Federal Ministry
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Potsdam Institute for
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Climate Risk Analysis for Identifying and Weighing Adaptation Strategies for the Agricultural Sector in Northern Ghana

– A Study at District Level in the Upper West Region –

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2021

A report prepared by the Potsdam Institute for Climate Impact Research (PIK) for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), in cooperation with the Ghanaian Ministry of Food and Agriculture (MoFA), the Department of Planning and Land Management at the University for Development Studies (UDS) in Wa, the Resilience Against Climate Change (REACH) project, the HFFA Research GmbH and other Ghanaian stakeholders from local and national governmental institutions, civil society, academia, the private sector, practitioners and development partners. The study "Climate Risk Analysis for Identifying and Weighing Adaptation Strategies for the Agricultural Sector in Northern Ghana - A Study at District Level in the Upper West Region -" builds upon the climate risk study for Ghana's agricultural sector at national level and both studies aim at contributing to Ghana's NDC implementation and to the objectives of the NDC Partnership.

Climate Risk Analysis for Identifying and Weighing Adaptation Strategies for the Agricultural Sector in Northern Ghana

- A Study at District Level in the Upper West Region -

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Authors' contributions:

Christoph Gornott and Paula Aschenbrenner 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 Paula Aschenbrenner designed the study approach with steering input from stakeholders. Paula Aschenbrenner and Francis Jarawura coordinated the stakeholder engagement process as well as the cooperation with REACH and conducted expert interviews. Paula Aschenbrenner performed the climate analysis in Chapter 1 and contributed to Chapters 2 - 10. Francis Jarawura contributed to Chapters 3 - 9. Abel Chemura analysed climate impacts on crop yields in the Upper West Region, leading on to Chapter 2 and contributing to Chapters 5 - 8 with biophysical adaptation assessments. Lemlem Habtemariam conducted the farm level cost-benefit analyses in Chapters 5, 7 and 8. Julia Tomalka contributed to Chapter 8. Sophia Lüttringhaus contributed to Chapter 5. All authors contributed to Chapter 3 on methods and Chapter 9 on uncertainties. Felicitas Röhrig, Lisa Murken and Julia Tomalka provided overall research support.

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Abstract

Rain-fed agriculture in West Africa is highly influenced by climate-related factors and increasingly by climate change impacts. While climate change impacts show substantial differences within West Africa, only limited information is available on subnational level to guide adaptation planning and allow farmers to adapt to the changing climate conditions. Therefore, science-based climate impact assessments on a regional scale coupled with information on suitable adaptation strategies for the agricultural sector are highly required. The aim of the study is to provide a comprehensive climate risk analysis that can guide adaptation planning in northern Ghana, focusing on three districts in the Upper West Region (UWR): Lawra, Sissala East and Wa West. The region was selected due to its high dependency on small-scale agricultural production, its high vulnerability due to unfavourable climatic conditions and historical structural disadvantages within Ghana. As a first step we quantified possible future climatic conditions with five general circulation models under one high emissions scenario (SSP5-RCP8.5) and one low emissions scenario (SSP1-RCP2.6). We compared the future yields of the four widely used crops maize, sorghum, groundnuts and cow peas using a process-based crop model. Based on the projected climate change impacts on the agricultural production for local conditions we analysed different adaptation strategies with regard to their feasibility, (cost-)effectiveness and suitability for local conditions. The adaptation strategies were suggested by stakeholders from Ghanaian local governmental institutions, civil society, academia, the private sector, practitioners and development partners. The selected strategies include the use of improved seeds, applied irrigation, and two agroforestry measures, namely alley cropping with cashew and Farmer Managed Natural Regeneration (FMNR). For a holistic analysis we applied a crop model and a farm level cost-benefit analysis complemented by extensive stakeholder engagement including two workshops, semi-structured expert interviews, and a literature-based assessment.

The results of the impact analysis show that the mean annual temperature is on the rise in the whole Upper West Region and is projected to increase further by approximately 1.1 - 1.9 °C until 2050 compared to 2005 dependent on future greenhouse gas emissions. Some uncertainty exists for precipitation projections, with increasing values of precipitation sums and heavy precipitation events being more likely. The impacts of these climatic changes on crop yields are mostly negative. Maize, sorghum and cow peas yields are projected to decrease with high certainty, whereas groundnuts yields are projected to remain almost the same with only slight positive or negative changes. The already higher vulnerability of farmers in the Upper West Region will thus most likely further increase in the future under climate change conditions. However, the actual climate risks that different groups face as well as their adaptive capacity is not only shaped by a changing climate but also by a wide range of intersecting socio-economic factors such as gender, age, social class and migrant status. These differential vulnerabilities of farmers are in detail assessed to develop policy recommendations that can benefit also the most vulnerable farmers.

All four adaptation strategies were found to be economically beneficial according to the applied cost-benefit analysis and can mitigate climate risks under a wide range of possible future climate conditions as shown by the crop model results. However, barriers and potential negative outcomes are highly dependent on the implemented adaptation strategy and are side-specific. The broad uptake of FMNR systems can be recommended for smallholder farmers, resulting in various positive effects for societies and environment. Irrigation facilities for dry-season irrigation of cash crops have a high potential to improve livelihoods but are also a complex, costly and support-intensive adaptation strategy and can therefore only be implemented in suitable regions. Cashew plantations intercropped with legumes were found to be highly economically beneficial when the whole value chain is used. The potentially high negative effects of extensive cashew plantations for the environment and societies need to be carefully assessed. Improved seeds have a large potential to increase yields, but more research and institutional support is needed to fully profit from their use.

Tenure security, access of farmers to credits, input, markets, decision-making processes and information were found to drive the implementation of adaptation strategies. Therefore, to improve the adaptive capacity of the whole community the focus must be on the people and groups that are to date structurally disadvantaged in accessing these.

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List of abbreviations

AFD	Agence Française de Développement
APSIM	Agricultural Production Systems Simulator
BMZ	German Federal Ministry for Economic Cooperation and Development
BCR	Benefit-Cost Ratio
CA	Conservation Agriculture
CBA	Cost-Benefit Analysis
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CORDEX	Coordinated Regional Climate Downscaling Experiment More
CORE	Coordinated Output for Regional Evaluations
CRU	Climate Research Unit of the University of East Anglia, Norwich
DCACT	District Centre for Agriculture, Commerce, Technology
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	Environmental Protection Agency
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
EU	European Union
EU GAP	EU Agriculture Development Programme
FAO	Food and Agriculture Organisation of the United Nations
FSD & WD of FC	Forestry Services Division and Wildlife Division of the Forestry Commission
GCM	General Circulation Model
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GLSS	Ghana Living Standards Survey
HFFA	Humboldt Forum for Food and Agriculture
IAM	Integrated Assessment Models
ICRAF	World Agroforestry Centre
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
IRR	Internal Rate of Return
MMEM	Multi-model ensemble median
MoFA	Ghanaian Ministry of Food and Agriculture
MTDPs	Medium-Term Development Plans
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NPV	Net Present Value

piControl	pre-industrial control run
PIK	Potsdam Institute for Climate Impact Research
RCM	Regional Climate Model
RCP	Representative concentration pathways
REACH	Resilience Against Climate Change Project
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathways
SWIM	Soil and Water Integrated Model
UDS	University for Development Studies, Wa
UWR	Upper West Region
WAM	West African Monsoon
WUA	Water Users Association

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Introduction

More and better climate information on a local scale is needed to support adaptation planning in northern Ghana.

While many countries increasingly recognise the importance of adaptation in a world of changing climate, guidance on how to operationalise adaptation goals is still little. As part of their international commitments such as under the Paris Agreement, countries seek to develop and implement adaptation policies and investment plans, for instance as part of their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). However, adaptation decisions often take place at the sub-national level, where decision-makers have to cope with a lack of locally specific data on current and projected climate risks and their impacts, as well as on costs and benefits of suitable adaptation strategies. The absence of climate information on a high spatial resolution is also especially problematic since climate impacts on crop yields may show high local variability. This calls for fine-grained climate risk analyses and assessments as a foundation of risk-informed and economically sound investment decisions at district level. A better understanding of projected climate impacts on agricultural production, associated climate risks and possible adaptation benefits on a regional scale is important to guide, incentivise and accelerate public and private sector investments for climate-resilient agricultural development.

This study assesses climate impacts on the agricultural sector in the Upper West Region and presents policy recommendations on the use of four different climate adaptation strategies.

This study seeks to deliver the base for risk-informed and economically sound adaptation decisions for the agricultural sector in the Upper West Region (UWR) in Ghana by providing information on climate impacts as well as recommendations on suitable and effective adaptation strategies. The UWR was selected due to its high dependency on small-scale agricultural production, its vulnerability due to unfavourable climatic conditions and historical structural disadvantages within Ghana. The study is carried out for three districts in the UWR, namely Lawra, Sissala East and Wa West, including an assessment of the up-scaling potential to other regions in northern Ghana. The three districts have been selected according to the accessibility to necessary research data and with the aim to cover the range of different environmental and social conditions within the UWR.

The Study Area

The UWR is one of 16 administrative regions in Ghana and is located in the north-western part of the country. It borders Burkina Faso in the north, Ivory Coast in the west, the newly created Savannah Region in the south, and the Upper East Region in the east (Figure 1).

The Guinea Savannah agro-ecological zone, which covers the UWR, is characterised by a single rainy season including high year-to-year variability in the amount of precipitation and onset of the rainy season. The annual precipitation total is about 1000 mm with most of the precipitation falling between May and September. The region's population is estimated to be 850 000 people for 2020 of which 84.7 % are living in rural areas (REACH, 2020).

The Ghana Living Standards Survey 7 (GLSS 2018) reveals that the UWR is the poorest region in the country, with a rate of 71 % of the population having income levels below the poverty line. Poverty in the region has been consistently higher than the national average since 2005/06 and is widely spread in its rural areas (Ghana Statistical Service, 2018). The high poverty rates partly emanate from unfavourable government agricultural policies stretching from deliberate colonial neglect in favour of the creation of labour reserves to the poor and uncoordinated agricultural policies and strategies of independence-era governments (Yaro, 2006; Van der Geest, 2011). The majority of the households (77 %) in the region rely on agriculture for their livelihoods. In rural areas, an even larger share of the population is mainly engaged in smallholder subsistence farming. Rural households in the UWR produce a large share for household consumption. The main crops cultivated are maize, groundnuts, sorghum, rice, yams, cow peas, bambara beans and soybeans (Ghana Statistical Service, 2013; Ghana Statistical Services, 2019). Farmers in northern Ghana depend largely on precipitation to water their crops as irrigation infrastructure is poorly developed. Less than 2 % of the land is under irrigation (Savannah Accelerated Development Authority (SADA), 2016), which limits most agricultural activities and at least 98 % of the cultivated area to the six-month rainy season.

