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

Annex I Additional information on methods and data

1. Changing climate conditions (Chapter 2)

The basis for the evaluation of the current and near-past climate in this study is the climate observational dataset W5E5 (Cucchi et al., 2020; Lange et al., 2021), a dataset based on a combination of simulations from global weather models, satellite data and in-situ observations. The dataset covers the time period 1979–2016 at daily temporal resolution and the entire globe at 0.5° × 0.5° grid spacing (corresponding to approximately 55 km × 55 km in Uganda).

Future climate projection data simulated by Global Climate Models (GCMs) was obtained from ISIMIP3b (phase 3b of the Inter-Sectoral Impact Model Intercomparison Project; see Lange (2019b) and Lange and Büchner (2021)). Historical simulations cover the years 1850–2014 and future projections under both greenhouse gas emissions scenarios cover the years 2015–2100. W5E5 is the observational reference dataset used for bias adjustment and statistical downscaling of ISIMIP3b. The GCMs included in ISIMIP3b are CanESM5 (short: Can), CNRM-ESM2-1 (short: CNES), CNRM-CM6-1 (short: CNCM), EC-Earth3 (short: EC), GFDL-ESM4 (short: GFDL), IPSL-CM6A-LR (short: IPSL), MIROC6 (short: MIROC), MPI-ESM1-2-HR (short: MPI), MRI-ESM2-0 (short: MRI) and UKESM1-0-LL (short: UKE) (Lange, 2019b; Lange & Büchner, 2021).

GCMs cannot perfectly represent the current and future climate. They naturally show slightly different projections in modelling the climate, even if they are driven by the same emissions scenario. Different projections of all individual models indicate the range of uncertainty and the multi-model mean provides a conservative estimate of possible climatic changes. Thus, in this report, the multi-model mean is shown in figures and maps and an uncertainty range based on all GCM results is either shown or discussed. Climate change analyses are based on 20-year averages[1], meaning that the mean annual temperature in e.g. 2030 is calculated as an average over the mean temperature between 2021 and 2040. Changes in the past are analysed by comparing the W5E5 data from 2000–2019 with 1979–1998. The reference climate, used as the baseline in this study, refers to the climate in 2004 (1995–2014), as the period is included in the historical simulations of ISIMIP3b. The projected climate data is evaluated for the periods 2030 (2021–2040), 2050 (2041–2060) and 2090 (2081–2099) in differentiation to the baseline (2004) for each model and scenario.

The indicators analysed in this study are the annual average mean air temperature, the number of hot days per year (maximum temperature above 35 °C), the number of hot nights per year (minimum temperature above 25 °C), the mean annual precipitation sum, the heavy precipitation intensity, and the rainy season onset, cessation and length.

The indicator for heavy precipitation intensity is defined as the value of the 95th percentile considering only days with precipitation (>0.1mm).

We used the method of percentage cumulative mean rainfall for determining rainfall onset and cessation dates. The method was adopted from Liebmann et al. (2012) and it has been successfully applied to the complete African continent.

2. Climate risk analysis for maize value chains (Chapter 3)

Crop modelling

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 on a daily time step under current and projected climatic conditions. Moreover, the model is used to evaluate potential adaptation strategies. The model requires daily weather data, soil profile information, detailed crop management information, and genetic coefficients of varieties as inputs to simulate maize growth and yield. DSSAT calculates plant and soil water, nitrogen, phosphorus, and carbon balances, as well as the vegetative and reproductive development of crops at the daily time scales. For the assessment, we used various sources for parameterising and calibrating the model. We modelled maize yield under rain-fed conditions as this is the dominant system for maize production in Uganda. Planting dates, harvest dates, planting depth, row spacing and plant density were obtained from the Maize Training Manual for Extension Workers by the Ministry of Agriculture, Animal Industry and Fisheries (2019). The Harvest Choice Soils (Han et al., 2015) were used as soil profiles for each grid while fertiliser applications were obtained from the SEDAC estimates of fertiliser use at grid level (Potter et al., 2010, 2012). We use the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario for yield projections in the years 2030 (2015–2064), 2050 (2035–2064), and 2090 (2075–2094). Future climate projection data simulated by GCMs were obtained from ISIMIP3b (Lange, 2019a; Lange et al., 2021). Model validation was done by comparing simulated yields to reported district level yields in Uganda and the Spatial

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1) Climate variables (such as temperature and precipitation) show high annual variability. In order to analyse long-term climatic changes instead of annual variabilities, means of climate variables over 20–40 years are compared with one another.

Production Allocation Model (SPAM) yield database for 2005, 2010 and 2017 (IFPRI, 2019, 2020; IFPRI & IIASA, 2016). Model validation showed that the model performance was satisfactory with a coefficient of determination (R2) of 0.79 and an index agreement of d=0.83 with observed yields.

