger than maximum daily temperatures. Future projections of temperature show an overall continuation of the recent increasing trend (Figure 5). In response to increasing GHG concentrations, mean annual temperature is projected to increase by 1.1 °C under the SSP1-RCP2.6 low emissions scenario and 1.5 °C under the SSP3-RCP7.0 high emissions scenario by 2050, compared to 2004. Temperatures will stabilize under low future emissions after 2050 and will further rise until the end of this century under high future emissions (Figure 6). The increases are projected over all of Uganda with slightly higher values in the west of the country. The temperature projections are robust with all models clearly agreeing on this trend.

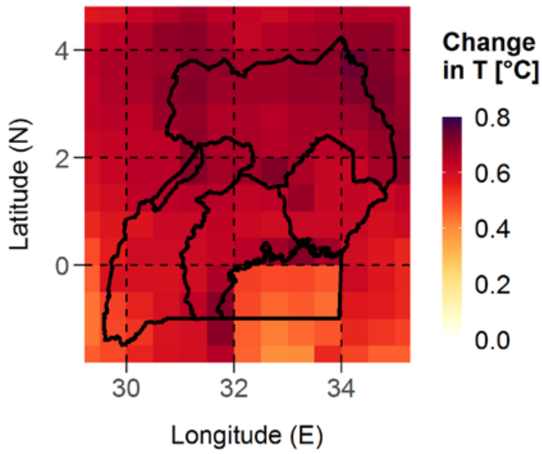


Figure 5: Changes in mean temperature in °C over Uganda comparing the periods 2000–2019 to 1979–1998.

> By 2050, mean annual temperature is projected to increase by 1.1 °C under the low emissions scenario and 1.5 °C under the high emissions scenario compared to 2004.

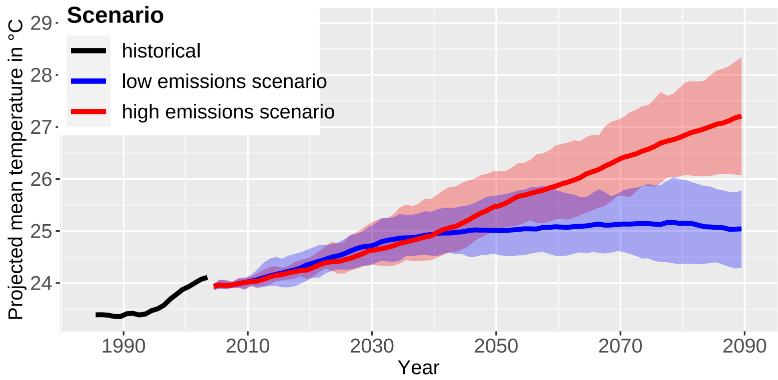


Figure 6: The 10-year moving average of historical and projected mean temperature in °C.

*The black line displays historical observations, the red and blue lines show projections under the high and low emissions scenario. Solid lines display the multi-model mean and shades display the range given by all ten models. Values are averages over Uganda.**The black line displays historical observations, the red and blue lines show projections under the high and low emissions scenario. Solid lines display the multi-model mean and shades display the range given by all ten models. Values are averages over Uganda.*

2.2.2 Temperature extremes

North Uganda currently experiences up to 100 hot days per year (days in which maximum temperatures exceed 35 °C) whereas no hot days occur in the south of the country (Figure 7a). Temperature extremes can limit crop growth or even lead to crop failure, depending on the crop type, cultivars and the phenological development stage. In line with the recent mean temperature increases, the frequency of temperature extremes augmented as well.

> The number of hot days per year (>35 °C) is projected to steadily increase in north Uganda. South Uganda, which is currently experiencing no hot days, is projected to face hot days only by the end of the century in case of high future emissions.

In the future, the number of hot days is projected to increase steadily in the north (Figure 7b) with high agreement between climate models. Under the SSP1-RCP2.6 low emissions scenario, the numbers stabilize in 2050. South Uganda is projected to continue to experience no hot days. Under the SSP3-RCP7.0 high emissions scenario, most of the days per year are projected to be hot days in north Uganda and also for the south it is projected to experience hot days by the end of the century, which is currently not the case.

> The number of hot nights per year (>25 °C) is projected to steadily increase in north Uganda, especially in the North of the country. In the north-west, hot nights are projected to increase to 100 a year, compared to almost none at the moment.

Hot nights (minimum temperatures exceeding 25 °C) are currently occurring only very few times per year in the most north-western part of the country (Figure 8a). However, hot nights are projected to increase in the north of the country. At the end of the century under the SSP3-RCP7.0 high emissions scenario, the number of hot nights are projected to be above 100 in the north-west of the country (compared to almost none at the moment) and a considerable increase in hot nights is also projected for the north-east and central part, as well as the northern parts of the western region Figure 8b.

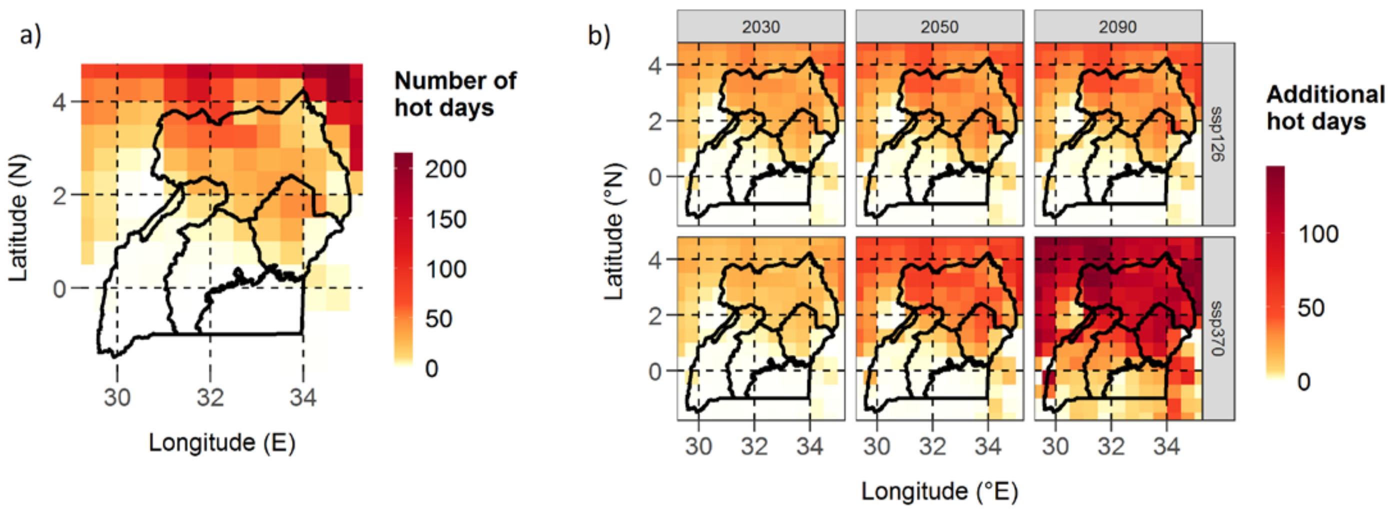


Figure 7: Maps with the a) observed (1995–2014) and b) projected changes in the number of hot days per year for the 20-year period averages 2030, 2050 and 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario.

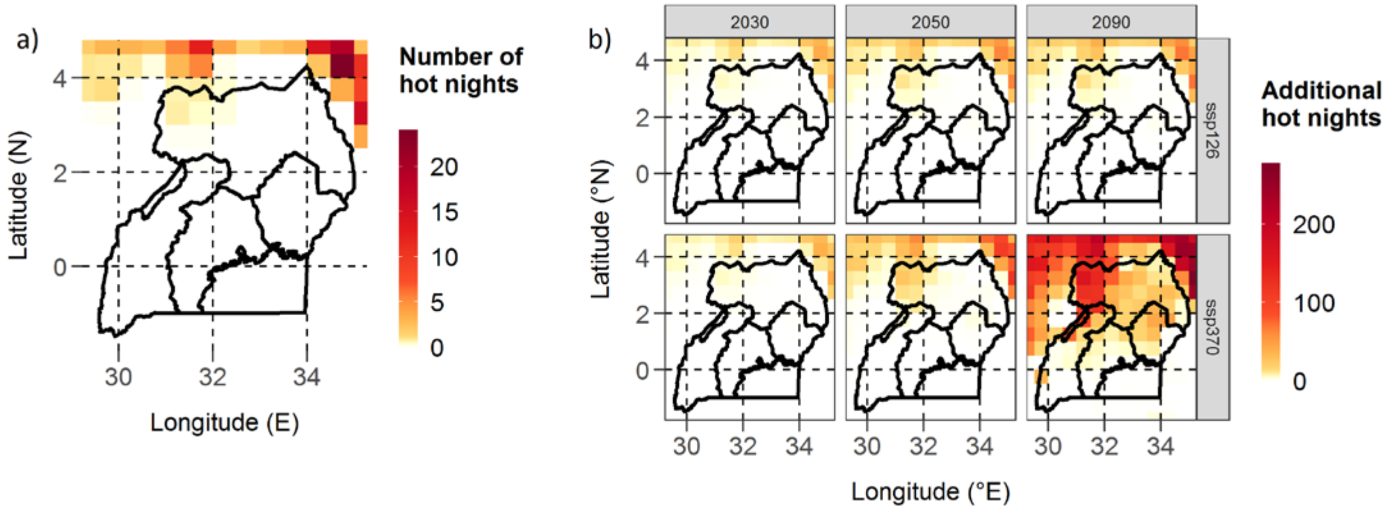


Figure 8: Maps with the a) observed (1995–2014) and b) projected changes in the number of hot nights per year for the 20-year period averages 2030, 2050 and 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario.

2.2.3 Precipitation

Annual precipitation amounts have changed in parts of the country over the last four decades with regional differences in the direction of change. Precipitation in central Uganda decreased while it remained stable or increased in the rest of the country (Figure 9).

> Precipitation projections are much more uncertain than temperature projections. The model mean projects an increase in precipitation, which is stronger under the SSP3-RCP7.0 high emissions scenario. Under the latter, the projected increases in heavy precipitation intensity are also stronger.

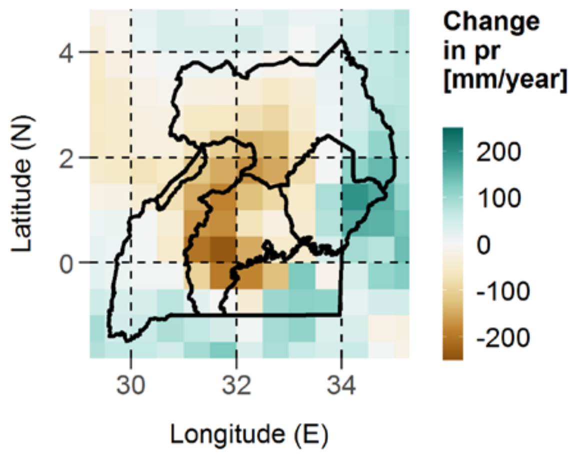


Figure 9: Changes in mean annual precipitation in mm over Uganda comparing the periods 2000–2019 to 1979–1998.

There is much less confidence in projected precipitation changes than in temperature changes, as not all models agree on a changing trend in precipitation. The multi-model ensemble mean and the majority of models projects slight future increases of annual precipitation sums over Uganda. Higher GHG emissions are projected to lead to higher increases in precipitation towards the end of the century (Figure 10). Even though the majority of climate models point to a slightly wetter future climate in Uganda, it cannot be ruled out that the country could experience a drier future climate in parts of the country as some models suggest. Additionally, parts of the increases in precipitation will not be available for crops due to increased evaporation under hotter future conditions.

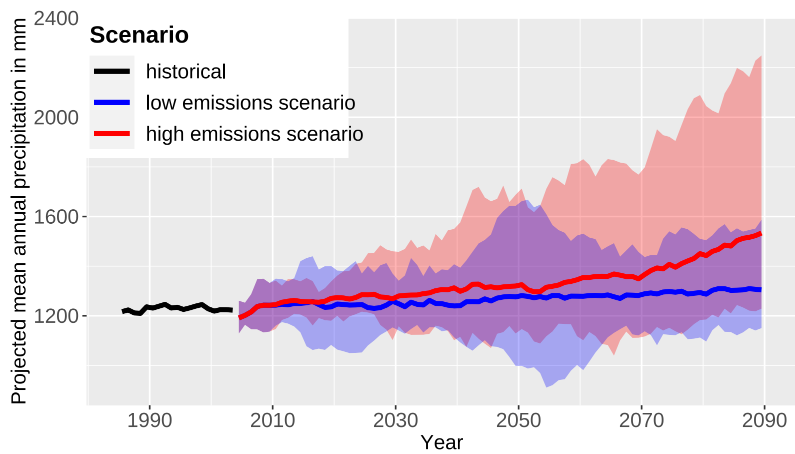


Figure 10: The 10-year moving average of historical and projected annual rainfall in mm per year.

The black line displays historical observations, the red and blue lines show projections under the high and low emissions scenario. Solid lines display the multi-model mean and shades display the range given by all ten models. Values are averages over Uganda.

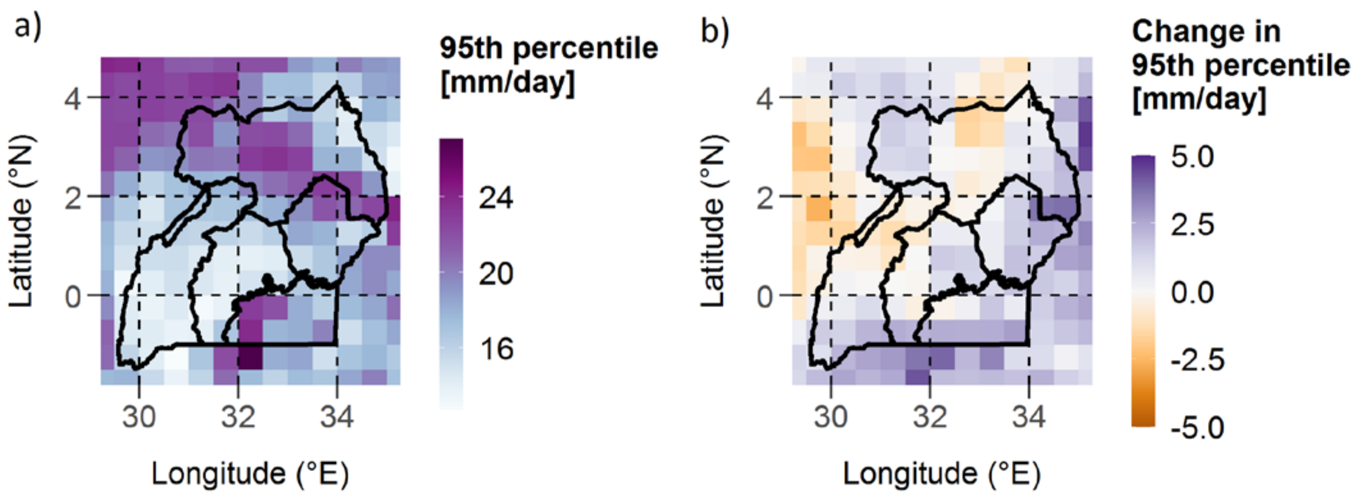


Figure 11: a) 95th percentile of daily rainfall in the period 2000–2019; b) change in the 95th percentile comparing the periods 2000–2019 to 1979–1998.

2.2.4 Heavy precipitation events

Heavy precipitation intensity is subject to large spatial variations in Uganda. To quantify changes in heavy precipitation we analysed the 95th percentile of days with precipitation (>0.1 mm). According to this indicator, some parts of the north and areas over the Lake Victoria experience the highest heavy precipitation intensity with the 95th percentile of rainfall above 20 mm per day (Figure 11a). Heavy precipitation in the most north-eastern part and the south-west is weaker. Past changes in heavy precipitation intensity showed only very small changes in most of the country and the trend was not uniform over Uganda (Figure 11b). Despite the past decrease in precipitation in central Uganda, heavy precipitation intensity has not decreased in the region.

Heavy precipitation intensity is projected to increase slightly under the low emissions SSP1-RCP2.6 scenario (Figure 12) whereby not all models agree on this trend. Under the SSP3-RCP7.0 high emissions scenario, the projected increases in heavy precipitation intensity are stronger and subject to high model agreement.

2.2.5 Rainy seasons

Rainy season onset, cessation and length are subject to a high year-to-year variability. The past trend in the onset of the first rainy season points at a later onset in most parts of Uganda compared to the late 20th century except of an earlier onset in the south-western part of the country (Figure 13). Combined with an earlier cessation of the first rains in the central parts of Uganda, the rainy season shortened in the eastern and central parts and became longer in the south-western part.

The second rainy season, on the contrary, has shortened in the south-western part due to an earlier cessation and lengthened in the central part due to an earlier onset. Projections of rainy season onset, cessation and length are uncertain. Climate models tend to project a large year-to-year variability in rainy season characteristics for the future. Shorter first rainy season caused by an early cessation are possible in the future.

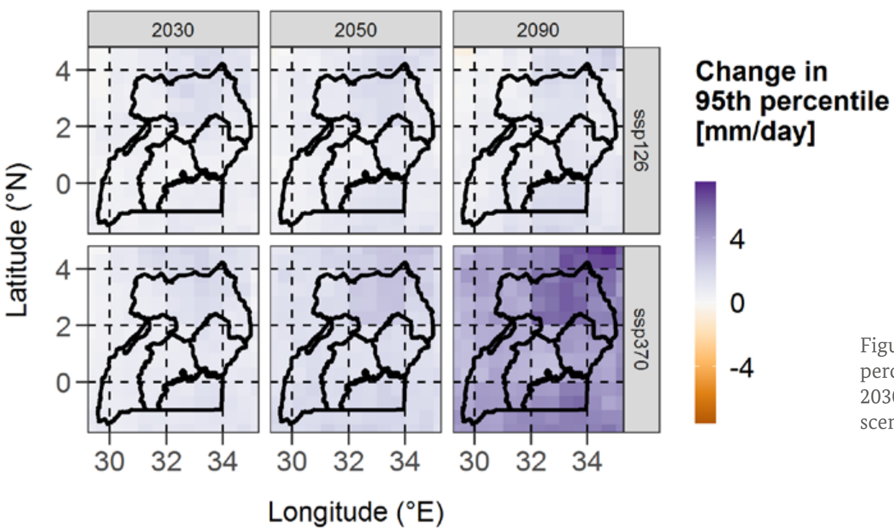


Figure 12: Maps with projected changes in the 95th percentile of daily rainfall for the 20-year period averages 2030, 2050 and 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario.

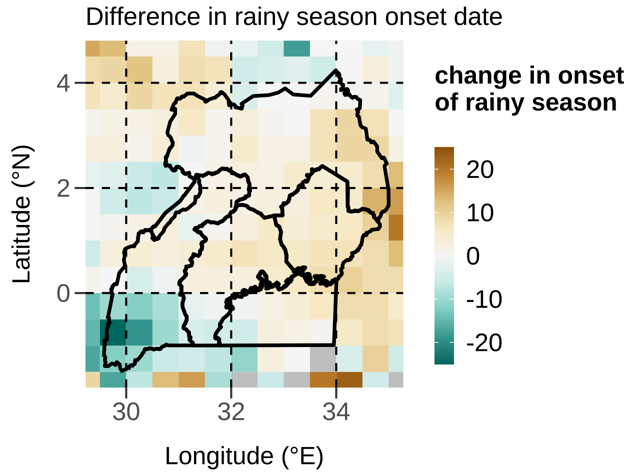


Figure 13: Changes in the onset date of the first rainy season comparing the periods 2000–2019 to 1979–1998. Brown colour indicates a later onset and blue colour an earlier onset in recent years.

2.3 Conclusion

Uganda currently experiences a mean annual temperature between 19–25 °C, with higher values in the north of the country. The mean annual precipitation sum is between 500 and 1500 mm/year with the lowest values in the most north-eastern part of the country. Three climate change pathways are projected in Uganda, although with differing certainty: warming and drying, warming and no precipitation change, and warming and precipitation increases. Climate change models show a clear trend for temperature increases. By 2050, mean annual temperature is projected to increase by 1.1 °C under the low emissions (SSP1-RCP2.6) scenario and 1.5 °C under the high emissions (SSP3-RCP7.0) scenario, compared to 2004. The number of hot days and hot nights are projected to steadily increase, especially in the northern part of the country. Precipitation projections also show an increasing trend but are much more uncertain than temperature projections. Even though the majority of climate models point to a slightly wetter future climate in Uganda, it cannot be ruled out that the country could experience a drier future climate in parts of the country as some models suggest. Precipitation extremes are projected to increase, whereby not all models agree on this trend. Rainy season onset, cessation and length are projected to change, depending on the region, but these projections are equally subject to model uncertainty.

Climate Impact	Past trend[1]	Future trend[1]	Certainty[2]
Mean annual temperature	Increasing	Increasing	Very high
Number of hot days & nights	Increasing	Increasing	Very high
Mean annual rainfall sums	Increasing (not significant)	Increasing	High emissions: Medium Low emissions: Low
Heavy rainfall intensity	Increasing	Increasing	High emissions: Very high Low emissions: Low

Table 1: Summary of climate change trends in Uganda

1) The trend is determined by a Mann Kendall Test with significance level 0.05 for the years 1979–2016 in the past and the years 2015–2070 under the respective emissions scenario in the future. If at least 60 % of the models show a trend (on any significance level) in the same direction, we speak of a trend with a specific uncertainty level (see next foot note).

2) The certainty level of future climate projections is determined by the percentage of models agreeing on the trend (with significance level of 0.05) (compare IPCC, 2014). ≥ 90 %: very high; ≥ 80 %: high; ≥ 50 %: medium; ≤ 50 %: low.

3. Climate risk analysis for maize value chains

Maize is cultivated by about 1.8 million farmers all over Uganda for food security and income, and is also playing an increasing role in export (Daly et al., 2017; Kilimo Trust & Heifer International, 2018; MAAIF, 2016). Since maize can easily be stored and prepared, maize flour forms the basis of institutional feeding in Uganda for schools, hospitals, prisons, the military, and emergency food relief. Among food crops, maize is the most dominant crop and a top priority for the Agricultural Sector Strategic Plan (ASSP) (MAAIF, 2016). Given the high relevance of maize both as a source of food and income, the crop represents a top priority for the ASSP (MAAIF, 2016). Maize is mostly produced in the Eastern (Kapchorwa**,** Mbale), Central (Masaka, Mubende, Kibale) and Western (Masindi, Kasese, Kyenjojo) regions and least produced in the areas around Karamoja and Kigezi. All in all, the crop has shown an increasing trend in terms of production between 2000 and 2019 (FAO, 2023). Since then, Uganda has become Africa's third largest exporter of unprocessed maize and second-leading exporter of maize flour, exporting a high share of its maize surplus and flour to Kenya, the DRC, South Sudan, Tanzania and Rwanda (Daly et al., 2017; Kilimo Trust & Heifer International, 2018).

> Using a value chain approach, we analyse projected and experienced climate impacts on the different steps of the maize value chain followed by an assessment of the risk mitigation potential and economic feasibility of selected adaptation strategies.

Most of Uganda's maize production is rain-fed and characterized by smallholder farming systems that use primarily manual inputs – making maize production particularly vulnerable to negative climate impacts. Maize is sensitive to hot temperatures above 35 °C (USAID, 2019) and negatively affected by heat and drought during its leaf development, stem elongation, and anthesis (USAID, 2013). Inter-annual rainfall variability and the amount of precipitation can also negatively impact maize production (USAID, 2013). Furthermore, water stress, hail and potential waterlogging of fields is likely to create favourable conditions for crop diseases and pest infestations, which can negatively affect maize production and quality (MWE, 2015). Erratic rainfall may also reduce soil fertility and structure which can reduce the soil's capacity to retain water and diminish available nutrients to the plants.

In this chapter, we analyse climate change impacts on the maize value chain and assess the potential of selected adaptation strategies. First, the maize value chain in Uganda is mapped based on literature, as well as on expert interviews. To assess the impact of climate change on maize production, we use the process-based crop model Decision Support System for Agrotechnology Transfer (DSSAT), which simulates maize yields and identifies potential losses due to climate change in Uganda by 2030, 2050 and 2090. This analysis is complemented with an abductive thematic analysis of interviews conducted with maize value chain actors to better understand how climatic factors are affecting later stages of the value chain, including during processing, aggregation and marketing and distribution stages. Based on the impact analysis, the second part of this chapter assesses the potential of two adaptation strategies: (a) **improved maize varieties** and (b) **improved storage**, which were selected based on the interest of local stakeholders. The assessment focuses on the strategies' economic as well as risk mitigation potential.

3.1 The maize value chain

The maize value chain in Uganda is largely unstructured, although it involves a large number of actors (Kilimo Trust & Heifer International, 2018). **Inputs** to the maize value chain include financial inputs such as loans, credits and market information but also land, water, seeds, fertilizers, agrochemicals (herbicides, fungicides and pesticides) as well as farming and irrigation equipment. In Uganda, inputs such as fertilizers, and agrochemicals or agricultural machines, are not commonly used in maize production (Daly et al., 2017; USAID & AVSI, 2019). Access to credits is mainly sought after from the Village Saving Loans Associations (VSLA), but also from cooperatives, farmer groups and to a smaller share from banks (USAID & AVSI, 2019). Input suppliers include both, research institutes through the development of new varieties, as well as private suppliers, including large agribusinesses, local dealers and stockists, which often operate in an informal manner at local level (Kilimo Trust & Heifer International, 2018).

> The maize value chain in Uganda is largely unstructured and involves a large number of actors who bring the product from its on-farm production through the different steps of aggregation and processing to marketing and selling the final product.

The **production** stage of the value chain includes sowing, growing, and harvesting. The country's Eastern and Western regions account for about 70 % of the national production (UBOS, 2017). Apart from a few large-scale farms (e.g. Afgri Limited and Amatheon Agri), most of Uganda's maize is produced on rain-fed, smallholder farms that allocate less than 2ha to maize production for both household consumption and trade (Dilling et al., 2019; Kilimo Trust & Heifer International, 2018). After harvesting, farmers initially process the maize by drying and sorting it on site, either on tarpaulins or on uncovered ground, before either consuming it, selling it or further processing it at a specialized facility.