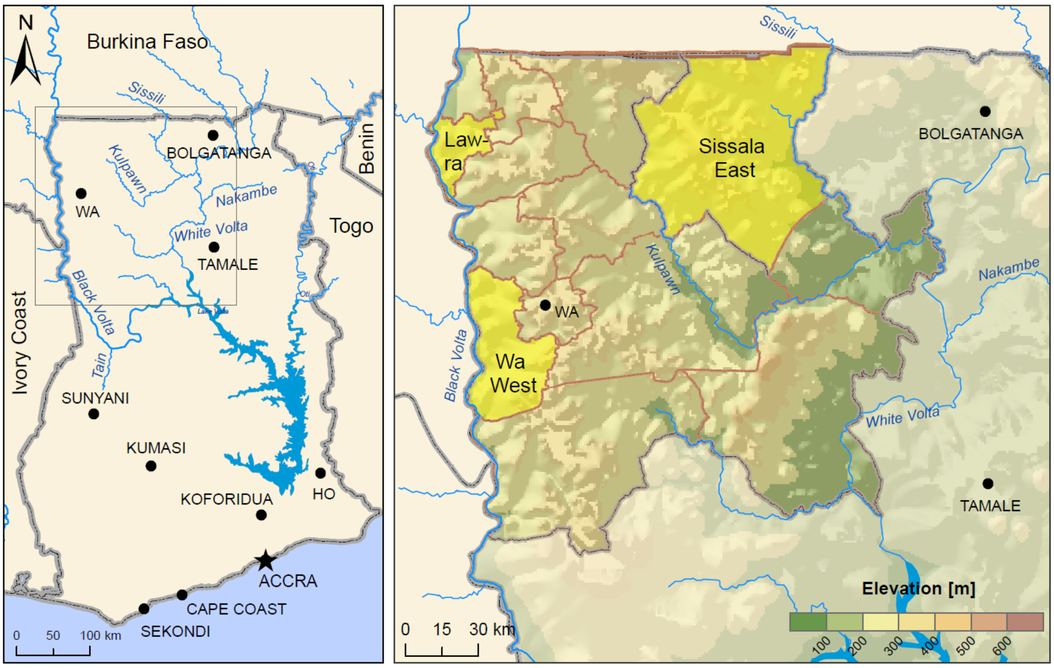


Figure 1: Left: Map of Ghana indicating the section displayed in the map on the right. Right: Topographical map of north-western Ghana including the three selected districts of the UWR.

In addition to the high poverty rates and the short rainy season compared to southern Ghana, deforestation, bush burning, and soil degradation pose further challenges to smallholder farmers in the region. Farmers face difficulties in devising and implementing effective adaptation strategies against droughts and floods. Furthermore, in the subsequent chapter it will be shown that future changing climatic conditions are likely to further increase the vulnerability of local farmers calling for planning robust climate adaptation.

High dependency on agriculture, unfavourable climate conditions, land degradation and additional pressure from climate change determine the high vulnerability of the UWR.

The Study Approach

The need for scientific evidence regarding climate change includes more information on climate impacts as well as accessible information on the costs and benefits of potential adaptation strategies. Consequently, the study combines a model-based climate impact assessment with an economic and a multi-criteria analysis to evaluate adaptation strategies under different emissions scenarios. We thereby consider one emissions scenario following strong mitigation being in line with the Paris Agreement (SSP1-RCP2.6), and one scenario without climate policy (SSP5-RCP8.5). In this way, the study results can inform key stakeholders on the district, regional and national level on how to scientifically underpin decision-making for climate change adaptation. Climate finance is often bound to detailed baseline information on climate impacts and subsequent adaptation strategies. Therefore, the study can serve as a support for stakeholders in their access to climate finance, which is crucial for implementing adaptation strategies. To ensure the sustainability and suitability of the study approach and to deliver tailored policy advice, Ghanaian stakeholders from local and national governmental institutions, civil society, academia, the private sector, practitioners and development partners were consulted and engaged from the outset. Furthermore, researchers from the University for Development Studies (UDS) in Wa were integral partners in designing and implementing the study, ensuring the local suitability and building up capacities in local universities. In order to promote the implementation and uptake of the study results, the Potsdam Institute for Climate Impact Research (PIK) closely collaborated with the ongoing development project Resilience Against Climate Change (REACH). REACH is jointly co-financed by the European Union (EU) and the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Within the project AGRICA - Climate risk analyses for identifying and weighing adaptation strategies in sub-Saharan Africa (AGRICA project), with the support of the GIZ and on behalf of the BMZ, PIK already conducted a study at the national level in Ghana. In close collaboration with the Ghanaian Ministry of Food and Agriculture (MoFA) a comprehensive Climate Risk Analysis for Ghana's Agricultural Sector at national level (Murken *et al.*, 2019) was developed in 2019. The findings and recommendations of the study informed national policy processes in the field of climate change adaptation and fed into Ghana's NDC Investment and Implementation Plan for the Agricultural Sector and the National Communications to the UNFCCC. During the stakeholder engagement of the climate risk analysis at national level, the need for climate information at sub-national level was raised to account for the fact that many adaptation decisions and the actual implementation take place at the sub-national level, where farmers and extension officers jointly test and implement different adaptation strategies. By integrating more fine-grained data sets into the analysis as well as engaging with relevant stakeholders at the regional and district level, this study aims at providing relevant recommendations on suitable and effective adaptation strategies at district level.

The adaptation strategies that were selected by local stakeholders and analysed in this district study are the use of improved seeds, applied irrigation, and two agroforestry measures, namely alley cropping with cashew and Farmer Managed Natural Regeneration (FMNR). The recommendations on the selected adaptation strategies can be directly used in political processes as well as ongoing and up-coming projects, including several project activities of the REACH project, such as curricula and training material.

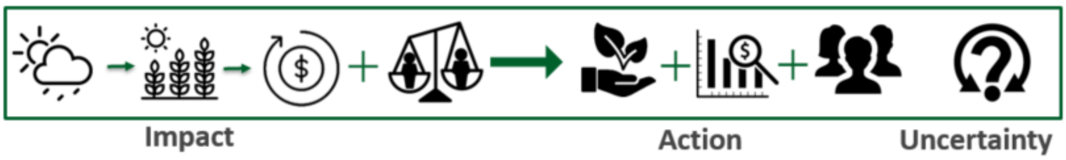


Figure 2: Study approach showing the impact-action-uncertainty chain applied in the study.

The study makes use of a diverse set of models based on impact modelling, data analyses, literature and local expert knowledge.

The study includes modelling the full impact chain from a changing climate (Chapter 1) to resulting impacts on crop production and subsequent economic consequences for the four widely used crops maize, sorghum, cow peas and groundnuts (Chapter 2) in the three selected districts. It includes socio-demographic variables such as gender, social class, district, and migration status to highlight the differential vulnerabilities and subsequent differential needs of groups in facing climate risks (Chapter 4). The results feed into an action dimension to assess different adaptation strategies with regard to their risk reduction potential, their cost-effectiveness, as well as other socio-economic evaluation criteria, such as stakeholder interest and development co-benefits (Chapters 5-8). Finally, the uncertainty attached to the results is critically discussed (Chapter 9) and recommendations targeting decision-makers are given (Chapter 10).

- Chapter 1 gives an overview of climate change in the last decades and projected future climate change impacts in the UWR, which are derived from global General Circulation Models (GCMs) and Regional Climate Models (RCMs) for one high and one low emissions scenario.
- Chapter 2 provides a comprehensive overview of climate change impacts on the agricultural sector in the UWR, ranging from the importance of weather influences on current crop yields to projected yields of maize, sorghum, cow peas and groundnuts under climate change.
- Chapter 3 presents the assessment framework and methodological approach for evaluating the suitability and effectiveness of different adaptation strategies under climate change in three districts in the UWR, Lawra, Sissala East and Wa West, spanning from biophysical, economic to societal assessment indicators. It further introduces the stakeholder engagement process and the collaboration with partners (UDS, REACH), who guided the study development.
- Chapter 4 introduces the concept of differential vulnerabilities meaning that the vulnerability of people and groups to climate risks is differently shaped by several socio-demographic variables like inter alia: social class, gender, migration status and age. This allows highlighting the different needs of people and groups in increasing their adaptive capacities.
- Chapters 5 to 8 assess the four selected adaptation strategies: Chapter 5 evaluates the use of improved seeds; Chapter 6 analyses the agroforestry measure Farmer Managed Natural Regeneration while chapter 7 discusses alley cropping with cashew and legumes and, Chapter 8 presents the assessment of irrigation.
- Chapter 9 discusses sources of uncertainty and presents limitations of the study to facilitate the interpretation of results.
- Chapter 10 concludes with a synthesis of the study results and gives policy recommendations. The results are meant to inform and support local and national government authorities, non-profit, and private sector stakeholders in prioritising and designing their adaptation investments to increase the resilience of smallholder farmers under climate change.

PART I - CLIMATE CHANGE IMPACTS

In the first part of this climate risk study, we look at the interplay between changing climatic conditions, water availability and agriculture in the UWR. The part aims to answer two main questions:

How will the climatic conditions change in the next decades? And how are these changes going to influence agricultural activities of smallholder farmers in the UWR?

Chapter 1 – Changing Climatic Conditions

This Chapter shows the climatic conditions farmers need to adapt to at present and in the future until 2090. First, climatic changes in the UWR during the last four decades are identified based on observational data sets. Next, we analyse in how far the identified current trends are projected to continue over the next decades using projections from global and regional climate models. We use two different greenhouse gas emissions scenarios, which cover the range of possible CO_2 emissions pathways: one low emissions scenario in line with the Paris Agreement (called SSP1-RCP2.6) and one high emissions scenario with continuously high greenhouse gas emissions (called SSP5-RCP8.5). The range of possible future climatic conditions derived from differences in the emissions scenarios and uncertainties in the climate models will set the base for adequate and feasible adaptation planning.

More and better climate information on a local scale is needed to support adaptation planning in northern Ghana.

Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs)

Figure 3: The SSPs of the IPCC guided scenario set (O'Neill et al., 2016).

The standard set of future scenarios, which will be used in the 6th Assessment Report of the IPCC (AR6) to be released in 2021, is based on a new set of emissions and land-use scenarios: pathways of societal development, the shared socioeconomic pathways (O'Neill *et al.*, 2017), linked with forcing levels of the representative concentration pathways (Eyring *et al.*, 2016; O'Neill *et al.*, 2016).