Qualitative interviews with value chain actors

Seven semi-structured interviews were conducted in March and April 2022 with a total of eight actors along the maize value chain including processors, aggregators and traders ranging from small-scale to large-scale businesses. The interviewed businesses are located in Lira and Agago districts in the Northern region of Uganda. The interviews were complemented with expert interviews and focus group discussions. In both districts, maize production is predominantly driven by rain-fed smallholder farming systems. However, the communities selected differ on a few significant characteristics, particularly in terms of access to information, markets and infrastructure. The actors interviewed in Lira represented a wider range of business structures ranging from a small service mill to a large multi-grain processing factory involved in international trading. As they are located within the city of Lira, they work in an export-oriented environment and are well connected to major national and international trading hubs. The actors interviewed in Agago are mainly small aggregation, processing and trading businesses either located within village structures or the small town of Patongo. They are embedded within more socioeconomically disadvantaged structures, have less access to infrastructure and markets and are thus far more domestically oriented in terms of their production.

The interviews were conducted in English together with local research assistants, recorded, transcribed and analysed in MaxQDA. The transcripts were analysed using abductive thematic analysis (Tavory & Timmermans, 2014). An initial coding scheme was derived from the IPCC (2014, 2021) climate risk framework reflecting the main functions of climate risk, i.e. hazard, exposure and vulnerability (see blue box. Iteratively, these were expanded by codes emerging during the analysis of the interviews, creating a comprehensive analysis framework for climate risks in maize value chains. The coding scheme was developed in an interactive session by two participating researchers, including a researcher from Uganda. The final coding scheme was validated by both local and international experts on the topic. The results were cross-checked with data collected from expert interviews and focus group discussions with experts including local and international organisations and research institutes.

Cost-benefit analyses

1. Cost benefit analysis for improved maize varieties

Input data
The CBA calculations are based on economic and agricultural production data provided by NARO as well as on literature reviews. To identify the changes in market revenues and production costs associated with the switch to an improved maize variety, the following aspects are considered: costs for seeds, costs for fertilizer and pesticides, production and harvest costs, labour costs and market prices.

Moreover, we complemented the input data with some assumptions on climate change and technological impacts as well as on inflation rates:

- Climate change induced yield developments in Uganda under the SSP1-RCP2.6 low emissions scenario and under the SSP3-RCP7.0 high emissions scenario are projected to lead to moderate annual yield declines between 0.1 and 0.5 °C per annum until 2050 (see results Chapter 3.2).
- We assume that the plot productivity increases due to autonomous technological change by 1.58 °C per annum. This is an extrapolation of maize yield increases between 1961 and 2021 in the target region (FAO, 2023).
- To depict the discount rate that is applied in the calculations, the exponential growth rate of the Gross Domestic Product (GDP) per capita of Uganda since 1970 has been applied. The discount rate amounts to 4.10 °C (FAO, 2023).

Assumptions

The following additional assumptions were taken into consideration for the cost benefit analysis on improved maize seeds (Chapter 3.2):

- The use of Longe 10 varieties does not require any additional equipment which would necessitate an investment. The main cost factor is the acquisition of seeds, which has been obtained from FAO (2020a) for the maize varieties Longe 4, 5 and 10. The prices were adjusted for inflation. For Scenario 1, the average between seed costs for Longe 4 and 5 has been applied, which amounts to 3,144.57 UGX / kg of seed. Additionally, seed costs are assumed to only occur every third year in Scenario 1, as self-saved seeds are very common in Uganda (Longley et al., 2021; Astrid Mastenbroek, Otim, et al., 2021; Astrid Mastenbroek, Sirutyte, et al., 2021). For scenario 2, seed costs of 5,990.00 UGX / kg for Longe 10 seed are assumed. The sowing rate is kept constant in both scenarios and amounts to 25 kg / ha (MAAIF, 2019).
- In addition to acquisition costs for seeds, the farmers in scenario 2 will increase the use of fertilizers and pesticides, as it is assumed that production intensity increases with the switch to the higher yielding hybrid variety. This increases production costs from 928,128 to 2,302,026 UGX / ha. Cost data for both scenarios has been obtained from MAAIF (2019). For scenario 1, data for a low input farmer using OPV has been adopted. Due to the switch to a higher yielding hybrid maize variety, accompanied by an assumed intensification in the use of inputs, for scenario 2, data for a conventional farmer has been selected. Cost data from production until and including harvest has been included; costs for packing, drying and transportation are not covered.

- The higher yields of the hybrid Longe 10 maize variety increase the workload for harvesting. Therefore, the labor costs for these activities are annually adjusted by applying the unit costs of harvest for one kg of maize in the baseline period for all subsequent yield changes and the accompanied costs for harvest. Data for the unit cost of harvest are also obtained from MAAIF (2019) and amount to 44.35 UGX / kg of maize.
- To calculate the market revenues, we use a market price of 700 UGX for one kg of harvested maize. Price data has been taken from MAAIF (MAAIF, 2019) and was cross-checked with ACSA (2022) and FEWS (2022). It is further assumed that the price stays constant after switching to the new variety. Hence, no price premium for higher quality or other factors is included in the calculations.