Aggregation and storage after the harvest occurs either at farm-level, within cooperatives or by village agents, small- and medium traders and processors, depending on the geographical context, the scale of production and most importantly, the financial capacity of renting or owning a warehouse. Often, maize is bought by traders who move from one production area to another buying from local traders or farmers aggregating the maize to sell it to processors in major towns. Storage and aggregation allow for market power thus raising the grain's value.

The **processing** step of the value chain includes any modification of the product with the aim to add value, including cleaning, drying, grading, milling and usually some kind of packaging. This is mainly done at small- or medium scale levels across the country and often works on a service-basis (against a milling fee). Primary processing includes the weighing of grains, often further drying, sorting or quality checks and cleaning. As a secondary processing step, grains are hulled (usually twice) and milled to produce flour for final consumption. The degree of hulling and milling depends on the desired quality of the final output. There are three grades of flour with number one being the most refined. An important by-product is bran, which also exists in different grades and is sold as animal feed. Other outputs include chemical compounds including starch for the food industry and ethanol for global fuel value chains.

After processing, the final maize product is **marketed** and **distributed**, either directly for **consumption** or to local, regional or export markets, from where the consumer can access the product. Figure 14 provides a simplified overview of the Ugandan maize value chain. The main maize products that can be found on the Ugandan market are grain, flour and bran for animal feed. Maize flour is widely used to prepare the traditional food Ugali. Other derivatives are roasted and boiled green maize, popped corn, puffed corn, brews as well as starch. Around 70 % of maize produced is for human consumption (USAID, 2013). Half of the formal maize trade takes place in Kampala and the World Food Programme (WFP) and private traders purchase approximately 20 % of the total national maize supply (Kilimo Trust & Heifer International, 2018)

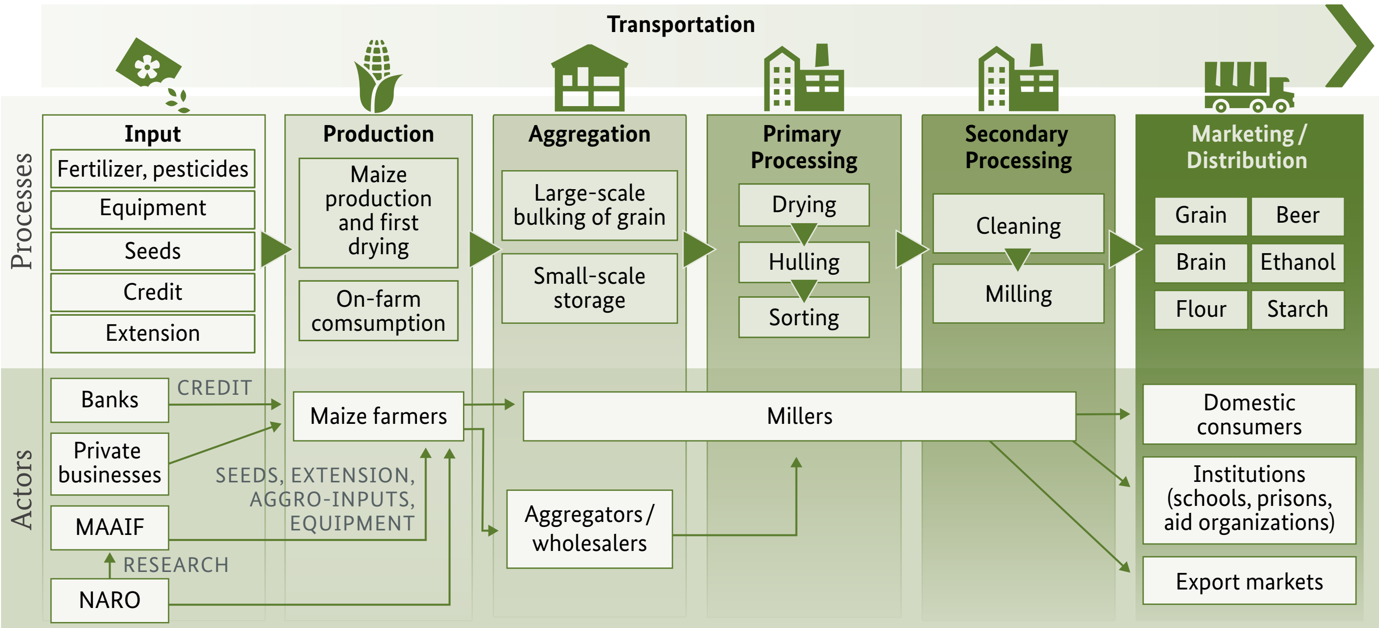


Figure 14: simplified mapping of a maize value chain in Uganda, based on expert interviews and literature.

3.2 Climate change impacts on the maize value chain in Uganda

3.2.1 Climate change impacts maize production

We used the process-based crop simulation model DSSAT Cropping System Model v4.7 (Hoogenboom et al., 2019; Jones et al., 2003) to simulate maize yields under current and future climate conditions for a low and a high emissions scenario. The model was calibrated using soil profile information, detailed crop management information, and genetic coefficients of varieties as inputs to simulate maize growth and yield (for more information on the method and input data, please see Annex I.2).

> The process-based crop model DSSAT was used for projecting maize yields under climate change. DSSAT simulates maize growth based on weather data, soil characteristics and information on crop management.

3.2.1.1 Current trends in maize production

Our model yield estimates for Uganda are similar to the reported yields: the models estimate 2424 kg/ha national long-term average of maize yields model compared to 2362 kg/ha reported in FAOSTAT as the national average maize yields between 2007 and 2017 (FAO, 2023). The distribution of maize from the model is shown in Figure 15. The major high maize zones are in Elgon, East Central and Teso on the east and at the intersection of the Western, Central 1 and Central 2 subregions. Parts of the West Nile sub-region also show high maize yields. There is a general northward decrease in yields, except for patches in the West Nile subregion (Figure 15a).

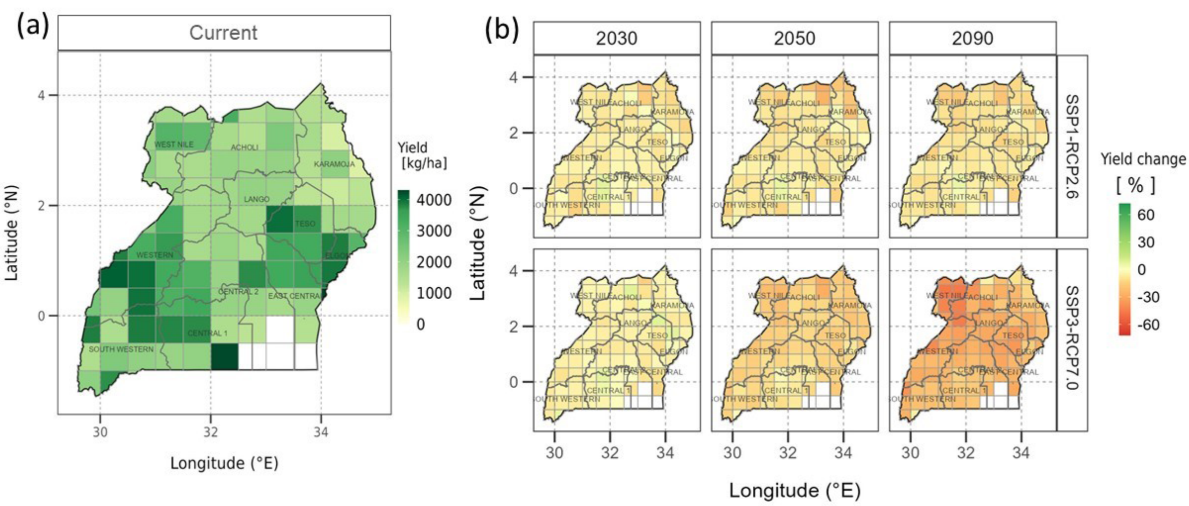


Figure 15: (a) Current and (b) projected future maize yield changes (%) in Uganda at 0.5° grid spacing under the SSP1-RCP2.6 (top row) and SSP3-RCP7.0 (bottom row) for around 2030, 2050, and 2090.

3.2.1.2 Projected maize yield changes under climate change

The impact of climate change on maize yield shows spatial and temporal disparities with general trends showing declines in maize yield accelerating over time (2030–2090) and scenario (SSP1-RCP2.6 to SSP3-RCP7.0; Figure 15b). At national level, yield losses of 6.2 % by 2030, of 8.6 % by 2050 and of 8.8 % by 2090 are projected under the SSP1-RCP2.6 low emissions scenario. Under the SSP3-RCP7.0 high emissions scenario, expected losses are initially lower than under the low emissions scenario amounting to 4.4 % by 2030. This is due to the expected increase of rainfall in some parts of Uganda and slight temperature increase until 2040. In 2040, temperature is expected to increase under the SSP3-RCP7.0 high emissions scenario to a level that harms maize growth amounting to much higher yield losses of 14.3 % by 2050 and 26.8 % by 2090 (Figure 15). In northern parts of the country, already by 2030, there are projected maize yield losses of up to 18.9 % (SSP1-RCP2.6 low emissions scenario) and 14.2 % (SSP3-RCP7.0 high emissions scenario). By the end of the century (2090), maximum losses of up to 47.3 % are projected especially in the West Nile subregion. Positive impacts of climate change on yield are projected for very limited areas in parts of the Central region of up to 7.8 % (SSP1-RCP2.6 low emissions by 2030) and 8.2 % in the Teso region (SSP3-RCP7.0 high emissions by 2050) (Figure 15b).

> The analysis shows that climate change will have a negative impact on maize yield in Uganda especially in high maize potential areas. This is worsening with time with high yield losses expected towards the end of the century under the high emissions scenario.

Of the three high potential maize zones, the West Nile and the Elgon regions are projected to have the most severe climate change impacts on maize yield. The sub-regional distribution of yield losses is shown in Figure 16. In this sub-regional distribution, two trends can be observed: (i) until 2030, we project higher yield decreases under the SSP1-RCP2.6 low emissions scenario than under the SSP3-RCP7.0 high emissions scenario, but by 2090 yield losses will be much higher under the high emissions scenario than under the low emissions scenario; (ii) yields progressively decrease in all regions between 2030 and 2090 under both emissions scenarios. The highest yield losses of over 30 % are projected for the West Nile, Teso, Lango and Western sub-regions under the high emissions scenario. The least yield losses are projected in Central, Central 2 (high maize potential) sub-regions, Karamoja (low maize potential) subregion, where projected losses do not exceed 20 % under all scenarios and periods. In some areas within these sub-regions, there are positive changes, but these do not offset the negative changes of the rest of the areas within the below mentioned sub-regions.

Concluding from this assessment, climate change will have a negative impact on maize yield in Uganda, especially in high maize potential areas, starting around 2030 and these impacts worsen with time and emissions scenario. Our findings concur with previous studies that also projected decreases in maize yield in some parts of Uganda under climate change (Babel & Turyatunga, 2015; Bwambale & Mourad, 2022; Zizinga et al., 2022). Three climate change pathways are distinct in Uganda, namely warming and drying, warming and no precipitation change, and warming and precipitation increases (chapter 2). Therefore, providing a spatialised modelling framework, as done in this analysis, is important to provide an unbiased estimate of climate change

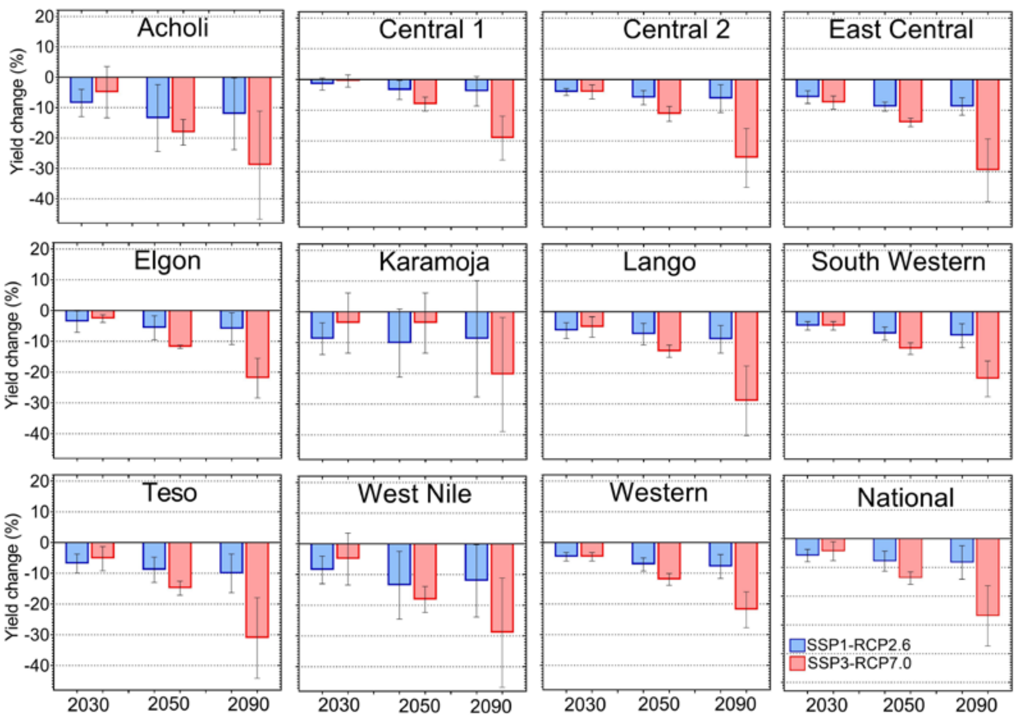


Figure 16: Simulated climate change impacts on maize yield at sub-region level in Uganda for around 2030, 2050 and 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario.

impacts on yield in the country as all areas are captured in the modelling. The projected yield losses appear to be driven more by the warming trend in the country than by precipitation changes. Increases in temperatures are more important in regard to maize productivity as they have a dual effect in the maize development, i.e. they affect metabolic processes such as photosynthesis and nutrient assimilation while increasing plant water demand and reducing water use efficiency (Chemura et al., 2022; Lobell et al., 2014)at the same time many communities in the region are dependent on rain-fed agriculture, which is vulnerable to these rainfall and temperature extremes. The aim of this study is to understand changes in extreme indices during the agricultural season under climate change and how that affect the modeling of maize suitability in Southern Africa. We analyze the changes in rainfall and its extreme indices (consecutive dry days, heavy rain events and prolonged rainfall events. With population growth, the projected declines in maize yields can further contribute to food and nutrition insecurity (as maize is an important source of calories across the country) and negatively impact farmers economically. Moreover, declining yields can lead to land expansion and biodiversity loss as farmers attempt to compensate for reduced yields to meet requirements.

3.2.2 Climate change impacts beyond maize production – experiences of processors, aggregators and traders

> To better understand how climate change impacts could play out at post-harvest steps of the maize value chain in the future, we conducted and systematically analysed interviews with actors working in aggregation, processing and marketing and distribution about how climatic factors are already impacting their work today.

The impacts climate change may have on maize production are not only felt by maize producers but can have a significant effect on other value chain actors as well, such as processors, aggregators and traders. These actors make up 30–40 % of the added value in food value chains and are key in determining the prices farmers receive and the costs that consumers pay. Nevertheless, they are often neglected when studying climate impacts on agriculture (Reardon, 2015). The post-harvest steps of the maize value chain are also exposed to climate conditions. Maize is often dried on the bare ground and not stored properly, leaving it particularly exposed to erratic rain and consequential moist conditions that could increase post-harvest storage losses due to degraded grains and increased decomposition. Aflatoxin, which is a mould toxin that can be found in maize exposed to such conditions, poses a threat to Uganda's maize export market already today. This is expected to worsen if rainfall increases during dry seasons (USAID, 2013). To capture these impacts, we conducted and systematically analysed in-depth interviews with actors working within the Ugandan maize value chain beyond production, including in processing, aggregation, marketing and distribution. The interviewed businesses are located in Lira and Agago districts in the Northern region of Uganda. The interviews were analysed using abductive thematic analysis (Tavory & Timmermans, 2014). An initial coding scheme was derived from the IPCC climate risk framework (2014, 2021) reflecting the main functions of climate risks (hazard, exposure and vulnerability). The codes were iteratively expanded during the analysis, creating a comprehensive analysis framework for climate risks in the maize value chain (for more information on the methods and data collected please see Annex I.2). The results were cross-verified with interviews and focus group discussions (FGDs) with national maize value chain experts.

> *Because now, the rains left in October last year. This is April. The rains are not yet there. And we're sitting and looking up and waiting. That's not right.*
>
> — Processor from Lira

3.2.2.1 Perceived climate impacts on the maize value chain

Climate-related **hazards** that are already experienced today by the interviewed actors include **temperature rise**, **drought** and **prolonged dry seasons**, and **changes in precipitation** or **extreme precipitation**. Several interviewees even reported hazards occurring at the time of the interviews (March and April 2022). Such hazards often spark further hazards which impact the maize value chain, including humidity, **floods**, **pests and diseases**, e.g. weevils or the fall army worm.[3]

The experienced hazards lead to impacts that were identified iteratively throughout the analysis process. **Direct impacts** are immediately felt at aggregation, processing, marketing and distribution steps of the country's maize value chain. **Indirect impacts** occur at other stages of the value chain, such as during production and consumption stages and trickle down or up the other value chain steps. Figure 17 shows a simplified version of the maize value chain. The orange coloured boxes represent overall themes. The white boxes inside the orange bounding square show direct impacts, the boxes outside the square indirect impacts.

3) The mentioned hazards and their impacts are experienced by interviewed actors on the ground. While such climate-related hazards cannot be directly attributed to climate change impacts, climate change is likely to exacerbate them (see Chapter 2 on projected climatic changes).

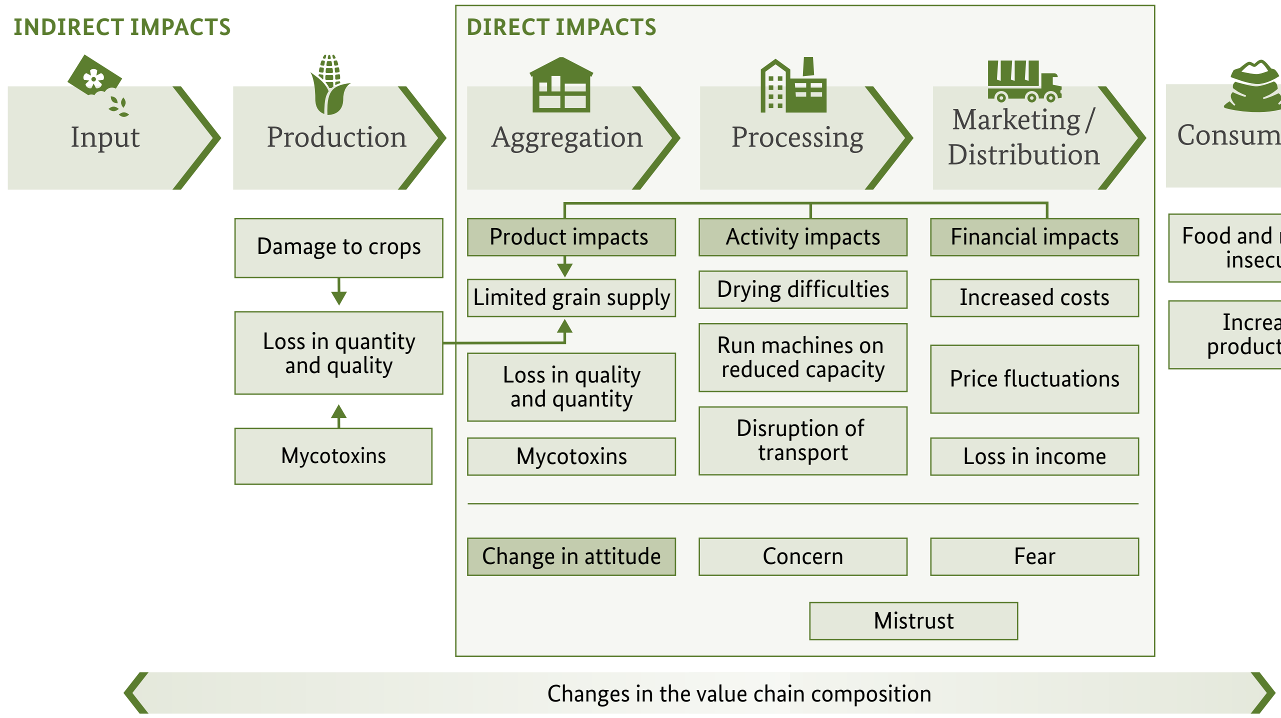


Figure 17: Experienced impacts of climate risks on the aggregation, processing and trading stages of the maize value chain.

a. Direct and indirect impacts on the post-harvest steps of the value chain

Yield losses due to extreme weather events, mainly droughts and prolonged dry seasons, can be clustered as an indirect impact, which has significant repercussions for post-harvest steps of the value chain. Yield losses are often caused by damage or destruction of crops right after planting due to lack of rains. In Lira, for example, a prolonged drought was reported to cause that *"most (...) maize plants were destroyed at infant stage"*. Later during the cropping cycle, droughts can hinder the growth and development of the plant either leading to further yield losses or reduced quality of the grain, e.g. in the form of reduced weight of the grains. This has repercussions on the amount of grains available to mill. Another cause for yield losses is the infestation of pests and diseases, which is often favoured by specific climate conditions. In Agago, infestations of the weevil beetle were reported to lead to either a total damage of the crop, or partly damaged grains that can still be milled but leading to a lower output both in terms of quantity and quality.

> *When there is no maize, [there is] also no miller.*
>
> — Miller from Agago

Both, quantity and quality losses at production stage lead to fluctuations in maize supply. Many processors have to run their machines at reduced capacities, impacting the finances of a business, e.g. leading to a loss in income: *"But when the production is low and the quantity supplied to the unit is low, then it makes the machine almost redundant."*, described a miller from Agago.

In such scenarios, processors or traders have to source maize from other regions, which makes sourcing significantly more expensive. Lack of maize supply due to climate-related hazards also leads to stark **price fluctuations**.

> *(...) Harsh weather (...) affects production of maize. And when there is no production of maize, it means we shall buy maize at a higher price. So that one has a cross-cutting effect. But if the weather is good, there will be high production of maize. Then we shall buy at a low price. There will be less competition. So that means we can bulk more than when there's scarcity.*
>
> — Processor from Lira

Post-harvest steps of the value chain are not only indirectly impacted, but are also experience direct impacts from climate risks. Storage and processing, for example, are especially sensitive to heavy rainfall and extreme humidity, as not sufficiently dry storage conditions favour the emergence of mycotoxins, especially **aflatoxins** (*Aspergillus Flavus*), a mould toxin. Mould contamination can already develop during the production stage at farm-level, depending on farmers' drying storage practices or at later stages of storing maize. Since farmers usually do not have stores, they have to dry the grains at their homes, where they are exposed to moisture in the air. During the rainy season, when there is high moisture and humidity, aflatoxins become an issue for several steps of the value chain. High precipitation is reported to result in **drying difficulties**. This applies not only for sun-drying the grains, but even to machine drying. When the external air is too humid, it cools down the drier and thereby slows down the drying process. More energy is required to operate the drier.

> *When there's too much rain, the biggest problem comes in the drying. (...) The drying process is not done well because most farmers do not have stores. (...) The moisture in the atmosphere is high. Then we will receive most likely not very good maize.*
>
> — Processor from Lira

Moreover, several processors and traders report that heavy rains, rainfall variability and storms affect the transport of maize grains and final products. Grains are often transported in open trucks, so sudden unexpected rainfall can wet the transported grains. These grains then need to be re-dried before milling. Heavy rainfall can also lead to **transport disruptions**, as roads become impassable, leading to delivery delays.

The above-mentioned impacts are passed on to consumers. For example, consumers are faced with higher prices for their food, if production becomes more expensive due to the above-mentioned factors. In combination with the reduced availability of the final product, this can have significant impacts on **food security**.

Generally, the described impacts are further exacerbated by factors influencing the functionality and general resilience of the maize value chain, including poor infrastructure of roads and long distance to markets, lack of capital to invest in the businesses, a lack of transparency and regulation causing high fluctuation in prices.

Overall, there is a stark sentiment across all interviewed value chain actors of carrying a major burden when it comes to climate risks impacting their respective value chain stages: "*Climate change is actually a very big issue for the business like this"*, notes one processor in Agago. A processor from Lira states *"We are always on our knees"*, while another processor in Lira worried *"We've not experienced this before"*.

> *So, yes, that puts not only the millers, but it puts the population in danger. If we can't give them flour, there is nowhere for them to turn.*
>
> — Processor from Lira

> *Because we are headed for very uncertain times. If we do not respond, I think livelihood is threatened.*
>
> — Processor from Lira

b. Changes in the composition of the value chain

In addition, we also identified impacts of climate-related hazards on the **composition** of the maize value chain in Uganda. This includes **changes in relations** between the different value chain steps and related changes in how products and finances flow through the value chain. Several interviewees have reported losing business partners due to climate shocks. This can happen upstream in the value chain, e.g. customers not buying from a certain business anymore because the business is unable to deliver the requested quantities due to lack of access to grains. Reduced maize supply in terms of both quality and quantity due to climate risks may also lead to processors switching supplier and buying grains from other farmers. Processors report they start sourcing from other suppliers, often in other regions within Uganda, such as Masindi, the major maize producing district, or even abroad in neighbouring countries like Kenya or Tanzania. A study by Suubi and Friis-Hansen (2017) showed that private grain traders in Uganda enhanced rather than buffered the impacts of an extreme drought which occurred in the Teso region in 2013 due to their hoarding behaviour. By delaying the sale of stored grains, traders kept the prizes high and maximized their profits. This shows the importance of taking the power dynamics within a value chain into consideration.