The SSPs comprise five alternative narratives that describe socioeconomic trends that shape future society. They include quantitative descriptions for key elements like population, economic growth and urbanisation (O'Neill *et al.*, 2016). SSP1 envisions an optimistic trend for human development with substantial investments in health, education, well-functioning institutions, and economic growth and, at the same time, a shift towards sustainable practices. SSP3, on the contrary, shows a pessimistic development trend with increasing inequalities and prioritisation of regional security (O'Neill *et al.*, 2016). To translate the socioeconomic conditions of the SSPs into possible greenhouse gas emissions trajectories, different integrated assessment models (IAMs) were employed (Hausfather, 2018). The IAMs project different emissions pathways for individual SSPs.

These different emissions pathways are grouped and represented by the seven representative concentration pathways (RCPs), which are defining a radiative forcing[1] achieved in 2100. The RCPs are labelled after the additional radiative forcing level reached in the year 2100 relative to pre-industrial times (+1.9, +2.6, +3.4, +4.5, +6.0, +7.0 and +8.5 W/m², respectively) (van Vuuren *et al.*, 2011; Wayne, 2013).

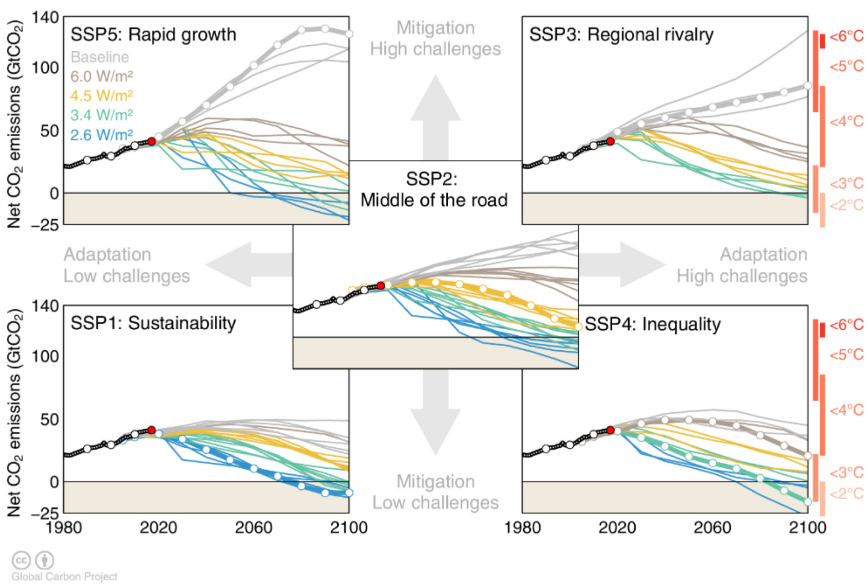


Figure 4: Global CO_2 emissions (GrCO_2) for all IAM runs in the SSP database. Chart produced by Global Carbon Project.

To show a wide range of possible future socioeconomic and emissions scenarios, this study includes the scenarios SSP1-RCP2.6 and SSP5-RCP8.5. SSP1-RCP2.6 pictures a sustainable future where global warming is likely to be well below 2 °C and is thereby in line with the Paris Agreement. SSP5-RCP8.5 depicts a fossil-fuelled development path in a world with no climate policy interventions and temperature increases of up to 6 °C until the end of this century. SSP5-RCP8.5 is the 'worst case' scenario and thus on the upper range of the 'business as usual' scenarios (van Vuuren *et al.*, 2011; Hausfather, 2018). These two scenarios used for five global General Circulation Models (GCMs) give us the frame of possible future climates that will be plausible.

[1] Radiative forcing describes a change in the radiative energy budget of the Earth's climate system due to an externally imposed perturbation. A positive forcing (more incoming energy) warms the system, while a negative forcing (more outgoing energy) cools it.

1.1 Data and Methods

Data

To analyse past temperature (T) and precipitation (pr) changes, we used the following four data sources:

1. Climate Research Unit (CRU) data is based on the analysis of over 4000 individual weather station records (Harris *et al.*, 2014).
2. Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) which incorporates satellite imagery with stationary data to create gridded precipitation time series (Funk *et al.*, 2014).
3. EWEMBI which is a data set based on simulations from global weather models combined with satellite data and weather station observations.
4. W5E5 which is a data set based on a combination of simulations from global weather models, satellite data and stationary observations (Lange, 2019b; Cucchi *et al.*, 2020). W5E5 was compiled to support the bias adjustment[2] of climate data, which drive the impact assessments carried out in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; Lange, 2019a, 2019b).

We used different data sources for the same climate variables to test the robustness of the results and cover different time frames and spatial resolutions.

Table 1: Specification of the observational data sets used. A resolution of 0.5 ° x 0.5 ° corresponds to appr. 56 km x 56 km in the UWR.

Dataset	Variable(s) used	Period	Frequency	Resolution
CRU 4.03	T, pr	1901 - 2018	monthly	0.5 ° x 0.5 °
CHIRPS	pr	1981 - 2018	daily	0.05 ° x 0.05 °
EWEMBI	T	1979 - 2016	daily	0.5 ° x 0.5 °
W5E5	T, pr	1979 - 2016	daily	0.5 ° x 0.5 °

We obtained climate projections simulated by five global General Circulation Models (GCMs) from ISIMIP3b. Historical simulations cover the time period 1850 - 2014 and projected simulations (under SSP1-RCP2.6 and SSP5-RCP8.5) cover the time period 2015 - 2100. To ensure that the model simulations are similar to the observed climate, ISIMIP3b was bias-adjusted and statistical downscaled with the observational reference data set W5E5. The five GCMs[3] included in the analysis are: GFDL-ESM4 (short: GFDL), IPSL-CM6A-LR (short: IPSL), MPI-ESM1-2-HR (short: MPI), MRI-ESM2-0 (short: MRI) and UKESM1-0-LL (short: UKE) (Lange, 2019a, 2019b).

To take the heterogeneous climate and climatic changes in West Africa into account and to obtain more fine-grained results, additionally, Regional Climate Models (RCMs) were used for the analysis. The RCMs used are models participating in the Coordinated Regional Climate Downscaling Experiment (CORDEX) and provide projections at a higher spatial resolution of 0.22 ° x 0.22 ° (approximately 22 km x 22 km at the equator). More specifically, the applied model ensemble is based on models from the CORDEX Coordinated Output for Regional Evaluations (CORE), a simulation framework which intends to provide an output that supports the IPCC AR6 assessments. The higher resolution of the RCMs compared to the GCMs allows for more fine-grained results relevant at district level. The six models in the CORDEX-CORE framework comprise the two RCMs REMO and RegCM that are downscaling the three GCMs HadGEM2-ES, NorESM and MPI-ESM for the two emissions scenarios SSP5-RCP8.5 and SSP1-RCP2.6. The RCMs of CORDEX-CORE are integrated continuously from January 1989 to December 2018.

[2] Climate models is only an approximate representation of the real-world climate. To remove biases in the climate simulations and thus make the models suitable for our crop model analysis, climate data is statistically processed (bias-adjustment) with the help of observational climate data sets. This brings the simulated climate close to the observed values but comes with its own limitations (compare Chapter 9 on uncertainties).

[3] An information box on global circulation models and their functioning can be found in the supplementary material.

Since CORDEX-CORE data is not bias-adjusted, it is not suitable for the analysis with crop models (Chapter 2). For reasons of consistency, we chose the bias-adjusted ISIMIP3b data as the primary data for the analysis of changing climatic conditions. To take advantage of the down-scaled and fine-grained CORDEX-CORE data, the regional climate model data is still used as secondary data and serves as validation of the results obtained from the GCMs of ISIMIP3b.

We use 4 different observational data sets to obtain information on the past climate conditions. For information on future climate trends, we use one global and one regional climate model ensemble.

Indicators

The indicators analysed in this study are: the annual mean air temperature, the number of very hot days per year (maximum temperature above 35 °C), the number of tropical nights per year (minimum temperature above 25 °C), the mean annual precipitation sum, the number of dry spells within the rainy season, the frequency and intensity of heavy precipitation events and the rainy season onset.

The indicator for heavy precipitation intensity is the maximum daily precipitation of a year. The indicator for heavy precipitation frequency is the number of days exceeding a threshold. The threshold is defined as the 95th percentile of days with precipitation (defined by days with more than 0.1 mm precipitation) during the baseline period 1995 - 2014 for each grid cell.

Dry spells were defined as 5 or 10 consecutive days without precipitation (defined by amounts smaller than 0.1 mm) during the rainy season between May to September.

Rainy season onset was obtained using a definition adapted from Laux, Kunstmann, & Bárdossy (2008) and Stern, Dennett, & Garbutt (1981), which was designed for West Africa, in particular northern Ghana and Burkina Faso. Rainy season onset is thus considered to be the first day of the year on which these three conditions are simultaneously met:

1. At least 20 mm precipitation within 5 days,
2. The starting day and at least two other days in this 5-day period are wet (defined as days with more than 0.1 mm precipitation),
3. No dry period of seven or more consecutive days within the next 30 days.

GCMs naturally show slightly different projections due to inherent insufficiencies in modelling the climate, even if they are driven with the same emissions scenario. Different projections indicate the range of uncertainty and multi-model ensemble median (MMEM), the median model values of a set of models, provide a conservative estimate of possible climatic changes. Thus, the MMEM is shown additionally to the individual model results. Within the report, climate change projection analyses are based on 20-year averages[4], meaning that the mean annual temperature in 2030, for instance, is calculated as an average over the mean temperature between 2021 and 2040. 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. For the analysis of observational data sets, the present climate was obtained by averaging over 1997 - 2016.

To quantify the influence of anthropogenic and natural factors on climate change in the past and near future, we compared the climate of a pre-industrial control run (piControl) over 120 years with historical simulations and SSP1-RCP2.6 as well as SSP5-RCP8.5 projections from ISIMIP3b data. The piControl run is a long-time scale simulation with no variations in external forcing, thus greenhouse gas concentration is set to pre-industrial level.

If not specified otherwise, the results display averages over the UWR: around 1 °W - 3 °W longitude and 9.5 °N – 11 °N latitude with slight variations depending on the grid size of the respective data set.

4 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.

1.2 Current Climatic Conditions

The climate in the UWR is dominated by high, tropical temperatures and variable precipitation (Figure 5). Agricultural production is largely determined by the course of the West African Monsoon (WAM) bringing precipitation to large parts of West Africa.