2. Cost benefit analysis for improved storage

The CBA for improved storage is a model calculation based on a set of input data complemented with several assumptions:

- According to Dijking et al. (2022), it is assumed that a farmer invests every three years into new hermetic bags to store his maize harvest. In the meantime, the bags can be reused.
- The associated investment costs were calculated as the price difference between 12,539 UGX for hermetic bags and 1,749 UGX for low-quality jute / polypropylene bags. To calculate the number of bags needed for the storage of one hectare maize, a filling quantity of 90 kg per bag was assumed (Dijkink et al., 2022; Stathers et al., 2020). For the calculation, these costs were annualized.
- By switching from low quality jute (or polypropylene) bags to hermetic bags, the model assumes a postharvest loss reduction from 19.1 °C to 1.6 °C per season (Dijkink et al., 2022; Stathers et al., 2020)
- To monetize the additional benefits of the investment, the revenues of the avoided post-harvest losses were calculated based on Longe 4 and 5 yield projections from chapter 3.2.1 and an inflation-adjusted producer price of 700 UGX per kg maize (MAAIF, 2019).
- The maize yields used for this calculation were projected under two different emissions scenarios (SSP1-RCP2.6 low emissions and SSP3-RCP7.0 high emissions) assuming climate change induced annual yield declines of between 0.1 °C and 0.5 °C per annum until 2050 (see chapter 3.2.1)
- It is further assumed that maize yields benefit from a productivity increase due to autonomous technological change by 1.6 °C per annum. This is an extrapolation of maize yield increases between 1961 and 2021 in the target region (FAO, 2023).
- To calculate the discount rate, the exponential growth rate of the gross domestic product per capita of Uganda since 1970 has been used. The discount rate amounts to 4.1 °C (FAO, 2023).

3. Climate risk analysis for coffee value chains (Chapter 4)

Crop modelling

The crop suitability was derived using a machine learning species distribution model approach based on an ensemble mean of random forest (RF), boosted regression trees (BRT) and support vector machine (SVM) algorithms. Species presence points for coffee were obtained from the Global Biodiversity Facility (GBIF) and secondary sources of Robusta and Arabica farms in the country. Banana presence points were obtained from a mapping study by Ochola et al., (2022). We used climate projections of the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP 3b) at 0.250 resolution with ten general circulation models (GCMs). Using this climate data, we derived precipitation and temperature-related variables that are most vital for the growth of the three crops following their growth calendars. In addition, we used soil PH and elevation since they are essential determinants of coffee growth and ecological distribution. Before application, we calculated the specificity, sensitivity and balanced accuracy, as well as the area under the curve (AUC) to determine the performance of the models for each individual crop. Then, the models were further validated using the confusion matrix method taking the Spatial Production Allocation Model (SPAM) yield database as a reference. We achieved a good model fit (AUC > 0.75) for all crops. In addition, the model accuracy from the confusion matrix evaluation against the SPAM data set was high (accuracy > 0.75). The high model accuracy levels give us the confidence to apply the models for predicting future crop suitability in Uganda.