Several interviewees have also reported a **change in attitude** of value chain actors which has been caused by climate risks. One maize processor in Lira voiced his **mistrust** in farmers: *"Farmers are not doing enough in the post-harvest sampling of the product and it is deliberate. It is intentional"*, commenting on the reduced quality or quantity of the maize grains that farmers try to compensate for and that is often a result of climate hazards, such as droughts or changes in precipitation. In addition, many of the processors, aggregators and traders voiced their **concern** about how climate is impacting their business leading to planning insecurities. Some even shared feelings of **fear** of what the future might bring, worrying about e.g. the *"business collapsing"* or

the need to reduce salaries of staff or even cut staff. This may have impacts on the perceived agency of actors and could lead to lower investments in the future, as for example also shown in Nigeria, where maize traders who perceived high climate-related trading risks were less likely to invest in storage or adopt other price-enhancing strategies (Liverpool-Tasie et al., 2020).

To summarize, this assessment shows that climate impacts are experienced today not only at the production stage of maize value chains, but also at aggregation, processing and trading steps and even consumption. Impacts are experienced both directly, meaning climate hazards directly impact aggregation, processing and trading through e.g. aflatoxins due to higher humidity or infrastructure damage due to extreme rains, as well as indirectly, when climate hazards hit the production stage and their impacts trickle down to later stages of the value chain and, for instance, cause high fluctuations in maize supply and prices. Future increases in temperature and precipitation, including extremes, as projected in Chapter 2, are likely to further exacerbate the climate impacts currently experienced. In addition to these direct and indirect impacts, climate risks can have significant effects on the composition of the value chain, as well as the value chain actors' attitudes, which are all factors that need to be taken into consideration when designing adaptation strategies for the maize value chain.

> All assessed steps of the value chain are exposed to the impact of climate hazards with strong feedback loops between the different steps. Loss of quantity and quality at production level can lead to indirect impacts at later stages. If a climate hazard hits one or more value chain steps, the product and related financial flows may be diverted, new actors join the value chain, while others are forced out.

> *Above all, because of these changes in weather, which have reduced on the number of farmers who bring maize for milling, it affects [the] business in a way that [I] no longer make money that [I] used to make. And in a way that [I have] to either layoff some workers or cut their payments.*
>
> — Miller from Agago

3.3 Adaptation strategies for maize value chains

To promote the uptake of adaptation strategies, there is a need for quantitative information on their potential to increase crop yields under current and projected climate scenarios and how economically feasible the adoption of these proposed adaptation strategies may be. Our analysis aims to bridge this gap by assessing the yield buffering potential and economic feasibility of concrete adaptation strategies. We selected two adaptation strategies for our assessment, based on stakeholder interests, national priorities and methodological feasibility. For the production step of the maize value chain, we assess whether switching from a local variety to an **improved variety** is an economically viable adaptation strategy. For the aggregation stage of the value chain, we assess the economic feasibility of **improved post-harvest storage**. The analysis is meant to showcase examples of how specific measures can help value chain actors adapt to climate change. They should therefore be considered as only one piece to the puzzle of building climate-resilient agri-food systems.

3.3.1 Improved maize varieties

To counter the projected maize yield losses described in Chapter 3.2.1, one adaptation option for farmers is to adjust their crop varieties over time. An improved or modern variety is a new variety of a plant species which produces higher yields, higher quality or provides better resistance to plant pests and diseases while minimizing the pressure on the natural environment (Anderson et al., 2020). It is expected that improved varieties offer many advantages compared to their predecessors including uniformity, higher tolerances to abiotic stressors such as drought, resistances to biotic stressors, improved resource use efficiency, easier management and/or shorter growing cycles for risk avoidance (Atlin et al., 2017; Martey et al., 2020; Simtowe, Amondo, et al., 2019). Improved plant varieties therefore offer a more durable solution to adapt to climate variability, withstand biotic pressures and ensure profitability at farm level.

Improved maize seeds comprise Open-Pollinated Varieties (OPV) and hybrid varieties. Improved OPVs lead to higher yields than traditional varieties and can be recycled for two years without yield reduction. Hybrid varieties are even higher yielding than improved OPVs, but their seed have to be repurchased each season to maintain their yield potential (NAADS, 2020). All hybrid seeds are produced in the formal system, while 66 % of the OPV seeds are generated within the informal system and only 34 % in the formal system (MAAIF, 2015). Over the years, around 71 different improved maize seeds have been introduced to the market, many of them released by NARO, carrying attributes such as resistance to pests and diseases, drought tolerance, high yields, early maturity, nutritional benefits or tolerance to acidic soils (Barungi, 2019; Simtowe, Amondo, et al., 2019).

The current popular improved OPVs released by NARO and which are used in Uganda include Longe 1, 4, 5, 5D and MM3. Hybrid varieties include Longe 2H, 5H, 6H, 7H, 9H, 10H, 7H-IR, Bazooka as well as Tego series or Water Efficient Maize for Africa (WEMA) varieties, including amongst others 3109, 3106, 2114 and 2115. These seeds show differences in adaptability and yield potential, length of growing season, suitable production areas and resistance to pests and diseases (NAADS, 2020). However, according to USAID (2015), only 14–20 % of farmers who grow maize for subsistence use of improved varieties in Uganda, meaning that most of the farmers use local maize landraces (Nafa, Ndele) or older hybrids (Longe 1, Longe 4 etc). According to Longley et al. (2021), up to 89 % of seed planted by smallholder maize farmers in Uganda is informally sourced through self-saving, or sourced from family, friends, or local markets.

> Using crop models and a cost-benefit analysis, we assess whether switching from a local maize variety (Longe 4 or 5) to improved maize varieties (Longe 10H and Longe H628) is an economically viable climate change adaptation strategy.

In our assessment, we use Longe 4 or 5 or a local OPV as the baseline scenario and Longe 10H (up to 1500 mASL) or H628 (from 1500 mASL) recommended by MAAIF (2019) as improved variety. This choice sought readily available improved varieties that can be used by the farmers or form a foundation for further varietal improvement for resilience. Longe 4 and 5 are open-pollinated maize varieties that are popular in Uganda because of their drought tolerance and improved nutritional quality. However, this comes at the cost of lower yield potential. As a hybrid variety, Longe 10 can produce much higher potential yields than Longe 4 and 5. In addition, it was bred for drought and storage pest resistance and therefore has good storability.

3.3.1.1 Climate risk mitigation potential of improved maize varieties

Using an improved variety results in at least double the maize yields under current climatic conditions (113.2 %) compared to the current varieties, with maize yields from improved varieties able to exceed 10t/ha in the south-western, western and eastern parts of the country (Figures 18, 19 and 20). This yield benefit was realised across all grids but substantially varied from around 10 % to 500 % yield increase between the different grids. The highest yield response from using an improved variety under current climate conditions are in in the Elgon sub-region (+253 %) and south-western sub-region (+244 %) while the least, although still significantly high, are in the Teso (+83 %) and West Nile (+55 %) sub-regions.

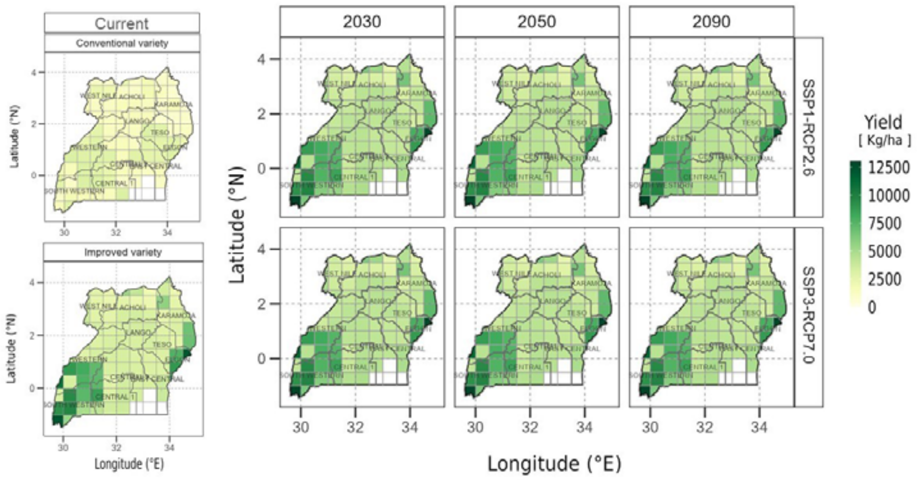


Figure 18: The grid-level spatial distribution map for projected yield of improved variety in Uganda under different projected scenarios and periods.

Projections show that improved varieties are stable across scenarios and periods (see Figure 18). Comparing the effect of climate change with an improved variety versus with what is possible with a conventional variety shows that using an improved variety is able to buffer all projected yield losses and actually has a positive effect under climate change, especially under worse case climatic conditions: at national level, improved maize varieties will produce 2.9 % and 8 % more yield by 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario respectively (Figure 18). This positive effect of improved varieties is due to the fact that improved varieties are projected to have stable yields under a changed climate, compared to high losses projected for conventional varieties. Since more losses are projected under climate change, the adaptation effect is the difference between the impact and the stable value. The highest adaptation effect of an improved maize variety is projected for the Karamoja sub-region progressively with time and scenario, being highest under the SSP3-RCP7.0 high emissions scenario by 2090 (17 %) and lowest under SSP1-RCP2.6 low emissions scenario by 2030 (1.7 %) (Figure 18, Figure 20). Other sub-regions with high adaptation effects of an improved variety are South-Western, East Central, Central 1, Central 2, Teso and Western sub-regions.

> Improved crop varieties perform equally well under projected climatic conditions as they do under current conditions, showing that they are a climate impact reducing measure in most parts of the country, for all periods and scenarios.

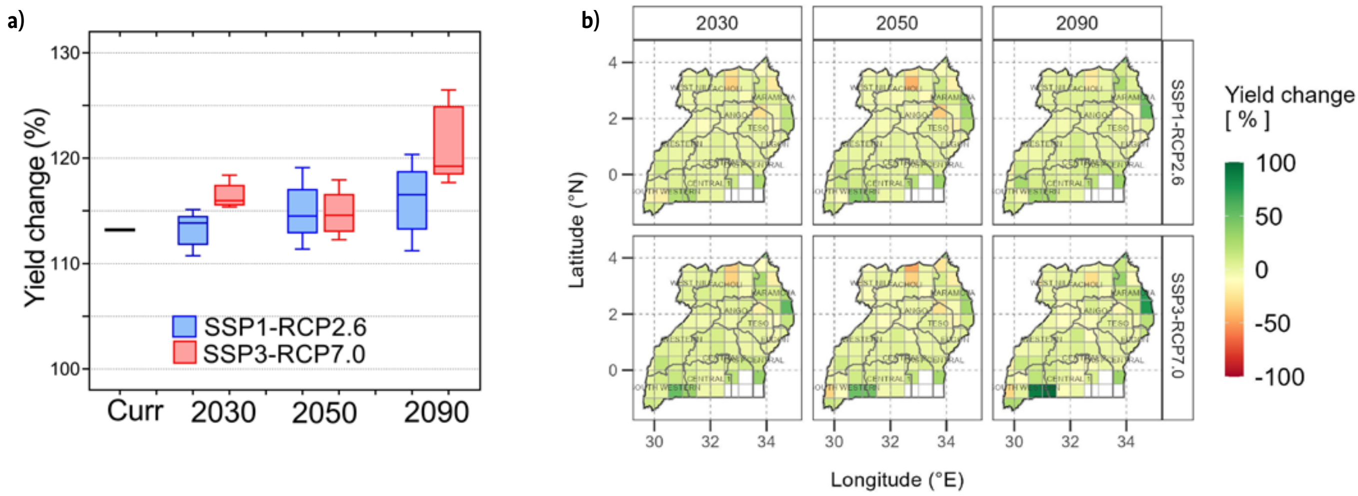


Figure 19: (a) The national level yield impact of an improved maize variety and (b) grid-level spatial distribution for projected adaptation effects of an improved maize variety in Uganda under different projected scenarios and periods.

Similar yield increases are projected with an improved variety for Acholi, Elgon and West Nile sub-region (Figure 20), indicating that using an improved variety in these regions is a good agronomic practice that will increase yields but does not buffer climate change impacts. Since the climate change buffering potential of an improved variety is positive for the majority of the regions and at national level, the results support the use of improved varieties as a viable climate change adaptation strategy in Uganda.

The results show that using improved varieties is a viable climate change adaptation method in two principal ways. First, increasing yield means that any projected losses will be happening on higher baseline yields, meaning that farmers may be able to avoid total losses. Secondly, and most importantly, the results indicate that the improved crop varieties perform equally well under projected climatic conditions as they do under current conditions, showing that they are a climate impact reducing measure in most parts of the country, for all periods and scenarios. The potential doubling of yield with an improved maize variety is in tandem with the genetic potential of the current varieties (potential yield 6t/ha) compared to improved varieties (potential yield 9t/ha) (MAAIF, 2019). Therefore, while keeping all other agronomic management constant, just changing the variety has the agronomic potential to more than double the yield in many areas across the country.

3.3.1.2 Costs and benefits of improved maize varieties under climate change

Using a cost-benefit analysis (CBA), we assess whether switching from local maize varieties to an improved variety is economically viable for the farmer on a national level. Following up on the previous section, we compare the costs and benefits of using Longe 10 seeds (adaptation) to the continued use of Longe 4 and 5 seeds (non-adaptation). The analysis will be conducted taking into consideration climate impact projections up to 2050 described in Chapter 3.2.1 "Climate Change Impacts on Maize Production", considering the two different climate scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario). As reference we use a baseline describing the status quo in 2022.

> Improved crop varieties perform equally well under projected climatic conditions as they do under current conditions, showing that they are a climate impact reducing measure in most parts of the country, for all periods and scenarios.

In order to analyse the economic feasibility of this adaptation strategy, we hereafter work with the following scenarios:

- **Baseline (no action, no climate change impacts)**: A rainfed maize production system that uses Longe 4 and 5 varieties under current climatic conditions and agronomic practices in Uganda.

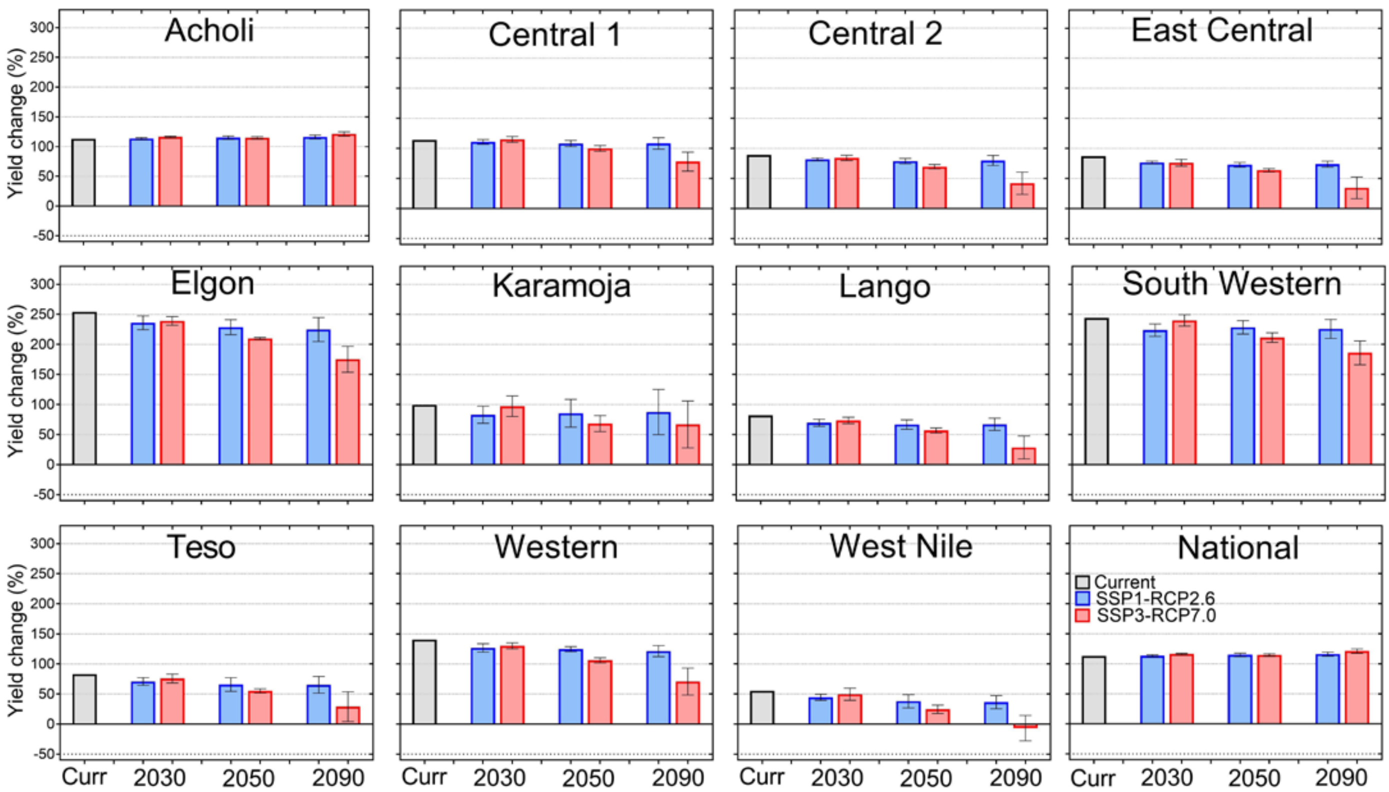


Figure 20: Yield impacts of using an improved variety across sub-regions over different scenarios and periods. The adaptation effect is the difference between the projected yield and the current with and without the adaptation measure.

- **Scenario 1: Non-adaptation (no action, climate change impacts)**: In the non-adaptation scenario, a rainfed maize production system with Longe 4 and 5 varieties is assumed, which means that in terms of management nothing changes compared to the baseline. The market revenues and costs of the production system are extrapolated until 2050 assuming a climate change yield impact under both emissions scenarios (SSP1-RCP2.6 low emissions and SSP3-RCP7.0 high emissions scenario).
- **Scenario 2: Adaptation (action, climate change impacts):** In the adaptation scenario, a rainfed maize production with the hybrid variety Longe 10 is assumed. The market revenues and production costs are extrapolated until 2050, assuming a climate change yield impact under both emissions scenarios (SSP1-RCP2.6 low emissions and SSP3-RCP7.0 high emissions scenario).

Annex I.2 includes a full description of the underlying data and assumptions.

	Adaptation under SSP1-RCP2.6	Adaptation under SSP3-RCP7.0
IRR	133.85 %	131.64 %
NPV	25,423,327 UGX	22,343,673 UGX
BCR	1.57	1.50

Table 2: Summary of major CBA indicators for switching from Longe 4 and 5 maize varieties to Longe 10 improved maize variety.

Results and key economic indicators

> The initial investment needed to switch from local maize varieties to improved maize varieties already becomes economically beneficial after one year with returns increasing in the future under both climate change scenarios of up to 133,85 %.

In economic terms, using improved maize varieties as an adaptation strategy to climate change is highly beneficial in comparison to the no adaptation scenario. All three considered indicators of the CBA show that the investment in the Longe 10 improved variety is profitable:

- The high **Internal Rate of Return (IRR)** of 133.85 % under the SSP1-RCP2.6 low emissions scenario and 131.64 % under the SSP3-RCP7.0 high emissions scenario indicates that improved maize varieties generate a return that exceeds the target rate of return. Under a global rentability perspective, any IRR higher than 6 % can be considered a profitable investment. The very high IRR values presented here are not uncommon for investments in improved varieties as only considerably small changes in expenditures are contrasted with often very substantial yield increases and subsequently greater revenues (Lotze-Campen et al., 2015).

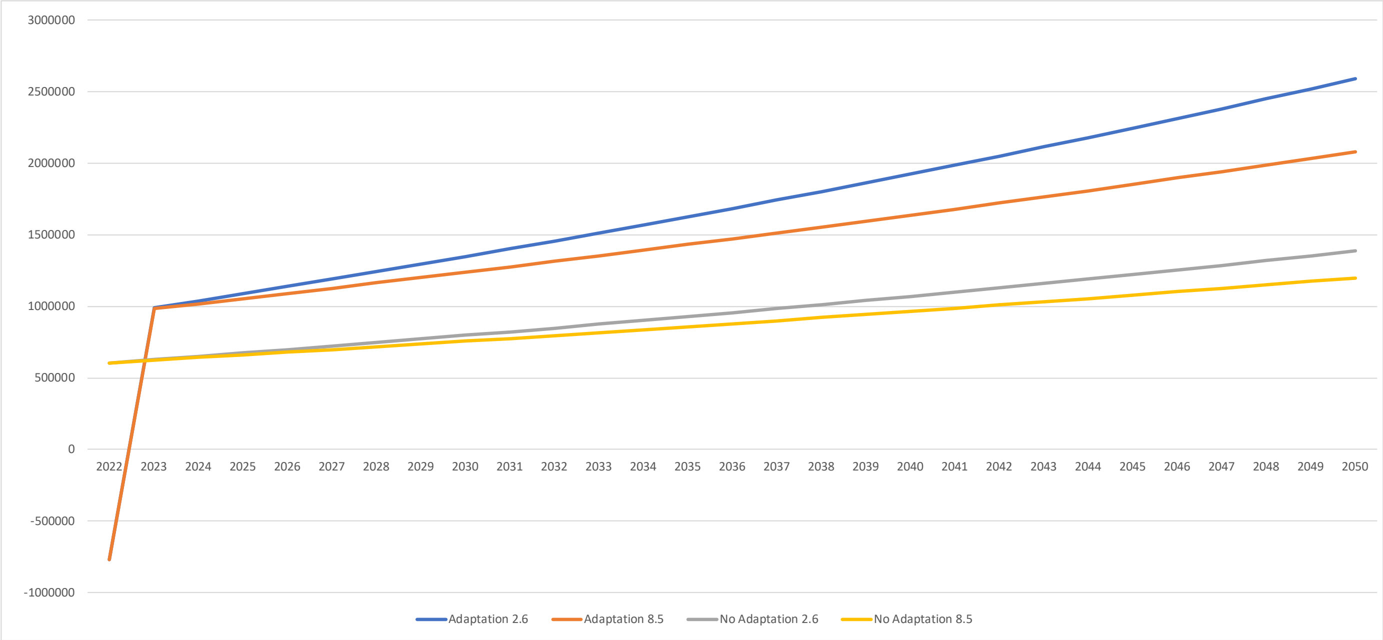


Figure 21: Net cash flow in UGX per ha up to 2050 for the adaptation (improved maize variety) and the non-adaptation scenario (local maize varieties) under the high and under the low emissions scenario.

- The positive **net present value (NPV)** of roughly 25.5 million UGX under the SSP1-RCP2.6 low emissions scenario () and 22.3 million UGX under the SSP3-RCP7.0 high emissions scenario shows that the present value of the expected cash flows exceeds the initial investment.
- In both cases the **benefit-cost-ratio (BCR)** is greater than 1, indicating that the benefits generated by the adaptation strategy are greater than its costs. Under the low emissions scenario (SSP1-RCP2.6), a BCR of 1.57 and under the SSP3-RCP7.0 high emissions scenario a BCR of 1.50 can be observed.

The improved variety brings higher benefits under the SSP1-RCP2.6 low emissions scenario than under the SSP3-RCP7.0 high emissions scenario, but in both cases the results show that the farmers' investment into an improved maize variety pays off. Figure 21 shows that both adaptation scenarios start with a lower net cash flow, compared to the net cash flow of the non-adaptation scenario in 2022. This is due to the investment costs for the Longe 10 variety and resulting higher production costs (i.e. for harvest and labour) due to higher yields. Over the years, the net cash flows of all scenarios increase steadily. The year 2023 marks the break-even point between accumulated net production costs and net market revenues for both adaptation scenarios. In the same year, the net cash flow of both adaptation scenarios surpasses the net cash flows of the non-adaptation scenarios. This fast increase in profitability within one year highlights the positive economic potential of a switch to improved higher yielding varieties for many farmers.

Generally, and as confirmed by this study, the use of improved varieties has a very high IRR (Lotze-Campen et al., 2015) and can thus be considered a highly profitable adaptation strategy. The economic advantages of improved hybrid maize varieties are expected to be similar for other improved varieties besides Longe 10. However, it is important to note that the extent of these benefits may vary depending on a range of factors, such as the specific agroecological conditions, the management practices used by the farmers, the market demand for the crop, and the level of adoption of improved varieties by farmers. Therefore, while the economic advantages of improved hybrid maize varieties are expected to be similar across different varieties, the magnitude of these benefits may differ depending on specific factors that affect maize production and marketing in different regions of Uganda or in other countries (Kaliba et al., 2017).
It is also important to note that since hybrids often require higher input costs, under certain circumstances, OPVs can have better gross margins than hybrids, even though hybrid varieties generally perform better (Sibanda et al., 2016). Hybrid seeds need to be purchased each planting season as saved seeds from hybrid plants do not reliably produce offspring with the same traits as the parent plant. Additionally, hybrid varieties often need higher rates of fertilizers and plant protection to generate a yield advantage. These variables were taken into consideration in our analysis.

3.3.1.3 The role of gender in the adoption of improved maize varieties as an adaptation strategy

Gender and other social factors can influence the uptake of climate change adaptation strategies. Women face difficulties more often than men in adopting improved maize varieties, which is reflected in low adoption rates of women (Fisher et al., 2019; Gebre et al., 2019). Awareness of the benefits as a combined result of access to information, education, credit and extension services has been highlighted as an important factor which influences the adoption of improved maize seeds (Fisher et al., 2019). For female household heads, especially when they are older, poorer, less educated and more socially isolated, these factors present constraints to the adoption of improved maize varieties, as shown by a study conducted in eastern Uganda (Balikoowa et al., 2019).

> Women are often less likely to have access to improved maize seeds. Taking into consideration women's role in making on-farm decisions will help to better promote the uptake of improved seeds.