The West African Monsoon – a main influencing factor of the climate in the UWR

The atmospheric and oceanic processes influencing the WAM are complex and sensitive to external forcing. The WAM develops around March and brings precipitation from the ocean towards the inland, reaching the UWR in the beginning of April and lasting until the beginning of October. The WAM is mainly driven by the temperature difference between the ocean and the land surface in boreal summer[5]. High temperatures over the Sahara in boreal summer create a heat low, which drives the moist air from the Atlantic Ocean inland towards the Sahel[6] region and brings precipitation northwards until the temperatures over the Sahara cool down in boreal autumn. Thus, the energy source of the WAM terminates and the precipitation retreats. (Herzschuh *et al.*, 2014; Minka and Ayo, 2014).

At interannual timescales, the strength of the WAM is influenced by sea surface temperatures in the Atlantic Ocean and the Mediterranean as well as temperatures over the Sahara (Chauvin, Roehrig and Lafore, 2010; Schewe and Levermann, 2017a), land-use changes (Davin and de Noblet-Ducoudre, 2010; Kothe, Lüthi and Ahrens, 2014) and increases in freshwater content due to Greenland ice sheet melting (Defrance *et al.*, 2017) with pronounced impacts on the livelihoods in the UWR now and in the future. The changes in the complex dynamics of the WAM in recent decades have shown to lead to high multi-decadal variability of precipitation in the whole Sahel region and thus also in the UWR. This includes a severe drying of the extended Sahel region in the 70s and 80s. Studies have shown that this dry period is indirectly caused by the unique combination of aerosols and greenhouse gases that characterised the period after 1950 (Giannini and Kaplan, 2019). The multifaceted climate interactions also lead to uncertainties in the future projections of WAM development. The uncertainties are discussed in detail in the individual Chapters, and additionally in Chapter 9 on uncertainties.

The climate in northern Ghana is dominated by the West African Monsoon. The system is highly sensitive, leading to yearly varying precipitation amounts and uncertainty about future precipitation trends.

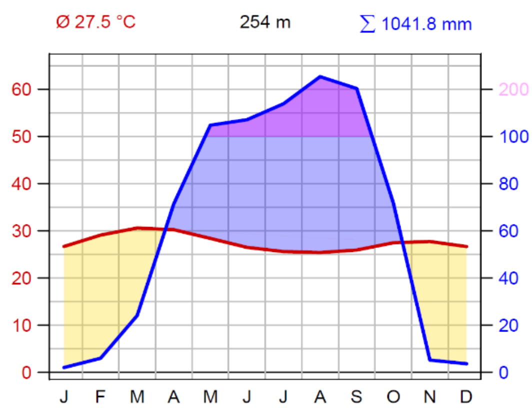


Figure 5: Climate diagram in the UWR at 12.25 °N and 2.25 °W based on W5E5 data. The red line indicates the mean monthly temperature and the blue line the monthly precipitation sum.

The WAM forms two seasons in the region. The dry season, lasting from October to March followed by the hottest period in March and April and the rainy season, from the beginning of April until the beginning of October (Figure 5). The mean annual precipitation sum is about 1000 mm per year with high year-to-year variability. The comparably short rainy season largely determines the agricultural season. Since the southern part of Ghana has two rainy seasons and higher annual precipitation sums, the north is even more vulnerable to extreme events or dry spells in the single rainy season.

The UWR has a mean annual temperature of around 28°C and a mean annual precipitation sum of 1000mm. Precipitations falls dominantly in the rainy season between April and October.

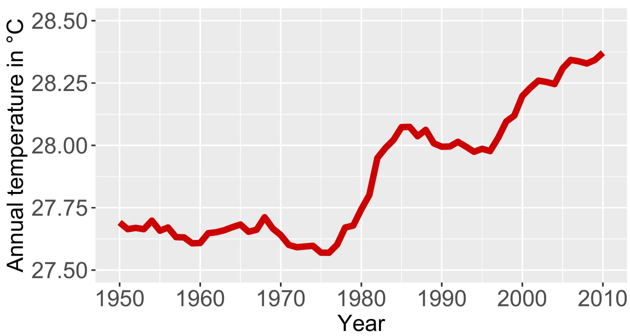
[5] Boreal refers to northern hemisphere; thus, boreal summer is the summer as defined from the perspective of the northern hemisphere.

[6] Sahel region in this report is referring to the region between 8 °N and the Sahara desert, to include the region which might be most affected by changes of the WAM.

The mean annual temperature is around 28 °C. Maximum daily temperature exceeds 35 °C on 160 days per year and thus shows slightly higher values than further south. Temperatures are especially high in March and April, after the Harmattand, a dry desert wind blowing from the north between December and March. Additional to slightly regionally varying climatic conditions, different land-use patterns create different microclimates within the UWR. However, the differences between single observational data sets are higher than the regional differences shown by the individual observational data sets. Thus, assertions of climate on very fine resolution carry high uncertainties. The results on climate in the UWR are in the following mainly displayed as averages over the UWR due to the high uncertainty associated with results on a smaller scale.

1.3 Climate Change and Variability in the Past and Near Future

Temperature



The mean annual temperature has increased with a steep rate of +0.15 °C per decade since the 1980s (Figure 6).

Temperatures and heat extremes are rising in the UWR. Mean annual temperature has increased by 0.15°C per decade since the 1980s.

Figure 6: The 21-year moving average of past mean annual temperature in the UWR based on CRU data.

Maximum daily temperatures have increased more than minimum daily temperatures. The number of very hot days exceeding maximum temperatures of 35 °C in a year has increased by 9 days per decade in the same time frame with current values of 160 days per year. The temperature range has become wider, thus the occurrence of very hot months has particularly increased (Figure 7).

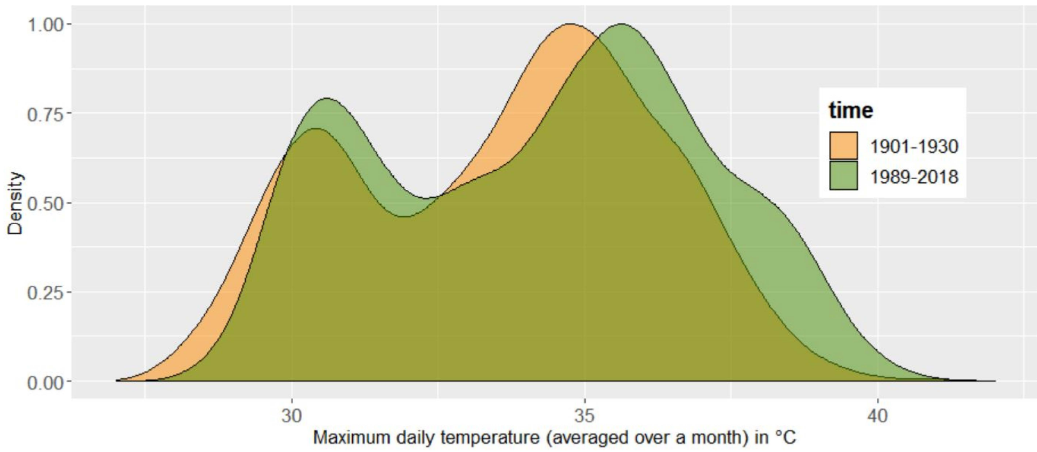


Figure 7: Distribution function of maximum monthly temperature. Results are based on CRU data averaged over the UWR from 1901 - 1930 and 1989 - 2018 respectively.

All the GCMs and RCMs project an increase in minimum, maximum and average daily temperature in the future with no regional differences within the UWR. Under the high emissions scenario there is a high model spread, especially since the MPI model projects only slight temperature increases (Figure 8). This is partially induced by the low climate sensitivity of this model compared to the other four and partially due to the high precipitation increase with a subsequent cooling effect that is projected by the same model.

Until 2050, the multi-model median (MMEM) indicates an increase in mean annual temperature of 1.9 °C under the high emissions scenario (SSP5-RCP8.5) and 1.1 °C under the low emissions scenario (SSP1-RCP2.6) compared to 2005. Especially after 2040, the models project different temperature increases for the different emissions scenarios (Figure 8).

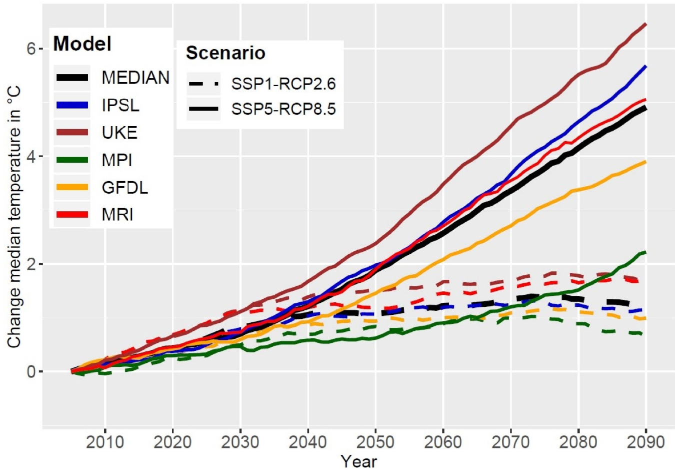


Figure 8: The 21-year moving average of the change in mean temperature in °C compared to 2005. Values are averages over the UWR. Each variegated line indicates a projection of an individual model. The black line displays the MMEM.

Potential evapotranspiration

Potential evapotranspiration[7] has also increased in the last three decades in line with the temperature trend and is further projected to increase, especially under the high emissions scenario. This can lead to increased water demand for irrigation if precipitation does not increase sufficiently.

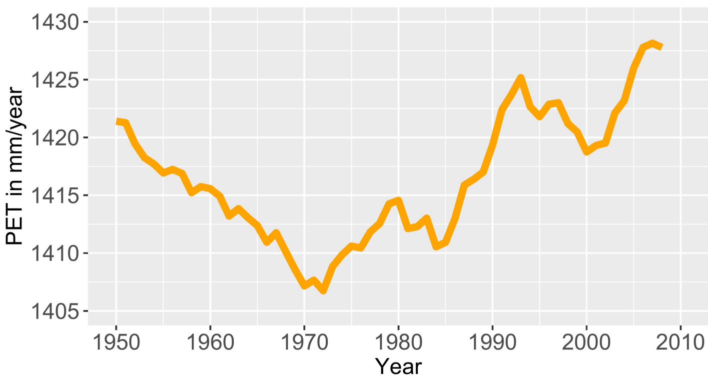


Figure 9: The 21-year moving average of potential evapotranspiration in the UWR based on CRU data.

[7] Potential evapotranspiration is the amount of evaporation that would occur if sufficient water sources would be available.