Important variables for crop suitability

The determinants of crop suitability in Uganda vary amongst crops. Generally, precipitation-related variables strongly influence the suitability of coffee and banana compared to other factors. For example, precipitation-related variables explain 21 °C, 51 °C and 62 °C of the suitability of Arabica coffee, Robusta coffee and bananas, respectively. On the other hand, the temperature-related factors contribute only around 14 °C to the suitability. The suitability of Arabica coffee is highly influenced by soil pH, the growing season average temperature, and the flowering season precipitation with soil pH being the most significant variable (14.6 °C). On the other hand, the precipitation in the warmest quarter, elevation and the precipitation in the growing season are the major variables affecting the suitability of Robusta coffee contributing 27 °C, 16 °C and 13 °C respectively. The suitability of bananas is mostly influenced by precipitation in the warmest quarter (26 °C), elevation (19.3 °C) and soil pH (19.1 °C) (Figure 1).
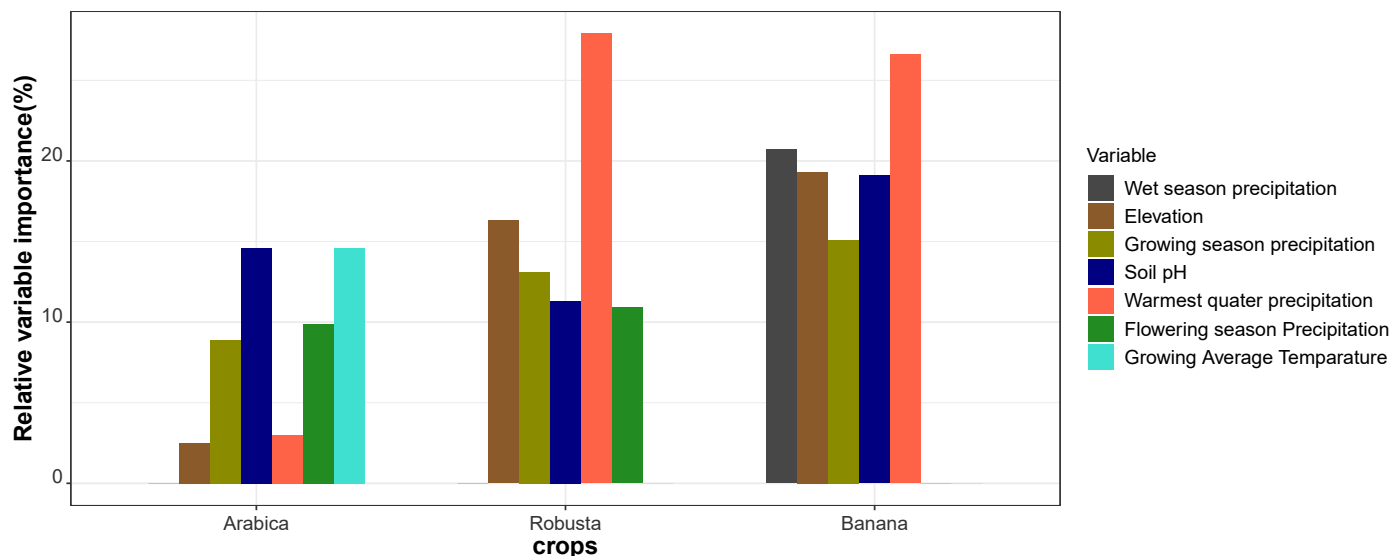
Figure 1: Relative importance of variables used in modelling the suitability of coffee (Arabica and Robusta) and bananas in Uganda.

Results climate change impacts on the suitability to grow banana

To be able to assess the climate change impacts on coffee-banana intercropping, we need to understand how climate change may impact the production of banana. The suitability of bananas will highly reduce with time under both emissions scenarios with the highest net reduction (25 °C of the current suitable area) occurring under the SSP3-RCP7.0 high emissions scenario in 2090. Under both time frames, the reduction in the suitability of bananas will occur in West Nile, Acholi and south-western Uganda. By 2050, a reduction of 4.6 °C and 6.6 °C relative to the current suitable area is expected under the SSP1-RCP2.6 low emissions scenario and under the SSP3-RCP7.0 high emissions scenario respectively. By 2090, there will be further reductions by 0.1 °C and 10 °C under the SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario respectively by 2090 (Figure 2). Despite these reductions, the central and south-western regions will remain the most suitable for banana production. Karamoja region will remain unsuitable for bananas under both emissions scenarios and time frames. Being a staple crop for many communities in Uganda, the reduction in the suitability of bananas across the country poses a threat to food and nutrition security. The crop also majorly contributes to household incomes. Reduction in its suitability cripples household income inflows and increases poverty risk.

Data input for agroforestry modelling

We attained a high model fitting for both tree species (AUC > 0.8). The suitability of both species is mostly influenced by the precipitation in the warmest quarter of the year and the annual precipitation contributing at least 40 °C and 27 °C respectively.

Trees presence points for *Ficus natalensis* and *Cordia africana* were obtained from literature and the Ecocrop database respectively.

The future changes in the areas suitable for the agroforestry trees were determined by replacing the current climate variables with the projected climate by 2030, 2050, and 2090 in the model. Using the suitability index overlaying methodology as described by Chemura (2020), we identified areas where the projected loss of coffee suitability assessed in Chapter 4.2 could be buffered by respective agroforestry trees under the two emission scenarios (SSP1-RCP2.6 low emissions scenario and SSP3-RCP7.0 high emissions scenario). The assessment follows the concept of the potential shift in the suitability of agroforestry trees which are thought as the high adaptation measure in coffee fields.

Results climate change impacts on the suitability of the tree species *Ficus natalensis* and *Cordia africana*