However, the gender of the household head is not always a sufficient indicator of women's decision-making power over the entire farm (Fisher et al., 2019). Results from such studies provide information about a small segment of female farmers, ignoring the majority of female farmers in male-headed households, who are often the actual decision makers, in particular on the farm plots which they manage (Ndiritu, Kassie, & Shiferaw, 2014). Indeed, agricultural technology adoption is not an isolated decision but part of a larger household strategy (Ngigi et al., 2017; Zepeda & Castillo, 1997). Evidence from Kenya suggests that, if women plot managers frequently experienced climate shocks and dry spells during the growing season, they are significantly less likely to adopt both non-drought tolerant and drought-tolerant maize varieties on their plots (Ngigi et al., 2017). These findings suggest that women farmers are more risk-averse (Dohmen et al., 2005; Doss & Morris, 2001) and respond negatively to adopting technologies when they experience shocks (Ngigi et al., 2017). Furthermore, different studies emphasize the role of networks for the adoption of improved seed varieties (Fisher et al., 2019; Otieno et al., 2021). While men tend to have better access to improved varieties via formal seed networks and extension services, women are more likely to rely on local and more informal farmer-to-farmer networks, with poorer access to improved varieties and, in turn, negative consequences for their income and food security (Otieno et al., 2021).

Even where improved varieties are adopted, they can lead to maladaptive outcomes for different social groups. For example, a study of an improved rice variety in the Hoima district in Uganda found that in particular for women and children, the adoption of this variety increased the need for bird scaring and weeding, both of which are traditionally performed by women and children (Bergman Lodin et al., 2012). Hence, the increased need for these tasks led to greater time poverty and physical exhaustion among women and children, with negative impacts on children's attendance and performance in school. Maladaptive outcomes like these need to be carefully weighed with the potential benefits when promoting different climate adaptation strategies. Consequently, efforts aimed at strengthening resilience and enhancing adaptive capacity must deal with root causes of vulnerability and tackle structural barriers such as rights, representation and access to resources.

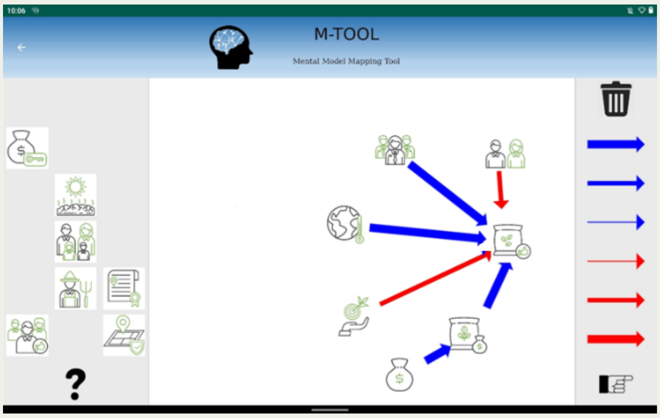
Box 1: The role of tenure security for improved seed varieties as climate change adaptation strategy

Land access is crucial for the livelihood of farmers, especially in low- and middle-income countries (LMICs), where most of the population depends on agriculture. However, in LMICs, the land tenure systems are often complex and fragmented, resulting in varying levels of tenure security for farmers. Land registration and demarcation programs are used to strengthen tenure security and reduce land conflicts. As secondary effects, such tenure strengthening interventions are thought to improve access to credit, make land markets more efficient, and increase investment in land. However, despite the theoretical expectation that tenure security will result in increased agricultural investment (and adaptation to climate change), empirical evidence is mixed.

We conducted a study in Soroti District in Eastern Uganda to better understand the importance of tenure security for agricultural investment and adaptation. We used the example of investing in improved seeds, because improved seeds are an important determinant of agricultural production and are often used as a proxy for climate change adaptation. Based on a method from psychology, so called mental models, we evaluated farmers' perception of the decision-making process to use improved seeds. Mental models are the way humans make sense of the outside world and underlie our thinking. The method allows for nuanced insights into perceptions of the decision-making process of farmers. The study thereby contributes to the understanding of the relative importance of factors in agricultural decision-making and provides insights into the complexity of the tenure security-investment link.

As part of the study, 253 smallholder farmers in Eastern Uganda were interviewed and elicited their mental models on improved seed investment. For eliciting the mental models, we used the M-Tool, an application that was developed by researchers at the University of Heidelberg specifically to collect mental models in a systematic way with low researcher influence and hence bias. In addition, the tool is well suited for applications in rural context and in populations with low literacy levels. Participants were able to choose from 15 pre-selected drivers or factors in the app, that potentially influence their decision to use improved seeds, and then drew influence diagrams showing their mental models of this decision-making process. An example mental model is shown in Figure 22a. With the option to add arrows of different strength to connect the drivers, participants were able to indicate how strong an influence is and whether it is positive or negative (ranging from −3 to +3). The study region in Soroti district is depicted in Figure 22b. We collected data in Katine and Gweri sub-county of Soroti district, to compare between households that were part of the GIZ project Responsible Land Policy in Uganda (RELAPU) on systematic land demarcation ("treatment" group) and households who were not part of this project ("control" group). RELAPU was only active in Katine for non-systematic reasons, which makes Gweri (and some households in Katine that were not part of RELAPU) a suitable control group, even if the intervention was not randomly assigned.

a)



b)

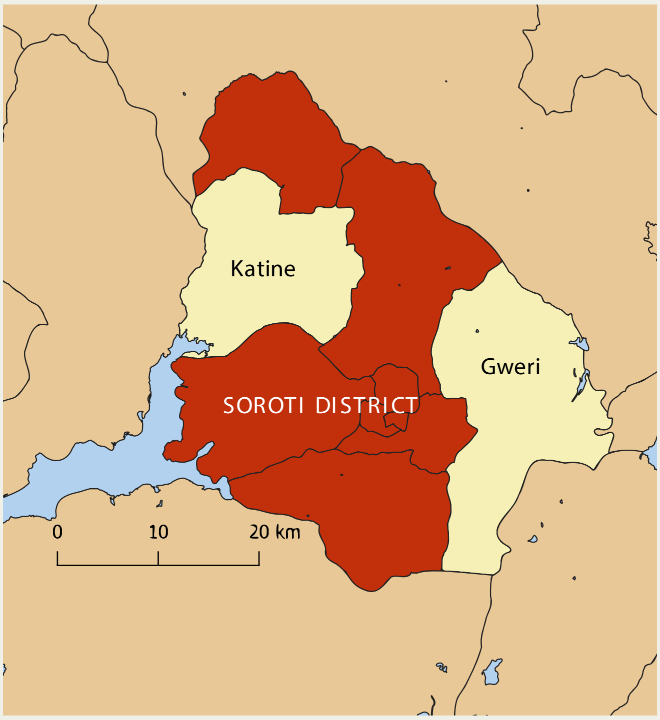


Figure 22: a) Example of a mental model mapping screen in the M-Tool application. b) Study region in Soroti district with the two sub-counties Katine and Gweri highlighted in yellow.

The results can be summarized as follows:

1. Households generally consider tenure security and land certificates less important than other drivers, such as financial capital, expected benefits, and extension advice.
2. For households who consider tenure security important, it has a strong positive effect on the decision to use improved seeds.
3. Participating in a land demarcation project has no significant impact on the perceived importance of tenure security or land certificates for the decision to use improved seeds.
4. Female-headed households give more value to obtaining a land certificate and attribute an increased use of improved seeds to it, despite many not yet having one.

The study's results are in line with recent experimental studies on tenure security and land formalization, and they contribute to a better understanding of the potential effects of tenure security on investment. One explanation for the limited perceived influence of tenure security and land certificates on improved seeds use may lie in the measure that was studied: Using improved seeds is a relatively short-term investment, which may not require tenure security compared to more long-term investments such as agroforestry. In addition, the relatively low number of households that include land certificates and tenure security in their mental model limits the statistical power to identify significant differences, suggesting that potential effects of tenure security or land certificates on improved seeds likely concern a smaller group of people than expected, requiring larger sample sizes in impact evaluations.

Despite being a detailed study of one district in Uganda, the study can also offer lessons for other regions in sub-Saharan Africa with largely similar customary land tenure, subsistence farming, undocumented land, and uncertain land tenure. Concrete policy recommendations based on this study are to specifically target households that express interest in strengthening their land tenure and obtaining land certificates, such as women, households who own multiple plots and households that are more food insecure compared to their neighbours. Strengthening land tenure is potentially more important for investment and adaptation strategies with a longer time horizon, e.g. planting trees for the establishment of agroforestry systems.

3.3.2 Improved Storage

As shown in Chapter 3.2, climate change does not only impact the production stage of the maize value chain but has severe impacts on later stages of the value chains, including post-harvest processing, storage and trade. Resilience building therefore also needs to take adaptation strategies for later stages of the value chain into consideration. In Uganda, where post-harvest loss is considered to be high, especially at smallholder level (Strecker et al., 2022; Tibagonzeka et al., 2018; Tröger et al., 2020), post-harvest steps of agricultural value chains are particularly vulnerable to climate change.

> Improved storage, such as hermetic bags, could help to mitigate the expected increases of mycotoxins and mould caused by a changing climate.

One important measure against post-harvest losses due to climatic factors such as increased pests and diseases are so-called **Hermetic Storage Technologies (HST)**. HSTs in the form of hermetically sealed containers work by suffocating pests within a batch of grains and preventing them from reproducing. As time progresses, the concentration of oxygen decreases while the concentration of carbon dioxide increases, asphyxiating any live insects and larvae. This enables pest control without the use of pesticides. HST products can be safer and more affordable than the use of chemical substances and fumigants. They include hermetic bags, which consist of single or multiple inner hermetic liners enclosed by an outer woven bag, hermetic metal and plastic silos, and hermetic bulk storage solutions (such as silo bags and cocoons) (Mhando, 2021). A number of different studies recommend that increasing the access to adequate storage facilities is a key variable in controlling mycotoxin levels in maize as well as other agricultural crops (Lukwago et al., 2019).

This is especially important, as the projected climatic changes are expected to increase the levels of mycotoxins, such as aflatoxins, and mould formations due to higher levels of humidity caused by increased temperatures and rainfall. As highlighted by Lukwago et al. (2019), Uganda is experiencing weather conditions that are suitable for the proliferation of mycotoxins due to the impact of climate change in form of hotter and more humid conditions. Thus, one strategy to mitigate these potential effects of climate change in maize cultivation and potential negative consequences for the Ugandan maize sector is the introduction of better storage facilities.

There are multiple benefits in regard to lower storage costs and improved quality and safety of stored food commodities. First, HSTs reduce post-harvest losses from pest infestation up to 98 % (Kumar & Kalita, 2017; Mhando, 2021). This can increase famers' revenues and reduce price volatility in food markets, thereby contributing to the availability of food products (Mhando, 2021). Second, they preserve the product's quality by promoting the adherence to food quality and safety standards. Thereby, farmers are able to sell high-quality products, again resulting in higher incomes and reduced health risks. Third, they enable the effective storage of grains over long periods of time, which allows farmers to delay the sale of their produce until they consider market prices favourable, again increasing their incomes. And fourth, the storage with HSTs both by farmers and downstream actors is cost-effective, also because the costs for pesticides are avoided.

However, despite these advantages, a survey by the East Africa Grain Council (EAGC, 2018) found that the adoption rate of HSTs in Uganda accounts for merely 14 % (Mhando, 2021). Storage on smallholder farms is still often done in polypropylene woven bags. This can be explained by three main challenges: First, there are many products on the markets that do not adhere to required standards or are simply counterfeit. Examples are simple plastic bags that are declared to be hermetic bags. This undermines the adoption of genuine HSTs since it is difficult for farmers to distinguish between the genuine and substandard or counterfeit products and, since the latter ones are cheaper, often seem more attractive to farmers. Farmers who have purchased inferior products then may conclude that hermetic storage solutions do not achieve the desired results. Second, there is a lack of knowledge about the correct use of HSTs. Examples of wrong application are the storage of wet grains in hermetic bags, resulting in quality loss and high aflatoxin levels or the wrong handling of the bags which can cause perforation and thus eliminates the hermetic function. Third, relatively high taxes (Value-Added Tax – VAT of 18 %) on HSTs in Uganda make them much more expensive than conventional bags and thus inhibit their wide-scale adoption by farmers. This is exacerbated by the recent practice by the Uganda Revenue Authority of charging the VAT on each component of an HST (a HST with an inner and an outer bag is hence charged twice) (Mhando, 2021).

3.3.2.1 Costs and benefits of improved storage

The following cost-benefit analysis (CBA) assesses if the introduction of improved storage practices in maize production constitutes a profitable adaptation strategy in Uganda. By focusing on rather simple technological changes at farm-level, this CBA aims to show how a relatively small change in the post-harvest handling of maize can have a positive monetary impact in the long run (Dijkink et al., 2022). The CBA compares the costs and benefits of a farmer who invests into improved storage bags for maize (adaptation scenario) with the costs and benefits of a farmer who continues using poor quality bags (non-adaptation scenario). Over a period of 27 years (until 2050), the investment costs and additional benefits of the farmer who adapts are calculated on hectare basis assuming two different emission scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario).

In order to analyse the economic feasibility of this adaptation strategy, we hereafter work with the following scenarios:

- **Scenario 1: Non-adaptation (no action):** In the non-adaptation scenario, an average small-scale maize farmer continues with the status quo of using maize storage bags made of unfavorable material such as polypropylene, sisal or jute. After one season, he/she incurs 19.1 % crop losses due to insect infestation and/or toxin formation (Dijkink et al., 2022; Jenkins & Leung, 2013).
- **Scenario 2: Adaptation (action)**: In the adaptation scenario the farmer stops using the poor-quality storage bags and instead invests into hermetic bags. Thereby he/she reduces the losses from 19.1 % to 1.6 % (Dijkink et al., 2022). The additional market revenues and investment costs of the improved practice are extrapolated until 2050 assuming climate change impacts on maize yields under the two emission scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario; see Chapter 3.2.1).

	Adaptation under SSP1-RCP2.6	Adaptation under SSP3-RCP7.0
NPV	3,342,220 UGX	3,053,474 UGX
IRR	67 %	65 %
BCR	2.65	2.63

Table 3: Summary of key CBA indicators for switching from jute/polypropylene bags to hermetic bags for postharvest maize storage.

Results and key economic indicators

> Switching to hermetic bags for postharvest maize storage is highly profitable under both emission scenarios, generating returns of investment of up to 67 %.

The key economic indicators in Table 3 show that in 2050 the adaptation strategy of switching from jute/polypropylene bags to hermetic bags for postharvest maize storage is highly profitable under both emissions scenarios.

- The high Internal Rate of Return (IRR) of 67 % under the SSP1-RCP2.6 low emissions scenario and 65 % under the SSP3-RCP7.0 high emissions scenario, indicates that the investment generates a high economic return. Under a global rentability perspective, any IRR higher than six percent can be considered a profitable investment. For relatively small investments like the presented one, high IRR values are not uncommon as only considerably small changes in expenditures are contrasted with often high benefit increases (Lotze-Campen et al., 2015).
- The positive net present value (NPV) of approximately 3.3 million UGX under the SSP1-RCP2.6 low emissions scenario and 3.1 million UGX under the SSP3-RCP7.0 high emissions scenario, shows that the present value of the cumulated expected cash flows exceeds the initial investment, making the investment beneficial.
- In both cases the benefit-cost-ratio (BCR) is greater than 1, indicating that the benefits generated by the project are significantly greater than its costs. Under the SSP1-RCP2.6 low emissions scenario a BCR of 2.65 and 2.63 under the SSP-RCP3.70 high emissions scenario can be observed – meaning that the benefits are more than two times as large as the costs.

The development of the investment's net cash flow in Figure 23 shows, that the investment is beneficial right from the beginning: The farmer starts investing at the end of season 2022 and thereby immediately reduces the losses in year 2023. The revenues are higher than the costs and over the years the net cash flows under both emissions scenarios increase steadily. The fast increase in profitability highlights the high economic potential of reducing postharvest losses by introducing improved storage facilities on the farm.

In addition to economic benefits, there are also health benefits for famer households (Dijkink et al., 2022). For a holistic economic evaluation of the measure, these benefits would therefore have to be monetarized and also included in the calculation. Given such monetarization, it can be assumed that the CBA would show considerable higher positive results than it already does.

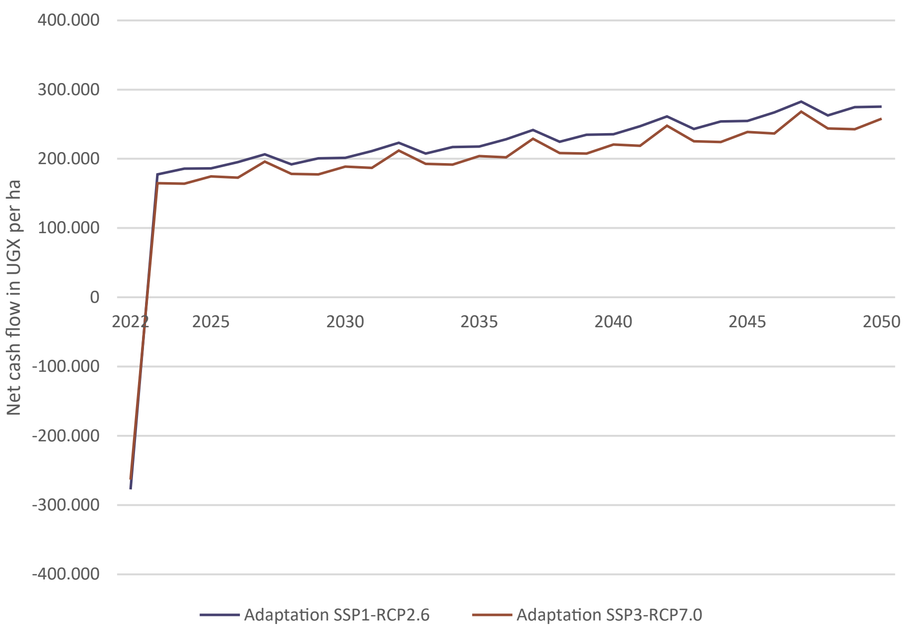


Figure 23: Net cash flow at current prices in UGX per ha up to 2050 for both adaptation and no-adaptation scenarios under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario.

3.3.2.2 The role of gender in the adoption of improved maize storage as an adaptation strategy

Previous studies assessing the effect of gender on the uptake of post-harvest storage technologies and specifically on the adoption of hermetic bags are limited. Dijking et al. (2022) stress the health benefit for famers households of using high-quality material for storage: "As the use of hermetic bags is a good intervention for preventing food loss, it is best promoted not only for providing direct profits to farmers but also for health benefits, as bag use implies a lower need for pesticides and a possible reduction in aflatoxin intake" (p.1). This is particularly important for women and children, as highlighted in a 2020 report by the International Development Research Centre (IDRC) which addresses the potential of hermetic technologies to reduce fungi-related chemicals in stored maize in Zimbabwe (Nyanga et al., 2020). For example, fungi-related chemicals like aflatoxin can cause cancer and can be transmitted via breastmilk (Asiki et al., 2014). Furthermore, in young children the chemical can cause stunting and hamper cognitive development (Nyanga et al., 2020). According to the IDRC report, women and children from households using hermetic bags showed a reduced occurrence and concentration of aflatoxin in urine samples (Nyanga et al., 2020). A study conducted in rural south-western Uganda confirms that aflatoxin exposure is widespread in rural populations, including individuals with relatively high aflatoxin levels (Asiki et al., 2014). In addition to health benefits, the IDRC report highlights saving time as another benefit for women, since the use of hermetic bags removed the need for chemical protectant application, while the higher quality of maize reduced the need for cleaning the crop from contaminants (Nyanga et al., 2020).

> Studies assessing the effect of gender on the adoption of improved post-harvest storage are limited. However, there is evidence on how reduced occurrence of aflatoxins due to the use of hermetic bags leads to reduced exposure of women and children whose health is particularly vulnerable to the fungus.

3.4 Conclusion

Maize is the most important staple crop in Uganda. As most of Uganda's maize production is rain-fed and characterized by smallholder farming systems that use primarily manual inputs, the maize value chain is particularly vulnerable to climate change. This chapter analysed how climate change impacts maize value chains and identified and assessed two possible adaptation options: improved maize varieties and improved storage.

3.4.1 Climate impacts on the maize value chain

Climate impact models project a **decreasing yield trend across the country** with mean yield losses between 4.4 % and 6.2 % by around 2030, 8.6 % to 14.3 % by 2050 and 8.8 % to 26.8 % by 2090. Higher yield losses are projected under the high emissions scenario than under the lower emissions scenario. Currently high-yielding areas will have the highest yield losses compared to areas where yields are marginal, i.e. western and eastern parts of the country. With population growth, the projected declines in maize yield may not only result in economic challenges for producers and wider food and nutrition insecurities, but could also lead to land expansion and exploitation of natural resources. Interviews with maize processors, aggregators and traders have revealed that **climatic factors influence maize value chains beyond production** and also **significantly affect the product, activities and finances at post-harvest steps** of the maize value chain with strong feedback loops between the different steps. High levels of humidity, for example, are reported to lead to aflatoxins and drying difficulties. Extreme precipitation events can disrupt transport. When climate hazards, such as drought, hit the production stage their impacts trickle down to later stages of the value chain and, for instance, cause high fluctuations in maize supply and prices. These impacts lead to changes in the value chain composition diverting financial product flows. They can also lead to a change in attitudes of the actors involved, including a loss of motivation, fear, as well as feelings of disadvantage and mistrust towards actors in other steps of the value chains, changing existing relationships between actors. Future increases in temperature and precipitation, including extremes, are likely to exacerbate the climate impacts currently experienced. In order to be able to design holistic climate change adaptation strategies, we therefore **need to take the complexity of the entire value chain into consideration**. Improved maize varieties and improved storage of maize grains are two potential strategies to promote and enhance the resilience of maize value chains under future climate conditions.

3.4.2 Adaptation options for the maize value chain

The analyses show that **switching from a local maize variety to an improved maize variety would be highly beneficial for farmers**, both in terms of buffering yield losses caused by climate change, as well as in economic terms. Improved varieties have the potential to increase maize yields in Uganda under current climate conditions by 113.2 % and also buffer yield from climate change-induced losses by 2.9 % and 8 % by 2090 under the SSP1-RCP2.6 low emissions and SSP3-RCP7.0 high emissions scenario respectively. The highest adaptation effect of an improved maize variety is projected for the Karamoja sub-region progressively with time and scenario, being highest under the SSP3-RCP7.0 high emissions scenario by 2090 (17 %). Investing in improved maize varieties brings quick returns of investment for the farmers, already becoming economically beneficial after one year with returns increasing in the future under both climate change scenarios up to 133,85 %.

Impact	Current	Future	Confidence
Maize yields with conventional variety		Decreasing	High
Maize yields with improved variety		Decreasing but at a lower rate than conventional varieties	High
Post-harvest steps of the maize value chain	**Product:** Loss in quality and quantity of grain, Mycotoxins **Activities:** Drying difficulties, Machines run at reduced capacity due to limited grain supply, Disruption of transport **Finances:** Increased costs of grains due to limited supply, Price fluctuations, Loss in income		Qualitative assessment based on perceptions of interviewees

Table 4: Summary of climate change impact on maize production.

As these **improved varieties** are already available in the country, with many in breeding pipelines, there is a need for strategic policy planning to increase the adoption of these varieties by maize farmers in Uganda, especially by overcoming the many barriers to adoption (Lee, 2020; Longley et al., 2021; Simtowe, Marenya, et al., 2019). These barriers include lack of resources (labour, land and cash) and high seed prices (Abate et al., 2017; Fisher et al., 2015). Simtowe et al. (2019) bemoan heterogeneous seed access and information asymmetry as leading factors limiting adoption of improved varieties in Uganda. There are furthermore gendered and class factors explaining access to these improved varieties (A Mastenbroek et al., 2020; Simtowe, Amondo, et al., 2019; Teklewold et al., 2020). Taking into consideration that improved seeds often require higher input costs and given the information asymmetry on their benefits for smallholder farmers, it is imperative for stakeholders in the agricultural sector to continue to accelerate access to not only elite germplasm for farmers, but also to inputs and credits. Rapid breeding cycles provide farmers with a steady stream of improved varieties. Furthermore, conduction information campaigns on the benefits of improved varieties under climate change as well as building a seed systems model that delivers new varieties to farmers quickly and cost-effectively will be crucial. However, it is also worthwhile to put similar efforts into the research and promotion of other crops that are naturally more nutritious and resistant to the effects of climate change than maize, while being already an integral part of the population's traditional dietary habits, such as sorghum.

Investing in **improved storage** is an important post-harvest adaptation strategy. As the climate changes, conditions to store maize may become less favourable. For example, projected climatic changes are expected to increase the levels of mycotoxins, such as aflatoxins, and mould formations due to higher levels of humidity caused by increased temperatures and rainfall. One strategy to mitigate these potential effects is the introduction of better storage facilities, such as hermetic bags. The results of our analysis show that **switching from jute/polypropylene bags to hermetic bags for postharvest maize storage is highly profitable under both emissions scenarios**. When a farmer starts investing, he or she can reduce post-harvest losses within one year. The revenues are higher than the costs and over the years the net cash flows of both emissions scenarios increase steadily generating returns of investment of up to 67 %. However, despite these advantages, there are very low adoption rates, due to factors such as lack of knowledge, low product standards on the market and relatively high taxes (Mhando, 2021). Providing access to high quality hermetic bags and sharing knowledge on their benefits could significantly increase the quality of maize and its resilience against climate change for various actors along the value chain.

Both assessed adaptation strategies are economically beneficial and can be recommended to adapt to the projected climatic changes. Successful implementation will depend on a context-specific design that takes the different biophysical realities in which they are implemented into consideration, for example the agroecological conditions as well as the realities of the actors involved, including socio-economic backgrounds, land tenure security and gender dynamics. We therefore suggest avoiding considering only one step of the value chain, when designing adaptation strategies but keeping in mind the complex systems of actors, processes and wider agri-food systems in which they are embedded in.