Precipitation

The amount of precipitation in northern Ghana is sensitive to land-use changes, changes in regional and global sea surface temperature, temperature changes in the Sahara and anthropogenic aerosol concentration (Biasutti and Giannini, 2006; Chauvin, Roehrig and Lafore, 2010; Schewe and Levermann, 2017b). Precipitation has decreased rapidly in the 1960s and 70s in northern Ghana (Figure 10). Giannini & Kaplan (2019) found that the drivers of the historical drying in the Sahel region and beyond were a combination of aerosols and greenhouse gases present in the atmosphere. This decline in precipitation amounts has only partially recovered in recent decades. Years with low precipitation sums combined with deforestation, the construction of new residential areas and unsustainable farming practices have led to increasing desertification. Around 35 % of the total landmass in Ghana has already become a desert area (Asante and Amuakwa-Mensah, 2014), a large part of it being located in northern Ghana. This loss of vegetation cover area and biodiversity is not only a greenhouse gas emissions source but also a loss of adaptive capacity for local communities and ecosystems.

Precipitation sums in the UWR are characterised by a high year-to-year variability. Precipitation amounts decreased rapidly in the 1960s and 70s and are slowly rising again since then.

Precipitation patterns in northern Ghana and beyond are characterised by high year-to-year variability. The different observational data sets do not show the same precipitation patterns in the UWR. Nevertheless, three out of four sets (e.g. CHIRPS, EWEMBI, W5E5) show slightly higher amounts of precipitation in the district Sissala East compared to the other regions.

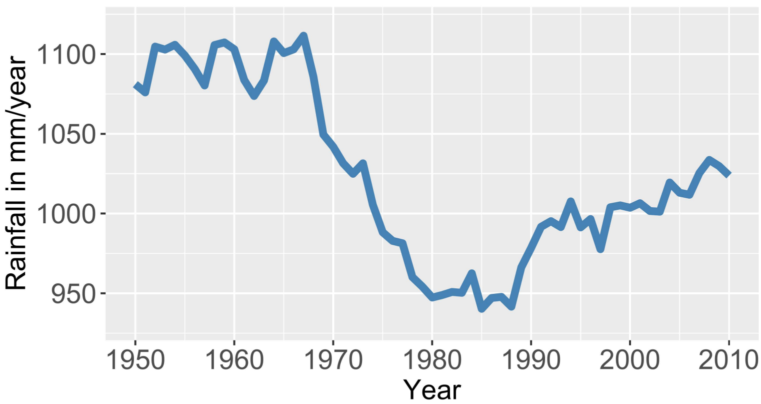


Figure 10: The 21-year moving average of mean annual precipitation in the UWR based on CRU data.

The past climate in northern Ghana has already shown to be highly sensitive to external forcing. Multi-model medians project a wetter future in the UWR, with four out of five models agreeing on this trend up to 2050. Nevertheless, the model projections show no consensus for projected precipitation amounts and indicate that a change in mean annual precipitation of -100 to +200 mm in the next three decades is possible in the UWR. After 2050, the model projections diverge more strongly. Overall, the regional variations of model projections within the UWR are small (Figure 11).

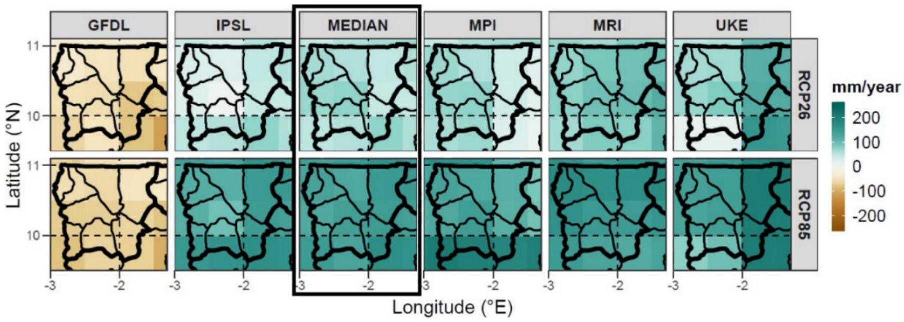


Figure 11: Projected change in annual precipitation sums in 2050 (2041 - 2060) compared to 2004 (1995 - 2014) under SSP1-RCP2.6 and SSP5-RCP8.5 for all five individual models and the MMEM.

Under the high emissions scenario, the range of possible future annual precipitation projected by the models is high, especially until the end of this century, whereby only slight changes in precipitation amounts are projected under the low emissions scenario. Thus, uncertainty about future water availability is higher under increasing greenhouse gas emissions (Figure 12).

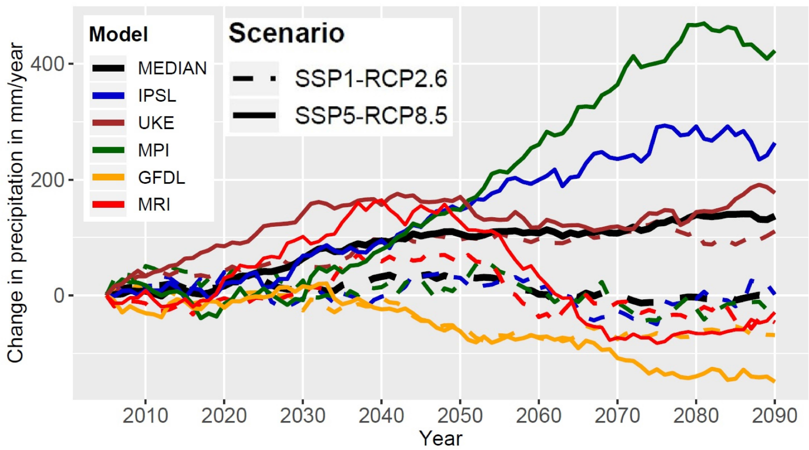


Figure 12: The 21-year moving average of projected change in mean annual precipitation sums compared to 2005. Values are averages over the UWR. Each variegated line indicates a projection of an individual model. The black line displays the MMEM.

The complex interactions between land, ocean, and atmosphere shaping the climate in the WAM region are not yet fully understood and captured by models, which can partially explain the disagreement between climate models. Most physical analyses of the climate system argue that the WAM is more likely to enhance with increasing emissions of greenhouse gases leading to increased precipitation sums in the UWR[8] (Roehrig *et al.*, 2013; Schewe and Levermann, 2017b; Aschenbrenner, 2018). On the contrary, a recent study by Defrance *et al.* (2017) found that the continuation of the rapid melting of the Greenland ice sheet could lead to a sudden weakening of the WAM[9]. This would outperform the strengthening of the WAM due to the above-mentioned processes.

The model projections of year to year variability of mean annual precipitation indicate continuous high variability.

8 Mainly due to two reasons: 1. Increasing sea surface temperature over the moisture source regions increases water availability for the WAM; 2. Temperature over land is rising faster than over oceans. This increases the temperature gradient between the Sahara and the Atlantic Ocean, which is the energy source for the WAM and thus brings more rain further inland.

9 High amounts of freshwater discharge due to Greenland ice sheet melting (of appr. 3 m sea level rise equivalent), can lead to a complex cascade of changing ocean circulations in regions where the sea surface temperature highly influences the WAM.

Heavy precipitation events

Results of a study by Derbile & Kasei (2012) realized in parts of northern Ghana show that heavy precipitation events often lead to low crop productivity. Observational data sets display annual maximum daily precipitation values between 50 mm and 120 mm depending on the region. A slight increase in heavy precipitation frequency and intensity[10] in the 2000s was observed with some spatial differences. Additionally, rising temperatures and land-use changes were shown to enforce runoff extremes (Yin *et al.*, 2018) and enhance the consequences of heavy precipitation events.

For the future, models project no significant change in heavy precipitation frequency and intensity under the low emissions scenario. Under the high emissions scenario an increase in heavy precipitation could arise as indicated by some models. Continuous land degradation could reinforce the impact of more intense extreme precipitation events (Figure 13).

Under future high greenhouse gas emissions, heavy precipitation events could occur more often. Further land degradation can reinforce the impacts of subsequent flood events.

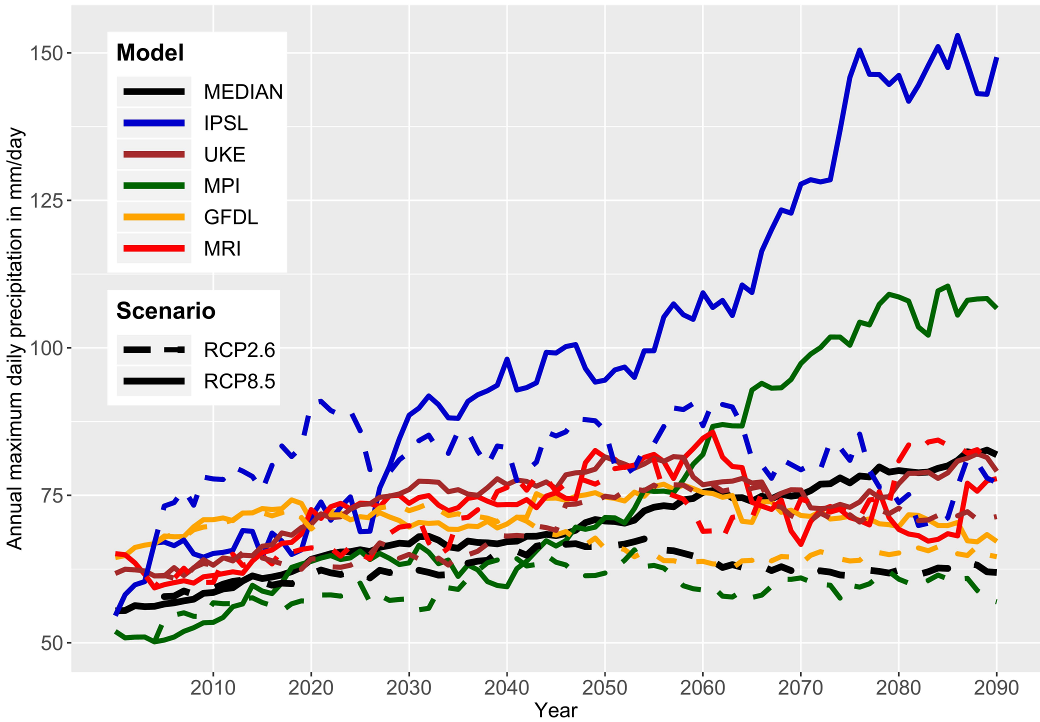


Figure 13: The 21-year moving average of heavy precipitation intensity – represented by the annual maximum daily precipitation in mm/day. Values are averages over the UWR. Each variegated line indicates a projection of an individual model. The black line displays the MMEM.