Before we can assess to potential of the selected tree species for buffering projected climate change impacts, we first need to understand where in Uganda they can grow and how their growth might be impacted by climate change. *Ficus natalensis* is currently suitable almost across the whole country, with the species being highly suitable in the central and south-western regions. The suitability of *Ficus natalensis* is expected to remain relatively stable throughout the century under both emissions scenarios, slightly expanding towards the Karamoja region. On the other hand, *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. This implies that coffee farmers within the Central and Western region who are currently using *Cordia africana* as a shading species should progressively shift to planting *Ficus natalensis* as a replacement of *Cordia africana*. Parts of Karamoja region are also expected to become unsuitable for this species. Both species will be suitable in the northern and eastern parts of the country by the end of the century. The modelled current and projected suitable areas of the two species are shown in Figure 3. The shift in areas where Cordia
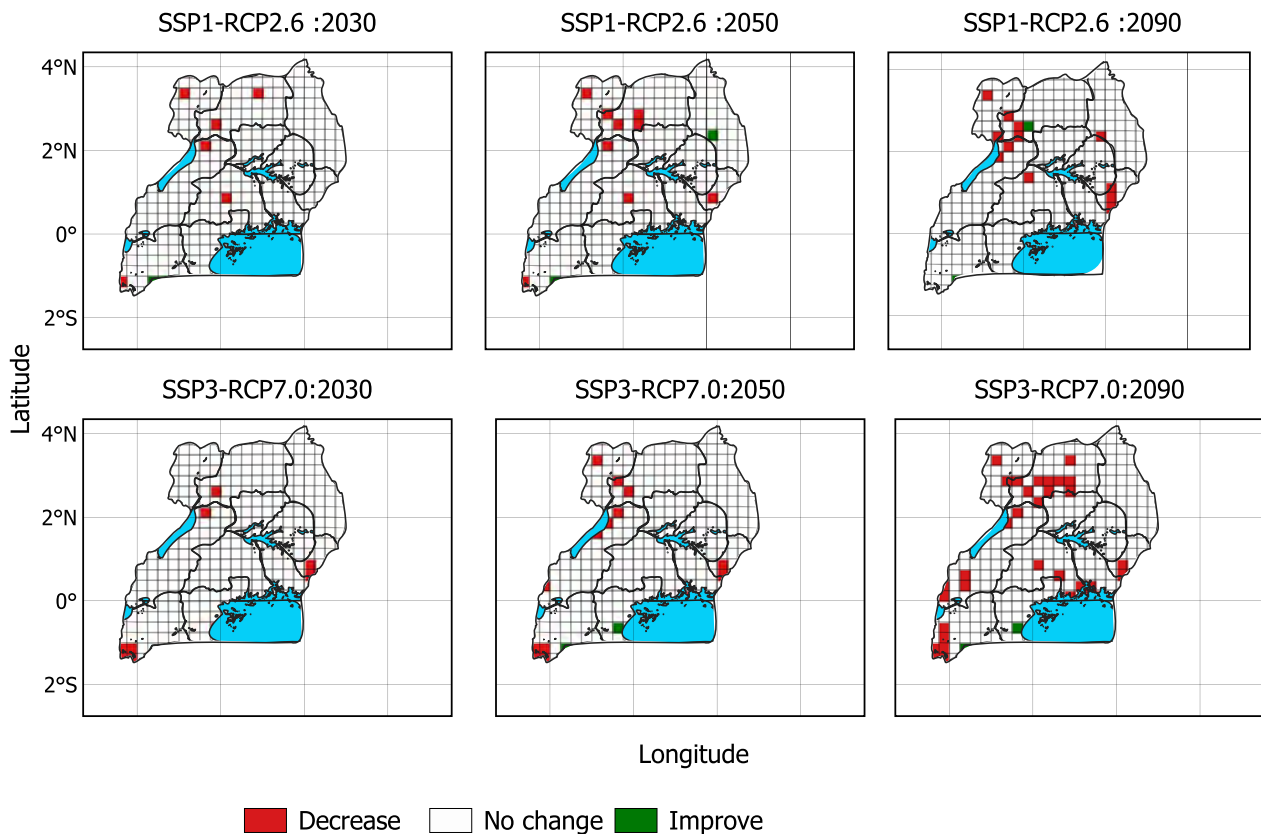
Figure 2: Projected changes in the suitability to grow Banana in 2030, 2050 and 2090 under two emissions scenarios (SSP1-RCP2.6 and SSP3-RCP7.0) at 0.25° grid level.

and *Ficus* can be grown for both the current and future emission scenarios is important to determine whether these species can buffer the projected effects of climate change in these areas.

Qualitative interviews with value chain actors

In April 2022, we conducted seven semi-structured interviews with a total of six actors along the coffee value chain including processors, aggregators, traders and roasters ranging from small-scale to large-scale businesses and covering all post-harvest steps of the 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 to process. The interviews were complemented with expert interviews and focus group discussions.

The interviews were conducted with the support of local research assistants either in English or in the interviewee's native language, recorded, translated when needed, transcribed and analysed in MaxQDA. Using abductive thematic analysis (Tavory & Timmermans, 2014) the transcripts were analysed with an initial coding scheme that was developed based on the IPCC (2014, 2021) climate risk framework, which defines climate risk as a function of hazard, exposure and vulnerability (see blue box. This helped to identify which climate risks are experienced by the interviewees at which stage of the value chain (blue info box below). The coding scheme was iteratively expanded by codes emerging during the analysis of the interviews, creating a comprehensive analysis framework for climate risks in coffee value chains. Two participating researchers were involved in the development of the coding scheme, including a researcher from Uganda. The final coding scheme was validated by both local and international experts on the topic and the results were cross-checked with data collected from expert interviews and focus group discussions with experts including local and international organisations and research institutes.