4. Climate risk analysis for coffee value chains

Uganda is one of the most important coffee producing countries worldwide. It is among the top ten global exporters of coffee and the second largest coffee exporter in Africa by volume (UCDA, 2019a). Uganda produces both coffea Arabica and coffea canephora (commonly referred to as Robusta). In Uganda, Robusta is more widely produced than Arabica coffee, contributing to approximately 77 % of the coffee production in the country. Robusta coffee is mostly grown in the lowlands within the altitudinal range of 900–1200 m above sea level. It is mostly grown in Central, Eastern, Mid North, West Nile, Western and South Western Uganda (UCDA, 2019b). Arabica coffee, on the other hand, is grown on relatively higher altitudes ranging between 1,200–2,500 m above sea level. This species is mostly grown around Mt. Elgon, Rwenzori, south eastern Uganda and the west Nile (UCDA, 2019a). Coffee is the largest contributor to exported commodities, which was valued at USD 492 million for the year 2017/18, representing 16 % of total Ugandan exports (UCDA, 2019b).

> Coffee is extremely sensitive to climatic changes. Climate change therefore poses a serious threat to coffee production, both in terms of quality and quantity of coffee.

As climate-sensitive perennial crops, both Arabica and Robusta coffee have high but differing sensitivities to climatic change (MWE, 2015). Optimal growing conditions for Arabica require a temperature range of 15–24 °C. Temperatures above 24 °C cause stress and can seriously damage the plant (UCDA, 2019a). While Robusta coffee is more tolerant to hot conditions than Arabica with an ideal temperature range between 22°–28 °C, it is much more sensitive to lower temperatures than Arabica (UCDA, 2019b). Over the past decades, coffee production areas in Uganda have become drier and hotter, with a trend towards higher temperatures in both Arabica and Robusta locations. Changing climate conditions lead to an unfavourable environment for coffee production. As Bunn et al. (2019) describe in the USAID "Climate-smart coffee in Uganda"-study, climate change is expected to have a high impact on coffee production in Uganda as it will change weeds, pests and diseases, such as coffee rust in coffee trees, and increase soil erosion, landslides, and irregular flowering. This may negatively impact yields and quality (MWE, 2015).

The following chapter will analyse climate impacts on the coffee value chain and assess the potential of selected adaptation strategies. First, we provide a mapping of the coffee value chain in Uganda, which has been conducted through a combination of literature research and expert interviews. To assess the impacts of climate change on coffee production, we apply crop suitability models which show how this could change due to climate change by 2030, 2050 and 2090. The projections are complemented with an abductive thematic analysis of interviews conducted with different coffee value chain actors to better understand how climate risks are already experienced at post-harvest steps of the value chain today, including during aggregation, processing, and marketing/trade. Driven by the interest of local stakeholders and informed by the projected climate impacts on agriculture, two adaptation strategies were selected and analysed in terms of their risk mitigation potential and economic feasibility. For the production step of the coffee value chain, we analyse the potential of agroforestry to buffer suitability changes and whether establishing agroforestry systems is an economically feasible strategy for farmers. For the aggregation stage of the value chain, we assess the economic feasibility of improved post-harvest coffee storage using jute bags and high-quality pallets. The results show the potential of promoting climate change adaptation along the coffee value chain and can help to make informed investment decisions.

4.1 The coffee value chain

> Coffee undergoes various value addition steps to turn the cherry into green beans ready for export. These include aggregation, wet or dry processing and grading.

Coffee is one of the leading commodities in Uganda with about five million people engaged in its production or through other coffee-associated businesses (UCDA, 2019b). Land, water, seeds, fertilizers, agrochemicals (herbicides, fungicides and pesticides) and farming and irrigation equipment are among the main **inputs**, although the use of purchased inputs is very low in Ugandan coffee production (Bunn et al., 2019). In terms of financial inputs, farmers mostly rely on their immediate surroundings by forming Village Savings and Loan Associations (VSLAs) or joining Savings and Credit Cooperative Organisations (SACCOs) to set up saving and loan schemes or linking up with other farmers to apply for farm loans from larger banks (UCDA, 2019a). The **production** stage of the value chain includes sowing (only when newly planting or re-planting trees), regular pruning, stumping of trees (recommended in 6–8-year cycles) and other farm management practices. Most coffee is produced by smallholder farmers who own less than 0.5ha of land. While monocropping exists, most farmers grow coffee intercropped with banana (*Musa acuminate*) and other food crops (Bunn et al., 2019). This intercropping system is a traditional climate-smart coffee farming method. The system was invented following the increase in population relative to the land available. Hence there was a need to utilize land more efficiently for income generation and food provision (van Asten et al., 2015a).

Coffee is harvested by picking the ripe coffee cherries from the tree. In Uganda, there are two harvesting seasons a year, the main season and a minor season, the fly season. In order to maintain the quality of coffee, selective interval picking of only ripe cherries is recommended (UCDA, 2019b, 2019a). In most cases, farmers either sell their coffee un-processed as cherries, or sun-dried. In rare instances, all processing steps are done at farm-level.

In Uganda, aggregators often link coffee producers to processors. At **aggregation** level, there are many players and levels of sophistication, including organized farmer groups, processors, small business owners specialising in aggregation or trading businesses (FAO, 2020b). The **processing** steps in coffee may be grouped into primary, secondary and tertiary steps. The two most widely used primary processing methods are dry and wet processing (Chanakya & De Alwis, 2004). Dry processing is a natural and simple process. The cherries are mostly dried in the sun with the seeds still in the fruit. After drying, the dried coverings (husks) are removed in a mechanical operation, called hulling. The dried coffee is locally known as Kiboko (UCDA, 2019b). Wet processing is more complex than dry processing, requiring specific equipment and the availability of large quantities of clean water. The first step of wet processing is the removal of unripe, immature and dried cherries by a floatation process. The cleaned cherries are then pulped.

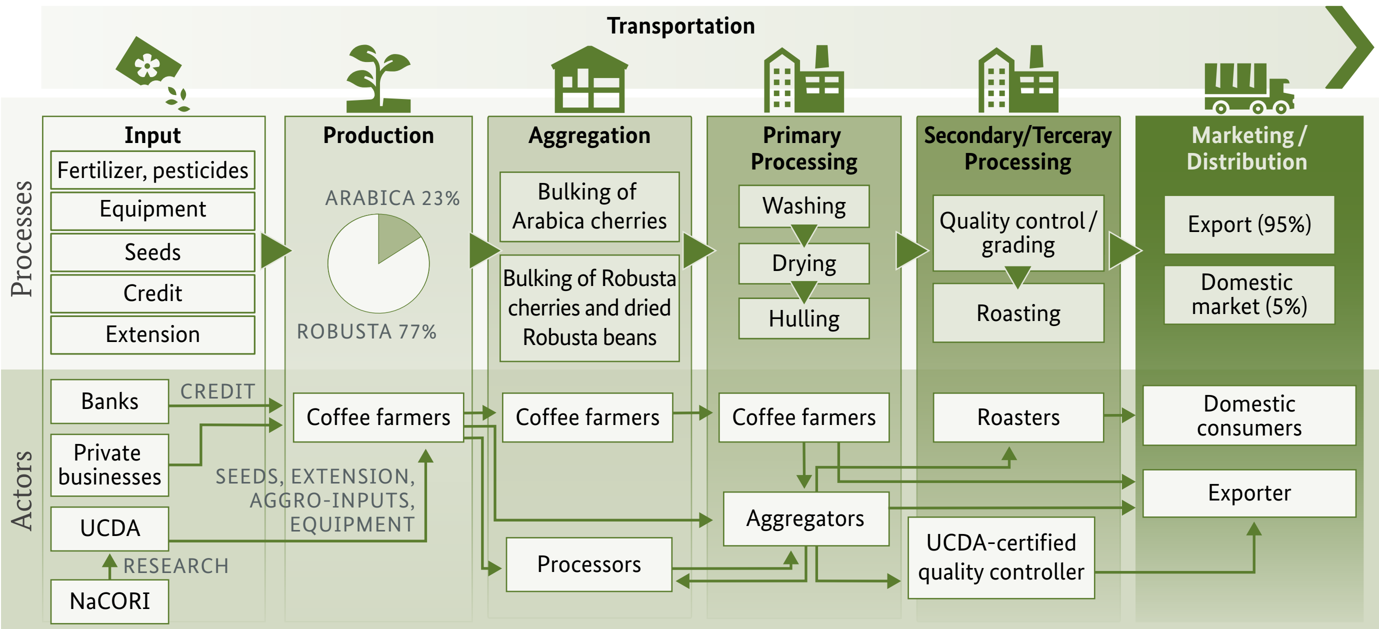


Figure 24: Simplified mapping of a coffee value chain in Uganda, based on expert interviews and literature.

The wet parchment beans have a mucilage layer around them that is removed by bio-chemical enzyme activity through controlled fermentation and afterwards washed to produce 'fully-washed' coffees, a water-intensive process. In a process called "semi-washed", the cherries are pulped, as in the washed process, but then the mucilage covered beans are dried in the sun instead of soaking. (UCDA, 2019b). The wet processing method is more widely used in the case of Arabica coffee and the dry processing method in the case of Robusta coffee, although production of speciality Robusta coffee is increasing, which often involves wet processing. The resulting clean coffee beans are in both cases referred to as FAQ (Fair Average Quality). Secondary processing also known as export grading transforms the clean coffee (FAQ) into the various coffee grades. The process involves cleaning the FAQ, drying the coffee if wet, followed by size grading. The graded beans are gravimetrically sorted to obtain a uniform specific density (UCDA, 2019). Figure 24 provides a simplified overview of the Ugandan coffee value chain.

The Ugandan coffee sector is vibrant, with many secondary processors, who are often also exporters. The largest companies in this segment are international trading companies who source the green beans in Uganda to sell to roasters in Asia, Europe and North America (FAO, 2020b). Most coffee is exported after the secondary processing step. The tertiary processing step involves further processing of the coffee beans, including roasting, producing instant coffee or other value-adding measures (Chanakya & De Alwis, 2004). After being packed, the final steps of the coffee value chain are its **distribution and marketing**. For marketing, farmers have several options. Coffee can be sold either as dried Kiboko, FAQ, graded coffee, roasted beans, or as a beverage/coffee cup. Coffee marketing options include trading Kiboko at farm gate, trading FAQ at the local processing plant, trading FAQ in national markets, trading with exporters, and trading graded coffee for export markets (UCDA, 2019b). Green coffee beans undergo quality controls by the Uganda Coffee Development Authority (UCDA), the governmental regulatory body for coffee in Uganda, before being exported. Depending on the destination, green coffee beans in Uganda are transported by road or rail to major harbours, for example Mombasa in Kenya, and shipped to the world markets.

4.2 Climate change impacts on the coffee value chain in Uganda

4.2.1 Climate change impacts on coffee production

We applied crop suitability models to assess the current and future suitability of two coffee species (Arabica and Robusta) as part of **coffee-banana intercropping systems**, the most common coffee intercropping system in Uganda. In addition to improved incomes, coffee-banana intercropping provides benefits such as erosion control, provision of mulch, reduced pest and disease pressure, spread of economic risks related with monocropping, and above all shading against extreme weather events, such as drought (Madsen et al., 2021). However, bananas are also highly sensitive to weather shocks hence making the crop highly susceptible to climate change (Kissel et al., 2015; van Asten et al., 2015b). The projected increase of these weather events due to climate change will therefore affect the area suitable for bananas across the country. This will in turn affect the ability of bananas to shade coffee plants in some regions. Therefore, we assess the potential changes in the areas suitable for coffee-banana intercropping in order to give an insight on whether this cropping system will still be able to provide the above-mentioned functions in the face of climate change by the end of the century.

> We assess the potential change in areas suitable for Arabica and Robusta coffee as well as their production in coffee-banana intercropping systems, a prominent cropping system for coffee production in Uganda.

Crop suitability refers to the ability of land to sustain a crop throughout its growing cycle, given the prevailing climatic and biophysical conditions (Chemura et al., 2020). Crop suitability models assume that biophysical and climatic factors are vital for crop production, which is valid for rain-fed agriculture such as coffee production in Uganda.

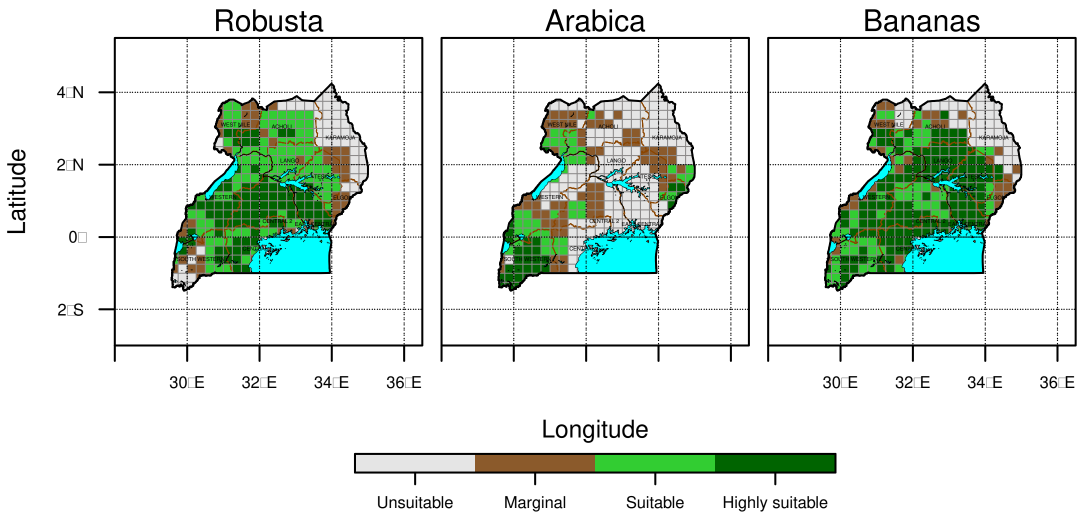


Figure 25: Maps showing modelled current suitability of coffee (Robusta and Arabica) and bananas (Musa acuminate) at 0.25° grid level.

4.2.1.1 Current suitability to produce coffee in coffee-banana intercropping systems

Our model results confirm that Arabica and Robusta coffee is suitable to be grown in distinct and differing areas under the current climate conditions, with few areas where both species can be grown (West Nile and Southern Uganda). Arabica coffee is only suitable in around 13.1 % of the total land area and only highly suitable in highland areas of Elgon in the east, Rwenzori in the west, Muhabura in southwestern, and Okoro in the West Nile region. Robusta coffee, on the other hand, is suitable in a relatively larger area (61 % of the total country area) and highly suitable in the lowlands. Bananas are suitable in over two-thirds of the total country's land area. The modelled current spatial suitability index of coffee and bananas is shown in Figure 25.

4.2.1.2 Impact of climate change on the suitability of coffee production

Model results show that the impact of climate change on each individual crop (Arabica coffee, Robusta coffee and banana) will be crop- and region-specific, with some areas gaining suitability while others becoming less suitable. The distribution of the projected changes in suitability of the three crops due to climate change until the end of the century are described below.

Arabica coffee

Our projections show that in the future, there will be less suitable land to grow Arabica. This trend is steady throughout the century and under both emissions scenarios. By 2050, we project a reduction of 20 % of the land under the SSP1-RCP2.6 low emissions scenario and 18 % under the SSP3-RCP7.0 high emissions scenario. A marginal increase of 2.5 % and 5.1 % in some areas is expected under the SSP1-RCP2.6 low emissions scenario and under the SSP3-RCP7.0 high emissions scenario respectively within the same period. Despite marginal increases in suitability in the south-west of the country by 2050, the overall country-wide suitability loss overshadows the increase. Hence a net reduction in area suitable for Arabica coffee is apparent. By 2090, a high net reduction of the area suitable to grow Arabica is expected: under the SSP1-RCP2.6 low emissions scenario we expect losses of around 20 % and under the SSP3-RCP7.0 high emissions scenario of about 25 %. The West Nile region is particularly hard hit and will become unsuitable by 2090 under both emissions scenarios. The south-western and Elgon regions will remain suitable for Arabica coffee by the end of the century while the central and Karamoja regions will remain unsuitable. Generally, lowlands that are currently suitable for Arabica coffee will become unsuitable by 2090. Farmers in West Nile will be able to shift to growing Robusta coffee, since this species will remain suitable in that region, as shown in the following subsection.

> By 2050, we project a 18–20 % reduction of land suitable to grow Arabica coffee.

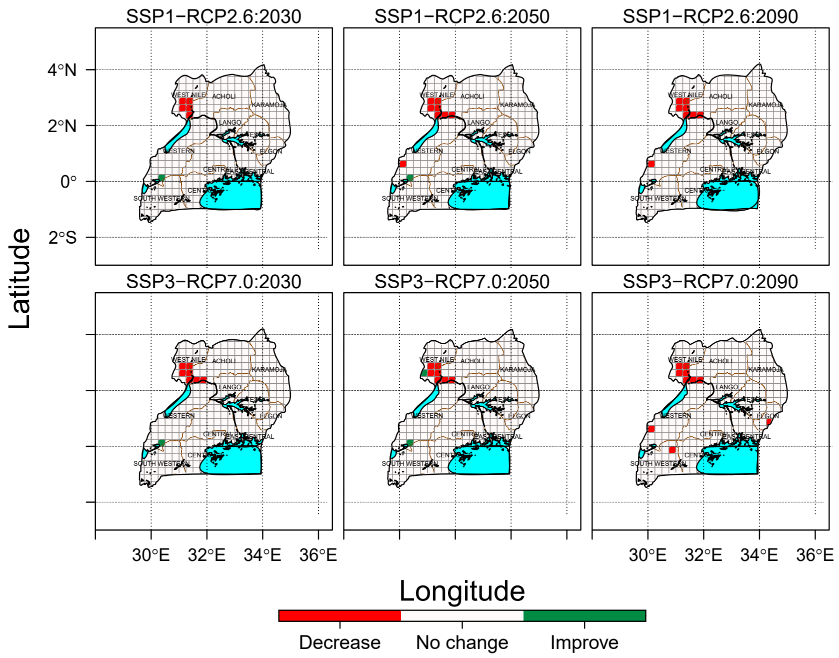


Figure 26: Projected changes in the suitability to grow Arabica coffee in 2030, 2050 and 2090 under two emissions scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario) at 0.25° grid level.

> Due to the shrinking suitability to grow coffee intercropped with banana, farmers may need to shift to other cropping systems, like agroforestry.

Currently, most of the land which is suitable for Arabica production is also suitable for Arabica-banana intercropping (11 % out of the 13 % of total land area) except a part of the Elgon region. Climate change will reduce the intercropping potential of the two crops, as the area suitable to grow both, Arabica coffee and banana will progressively shrink over time with the highest net reduction of 5 % of the current area in 2090 under the SSP3-RCP7.0 high emissions scenario.[4] This reduction is driven by the projected loss of banana suitability in the far south-western and west Nile regions where Arabica coffee is suitable. The spatial distribution of the changes in potential Arabica-banana intercropping is shown in Figure 27. This reduction implies that farmers will no longer be able to use bananas as an early shading crop but rather shift to other adaptation measures such as agroforestry, irrigation and planting drought resistant varieties. This has may have a significant effect on their incomes and food security.

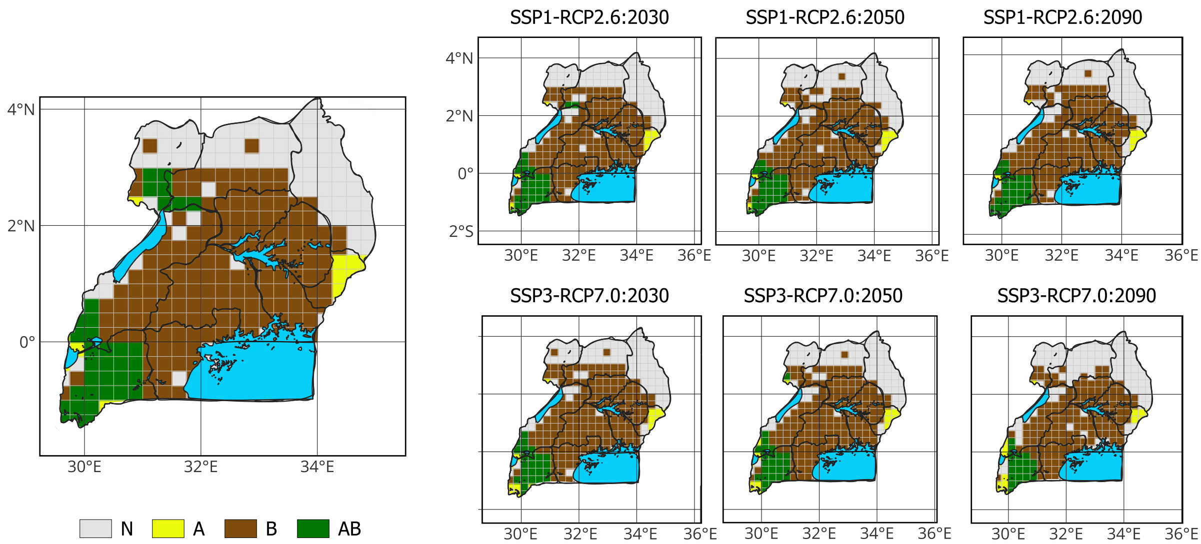


Figure 27: Current suitable areas for banana-Arabica intercropping (left), and changes in areas suitable for banana intercropping with Arabica coffee (right). White=None of the two crops is suitable, yellow=only Arabica is suitable, brown=only banana is suitable, green= suitable. The top row shows projections for the low emissions scenario (SSP1-RCP2.6) and the bottom row shows projections for the high emissions scenario (SSP3-RCP7.0).

4) For detailed results on projected climate change impacts on the suitability of banana, please see Annex I.

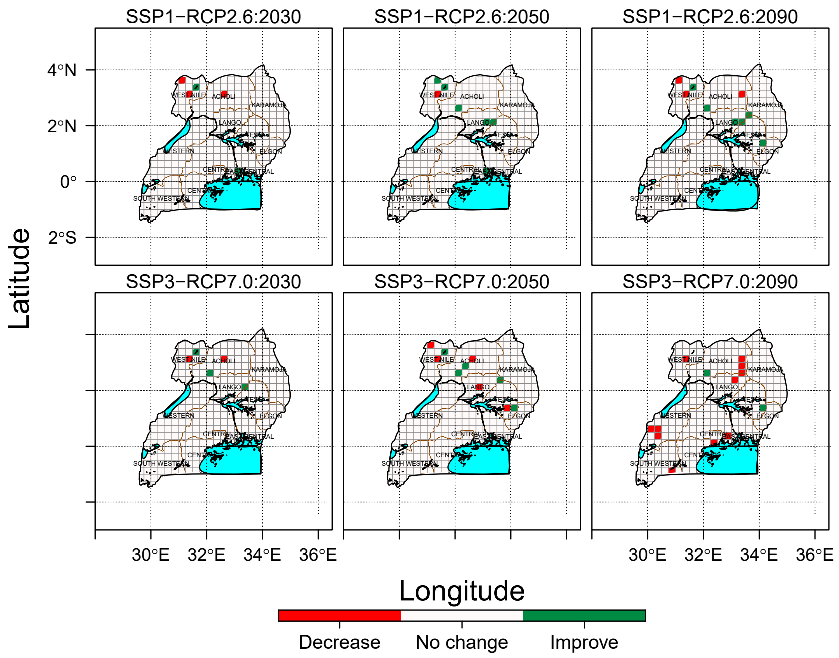


Figure 28: Projected changes in the suitability to grow Robusta coffee in 2030, 2050 and 2090 under two emissions scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario) at 0.25° grid level.

Robusta coffee

The area suitable to grow Robusta coffee will increase in some areas of the country and decrease in others. However, the overall suitability change is negative, reducing progressively over time with higher losses projected under the SSP3-RCP7.0 high emissions scenario, than under the SSP1-RCP2.6 low emissions scenario. The net reduction in areas suitable for Robusta coffee is expected to increase starting in 2050 under the high emissions scenario, with the highest net reduction of 5 % by 2090. Under the low emissions scenario, the area suitable for Robusta coffee will first increase by 3.2 % until 2050 but later reduce to an overall loss of 1.08 % in 2090 relative to the current suitable area. Geographically, the losses are expected to occur in the southwestern region and the Acholi region. The central region will remain stable, implying that it will remain highly suitable for Robusta coffee. Under both scenarios, parts of the Lango and Acholi regions are projected to increase in area suitable for Robusta coffee by 2050, but the overall national reductions will overshadow the increase. The Karamoja region will remain unsuitable for Robusta coffee under both scenarios by 2090 (Figure 28). Although the overall net suitability losses may sound marginal, there are some areas that will experience better growing conditions for Robusta coffee and other areas where substantial losses are projected, which has serious implications on the livelihoods of coffee farmers living in those regions.

> Until 2050, in some parts of the country the areas suitable to grow Robusta coffee will increase, but the overall national reductions will overshadow this increase. Until 2090, the overall area suitable to grow Robusta coffee in Uganda will slightly, but progressively reduce with time. Higher losses are expected under the high emissions scenario than under the low emissions scenario.

The area suitable for Robusta-banana intercropping will also continuously reduce under both emissions scenarios until the end of the century. Currently, 51 % of the area is suitable for Robusta-banana intercropping. This area is projected to reduce by 7 % relative to the current potential intercropping areas by 2090 under the SSP3-RCP7.0 high emissions scenario.[5] A lower net reduction of 5 % is expected under the SSP1-RCP2.6 low emissions scenario within the same period. The reduction in this intercropping potential will mainly occur in the southern parts of the country, as well as in Acholi, West Nile, and around lake Albert areas as a result of banana suitability losses (Figure 29).

> The area suitable for Robusta-banana intercropping will continuously reduce under both emissions scenarios.

5) For detailed results on projected climate change impacts on the suitability of banana, please see Annex I.