Rainy season onset

The rainy season onset day is highly variable from year to year in the UWR. Sufficient precipitation with no following dry period is important to start the crop season. Planting too early might lead to crop failure due to following dry spells, and in turn, planting too late might reduce valuable growing time. In the last three decades, the rainy season onset[11] started between 20th of March and end of May, depending on the location and year, with some exceptional years of reliable precipitation amounts only arriving in June. The rainy season starts later the further north one is within Ghana. Among the three study districts, Lawra showed the latest rainy season onset.

[10] As defined in methods in Chapter 1.1.

[11] As defined in methods in Chapter 1.1.

Future rainy season onset is projected to be continuously variable with no consistent trend for later or earlier onset shown by the models. Under the high emissions scenario, the MMEM projects a slightly earlier rainy season onset and a slightly later onset is projected under the low emissions scenario (Figure 14).

Current and future rainy season onsets vary from year-to-year.

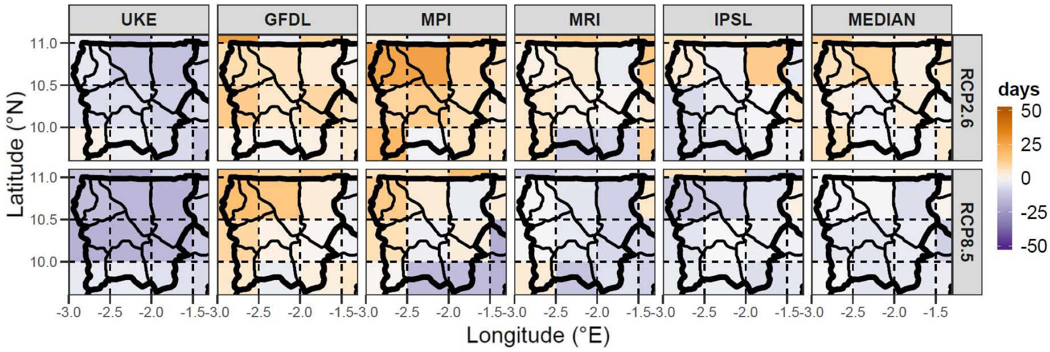


Figure 14: Projected change in rainy season onset in 2050 (2041 - 2060) compared to 2004 (1995 - 2014) under SSP1-RCP2.6 (upper row) and SSP5-RCP8.5 (lower row) for all five individual models and the MMEM. Values above 0 (orange) indicate a future later rainy season onset and values below 0 (purple) indicate an earlier future onset.

Dry spells within the rainy season

Dry spells occurring within the growing season can negatively impact the crop yield, especially when occurring early after planting or during the flowering period.

After decades of drought in the 60s - 70s, the number of dry spells of a period of 5 days occurring during the rainy season has slightly decreased, while the number of days with precipitation events between March and October has increased.

The MMEM of future projections of the number of dry spells within the rainy season from May to September shows no clear trend (Figure 15). The model spread is large and most individual models are not capable of reproducing the number of dry spells correctly for the current climate. Thus, the future projections of dry spells do not allow a robust conclusion on the trend.

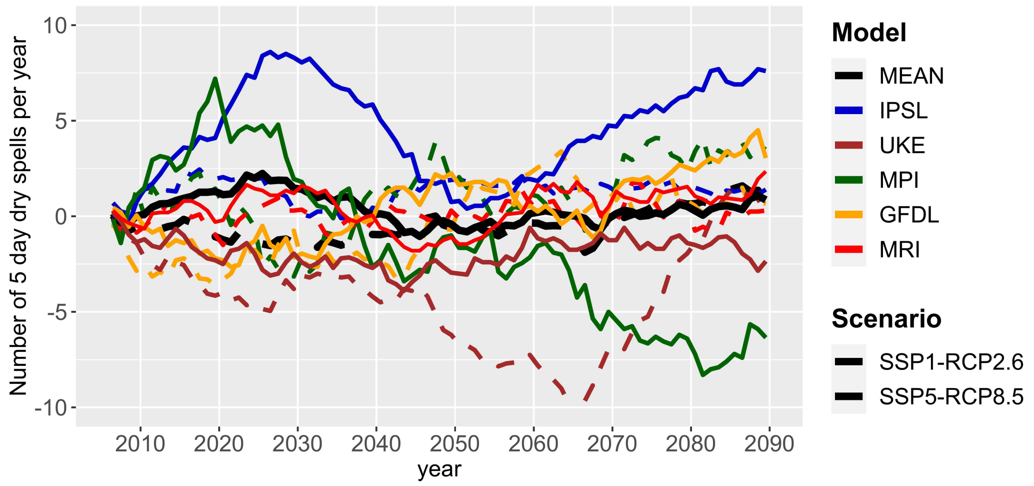


Figure 15: The 21-year running mean of change in the number of 5 consecutive dry days (<0.1 mm) during the rainy season between May and September.

Trends of Regional and Global General Circulation Models

The global climate model ensemble (ISIMIP3b) and the regional climate model ensemble (CORDEX-CORE) show similar possible future climatic conditions in the UWR. The CORDEX-CORE ensemble shows a wider range of future precipitation under both scenarios, including a model that shows a drier future under both scenarios. Neither the CORDEX-CORE nor the ISIMIP3b data can provide reliable information on varying trends between the different districts of the UWR, since the inter-model differences are by several magnitudes higher than inter-district differences projected by the models.

Neither the analysed Global nor Regional Climate Model projections allow for differentiated results of the individual districts.

1.4 Natural and Human Influence on the Climate

Quantifying the attribution of climate change on current and future climate-induced crop yield losses can help to show the necessity and benefit of climate adaptation in the agricultural sector. Climate Change specific funding might be leveraged and strategic long-term decisions in the agricultural sector made accordingly. As the first step in this process, we look at the difference between a climate under anthropogenic global warming and a climate under pre-industrial forcing. The difference of mean annual precipitation sums and temperature simulated by the five ISIMIP3b GCMs in a world of current forcing compared to one of pre-industrial forcing is displayed in this sub-Chapter. While the current forcing levels contain natural and anthropogenic influences, the anthropogenic factor is very likely of several magnitudes higher than the change due to natural forcing (Rosenzweig *et al.*, 2008; IPCC, 2014). Thus, we can assume that the differences simulated by the models and displayed in the following graphs are to a large extent driven by anthropogenic greenhouse gases and aerosol emissions.

The models agree on a clear attribution of current anthropogenic and natural forcing on temperature and to some extent on precipitation values. Indicated by the MMEM, the climate with pre-industrial forcing would be now 1.6 °C (model range: 0.8 - 2.3 °C) colder in the UWR. This is well in line with the reconstructed temperature increase that has happened since 1860. For the future, the difference between the piControl and the projection data for temperature is further increasing with continuous rises after 2050 for the high emissions scenario. The attribution of current forcing to annual precipitation amounts varies over time and is not consistent for all models. For the recent past, the MMEM indicates that the UWR would experience similar amounts of precipitation under pre-industrial forcing while it will be wetter under the future forcing compared to the pre-industrial forcing (Figure 16). This is in line with literature which points at a likely wetting of the central extended Sahel region with increasing greenhouse gas concentration until the mid of this century (Roehrig *et al.*, 2013; Schewe and Levermann, 2017b; Aschenbrenner, 2018).

Temperature changes can be clearly attributed to anthropogenic activity.

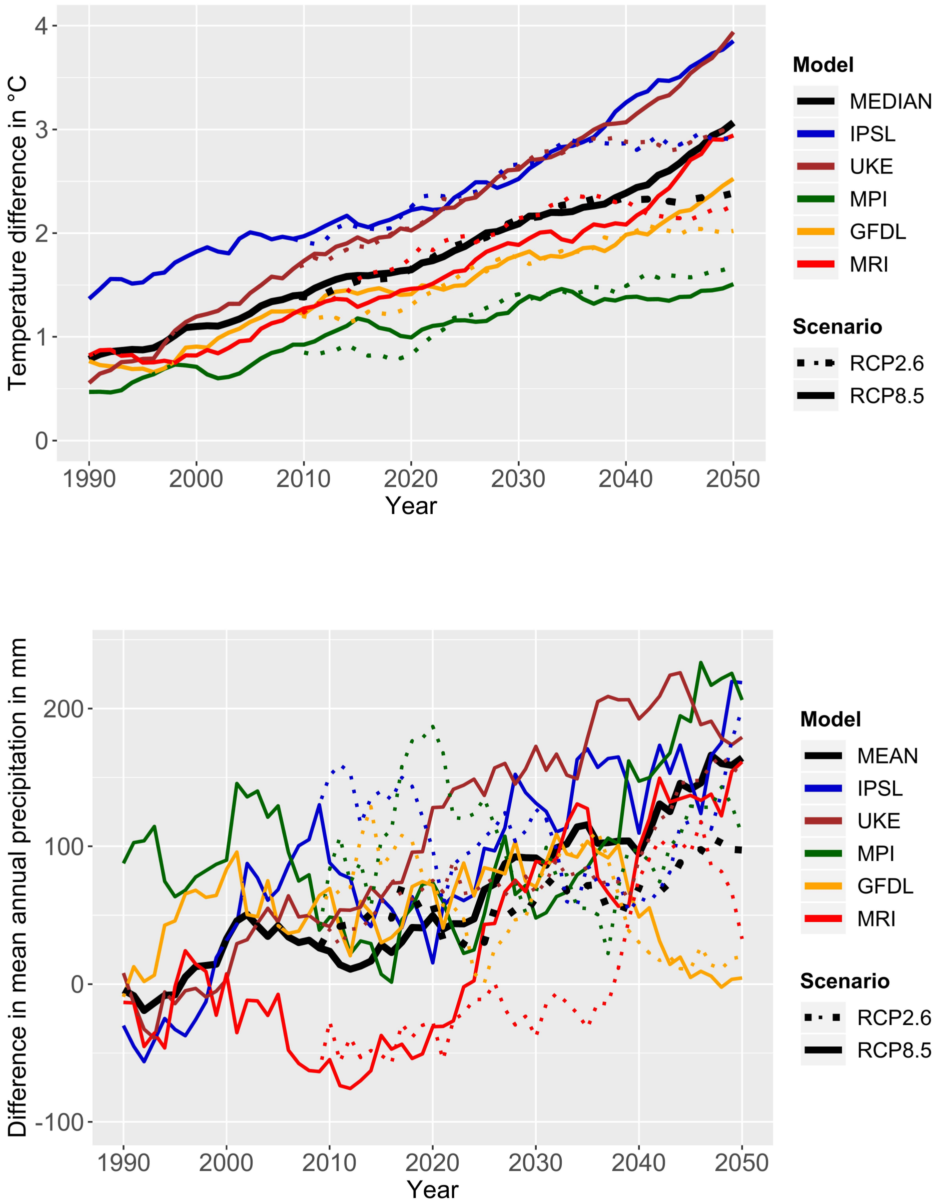


Figure 16: 11-year moving average of the difference between pre-industrial ISIMIP simulations and historical ISIMIP simulations combined with future ISIMIP projections of temperature (left) and mean annual precipitation (right).