Cost-benefit analyses

1. Agroforestry

To identify the changes in market revenues and production costs associated with the introduction of agroforestry into coffee-banana intercropping systems:

- Establishment costs per tree for the agroforestry system were extrapolated to the system of thirty trees analysed in this CBA. Additionally, data has been adjusted for inflation to reflect current cost structures. The following cost elements have been included for the establishment of the agroforestry trees: Seed and stem cutting cost, labour cost, equipment cost (Amale, 2020).
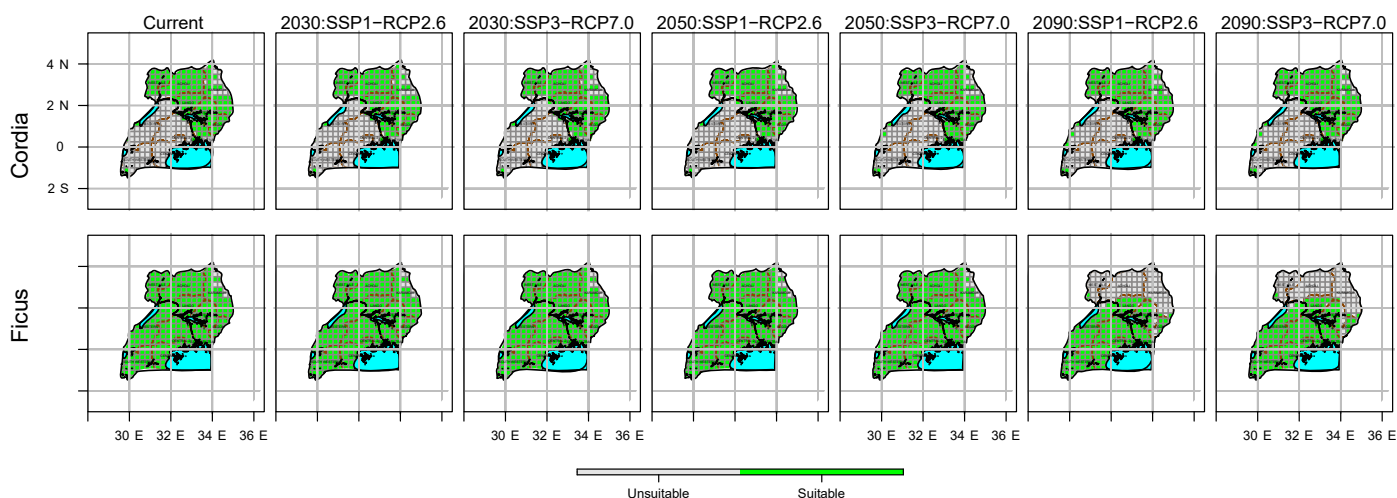
Figure 3: Modelled current and projected suitability at 0.25° grid level of Cordia africana (first row) and Ficus natalensis (second row) – the two dominant agroforestry tree species in coffee systems in Uganda.

- With respect to maintenance costs, no additional costs for weeding are assumed as this happens in the coffee-banana system anyway.
- Harvest costs were also adjusted for inflation. The harvested product are wooden poles which are often used for fencing. Even though harvests only occur every three years for both tree species, harvest costs have been annualized to achieve an equal distribution of costs for each year.
- Revenue is generated from the sale of wooden poles after each harvest. Lacking any price information on wooden products from *Cordia africana* and *Ficus natalensis*, we use price information of related tree species, i.e. for Eucalyptus and the Muzisi (Anguti et al., 2022; Held et al., 2010).
- Additionally, we assume that revenues increase by 2 °C per annum due to the increasing number of shoots after coppicing.

The following additional assumptions were taken into consideration for the cost benefit analysis on agroforestry:

- The model assumes that neither coffee nor banana plants must be removed to make space for the agroforestry trees. This is because shading trees are most often only planted along the edges of a given farm plot. Hence, no production loss from coffee and banana plants nor opportunity costs due to the introduction of the agroforestry trees are occurring.
- As consequence of the positive effects of agroforestry on coffee and banana yields, the model assumes no production losses due to climate change over time for the coffee-banana system with agroforestry (adaptation scenario). Instead, it is assumed that coffee and banana yields remain stable, because agroforestry offsets the negative climate change impacts. However, the full positive effect of shading is only assumed from the 7th year onwards. Before that, the effect

is only assumed to be partial. In the coffee-banana system without agroforestry (non-adaptation scenario) it is assumed that coffee and banana yields are declining over time due to changes in temperature and rainfall. For coffee, a yield reduction of 23 °C until 2050 is applied. This means a yearly reduction of 0.9 °C, based on the coffee yield declination of the last 20 years in Uganda (FAOSTAT, 2023). Due to lacking data on specific climate change induced impacts on banana yields, a similar reduction (of 20 °C) until 2050 is assumed.