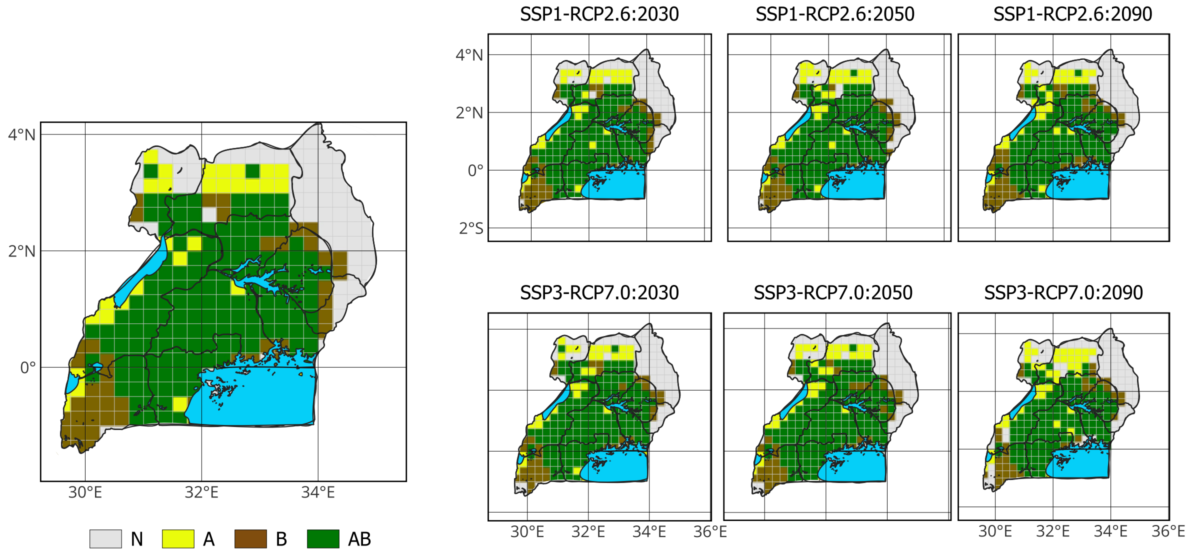


Figure 29: Current suitable areas for banana-Robusta intercropping (left), and changes in areas suitable for banana intercropping with Robusta coffee (right). White=None of the two crops is suitable, yellow=only Robusta is suitable, brown=only banana is suitable, green= suitable. The top row shows projections for the low emissions scenario (SSP1-RCP2.6) and the bottom row shows projections for the high emissions scenario (SSP3-RCP7.0).

The coffee-banana intercropping system in general is sensitive to climate change, with some areas remaining only suitable for bananas, while others will only be suitable for coffee. Figure 30 gives an overview of the above analyses, showing the net change in area suitable for coffee-banana intercropping relative to the current suitable area for 2030, 2050 and 2090. It shows that under both emissions scenarios and for all three time steps, an overall decrease in suitability to grow Arabica and Robusta coffee intercropped with banana is projected and will be more pronounced under the SSP3-RCP7.0 high emissions scenario than under the SSP1-RCP2.6 low emissions scenario. This is due to the reduction in the area suitable to grow bananas especially in the northern, West Nile and parts of southwestern regions of Uganda. The reduction in the intercropping potential can be overcome by shifting to planting more drought-resistant banana varieties which are less vulnerable to climate impacts. When designing adaptation strategies, the entire farming system should be taken into consideration. To buffer climate change impacts on the entire intercropping system, adaptation measures such as irrigation, agroforestry and better on field water harvesting and reuse through trenches are recommended.

In conclusion, this chapter shows that climate change is projected to have a substantial impact on the suitable areas for coffee cultivation in Uganda, particularly affecting Arabica coffee due to its specific environmental and ecological requirements. Our findings align with previous studies conducted by Bunn et al. (2019), Jassogne et al. (2013), and Mulinde et al. (2022), which also predicted a decrease in coffee suitability across various regions in Uganda. It is important to note that the overall suitability of coffee-growing areas is not solely determined by the total annual weather conditions but rather by the distribution of weather variables throughout the year. For instance, the total annual precipitation alone does not indicate suitability, but rather the distribution of precipitation across different months as more influential.

The suitability of both Robusta and Arabica coffee species is influenced by a range of rainfall and temperature factors during their flowering and growing seasons. Research has shown that decreasing precipitation and increasing temperatures during these phenological stages negatively impact coffee plants, leading to flower abortion and bud development failureThe suitable areas for coffee-banana intercropping are also expected to decrease over time, posing risks to both food security and economic constraints, as bananas are a significant food source for many households. The reduction in suitable areas for coffee and bananas may also drive farmers to encroach upon protected areas like forest reserves to expand agricultural land, thus posing a potential risk of environmental degradation. Therefore, it is recommended to implement adaptation measures such as agroforestry and irrigation, which aim to minimize the adverse effects of temperature and enhance soil water retention specifically during critical stages of the cropping cycle.

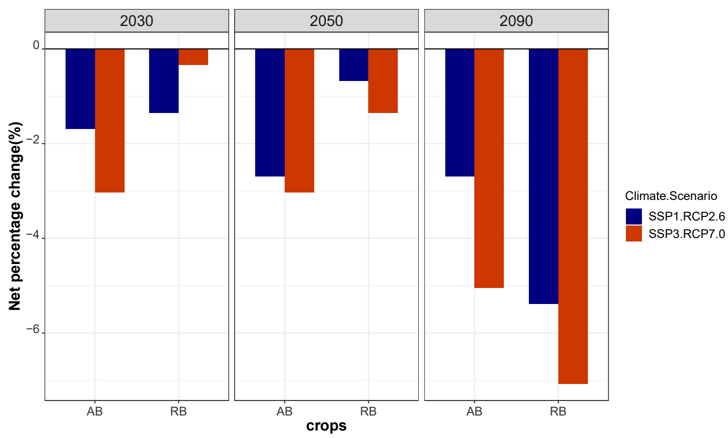


Figure 30: Net percentage changes in area suitable for coffee-banana intercropping until 2090. Letters, AB=Arabica banana intercropping, RB=Robusta banana intercropping.

4.2.2 Climate change impacts beyond coffee production – experiences of processors, aggregators and traders

Bringing coffee from the farm to exporting it across the world involves a number of activities which add considerable monetary value to the product. Post-harvest handling is key to ensure the quality of the coffee is kept at a high standard. At the same time, there are many environmental factors that can easily deteriorate the quality of the product. For example, air temperature and drying rate have a direct effect on the sensorial quality of coffee (Borém et al., 2018). Myotoxic fungi contamination is usually related to unfavourable climates for drying, especially sun-drying under humid conditions (Bucheli & Taniwaki, 2002)respectively, producing high amounts of OTA (5–13 mg kg-1. Changing climate conditions are therefore expected to significantly impact aggregation, processing and distribution steps of the value chain as well with potential impacts on prices and eventually the export revenues for the country.

> To better understand how climate change impacts post-harvest steps of the value chain, we conducted and systematically analysed interviews with actors working in aggregation, processing and marketing and distribution how climatic factor are already impacting their work today.

To better understand what kind of climate impacts are already experienced today, we conducted and systematically analysed in-depth interviews with six actors working in post-harvest steps of the Ugandan coffee value chain. The businesses interviewed are mainly located in Mityana and Mukono districts in the Central region of the country, both Robusta-growing regions. One interviewee is based in the capital city Kampala. Two of the interviewed businesses also deal with Arabica coffee, which they procure from other regions. The interviews were analysed using abductive thematic analysis (Tavory & Timmermans, 2014). An initial coding scheme was derived from the IPCC climate risk framework (2014, 2021), reflecting the main functions of climate risk (hazard, exposure and vulnerability). The codes were iteratively expanded during the analysis, creating a comprehensive analysis framework for climate risks in the coffee value chain (for more information on the methods and data collected please see Annex I.3). The results were cross-verified with interviews and focus group discussions (FGDs) held with national coffee value chain experts.

4.2.2.1 Perceived climate impacts on the coffee value chain

Drought and prolonged dry seasons are the most widely reported **hazards** interviewees have to deal with already today, affecting them both directly and indirectly. Dry conditions and higher temperatures are also reported to lead to an increase in **pests and diseases**. Compared to drought, **rainfall** was reported to be less of an issue for the value chain actors interviewed, especially as a trickle-down effect from production. Nevertheless, **unpredictable rainfall patterns**, **erratic rains** and **hailstorms** were mentioned as hazards affecting production. Generally, several interviewees described a **change in the seasons** and accompanying shifts in productivity, with the fly season becoming more productive and the main season becoming less productive.[6]

> *We see new diseases, new to the coffee farms, some of these get the whole plant.*
>
> — Trader from Kampala

The **processing, aggregation, marketing and distribution** steps of the value chain are also directly **exposed** to the hazards. There are several factors that shape the **vulnerability** of the coffee value chain, most of them are of financial nature. On the one hand, value chain actors are faced with stark **price fluctuations.** One processor reported that *"The price of coffee changes so often. This causes losses since we pay middlemen in advance. They fail to buy coffee at the expected price."* On the other hand, there are only few **financial services** available that could support with risk management. A further related issue are **bad roads**, which make transportation difficult. In addition, we noticed a general **mistrust** between value chain actors and within the coffee sector in general. This may stem from the liberalisation of the coffee sector and the pressure which large international competitors put on local actors who are exposed to international market volatility (FAO, 2020b).

6) The mentioned hazards and their impacts are experienced by interviewed actors on the ground. While such climate-related hazards cannot be directly attributed to climate change impacts, climate change is likely to exacerbate them (see Chapter 2 on projected climatic changes).

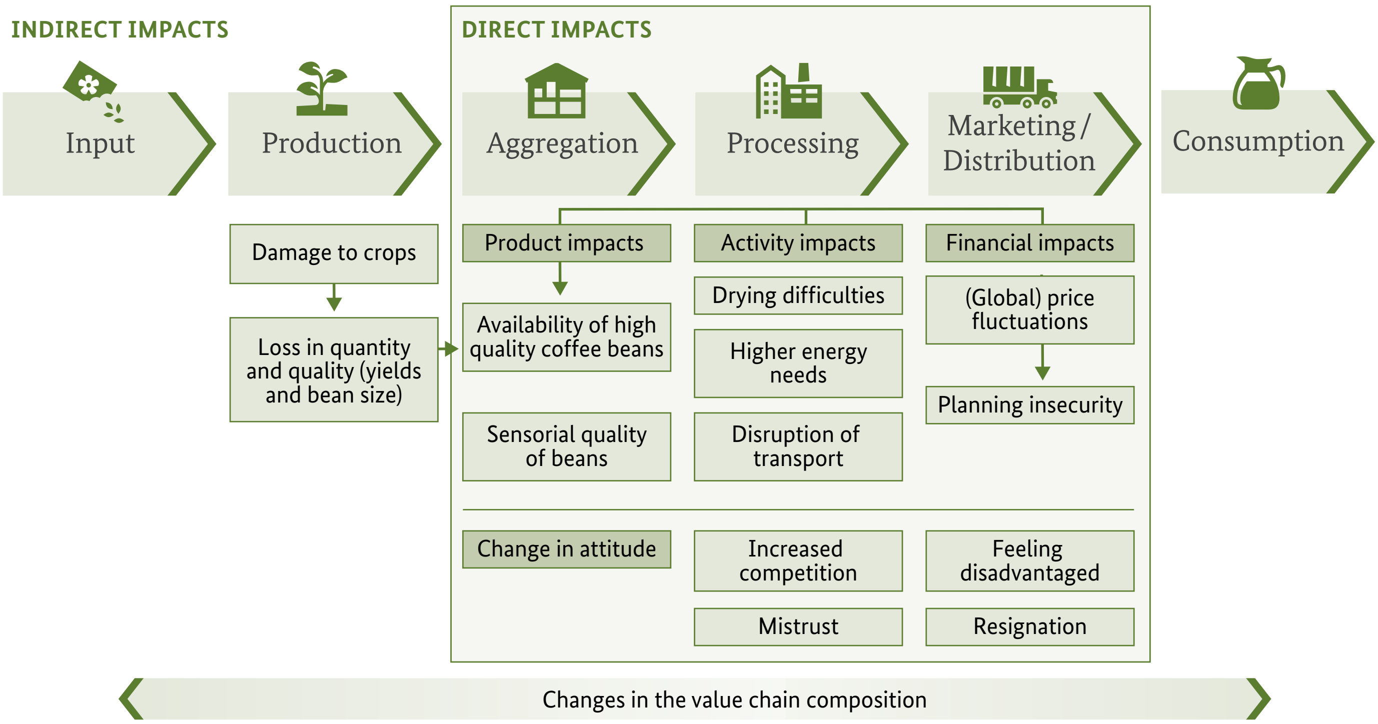


Figure 31: Climate impacts experienced by stakeholders working in the aggregation, processing and marketing and distribution of coffee.

> *This drought [we are experiencing now] started in December. It's now April [2022], but conditions are still dry. This means coffee will die, coffee beans won't develop well in pods, and coffee leaves will fall off. (...) With intense heat, coffee trees dry up, berries fall off and this limits the amount produced reaching us here in lesser quantities than expected.*
>
> — Processor from Mityana

a. Direct and indirect impacts on the post-harvest steps of the value chain

We were able to identify different direct and indirect impacts on post-harvest steps of the coffee value chain. **Direct impacts** are felt immediately at the aggregation, processing, and marketing and distribution steps. **Indirect impacts** occur at other steps, for example, at production stage, and trickle down to the later steps affecting products, activities and the financial flows. Figure 31 shows a simplified version of a coffee value chain. The orange-coloured boxes represent overarching themes. The white boxes inside the orange bounding square are direct impacts, the boxes outside the square are indirect impacts.

> *There are times when rains come and they are so heavy, plantations are destroyed, especially in the Robusta growing area.*
>
> — Trader from Kampala

> *Too much rain makes roads slippery and transportation of coffee becomes difficult.*
>
> — Processor from Mityana

Most of the **indirect impacts** stem from yield loss leading to decreased **quantity** or poor bean development negatively affecting the **quality** of the coffee due to hazards occurring at the production stage. A drought, for example, can cause beans to become lighter, which has impacts on the out-turn (quantity) and size of beans (quality) that comes out after processing. As previously mentioned, these impacts are mainly due to drought and shifts in dry seasons leading to negative impacts on flowering, fruiting and bean quality. Pests and diseases were also mentioned as a major cause of yield loss. While drought and related cascading hazards are reported to be the most prevalent cause for losses at production level, extreme rainfall or hailstorms can also destroy the coffee cherries or even the whole plant.

> *Where it's dry for a bit long the weight of the beans happens to be very poor, so we happen to get a lot of black beans.*
>
> — Processor from Mityana

> *But most importantly, when you come to the climate, what shows that the weather is affecting the crop, is what we are getting out of the coffee. We are having more rejected beans.*
>
> — Processor from Mityana

The observation that the seasons are changing, and the fly season is becoming more productive than the main crop is seen as a positive impact in terms of both coffee quality and quantity. One coffee processor described: *"We are getting more quantities in the fly crop than in the main crop because of the changes in weather"*, and later continued *"Right now, (...) we are preparing for the fly crop. But even the coffee quality is better. And the quantity is better and the beans."*

> *Coffee beans fail to develop in the pods yet the huller consumes a lot of power on empty coffee pods.*
>
> — Processor from Mityana

Climatic conditions also affect the quality and quantity of coffee at the processing stage and even at the point of sale. High levels of humidity or rainfall can lead to **drying difficulties**. The moisture content of green coffee beans is required to be less than 13–14 %. To be able to reach this level, secondary processors often need to re-dry the beans, if the parchment is not dried properly. In addition, pods, inside which coffee beans were not able to develop properly due to climatic stress factors, need more time in the huller compared to regular pods, leading to **higher energy needs**. More rain also leads to **difficulties in transportation**.

> *So, the little coffee that was there, there was high competition for that. The multinationals here chose to make a loss, but have their main companies abroad cover that. Or even have their stock markets cover that. Which here we didn't have Remember, (...) if they are buying at a higher price than you can buy, (...) you cannot do as much.*
>
> — Processor from Mityana

Since coffee prices are set by the New York Coffee Exchange, it is less the local availability of coffee that influences farm-gate prices than the global supply of coffee. In 2021, for example, a frost in Brazil and drought in Vietnam led to short supply of Robusta coffee on the world market and caused a spike in global wholesale coffee prices, leading to record export earnings for Uganda (UCDA, 2021). Local roasters, on the other hand, may not always profit from this. Since there low demand for roasted coffee, local roasters cannot raise the end price and therefore "*loose out*", as a roaster from Kampala claims. More generally speaking, stark global price fluctuations expose local businesses to **planning insecurity** which make them more vulnerable to the impacts of climate shocks.

b. How climate change impacts the coffee value chain composition

We also observed expressions of resignation with some interviewed actors. When describing the fluctuations in coffee supply and the resulting planning insecurity, one processor added: *"you can't do anything about is because it's a result of natural weather."* **Higher demand** also puts more pressure on the market and leads to **increased competition** between businesses. Generally, there is a common sense of **feeling disadvantaged** compared to other value chain actors, especially towards international companies, but also towards national stakeholders working in the value chain leading to feelings like **mistrust**: "*due to the high competition, you find that farmers are encouraged not to [handle] the coffee properly*", describes one processor. Climate risks are likely to exacerbate these feelings, as shocks may lead to **changes in relations, product and financial flows** between the different value chain steps. New actors join the value chain, while others are kicked out. The reduced local supply of coffee beans, for example, leads to processors and exporters sourcing the coffee from other places in the country, or even abroad. One processor, who is also involved in exporting, describes that due to the lack of available coffee to process in Mityana caused by a drought, processors instead buy graded coffee in Kampala to bridge the gap and to be able to export. Likewise, a scarcity in coffee also gives more decision power to the farmers who were able to harvest coffee. One processor explains that farmers, who have produced poor quality coffee due to drought, sell it to middlemen instead of processors.

> Aggregation, processing and marketing and distribution steps experience climate impacts on product, activities and finances. Examples include changes in quality and quantity of processed coffee, difficulties in drying and reduced income due to price fluctuations.

In conclusion, several climate risks are already experienced today throughout the post-harvest steps of the value chain. Direct impacts include for example difficulties in drying the coffee due to increased humidity. Indirect impacts occur at the production stage of the coffee value chain and trickle down to the post-harvest stages. For example, non-ideal climatic conditions lead to reduced quality of coffee beans, making them more difficult to process and sell at certain prices. Feelings of disadvantage and mistrust are commonly experienced. This is further exacerbated by the businesses' exposure to international market dynamics, which often put local businesses into an impaired situation compared to their international competitors. Since coffee prices are set on an international level and depend on the global coffee supply, climate shocks in other countries also need to be closely monitored when making business decisions.

4.3 Adaptation strategies for coffee value chains

Having established the current and expected impacts of climate change on the coffee value chain, we assess two adaptation strategies with regard to their economic potential under climate change. As an example of climate change adaptation in the production step of the coffee value chain, we analyse the potential of **agroforestry** to buffer suitability changes, as well as whether establishing agroforestry systems is an economically sensible strategy for farmers. For the aggregation stage of the value chain, we assess the economic feasibility of **improved post-harvest storage** using jute bags and high-quality pallets. The two strategies were chosen based on stakeholders' preferences, national priorities and methodological feasibility. The analysis is meant to showcase examples of how specific measures can help value chain actors adapt to climate change. The analysed adaptation strategies are not exclusive and should be considered as one part of more systematic climate-resilience building efforts in the coffee sector.

4.3.1 Agroforestry

Agroforestry is considered a key measure for both climate change mitigation and adaptation. It is a dynamic, ecologically-based natural resources management system that diversifies and sustains production and can therefore increase social, economic and environmental well-being on all levels (Leakey, 2017). It is defined as land use systems in which perennial woody plants are deliberately used in spatial arrangement or temporal succession on the same land as agricultural crops and/or livestock. Characteristic of these systems are that both ecological and economic interactions take place between the various components (Lundgren & Raint, 1983).

> Agroforestry practices can support adaptation to climate change in several ways: they can save water, improve the microclimate, and enhance soil fertility.

Agroforestry is a traditional farming system in Uganda and its benefits are recognized in national policies: in 2018, the National Adaptation Plan for the Agricultural Sector (NAP-Ag) was released proposing agroforestry systems as an adaptation option in crop production and forestry, land and natural resources management (MAAIF, 2018). The Ugandan National REDD+ Strategy and Action Plan assesses agroforestry as an important climate smart agriculture measure and informs that approximately 45 % of all farming households are already adopting agroforestry practices (MWE, 2020). The Ministry of Water and Environment (MWE) updated the country's NDC in 2022, which now states agroforestry as a priority mitigation and adaptation measure. Common agroforestry practices in Uganda include boundary planting, scattered tree planting, row planting and homestead gardening (Kabiru et al., 2018; Kiiza et al., 2016) where the selected tree species must meet a number of criteria, such as low labour intensity, optimal shade, soil nutrient enrichment, or product diversification (Kalanzi, 2014; Soto-Pinto et al., 2007; Souza et al., 2010).

Most coffee in Uganda is grown in coffee-banana intercropping systems, which are particularly prevalent in densely populated areas (UCDA, 2019b; van Asten et al., 2011). In those particular systems, coffee already benefits from shading of banana. However, contrary to other shade trees, banana plants are quite sensitive to drought (see results in Chapter 4.2.1 and Annex I.3) and in most regions, additional wooden shade trees are used in coffee-banana intercropped systems to yield the benefits of agroforestry described above (van Asten et al., 2011; Van Asten et al., 2012). UCDA (2019b, 2019a) officially recommends *Ficus natalensis*, *Ficus mucuso*, *Ficus ovata*, *Albizia coriaria* and *Cordia africana* for both Robusta and Arabica agroforestry systems depending on the region (Figure 32).

Shade trees have various benefits for coffee production when it comes to climate change. They protect coffee trees from high solar radiation, as well as from heavy rainfalls or hailstorms. They also help to stabilize the soil and serve as windbreaks that reduce soil erosion. In addition, shade trees reduce the decay rate of organic matter in soil, as well as the plant metabolism and encourage more regular flowering. Trees also limit evapotranspiration and can create a micro-climate that is favourable for coffee production. Higher levels of biodiversity can lead to a natural increase in predators of coffee pests and pollinators of coffee plants (UCDA, 2019b). This indirectly affects coffee quality by changing the biochemical composition, including the content of caffeine, oil, and chlorogenic acid. As a result, the flavour of the final product improves and can earn farmers a higher price (van Asten et al., 2015a).

In addition, agroforestry systems contribute to biodiversity conservation, phytoremediation, water conservation and carbon sequestration (Choudhary & Rijhwani, 2020; Mbow et al., 2014; Sheppard et al., 2020) trees and livestock are maintained together on same land to increase total yield and income. Agroforestry can alter the micro climate of soil under tree canopy. It plays an important role in enhancement of farm productivity, climate change mitigation, carbon sequestration, biodiversity conservation, phytoremediation, water conservation, improvement in quality of soil by addition of plant and animal waste. This land use system combines production with conservation of ecology. This paper examines the major benefits of agroforestry systems on agricultural landscape: (i. Agroforestry systems are already the third largest carbon sink in Africa after primary forests and long-term fallow lands (Oke & Odebiyi, 2007).

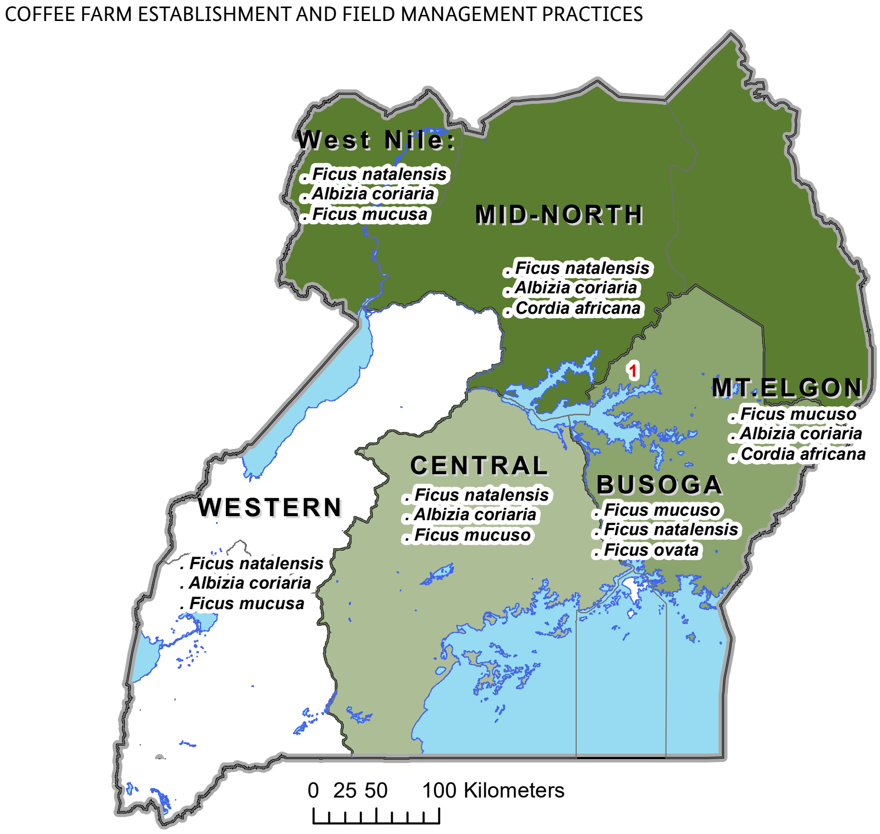


Figure 32: Map of Uganda showing recommended shade trees by region (UCDA, 2019b).