The models do not show a consistent message on the frequency and intensity of heavy precipitation events now compared to pre-industrial conditions (17). While three models simulate that there would be more and stronger heavy precipitation events under pre-industrial forcing, two models simulate the opposite. Thus, no conclusion can be drawn if heavy precipitation events have increased until now in the UWR due to changes in external forcing.

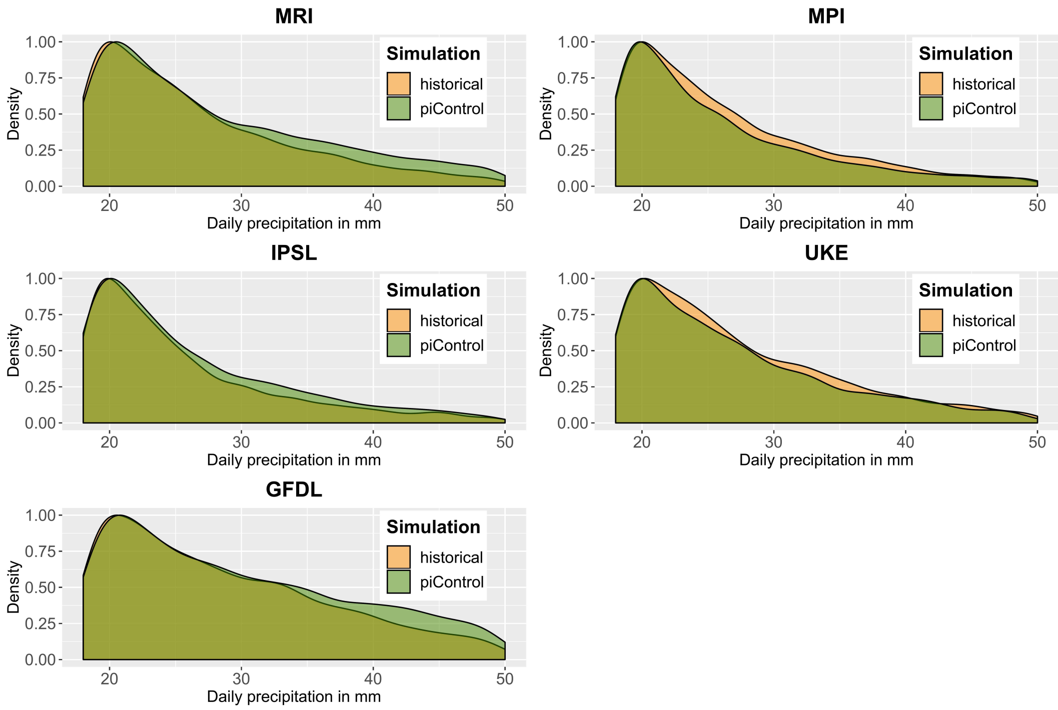


Figure 17: Distribution function of daily precipitation above 18 mm (high precipitation events). Results are based on the five ISI-MIP3b historical simulations compared to piControl runs from 1995 - 2014.

Summary Chapter 1

In addition to natural variability, the climate in the UWR showed a clear changing trend in recent decades, whereby the results point at the large contribution of anthropogenic activity driving this change. Future projections mainly show a continuation of the existing trends. With very high certainty mean annual temperatures, the number of very hot days as well as tropical nights are increasing. With less certainty, heavy precipitation events and mean annual precipitation sums are projected to increase under the high emissions scenario and remain stable under the low emissions scenario. The projections related to temperature are robust since the trend is consistent for all models and emissions scenarios, while this is not the case for projections related to precipitation. For higher future emissions, the projections show stronger climate changes and higher ranges of possible future climate. Due to the uncertainties related to the projections and the coarse resolution of the climate models, no differences of the projections between districts of the UWR can be identified.

Climate Impact	Trend past	Trend[12] future	Certainty[13]
Mean annual temperature	Increasing	Increasing	Very high
Number of very hot days & tropical nights	Increasing	Increasing	Very high
Heavy precipitation intensity & frequency	Increasing[14]	RCP8.5: Increasing	Low
		RCP2.6: No trend	High
Mean annual precipitation sums	No trend	RCP8.5: Increasing	Low
		RCP2.6: No trend	High
Rainy season onset	No trend	No trend	High
Number of dry spells within rainy season	No trend	No trend	Medium
Year to year variability of annual precipitation sums	No trend	No trend	Low

[12] 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 - 2100 under the respective emissions scenario in the future. If at least 40 % of the models show a significant trend in the same direction, we speak of a trend with a specific uncertainty level (see next foot note).

[13] 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.

[14] Heavy rainfall intensity has increased significantly, while heavy rainfall frequency has increased, but not significantly.

Chapter 2 – Climate Impacts on Agricultural Production

Most of the crops in the UWR are produced by smallholder farmers with low input use and no irrigation facilities.

In the UWR, the majority of the population are smallholder farmers, depending largely on rain-fed crop cultivation. About 95 % of households are engaged in crop farming and 63.7 % are additionally engaged in livestock rearing. Maize, groundnuts, sorghum, rice, yams, cow peas, bambara beans and soybeans are cultivated by a high proportion of farmers (Ghana Statistical Service, 2013; Ghana Statistical Services, 2019).

The high year-to-year variability in precipitation amounts and the onset of the rainy season as well as high impacts of extreme events on crop growth are significant influencing factors for crop yields. Besides weather factors, other drivers of crop yield in the UWR are soil fertility, seed types or the use of external inputs. The latter is often very limited, whereas the use of rudimentary equipment is common. Degraded land and subsequent infertile soils constitute the main challenge for local farmers. Furthermore, diseases and pests, especially the fall armyworm and variegated grasshoppers, are additional prevalent challenges for the crop production in northern Ghana. These challenges, combined with deficient management practices, can serve as an explanation for the high yield gap which is present across the country. For instance, while the potential yield of maize in northern Ghana is 3.28 t/acre, actual yield is only on average 0.53 t/acre resulting in a yield gap of 2.75 t/acre or 84 % (Global Yield Gap Atlas, 2020). Within the study region, the yield gap in Wa West and Lawra is larger than in Sissala East.

Variable precipitation amounts, pests and diseases, infertile soil on degraded land and deficient management practices limit crop yields in the UWR.

In this Chapter, we analyse climate impacts on crop production. At first, we assess the share of crop yield variation that is caused by variance in weather or other factors based on literature and data analysis. Building upon this, we analyse future impacts of climate change on crop suitability and crop yields with machine learning techniques and a process-based model.

2.1 Methods

To understand the impacts of climate change on crop production, two different models were employed: machine-learning ensemble crop suitability models and the process-based crop model APSIM (Agricultural Production Systems sIMulator) (Holzworth *et al.*, 2014).

Crop suitability assessments are based on the understanding that the biophysical parameters (e.g. soil organic carbon) and climatic variables (e.g. total amount of precipitation received in the growing season) play an important role in determining crop production. A suitability model, therefore, uses these variables to create a score for each crop, each period and each location depending on how the variables meet the crop requirements or conditions in known current production areas (Evangelista, Young and Burnett, 2013). Replacing the climatic variables with those projected under climate change shows the change in the potentially cultivatable arable land of an area for a specific crop. The suitability models identify the areas where adaptation measures are mostly required in order to avert the consequences of a predicted decline in climatic suitability of crops. We used machine-learning ensemble crop suitability modelling to evaluate the suitability of maize, sorghum, groundnuts and cow peas. Nine agronomically important biophysical parameters[15] are used in modelling the climatic suitability of the four crops under current and future climatic conditions. The eXtreme Gradient Boosting (XGBoost) machine learning approach (Chen and Guestrin, 2016) is used to model suitability. The crop production data for each of the four crops is split into four groups (optimal, moderate, marginal and limited) using percentiles of the average yield. For example, areas with optimal suitability are defined as areas that are above the 75th percentile of the long-term average crop yield, representing areas with no significant limitations to sustained production and stability over time. Moderate suitability corresponds to areas allowing for crop production within the 50th to 75th yield percentile, marginal suitability to the 25th to 50th yield percentile, and limited suitability to areas with less than the 25th percentile of long-term average yield, thus indicating that the biophysical conditions in these areas are not apt for the crop under analysis. To determine the climatic suitability for the cultivation of the four key food crops, we combined the suitability of the crops to understand which areas are suitable for which multiple crops and to what degree using the method by Chemura, Schauberger, & Gornott (2020). In this approach, the individual suitability maps are stacked to determine the number of crops that were suitable for each cell before counting the cells with the levels of suitability for each crop. Changes in suitability proportion and distribution between the current and the projected climatic conditions were assessed by comparing areas between times and emissions scenarios.

To understand long-term climate change impacts on crop yields and to test different adaptation strategies, we apply the process-based crop production simulator APSIM. APSIM simulates the plant growth on a daily time step in response to daily input of weather data (CHIRPS for precipitation and EWEMBI for temperature[16]), soil characteristics (ISRIC Grids for soil profiles[17]) and crop management actions (from field survey data, published papers and national agricultural survey reports). Planting windows, seed varieties, planting density and nitrogen fertiliser rates were the key management inputs that varied for each district. The simulated crop planting date was chosen at the point when sufficient first rain in a planting window has fallen.

To determine yield changes under climate change, projected climate data from the ISIMIP project[18] was used. The projected weather data from 1 January 2041 to 31 December 2060 for SSP1-RCP2.6 and SSP5-RCP8.5 from the five GCMs of ISIMIP was applied and averaged to obtain projected values for the year 2050. The yield changes that are attributable to the projected climatic changes and described in the following are modelled without CO_2 fertilisation effect as the effect on yields is not yet fully clear and would add a lot of uncertainty to the projections.

> With the help of a process-based model, future yields of four major staple crops, maize, sorghum, groundnuts and cow peas, were analysed.