- In the adaptation scenario, two different tree species, *Cordia africana* and *Ficus natalensis*, are introduced as agroforestry trees into a system of coffee and banana intercropping. Both trees provide several positive influencing factors for the intercropping system (please also see below for a discussion of additional co-benefits). Next to their positive effects on the agro-ecosystem, the wood from both trees is often used for construction purposes and as a fire and energy source in the form of fuel wood for cooking, heating or other relevant activities in the household. Especially the use of *Ficus* for poles (e.g. for fences) is widespread and creates additional income streams that have been monetarized for this analysis. Regarding timber as an additional income stream for farmers, it should be mentioned that *Cordia africana* can only be used for timber production at the age of 30 years. Since for this CBA market revenues are only extrapolated until 2050, this potential economic benefit is not within the timeframe of this analysis.[2]
- The two tree species are equally distributed across the production area. The spacing between trees is 60 feet by 60 feet (UCDA, 2019a, 2019b). This adds up to 30 trees per hectare – 15 trees of *Cordia africana*, 15 trees of *Ficus natalensis*. Hence, the number of seedlings needed to establish the agroforestry systems is 30.

2) Timber production as part of an agroforestry system bears additional challenges for the productivity of the main crop: First, there is a high risk of damaging surrounding coffee plants during the felling of trees, leading to potential negative impacts on the coffee yield. Second, growing Cordia africana for timber would mean letting the tree grow in the plantation until at least 30 years – which in turn might lead to overshading of the coffee plants and again to negative yield impacts.

- Based on Takaoka (2008), Bamwerinde (2013) and Philipos (2013) it is assumed that both trees grow at a pace of one meter per year. The first harvest for firewood and pole production occurs for *Ficus natalensis* after three years and for *Cordia africana* after seven years. From then on harvesting is done subsequently every third year for both species (Bamwerinde, 2013; Philipos, 2013). During harvest, trees are not completely cut down but coppiced, therefore the tree re-grows.
- To calculate the discount rate that is applied in the calculations, the exponential growth rate of the gross domestic product per capita of Uganda since 1970 has been used. The discount rate amounts to 4.1 °C (FAO, 2023).

2. Improved storage

The cost-benefit analysis for improved coffee storage is a model calculation based on cost and benefit data retrieved from literature and interviews. Where specific data was missing, assumptions complemented the necessary data set.

- The model calculation refers to the improvement of FAQ coffee storage on farm. The clean coffee is stored in bags until it is collected and sold for further processing. By replacing polypropylene bags with jute bags and putting them on pallets, it is assumed that the durability of coffee beans can be improved, and losses reduced.
- The associated investment costs were calculated as the price difference between gunny bags (11,000 UGX / bag) and polypropylene bags (1,500 UGX / bag) used in the status quo plus the costs for pallets (expert interview). To calculate the number of bags needed for the storage of one hectare coffee, we assume a filling quantity of 60 kg per bag. The number of pallets needed were determined by calculating with a storing capacity of 20 bags per pallet. It was further assumed that the gunny / sisal bags must be renewed every three years and the wooden pallets every five years.
- By switching from polypropylene to jute bags, the model assumes a postharvest loss reduction in FAQ Robusta coffee from 5 °C to 2.5 °C per season (expert interview).
- To monetize the benefits created with this investment, the revenues of the avoided post-harvest losses were calculated based on a Robusta baseline yield of 1,200 kg per hectare (ICO, 2019) and a price of 6,500 UGX per kg FAQ coffee (UCDA, 2023).

- To take into account the influence of climate change and technology progress on yields until 2050, it is assumed that Robusta yields benefit from a productivity increase due to autonomous technological change by 0.27 °C per annum. This is an extrapolation of coffee yield increases between 1961 and 2021 in the target region (FAO, 2023). This yield increase, however, is offset by a 0.9 °C yield declination due to climate change until 2050 based on coffee yields of the last 20 years in Uganda (FAO, 2023). In total, a decline in coffee yields of 0.63 °C per year until 2050 can be expected.
- To calculate the discount rate that is applied in the calculations, the exponential growth rate of the gross domestic product per capita of Uganda since 1970 has been used. The discount rate amounts to 4.1 °C (FAO, 2023).

Annex II Uncertainties

The results presented in this study are subject to a number of uncertainties and limitations, which have to be thoroughly considered for correct interpretation as well as for drawing policy implications and recommendations. This chapter presents and discusses the uncertainties attached to the different types of analyses in this study and highlights their relevance in the Ugandan context.