Agroforestry systems need to be carefully designed to fully realize their benefits. Shading in coffee above 50 %, for example, reduces coffee yields since it stimulates more vegetative growth rather than bud development (Moreira et al., 2018). When water is limited, shade trees with high root-niche differentiation and noncompeting phenology should be selected (Cannavo et al., 2011; Padovan et al., 2015). Therefore, knowledge of appropriate shade tree species selection and management in terms of spacing, timing and extent of pruning is needed (UCDA, 2019b; van Asten et al., 2015a). To promote upscaling of agroforestry in the long term, there is also a need to better understand how the suitability of the agroforestry species will change under a changing climate. In this chapter, we therefore model the potential of agroforestry to buffer the loss in suitability of coffee shown in chapter 4.2.1 Despite the variety of agroforestry tree species used in coffee systems in Uganda, we used *Ficus natalensis* and *Cordia africana* in our modelling framework due to their unique economic, environmental and ecological functions described above, as well the availability of data needed for modelling.

Cordia africana has a high economic value to farmers due to its high value timber (Denu et al., 2016; Ebisa, 2014). Ficus species such as *Ficus natalensis* are preferably planted as windbreaks on coffee plots (UCDA, 2019b). In addition to being the most ancient coffee shading tree, *Ficus natalensis* provides a range of cultural, ecological and medicinal functions (Ipulet, 2007) These include live fences, building poles, fibre, bark cloth, fire wood and medicine. In the Central and Western regions, the tree is known for its bark cloth material that is used in traditional institutions (Ipulet, 2007). Such additional functions make this species highly desirable by farmers explaining its high adoption in coffee agroforestry systems.

4.3.1.1 Risk mitigation potential of coffee agroforestry systems

We applied a machine learning suitability modelling approach as described in chapter 4.2.1, based on a random forest, boosted regression trees and a support vector machine to determine the suitability of selected agroforestry trees across the country. Using the suitability index overlaying methodology as described by Chemura et al. (2020), we identified areas where the projected loss of coffee suitability assessed in Chapter 4.1 could be buffered by respective agroforestry trees frame under the two emissions scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario). The assessment specifically looks at a potential shift in the suitability of the selected shade trees to understand if they would still be a suitable adaptation strategy for coffee when the climate changes.

The buffering potential of *Cordia africana*

Cordia africana is suitable in northern and eastern Uganda and less suitable in the central regions. The suitability of *Cordia africana* is expected to reduce within the central and western regions under both emissions scenarios by the end of the century. Parts of Karamoja region are also expected to become unsuitable for this species.[7]

> Since *Cordia africana* is expected to suffer from climate impacts, it can buffer the impacts of climate change on coffee production only in certain areas of the country.

Growing *Cordia africana* as part of a coffee agroforestry system has the potential to buffer all areas where suitability of Robusta is projected to decline by 2030 under both emissions scenarios. However, the buffering potential will reduce with time. By 2050, all projected reductions in suitability of Robusta can be potentially overcome by growing *Cordia africana* as an agroforestry species under the SSP1-RCP2.6 low emissions scenario and 83 % of the areas can be buffered under the SSP3-RCP7.0 high emissions scenario. The buffering potential will further reduce by 2090, with *Cordia africana* potentially buffering only 75 % and 46 % of the suitability losses of coffee producing areas under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario respectively. This is due to the fact that the suitability of *Cordia africana* itself is expected to reduce within the central and western regions under both emissions scenarios by the end of the century. Parts of Karamoja region are also expected to become unsuitable for this species. The highest buffering potential will be in the north since the area will remain largely suitable for this tree. Therefore, any reduction in the suitability of Robusta coffee areas beyond the northern region cannot be buffered by implementing *Cordia africana* as an agroforestry species. The buffering potential of *Cordia africana* on Arabica coffee will remain stable over time and under both emissions scenarios. This will range between 50 %–62 % of all areas where Arabica is negatively affected by climate change. The spatial distribution of areas that could be potentially buffered by *Cordia africana* are shown in Figure 34. The red grids (no buffer) show areas where the suitability of coffee is expected to reduce, but *Cordia africana* is not suitable. The green grids (buffer) show areas where the suitability of coffee is projected to reduce, but *Cordia africana* is suitable and therefore has the potential to buffer the impacts of climate change on coffee production.

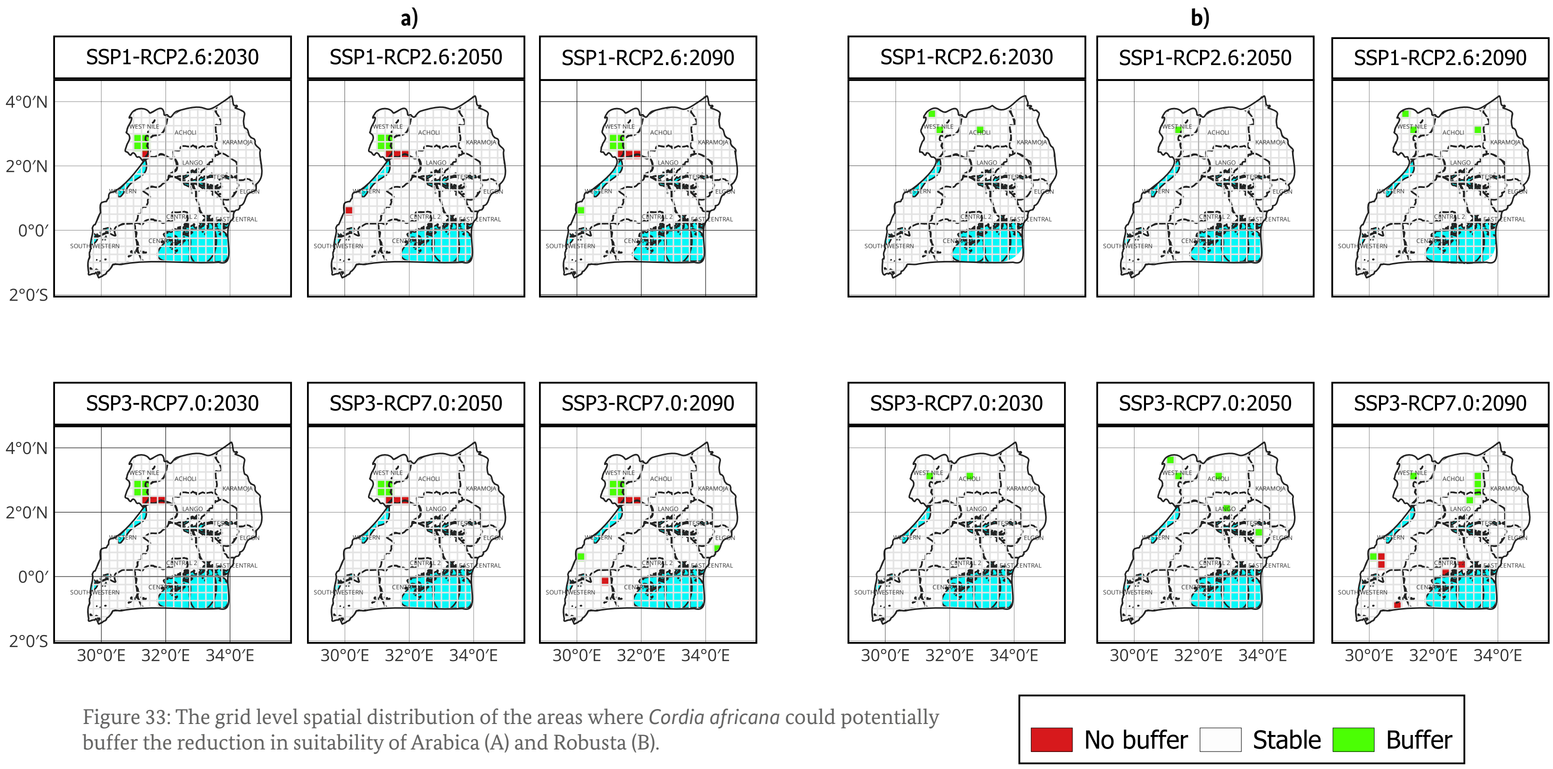


Figure 33: The grid level spatial distribution of the areas where *Cordia africana* could potentially buffer the reduction in suitability of Arabica (A) and Robusta (B).

7) For more specific information on how and where climate change is projected to impact the suitability of *Cordia africana*, please see Annex I.

The buffering potential of *Ficus natalensis*

Ficus natalensis is currently suitable almost across the whole country, with a particularly high suitability in the central and southwestern regions. The species is expected to remain relatively stable throughout the century under both emissions scenarios. The climate envelope of this species will slightly expand towards the Karamoja region.

> The potential of *Ficus natalensis* to buffer projected suitability losses of Arabica and Robusta coffee is very high under both emissions scenarios until 2090.

The potential of *Ficus natalensis* to buffer projected suitability losses of Arabica and Robusta coffee is very high under both emissions scenarios until 2090. *Ficus natalensis* will continue to grow well throughout the century and its suitability is actually expected to slightly expand towards the Karamoja region.[8] Our analysis shows that *Ficus natalensis* has the ability to provide shade in all areas where coffee suitability is projected to decrease under both emissions scenarios until 2090. This implies that *Ficus natalensis* will remain suitable in all regions where the suitability of the two coffee species is expected to reduce. The spatial distribution of the areas buffered by this species is shown in Figure 34. The red grids (no buffer) show areas where the suitability of coffee is expected to reduce, but *Ficus natalensis* is not suitable. The green grids (buffer) show areas where the suitability of coffee is projected to reduce, but *Ficus natalensis* is suitable and therefore has the potential to buffer the impacts of climate change on coffee production.

Our modelling results for the current suitable areas of the two-agroforestry species align with the mapping by UCDA (2019b) on the recommendation of coffee shade trees by region. Our results show that the implementation of agroforestry could potentially buffer between a half to all of the reductions in the area suitable for Arabica and Robusta coffee by the end of century. Therefore, agroforestry is a promising adaptation measure towards the potential effects of climate change on coffee suitability in Uganda. *Ficus natalensis* has the highest buffering potential for the two coffee species. This is explained by the fact that this shade tree species is a generalist, hence can and will survive in a wide ecological environment (Schmidt & Tracey, 2006). *Cordia africana* on the other hand will remain highly suitable in the northern and eastern parts of the country throughout the century. Therefore, a combined agroforestry system of *Cordia africana* and *Ficus natalensis* is recommended in the northern parts while *Ficus natalensis* only is recommended for the central, western and southern parts of the country. In addition to agroforestry, other strategies that cater to the preferences and needs of the entire value chain should be considered. For instance, the promotion of improved coffee varieties or traditional coffee species (wild Robusta or coffea Liberica) can be an option to diversify coffee production and increase its climate resilience, while at the same time accelerating innovation and introducing new and exciting coffees to the market (A. P. Davis et al., 2022).

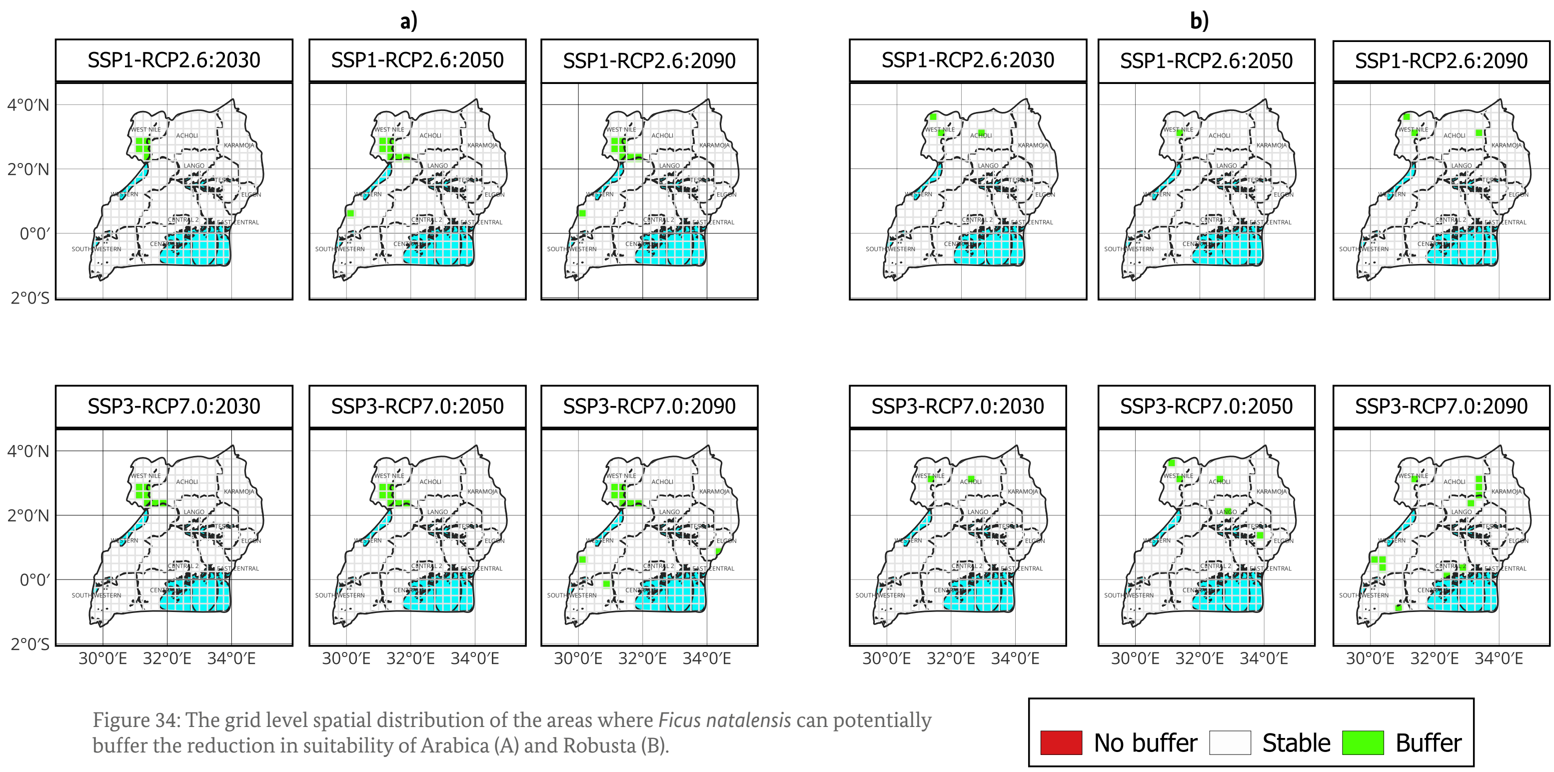


Figure 34: The grid level spatial distribution of the areas where *Ficus natalensis* can potentially buffer the reduction in suitability of Arabica (A) and Robusta (B).

8) For more specific information on how and where climate change is projected to impact the suitability of *Ficus natalensis*, please see Annex I.

4.3.1.2 Costs and benefits of coffee agroforestry systems under climate change

We used a cost-benefit analysis (CBA) to assess the economic feasibility of introducing shade trees into a coffee-banana intercropping system to create an agroforestry system at farm level over the next 30 years. Since Arabica coffee is expected to have much higher suitability losses due to climate change than Robusta coffee, the geographic focus of the analysis is the Arabica producing regions in east and south-west Uganda and the West Nile region. We follow up on the previous section and specifically look at the economic potential of introducing the tree species *Cordia africana* and *Ficus natalensis* into a coffee-banana intercropping system (see Chapter 4.3.1.1).

While some agro-ecological aspects are hard to quantify in monetary terms, for other aspects the data is simply lacking. To do justice to these co-benefits, will be discussed in a separate sub-chapter (see later section on co-benefits).

The planting of shade trees to create an agroforestry system is the adaptation measure in this calculation. As the CBA displays the changes made to the initial situation where an intercropping system already exists, only the additional costs and benefits that are associated to the introduction of the agroforestry system will be analysed und projected until 2050. The goal is to compare the profitability of a coffee-banana plantation in an agroforestry system with a coffee-banana plantation without agroforestry. The scenarios are defined as follows:

- **Baseline and Scenario 1: Non-adaptation (no action, climate change impact):** In the non-adaptation scenario (which also serves as baseline), a coffee-banana intercropping system without agroforestry is assumed. The ratio between coffee and banana plants is 4:1. Climate change is expected to affect coffee and banana yields negatively. Until 2050, a yield reduction of 20 % is assumed.
- **Scenario 2: Adaptation (action, climate change impact):** Two different tree species (*Cordia africana* and *Ficus natalensis*) are introduced into the coffee-banana intercropping system. Coffee and banana yields are expected to remain stable over time, since it is assumed that the positive effects associated with agroforestry, like shading (Koutouleas et al., 2022), offset the negative impacts of climate change. This means that unlike in the non-adaptation scenario, yields do not decline and thereby increase the total revenues in the adaptation scenario compared to non-adaptation. Furthermore, an additional income stream from the marketing of wood products from agroforestry trees is assumed. Both revenue streams as well as the additional investment and production costs associated with the agroforestry system are extrapolated until 2050.

Results and key economic indicators

The **CBA results**, as depicted in Table 5, show that in 2050 the adaptation strategy of integrating agroforestry trees into the coffee-banana intercropping system is beneficial. All three major indicators of the CBA indicate that the investment makes good economic sense:

- With an Internal Rate of Return (IRR) of 44.93 %, the investment yields a higher return than the 6 % that are usually assumed under a global rentability perspective. Under a global rentability perspective, any IRR higher than 6 % can be considered a profitable investment.
- A positive net present value (NPV) of 12,782,815 UGX indicates that the present value of the expected cash flows exceeds the initial investment.
- The benefit cost ratio (BCR) amounts to 19.70 which means that investing in this adaptation strategy can generate benefits that are more than 19 times higher than the costs.

> Economic benefits generated through agroforestry systems are more than 19 times higher than its costs. Investments into agroforestry systems are also profitable in the long run as they have the potential to increase not only yields, but also create additional income streams for farmers.

The results show that an investment into agroforestry trees pays off and that a much higher cash flow[9] compared to not investing into agroforestry can be generated. Figure 35 shows that the cash flow generated from agroforestry remains negative for the first two years. This is due to the initial investment costs and the delayed onset of income from the agroforestry system as the trees first have to grow to sufficient height, which is assumed after two years (see Annex I.3). After two years, the cash flow from the agroforestry system hits break-even and steadily grows, yielding only positive returns thereafter.

9) The net cash flow presented here is the additional cash flow of the adaptation scenario compared to the non-adaptation scenario and refers only to the additional costs and benefits of introducing agroforestry trees into the cropping system. It is not the net cash flow of the entire coffee-banana agroforestry system, which a would have a much higher net cash flow.

	Adaptation scenario
IRR	44.93 %
NPV	12,782,815 UGX
BCR	19.70

Table 5: Summary of key CBA indicators for switching from a coffee-banana intercropping system without agroforestry to one with agroforestry.

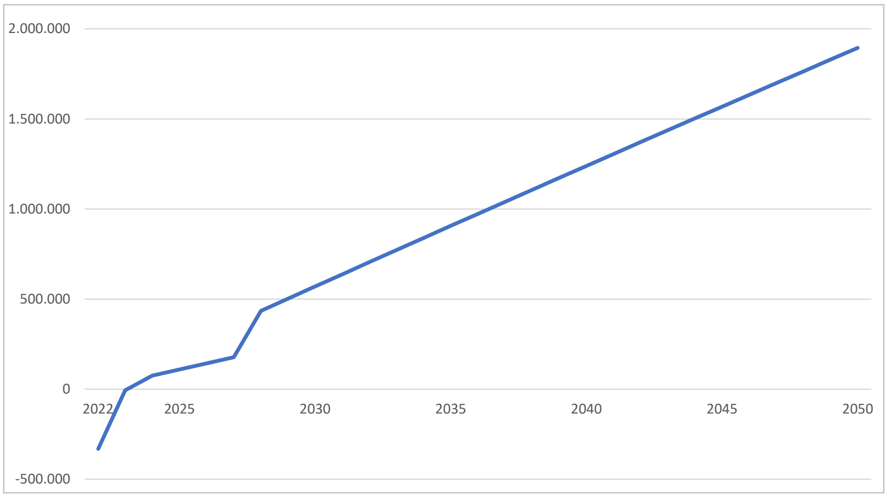


Figure 35: Additional net cash flow up to 2050 for the adaptation scenario in comparison to the non-adaptation scenario.

Co-benefits

The high number of co-benefits found in the literature indicates that the economic results for farmers displayed in the CBA above are conservative. In addition to that, environmental benefits – that can only be monetized with considerable effort and data availability – are numerous as well. Some of the frequently mentioned co-benefits of agroforestry are:

- A fertilization effect of trees via biomass transfer (e.g. through falling leaves) and/or nitrogen-fixing capacities of some tree species can be assumed. Also, the deep root system of agroforestry trees, like *Ficus natalensis*, stabilize the soil and thus prevent soil erosion (Bamwerinde, 2013, 2019; Kuyah et al., 2020).
- A shading effect for plants (e.g. coffee) growing beneath the tree canopy as well as wind regulation, natural fencing and microclimate improvement are often highlighted as benefits of agroforestry trees (Bamwerinde, 2013, 2019; Koutouleas et al., 2022).
- The provision of firewood through the agroforestry system can lead to positive social effects, especially for women. Firewood is a widely used energy source in Uganda that needs to be bought or collected. Collection is often done by women and children of the household (see also sub-chapter 4.3.1.3 on gender). Generating firewood via own agroforestry trees could hence reduce time spent on collecting firewood and/or reduce monetary spending for this energy resource. This can lead to positive gender effects, since the unpaid domestic work of women in a household can be significantly reduced (Anguti et al., 2022; Bamwerinde, 2013, 2019; Kuyah et al., 2020).
- The economic use of indigenous trees, like *Cordia Africana* and *Ficus natalensis*, through an agroforestry system contributes to the conservation of local biodiversity, thereby strengthening tree diversity in agricultural landscapes that are under the pressure of deforestation (Graham et al., 2021; Bamwerinde, 2019).

The results of this CBA show that investments into agroforestry systems for coffee (and banana intercropping systems) pay off and are profitable in the long run as they have the potential to increase not only coffee (and banana) yields, but also create additional income streams for farmers. However, when working with model calculations, it needs to be kept in mind that models are always based on a set of assumptions combined with selective input data, which may not always hold true in real-world situations.

For the presented calculation, particularly the assumptions regarding the yield effects of agroforestry and climate change on coffee and bananas, have a large influence on the results. If we were to assume weaker climate change effects and stronger positive effects of the agroforestry system, the results would be even more positive. Conversely, stronger yield reductions due to climate change and weaker positive effects due to the agroforestry system would significantly worsen the results. For correct interpretation and appropriate usage of the results, it is therefore important to carefully study the underlying information of this model (see Annex I.3). Keeping these points in mind, the CBA results can be used to analyse and understand the economic complexity of agricultural investments in times of climate change and inform climate-sensitive decision-making at farm as well as at policy level. The different co-benefits presented further highlight the importance of the economic, environmental, and social relevance of agroforestry systems as an adaptation measure for long-term livelihood improvements in the region.

4.3.1.3 The role of gender in the adoption of agroforestry as an adaptation strategy

Gender and other social factors can influence the uptake of agroforestry as a climate change adaptation strategy. Different studies show that more men than women tend to adopt agroforestry in Uganda (Basamba et al., 2016; Gachuiri et al., 2022). This may be linked to different barriers, including access to land, decision making, labour and finance. With limited control over land, along with the long-term returns of agroforestry, many women feel discouraged to engage in this practice (Kalanzi et al., 2021).

> To foster the adoption of agroforestry by women, access to land needs to be improved, in addition to greater decision-making power in the design and management of agroforestry systems.

A study conducted in eastern Uganda showed that women were less familiar than men when it came to the boundaries of plots, which is an important factor for the design of agroforestry systems (Kalanzi et al., 2021). In another study by Mieke Bourne et al. (2015), women reported having to ask their husbands for permission to plant trees or collect tree products. Limited decision-making power puts women at a disadvantage, also in light of different species preferences. For example, women tend to have a higher preference for species which produce easy access food year-round or can be used as medicine (Gachuiri et al., 2022). Furthermore, agroforestry systems that integrate trees, which can be used for firewood, can lead to a reduction of unpaid domestic work of women. Men, on the other hand, showed a higher preference for species which could provide timber and fuel, thereby generating income (Anguti et al., 2022; Bamwerinde, 2013, 2019; Kuyah et al., 2020). A study by Kalanzi et al. (2019) also showed that men control these resources, with women having limited access to higher value tree products. Women's access to managing agroforestry systems may further be restricted by cultural norms: Agroforestry systems with larger trees require physical activities like climbing on trees to cut twigs, which is considered to be an indecent practice for women of certain communities (Kalanzi et al., 2019). Hence, to foster the adoption of agroforestry by women, in particular access to land needs to be improved in addition to greater decision-making power in the design and management of agroforestry systems.

4.3.2 Improved Storage

The temperature and relative humidity within the storage facility has an effect not only on post-harvest losses, but also on the quality of the coffee and thus the potential price it can obtain. Re-wetting of beans due to leaky tarpaulins or high humidity inside storage facilities can result in mould or musty flavours through, for example, changing chemical compositions in green beans. Sixty percent humidity combined with a longer storage duration can negatively affect the level of acid in the oil of the coffee beans, resulting in lower quality levels (Haile & Kang, 2019). Therefore, to ensure high quality after processing, coffee beans must be kept in appropriate storage facilities until sale.

Mycotoxins also pose a threat to coffee storage. For instance, a study on Ethiopian coffee production shows that at farm-level most losses were associated with pest and moisture as well as mould that can be storage-related (Feed the Future, 2021). In Uganda, the coffee sector is strongly regulated regarding the drying process and recommended moisture content levels to prevent pest infection like mycotoxins. If a farmer does not adhere to specific recommended thresholds, products might need to be re-dried, sold at a lower price or can even be rejected (Lukwago et al., 2019). Mycotoxins therefore also pose an economic risk to farmers in Uganda.