1. Climate models

Despite vast improvements in recent decades, climate models continue to display substantial uncertainties in simulating the current climate (Müller et al., 2021; Tebaldi & Knutti, 2007). To remove the biases in the climate simulations and make the models suitable for our crop analysis, climate data is statistically processed (bias-adjustment) with the help of observational climate data sets (in our case W5E5). This approach has critical limitations (Ehret et al., 2012; Maraun, 2016) as it adjusts the simulated data to fit to the observations without fixing the inability of the models to represent some physical processes of the earth's system. Nevertheless, this step is necessary and does not change the fact that realistic simulations of climate impacts can still be obtained (Chen et al., 2013; Teutschbein & Seibert, 2012). We analysed the performance of each climate model to represent the current climate to ensure that none of the models show strong biases. Working with a climate model ensemble can additionally reduce individual model biases. In addition, the observational climate data sets themselves are imperfect, especially in areas with few weather stations. The used data sets are based on re-analysis models, satellite observations and stationary data. Due to the low density of long-term, reliable stationary data in Western Africa, the data sets have strong biases, especially on a fine-gridded scale.

The analysis of future climate in this report is based on ten bias-adjusted GCMs produced under phase 3b of the ISIMIP project and is a sub-ensemble of the Coupled Model Intercomparison Project Phase 6 (CMIP6) used for the next IPCC report AR6.

Furthermore, future climate projections come with uncertainties, which can be seen in the diverging temperature and precipitation projections of different climate models. The GCMs project the same temperature trend over Africa, whereas precipitation projections show agreeing trends only in some regions (Niang et al., 2014). For general conclusions on future climate impacts, it is important to select models that cover the whole range of climate model outputs, namely applying models with wet and dry trends in precipitation projections (if applicable) as well as different magnitudes of projected temperature changes in the target region.

The diverging trends related to precipitation projections of the ten chosen models show similar patterns as the earlier used complete CMIP5 model ensemble (Niang et al., 2014) and thus we can assume that the models are suitable to cover the range of possible future precipitation in Uganda.

The ten models cover a wide range of climate sensitivity with equilibrium climate sensitivity (ECS) values of 1.53–5.41 °C (Nijsse et al., 2020). Nevertheless, the selection of models shows a bias towards higher ECS, with five out of ten models having an ECS higher than 4.5 °C, which is, according to various studies, very unlikely (Nijsse et al., 2020). This means that the displayed temperature increases from five models show unlikely high future temperatures under increasing greenhouse gas concentrations and also the multi model median will shows a bias towards warm future projections.

2. Crop models

Crop models are used to determine the share of weather-related variation in yields and to project impacts of changing climatic conditions on crop yields. Such analyses can support farmers in taking decisions related to yield stabilisation and crop yield improvement to cope with uncertain climatic conditions in the future. Crop models are widely used to project these impacts – beyond the observed range of yield and weather variability – of climate change on future yields (Ewert et al., 2015; Folberth et al., 2012; Rosenzweig et al., 2014). However, when employing crop models some limitations need to be considered. For instance, limited data availability may restrict model fitting, such as a lack of information on growing season dates, yields, land use allocation, intercropping or information on fertiliser application (Müller et al., 2016). Also, the quality of soil data contributes to uncertain yield assessments (Folberth et al., 2016). Fragmented and imprecise weather data from regions with few weather stations further increase uncertainty, especially if highly localised weather data is needed as it is for this district study. Moreover, the selection of climate scenario data adds another layer of uncertainty (Müller et al., 2021). There are certain disagreements between the different model types – statistical, machine learning and process based – (Schauberger et al., 2017), but however, these two model types in this case study have been used in past studies and are unlikely to be inapt in general.

3. Cost-benefit analysis

The cost-benefit analysis was conducted to evaluate the economic costs and benefits at the farm level of the four selected adaptation strategies. The CBAs considered a representative farmer by taking detailed household data on yields, costs and prices derived from survey samples. In addition, average yield and cost data were used to supplement and verify the household survey, as it is done in many standard CBAs. Such CBAs are, however, limited in terms of shedding light on the distribution of costs and benefits that an adaptation strategy may cause on a spectrum of farm groups, since an adaptation strategy may not necessarily affect all kinds of farm groups in the same way.

Assumptions regarding yields under climate change with and without adaptation were made based on crop yield simulations, which in turn were based on climate data predicted by climate models. Therefore, any uncertainty in climate models and crop models (see above) also translated into the analysis.

Uncertainty on assumptions with regard to future changes in prices and costs and the choice of the discount rate are further increasing the uncertainty of the CBA results. However, the assumptions made in our study are based on studies conducted in comparable socio-economic conditions of Uganda, different data sources were triangulated, and expert opinion sought. The results of the CBA should not be taken as definite outcomes to expect when implementing the adaptation strategies, but they can guide decision-making and provide case studies for adaptation scenarios.