Apart from improving the conditions of the storage facility itself, also proper packaging material and the storage position of coffee inside the storage facility is of utmost importance. While several sophisticated storage techniques exist in professional warehouses to prevent mould formation and to preserve the quality of coffee beans (Kleinwächter et al., 2015) this analysis focuses solely on the prevention of essential post-harvest losses by exchanging poor quality storage material against gunny (jute) bags and high-quality pallets. Dry coffee should preferably be packed in clean sisal/jute gunny bags. The bags should be covered to prevent the coffee from absorbing moisture and growing moulds. Storing coffee in woven polythene bags, on the other hand, is not recommended. The coffee bags in the storage facility should further be placed on pallets raised to at least 15 cm to avoid re-wetting by ground moisture (UCDA, 2019a). Such a rather simplistic approach is expected to be comparatively easy to implement and at manageable investment costs for small-scale farmers.

	Adaptation
IRR	60 %
NPV	1,752,053 UGX
BCR	2.38

Table 6: Summary of key CBA indicators for switching from polypropylene bags to gunny (jute) bags and pallets for coffee storage.

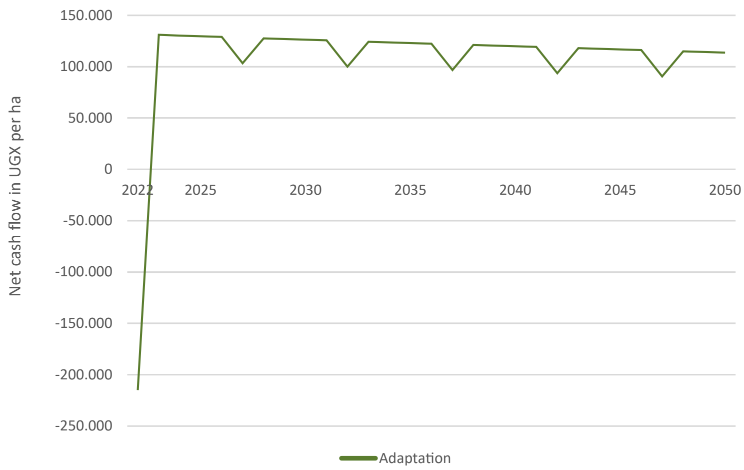


Figure 36: Net cash flow (at current prices) up to 2050 for the adaptation scenario with reference to the non-adaptation scenario.

4.3.2.1 Costs and benefits of improved storage

Using a cost-benefit analysis (CBA), we compare the costs and benefits of investing into gunny (jute) bags and pallets for coffee storage with the costs and benefits of maintaining the status quo over a period of 27 years (until 2050). The costs and benefits are calculated per hectare. The following scenarios were defined:

- **Scenario 1: Non-adaptation (no action):** In the non-adaptation scenario, the model assumes a Robusta coffee production system, in which poor quality storage equipment is used. After harvesting, the coffee is dried on tarpaulins for several weeks. The resulting fair average quality coffee (FAQ) is then stored on farm in polypropylene bags. The accumulated condensation in the plastic bags increases the moisture content, causes mouldiness, and ultimately leads to a loss of 5 % of the total produce. The costs and revenues of this practice are extrapolated until 2050.
- **Scenario 2: Adaptation (action):** In the adaptation scenario polypropylene bags are replaced by gunny (jute) bags and high-quality pallets lifted from the ground to improve the storage of FAQ coffee. By this the coffee beans are prevented from drawing moisture and moulding. Losses can be reduced by half to only 2.5 % of the total produce. The market revenues and costs of investing into better bags and pallets are extrapolated until 2050.

Results and key economic indicators

The key economic indicators shown in Table 6 indicate that investing into improved storage facilities for FAQ coffee is highly profitable.

- Any Internal Rate of Return (IRR) higher than 6 % usually assumed under a global rentability perspective indicates a profitable investment. An IRR of 60 % can therefore be interpreted as highly cost-effective.
- Also, the Net Present Value (NPV) of 1,752,053 UGX (per ha) indicates that the present value of the expected cash flows exceeds the initial investment.
- A Benefit Cost Ratio (BCR) of 2.38 means that the benefits of investing in the proposed improved storage material are 2.38 times higher than the costs.

The net cash flow (at current prices)[10] in Figure 36 shows that the investment pays off immediately due to the rapid effectiveness of the measure. The additional revenue that is generated by avoiding postharvest losses by far exceeds the investment costs. In the second year of the investment the net cash flow is already 130,973 UGX. While the costs for new bags were annualized, which means that every year one third of the bags are renewed, the pallets are completely replaced every five years. These investment costs are responsible for the low peaks in the graph every five years. The net cash flow is positive over the entire period, even though it becomes slightly smaller each year. The reason for this is the expected decline in coffee yields due to climate change until 2050.

The results of the CBA clearly show that the adaptation strategy makes sense from an economic perspective. The reason for this is that it is comparatively simple and cheap to implement, and no opportunity costs are to be expected. The manageable investment costs, which are spread over the years are presumably easier for smallholder farmers to afford than very high initial investment costs, as they often occur with infrastructure measures.

Since climate change is expected to make storing coffee increasingly difficult, investing in improved storage will help to adapt the coffee value chain to these impacts. Besides the above presented improved storage material, there are several other opportunities for improving the storage environment at farm level in coffee production. To prevent pest and mould infections as well as price and quality reductions after harvesting, first, packed parchment or dry cherry coffee should be stored in stores, silos or professional warehouse dedicated for coffee storage. A good coffee storage or even professional warehouses are one of the most important economic variables during the

10) The net cash flow presented here is the additional cash flow of the adaptation scenario compared to the non-adaptation scenario and refers only to the additional costs and benefits of investing into improved bags and pallets for storage. It does not depict the net cash flow of the entire coffee cultivation system.

post-harvesting process. The storage facility must be cooled and should have a cemented floor, plastered walls, a leak proof roof and should be well ventilated with a relative humidity of less than 60 %. The storage facility should not be used to store any contaminant product and strong-smelling liquids such as petrol or paraffin, diesel, or agricultural fertilizers and chemicals, because stored coffee quickly absorbs and retains foreign odours, which are eventually detected in the final cup and thereby spoil its quality. It should also not be used as storage for other farm produce such as beans, maize, or ginger to avoid pest infestation and contamination. The coffee storage facility should be kept clean to maintain hygiene and prevent rodents (UCDA, 2019a).

4.3.2.2 The role of gender in improved coffee storage as an adaptation strategy

Although women provide much of the labour in the coffee sector in Uganda, coffee has traditionally been considered a cash crop and coffee businesses are dominated by men (FAO, 2020b).

> Women need to be included in these later and most profitable stages of the value chain to guarantee them a fair share of the profit.

It is becoming increasingly clear in the literature that agricultural systems are most successful when women have the same access to resources and opportunities as men. Women form the backbone of the coffee industry but have little access to the returns generated by it. For example, the labour share of women in the coffee value chain in Kanungu in Uganda is 65 % compared to 35 % for men. Regarding the field work and the harvesting of the coffee, women perform the majority of the work (58 %), which includes, for example, tilling the soil or planting seedlings. During the post-harvest processing phase, they perform as much as 72 % of the work. This includes sorting, drying and bagging the coffee. In comparison to these relatively low profit stages of the value chain, women are rarely involved at all in the marketing and management of the coffee. Here, it is the men who carry out virtually all processing and marketing activities (Farm Africa, 2019). Women need to be included in these last and most profitable phases of the value chain to guarantee them a fair share of the profit.

4.4 Conclusion

Coffee is the most important cash crop in Uganda and key for Uganda's export revenue. This chapter analysed how climate change impacts will play out and the potential of two adaptation strategies (agroforestry and improved storage) to mitigate these impacts.

4.4.1 Climate impacts on the coffee value chain

Our crop modelling **results project pronounced changes in the suitability of coffee (Robusta and Arabica) and bananas** across the country, with mostly negative net changes. This implies that climate change will lead to considerable reductions in suitability of the three crops. These results align with studies by Bunn et al. (2019) and Wichern et al. (2019), who projected potential regional reduction in the suitability to grow coffee by mid-century. **Arabica coffee is more vulnerable to climate change** given the species' relatively narrow ideal growing conditions. By 2050, we project a reduction of 20 % of suitable land to grow coffee under the SSP1-RCP2.6 low emissions scenario and 18 % under the SSP3-RCP7.0 high emissions scenario. By the end of the century, the areas of West Nile that are currently suitable for Arabica coffee will become unsuitable hence farmers might need to shift to growing Robusta coffee or other more climate-resilient coffee species or varieties. The area suitable to grow Robusta coffee will only slightly, but progressively, reduce with time with higher losses expected under the SSP3-RCP7.0 high emissions scenario, than under the SSP1-RCP2.6 low emissions scenario. Under the low emissions scenario, the area suitable for Robusta coffee will first increase by 3.2 % until 2050 but later reduce to an overall loss of 1.08 % in 2090 relative to the current suitable area. The Karamoja region will remain unsuitable for Robusta coffee under both emissions scenarios by 2090. The suitability of the two coffee species will mainly be **affected by the precipitation and temperature** in the flowering months. In addition, the suitability of banana is expected to decrease significantly. Therefore, the coffee-banana intercropping potential will be negatively affected by climate change for both coffee species, hence farmers should progressively adopt other shading/adaptation measures.

Climate change does not only impact production but is also felt at later stages of the value chain. Interviews with value chain actors working in aggregation, processing, marketing and distribution have revealed that all other steps of the value chain are also exposed to climate risks. **Direct impacts** include impacts on the product, activity, or finances of a business working in aggregation, processing and distribution and marketing of coffee and include for example difficulties in drying the coffee due to increased humidity or change in the quality of the processed coffee (both negative and positive). **Indirect impacts** occur at the production stage of the coffee value chain and trickle down to the post-harvest stages. For example, yield losses lead to an increased demand, which causes price fluctuations and eventually reduced income and planning insecurities. In addition, climate impacts can lead to a non-linear value chain composition with some actors being kicked out of the value chain, while new actors join. If processors, for example, cannot source coffee from farms in their immediate vicinity due to harvest losses and resulting price spikes in the area, they sometimes revert to other sourcing regions of the country.

At the same time, we observed feelings of disadvantage and mistrust, both in relation to business partners, e.g. farmers, as well as in relation to competitors, especially international companies operating in the country. This is further exacerbated by exposure to international market dynamics, which often put local businesses into an impaired situation compared to their international competitors. Since the large majority of the coffee in Uganda is exported, any trends and changes in the international market will have a direct impact on the prices and conditions of the coffee value chain within Uganda (FAO, 2020b).

4.4.2 Adaptation options for the coffee value chains

Holistic climate change adaptation strategies need to be identified and designed with a value chain approach that takes the different dynamics into consideration. In the second part of the chapter, we therefore assess two adaptation strategies for different steps of the value chain: For the production step of the coffee value chain, we used a combination of crop models and cost-benefit analysis to assess the **potential of agroforestry systems** to buffer climate change impacts on coffee suitability and whether they make economic sense. For the aggregation stage of the value chain, we conducted a cost benefit analysis to assess the economic feasibility of **improved post-harvest storage**.

Our modelling results show that agroforestry has a high potential to mitigate the impacts of climate change on coffee production. **Growing shade trees could potentially buffer between half to all of the reductions in areas suitable for Arabica and Robusta coffee by the end of century**. *Ficus natalensis* is more resilient to climate change, hence has a higher buffering potential for the two coffee varieties than *Cordia africana*. Therefore, a combined agroforestry system of *Cordia Africana* and *Ficus natalensis* is recommended in the northern parts while *Ficus natalensis* is recommended for the central, western and southern parts of the country. We recommend policies tailored towards increasing the use of agroforestry systems across the country with emphasis on the right site-species matching for the respective agroforestry trees.

The results of the cost-benefit analysis show that investments into agroforestry systems for coffee-banana intercropping systems make good economic sense for the farmers, also in the long run as they have the potential to increase not only coffee and banana yields, but also create additional income streams for farmers. In addition, there are a number of co-benefits that make agroforestry a highly recommendable adaptation strategies for coffee production. This includes the regulation of wind, pests and diseases and the microclimate, increases in biodiversity, the diversification of livelihoods and carbon sequestration, which also helps with climate change mitigation efforts.

Coffee is not only climate-sensitive during production, but also during storage and processing. Temperature and humidity within the storage facility has an effect not only on post-harvesting losses, but also on the quality of the coffee and thus the potential price it can obtain. Changes in climate change will alter the conditions for aggregation and processing. Considering the expected increases of climate conditions that are suitable for the formation of humidity and resulting negative effects on the coffee bean quality as well as on mycotoxin contamination, it can clearly be argued that the improvement of storage facilities can help farmers to better adapt their post-harvest activities to changing climate patterns.

One strategy to mitigate these potential effects is the introduction of better storage condition. **Exchanging poor quality storage material, i.e., bags and pallets, against high quality ones in an on-farm storage facility** can significantly reduce the exposure of coffee to unfavourable climatic conditions and therefore reduce post-harvest losses. The results of the CBA clearly show that the adaptation strategy makes sense from an economic perspective. The reason for this is that it is comparatively simple and cheap to implement, and no opportunity costs are to be expected. The manageable investment costs, which are spread over the years, are presumably easier for a small farmer to afford than very high initial investment costs, as they often occur with infrastructure measures such as irrigation systems.

Overall, this analysis shows that while climate change is expected to significantly impact the coffee value chain in Uganda, there are promising adaptation strategies that can buffer these impacts. Designing these strategies needs a value chain approach, which takes into consideration the different actors and processes of a value chain. There is also a need to include women more proactively in the last, more profitable steps of the value chain. If designed properly, the discussed adaptation strategies can not only mitigate climate risks, but offer real business opportunities through, for example, the diversification of income or entering speciality coffee markets.

Impact		Current	Future	Confidence
	Arabica coffee suitability	3.1 %	**SSP1-RCP2.6 (low emissions)** ■ Decreasing ■ 10 to 20 % **SSP3-RCP7.0 (high emissions)** ■ Decreasing ■ 12 to 25 %	High
	Robusta coffee suitability	61 %	**SSP1-RCP2.6 (low emissions)** ■ Increasing 0.5 to 3.8 % ■ SSP3-RCP7.0 (high emissions) ■ Decreasing 1.6 to 5.9 %	High
	Post-harvest steps of the value chain	**Product:** ■ Availability of high quality coffee beans ■ Sensorial quality of coffee beans **Activities:** ■ Drying difficulties ■ Higher energy needs ■ Disruption of transport ■ Finances; ■ (global) Price fluctuations ■ Planning insecurity		Qualitative assessment based on perceptions of interviewees

Table 7: Summary of climate change impact on coffee production.

5. Conclusion and policy recommendations

This study provides a comprehensive climate risk analysis for Uganda's agricultural sector. It aims to offer an in-depth decision-basis for national and local decision-makers on current and future climate risks for agricultural value chains to guide suitable adaptation planning and implementation in the country. The study complements and confirms previous analyses on climate change adaptation in the agricultural sector in Uganda.

Climate change projections show a clear trend of continuously increasing temperatures across the country, as well as an increase in the frequency of temperature extremes, such as hot days and hot nights. In response to increasing GHG concentrations, mean annual temperature is projected to increase by 1.1 °C under the low emissions scenario and 1.5 °C under the high emissions scenario by 2050, compared to 2004. This can limit crop growth or even lead to crop failure and impact the aggregation and processing of the crops through increased levels of humidity. Precipitation projections are much more uncertain than temperature projections. Even though the majority of climate models point to a slightly wetter future in the country, it cannot be ruled out that Uganda could experience a drier climate in some parts of the country, as some models suggest. Similarly, precipitation extremes are projected to increase, but not all models agree on this trend.

These changes in the climate have significant consequences for both, maize and coffee value chains, which have been the focus of this study. By 2090, national maize yields are projected to decline by up to 8.8 % under the low emissions scenario and up to 26.8 % under the high emissions scenario. With population growth, the projected declines in maize yields can contribute to food and nutrition insecurity, as maize is an important source of calories across the country. Declining yields may also lead to land expansion and biodiversity loss as farmers may attempt to compensate for reduced yields to meet requirements.

Within the same time period, the suitability to grow Arabica and Robusta coffee is projected to reduce by up to 18 % and 5 % respectively under the high emission scenario. In addition, we project considerable losses in the area suitable to grow banana of up to 25 % of the current suitable area under the high emissions scenario and 7.7 % under the low emissions scenario by 2090. This leads to an average loss of 6 % of the total current area suitable for coffee-banana intercropping, hence a significant implication for rural households' incomes and food security. In turn, deforestation or land conflicts may occur, as farmers need to move to higher altitudes and protected areas to continue to grow coffee and secure incomes.

Interviews with key actors involved in post-harvest steps (including aggregation, processing, marketing and distribution) revealed that climate impacts are also felt at later stages of both value chains, maize and coffee, significantly affecting post-harvest products, activities and finances, as well as the overall composition of the value chain. Direct impacts include losses in quality and quantity of post-harvest products, difficulties in drying coffee or maize due to increased humidity or changing rainfall patterns, as well as challenges with transport due to extreme weather events.

The presented climate change impacts on the agricultural value chains of maize and coffee require strong adaptation efforts to support the transformation of Uganda's agricultural sector towards climate-resilient agri-food systems. We therefore assessed the risk mitigation potential, cost-effectiveness and gender aspects of four selected adaptation strategies: improved maize varieties, improved maize storage, agroforestry systems for coffee production and improved coffee storage.

Our assessments show that improved maize varieties are stable across scenarios and periods are therefore a viable adaptation strategy. Improved maize varieties are able to buffer all projected yield losses: at national level, improved maize varieties will produce 2.9 % and 8 % more yield by 2090 under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario respectively. For coffee, introducing shade trees Cordia africana and Ficus natalensis into coffee production to establish an agroforestry system could potentially buffer between a half to all of the reductions projected in areas suitable for Arabica and Robusta coffee by the end of century. In addition, the cost benefit analyses show that investing in improved maize varieties and agroforestry makes economic sense for the farmers. Beyond that, improved storage is also a cost-efficient approach for both, maize and coffee, to reduce post-harvest losses and secure the products' quality.

Nevertheless, there are substantial differences between maize and coffee value chains which need to be considered when designing adaptation strategies. Since coffee is a perennial crop, changes in management practices along the value chain are more long-term. Impacts of (global) climate extremes are not always felt in the same season. As an export crop, the coffee value is greatly regulated and embedded within a global system. Adaptation of the coffee value chain therefore requires a systemic approach that responds to both local requirements, as well as global demand. The maize value chain, on the other hand, is less regulated, but its importance for national food security makes it a priority for climate change adaptation. Maize is planted every year, with adjustments to the value chain requiring less long-term planning than for perennial crops, like coffee. Unlike coffee factories, which are highly specialized to the processing of the coffee cherry and bean, maize factories are often more flexible to adjust to prevailing market conditions. Hence, adaptation strategies need to be designed in a way that takes differences and variabilities of wider agricultural system into account as well as their impact on incomes and food security.

Generally, there is no single adaptation strategy that is suitable for the whole country or can "fix" one specific value chain, since their effectiveness and co-benefits ultimately depend on the projected climate impacts which differ by region, as well as on the concrete design tailored to the local context and specific needs of different value chain actors. The actual climate change impacts are not only shaped by the intensity of the projected changes, but also by the vulnerability and exposure of the affected farming communities or agricultural businesses. Differing social characteristics such as gender, age, education and health can substantially shape farmers' vulnerability and therefore their exposure to climate change. The ability of a company to withstand climate shocks can be influenced by its size and market power. Taking these characteristics into consideration is an important prerequisite to build resilience across agricultural value chains.

A value chain approach allows for the wider integration of the various actors involved in bringing a product from its initiation to the sale. While it is more complex to take different, often heterogonous actors into consideration, there is also a great opportunity that by joining forces, the transition to climate-resilient, inclusive and sustainable agricultural systems can be accelerated.

Based on the findings of this study, the following **policy recommendations** can be derived: →

A science-based approach to adaptation planning

- **Climate change adaptation needs science-based evidence**. The analysis shows that climate change increasingly impacts agricultural value chains in Uganda. These impacts include decreases of suitable land to grow certain crops, production losses, as well as deteriorating conditions which appear at later stages of the value chain. **National goals of agricultural development and intensification cannot be achieved without building resilience** of agricultural value chains against these climate change impacts.
- **Climate change adaptation should be mainstreamed across sectoral policies.** The study was designed in alignment with important policy documents and processes in Uganda, in particular the National Climate Change Policy (2015) and the third National Development Plan (NDP III), the Nationally Determined Contribution (NDC) and the National Adaptation Plan for the Agriculture Sector (NAP-Ag). **Results from this climate risk analysis can thus feed into further development and implementation of climate adaptation policies and agricultural development planning**, including the development of the next National Development Plan IV (NDP IV)**.** The Parish Development Model can be used to translate findings into action on the ground.
- A **value chain approach to climate change adaptation in the agricultural sector helps to ensure that interventions are effective, efficient, and sustainable**, and that they benefit all stakeholders involved in the production and distribution of agricultural products. It also offers the opportunity for public-private partnerships, which can leverage expertise, market efforts and resources to promote adaptation. However, value chains should not be considered in isolation, but as part of wider agri-food systems.

Building a climate-resilient maize value chain

- The introduction of **drought tolerant maize varieties is one option to make maize value chains more resilient to climate change**, as improved crop varieties perform equally well under projected climatic conditions as they do under current condition. Ideally, improved varieties are promoted that fulfil several conditions, such as farmer's preference, local suitability, agronomic management and that are available and accessible also for smallholder farmers. Equitable access to improved seeds, required inputs and knowledge should be ensured with a particular emphasis on the socio-economic differences of farmers.
- **Rapid breeding cycles** that provide farmers with a steady stream of improved varieties, **information campaigns** on the benefits of improved varieties under climate change and building a **seed systems model** that delivers new varieties to farmers quickly and cost-effectively is key to accelerate the uptake of improved (maize) varieties.
- At the same time the **research and promotion of other crops**, such as sorghum, that are naturally more nutritious and resistant to the effects of climate change than maize, should be fostered.
- **Climate change adaptation in post-harvest steps of agricultural value chains** is an often overlooked, but extremely important pillar of building climate-resilient agri-food systems. Boosting access to and knowledge on improved storage material, as well as encouraging community-based storage and processing facilities can help to **promote improved post-harvest storage and processing.** By pooling their resources and sharing the costs of storage facilities and management, farmers can improve their bargaining power and access to markets, and ultimately increase their income. For less regulated crops, such as maize, it is worthwhile to establish **regulations and standards for post-harvest storage infrastructure and services** to ensure planning security, quality control and consumer protection.

Building a climate-resilient coffee value chain

- **Agroforestry** offers multiple benefits in the context of Ugandan coffee production, such as shading coffee plants from extreme temperatures, improving soil health, increasing biodiversity, and thereby improving the quality of coffee. UCDA promotes a number of tree species that are suitable as shade trees for different areas of Uganda (UCDA, 2019b, 2019a). The **tree species should be chosen depending on local needs and according to the benefits they provide**, such as shade, food, energy, medicine, additional income etc. At the same time, the type of tree species should be carefully selected, based on the species' suitability to grow under a changing climate. The provision of tree seedlings and trainings on establishment and management of agroforestry systems should be provided to farmers.
- Building a **climate-resilient coffee value chain make a system change required.** In addition to agroforestry, other strategies that cater to the preferences and needs of the entire value chain should therefore be considered. For instance, promoting improved coffee varieties or using traditional coffee species (wild Robusta or coffea Liberica) can be an option to diversify coffee production and thereby increase its climate resilience. This will also help to promote agricultural production systems that facilitate farmers' compliance with the requirements of the new Deforestation Regulation of the European Union (EUDR).

- **Promoting high quality storage equipment**, including gunny (jute) bags and pallets and sharing knowledge on their benefits, is key to maintain the quality of coffee and helps to guard it against unfavourable climatic conditions. Climate-smart storage and processing practices such as solar drying and eco-pulpers can also reduce GHG emissions and improve energy efficiency. Organizing activities as part of cooperatives can help to pool expertise and resources to invest in improved storage and processing.

Creating an enabling environment to scale up adaptation efforts

- Next to the adaptation strategies which are presented and analysed within the framework of this study, there are of course **further methods to adapt agricultural value chains to climate change**. Other examples include water harvesting, integrated soil fertility management or other improved crop management practices. Depending on the circumstances, adaptation strategies different to the ones presented might be even more suitable, cheaper or better implementable. Agricultural value chains and especially farms are complex systems that require a targeted and tailored design of management practices. Regardless of the specific climate risks addressed, **combinations of adaptation strategies are often more effective than single approaches**. Adaptation strategies and combinations thereof should be carefully assessed and adapted to the value chain and agri-food system.

- Farmers and agricultural businesses need support in **bridging the financing gap** between investment and the break-even point when the adaptation strategy becomes profitable. In some cases, for example in the case of agroforestry, this can take a couple of years. In other cases, such as improved seeds, it requires high upfront investments for seeds and special input. This requires transitional financial support. Developing financing mechanism, such as access to loans or credits can support farmers transition to resilient farming systems. Carbon credit schemes might be another option to help farmers fund adaptation strategies that have mitigation co-benefits, such as agroforestry.

- **Research and development** are at the core of innovative, climate-resilient agriculture. Regular investments into national research institutes need to be upscaled. **Adaptation research should be mainstreamed into extension services and university curricula.**

- Context is key: **investing in adaptation strategies should be regionally specific**, as different areas in Uganda will be impacted by climate change differently. For instance, the Northern region will be hit particularly hard and should therefore require special attention.

- Gender aspects need to be carefully and systematically considered in the implementation of NAPs, NDCs and sectoral policies and plans. **Women and other marginalised groups should be moved to the centre of these processes**, both as a target group and leaders of action, so that agricultural systems can be transformed towards greater gender equity, inclusion and climate resilience. For this to materialise, gender-specific vulnerability assessments are crucial for generating a contextualised understanding of root causes of vulnerabilities and barriers to adaptation.

- **Adaptation strategies should not be developed in isolation, but rather in collaboration with stakeholders across the value chain**, including farmers, processors, traders, and policymakers. This would ensure that the strategies are context-specific, inclusive, and sustainable, and would increase their chances of success.

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