The crops maize, sorghum, groundnuts and cow peas were analysed focusing on the three districts Lawra, Sissala East and Wa West. The four crops were chosen based on their high use in the UWR, the interest of stakeholders, and their suitability for the crop-model analysis. We chose exemplary varieties of the four food crops that are integrated into APSIM and similar to typically used varieties for northern Ghana. Crop yield data to calibrate the crop models were obtained from the Ministry of Food and Agriculture's statistics department, which is a government institution that is responsible for collecting and compiling official agricultural statistics in Ghana. Crop yields for the four crops are reported in metric tons per hectare. This is the ratio of total production per year in a district divided by total land cultivated for that specific crop in that district and year. Although yield data was available for a longer period, much of the management data was only available for 2015 and, therefore, for purposes of model evaluation only the data from 2014 to 2016 was used.

15 The nine parameters were: 1) Total precipitation in the growing season; 2) Total precipitation between March and September; 3) Sum of precipitation in the crop sowing month; 4) Precipitation coefficient of variation; 5) Diurnal temperature range between March and September; 6) Mean temperature growing season; 7) Mean temperature between March and September; 8) Top soil organic carbon content; 9) Top soil organic carbon content in September

16 Details on the data sets are described in Chapter 1.1.

17 Global gridded soil information based on compilations of soil profile data and environmental lay ers

18 Details on the ISIMIP data is described in Chapter 1.1.

The results of the APSIM model performance are shown in Figure 18, where the measured yields are compared with the simulated yields. Considering the uncertainty related to the crop yield data, overall, the model performance for all crops for each district was satisfactory for the evaluation period as the index of agreement (d) between the measured and simulated yield is above 0.5, despite the overestimation of yield. Consequently, we applied the model with certainty in yield assessment and climatic change impact assessments.

As shown in the previous sub-Chapter, management decisions have a high influence on crop yield. As listed above, farmers in the UWR have different potentials of improving their management. To account for these different capacities in the crop model, we introduced three different types of farmers. Farmer A has limited access to fertiliser, applies manure, has the lowest planting density and uses a chisel for tillage. Farmer B is the "average" farmer having some amount of fertiliser, applies manure, has a medium planting density and uses a blade for tillage. Farmer C has good access to input and technology, resulting in a high amount of fertiliser, no application of manure, a disc plough for tillage and a higher planting density. A table with the exact parameters for each farmer for APSIM is found in the supplementary material.

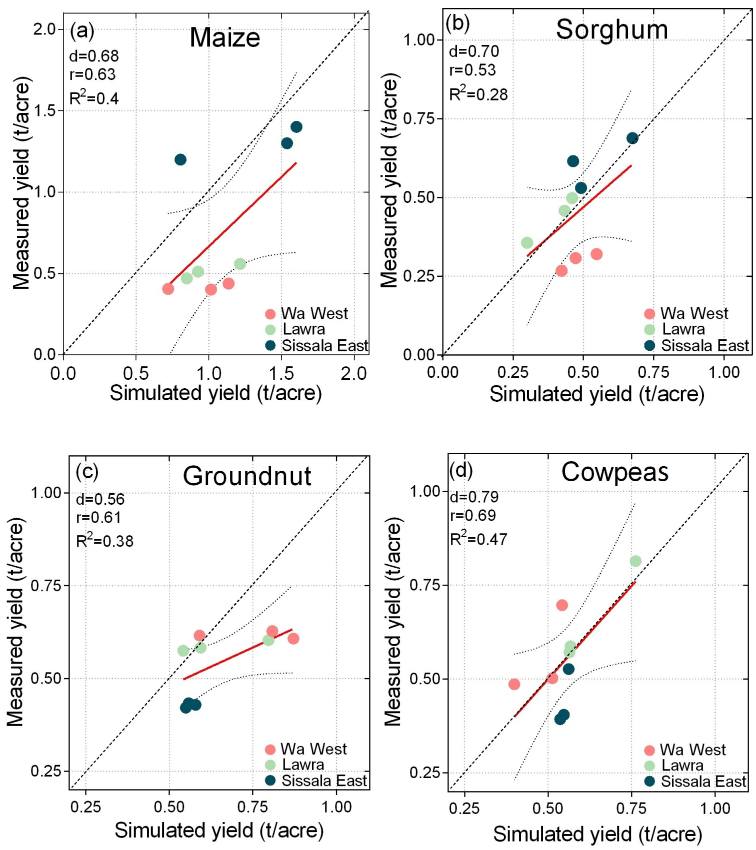


Figure 18: Simulated versus measured yield for the three districts in northern Ghana for (a) maize, (b) sorghum, (c) groundnuts and (d) cow peas between 2014 and 2016. The red line is the regression fit and the dotted line are the 95 % confidence limits.

2.2 Crop Characteristics and Weather Influence on Crop Production

Depending on the climate sensitivity of each crop, the crop yield is affected differently by extreme events and changes in precipitation and temperature. In the following, some key biophysical characteristics of the selected crops are provided based on information from FAO (2011), which are relevant for their performance under changing climatic conditions:

Cow peas:

Cow peas are an annual legume that is adapted to a semi-arid and hot climate and grows on sandy soils. The crop takes between 110 and 130 days to mature and is widely grown in sub-Saharan Africa, including in West, Central and East Africa. The photosynthetic pathway for cow peas is C3. In Northern Ghana, cow peas are an important local food crop as very little of it is sold but mainly consumed locally or given as gifts. At national level, cow peas are the second most common legume crop after groundnuts. In many households, cow peas are planted as an intercrop or on the edges of fields. Sowing is timed such that harvesting would coincide with the end of the rains so that moisture does not destroy the pods. Smallholder farmers occasionally also harvest tender cow pea leaves as a vegetable. The use of inputs and advanced machinery for the cow peas production is very limited in Ghana.

Groundnuts:

Groundnuts are an annual legume that can reach a height of up to 0.6 m and produces small yellow flowers whose ovaries, after fertilisation, are pushed into the ground where the nuts develop. It is usually eaten roasted or used for the production of peanut butter and edible oils. Groundnuts have a growing period of 90 - 140 days with sensitivity to precipitation amounts from flowering onwards. The photosynthetic pathway for groundnuts is C3. In Ghana, groundnuts are consumed as fresh, dry or roasted nut snacks and in soups with over 90 % of the production taking place in northern Ghana. Planting is done in April and May and the harvest takes place in July and August. Groundnuts are grown in monocultures, intercropped, or rotated with cereals due to their nutrient fixing capacity and usability as cover crops. There are many improved groundnut varieties available but agronomic practices remain low-external input with rudimentary instruments for stripping and shelling. Groundnuts are an especially important crop for female farmers.

Maize:

Maize is a vigorous annual grass and grain crop that can reach up to 2 m in height in Ghana. It is a monoecious plant that develops inflorescences with unisexual flowers in separate parts of the plant. The grains are widely used as food and fodder in many regions. The maturing period for maize depends on local conditions and can vary between 70 and 120 days in the UWR. Maize as well has a C4 photosynthetic pathway. In Ghana, maize is a staple crop produced across the country's agroecological regions mostly under rainfed conditions. Highest proportions of maize grain yields are kept by farmers as staple food while a part is marketed to others for food or feed. Soil fertility and water remain the main limiting factors for maize production in Ghana. Although there are many improved varieties in the country, maize farmers seem to prefer traditional seeds which are often low yielding. Pests and diseases in the growth phase as well as post-harvest losses also hinder maximum maize potential in the country.

Sorghum:

Sorghum is an annual grass species cultivated for its grain and reaching up to 5 m in height. The crop takes 90 - 120 days to mature with the grain being used for food, fodder, fuel and fibre. Sorghum is adapted to warm days and night temperatures above 22 °C throughout the growing season. Sorghum has a C4 photosynthetic pathway. Over 90 % of Ghana's sorghum is produced for food and malt in the northern regions (Northern, Upper East and Upper West Region) making it an important staple crop and economic crop in these areas. Plot sizes, technology adoption and general farming systems for sorghum remain less developed which limits yields for sorghum. Specific varieties are planted for food and for malt production used in local *pito* bars. Some of the limiting factors to sorghum production in northern Ghana are low soil fertility, lack of improved varieties, and slriga infestation.

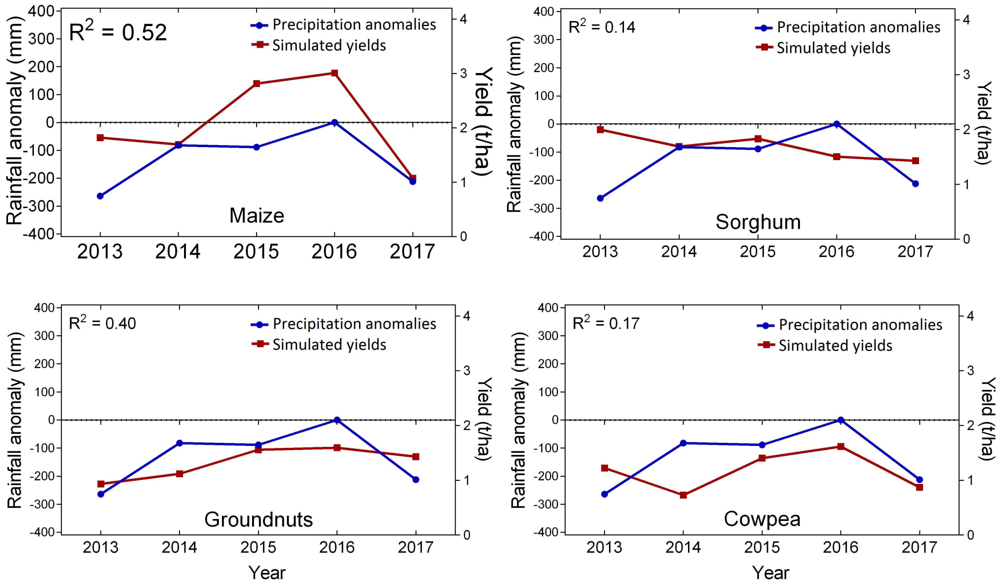


Figure 19: Relationship between precipitation anomalies and yields of the four selected crops in the past. The mean annual precipitation sums can explain a high proportion of yield variability of maize and groundnuts, but only a very minor part of yield variability of sorghum and cow peas.

Crops are differentially sensitive to extreme weather events, changes in precipitation amounts and mean temperatures.

While the precipitation amount and distribution highly determines the production of maize and groundnuts, sorghum and cow peas yield is influenced more by temperature factors, including the diurnal temperature range (Murken, L. *et al.*, 2019).

2.3 Current and Projected Climate Impacts on Crop Yields

2.3.1 Crop Suitability under Current and Future Climate

Chemura *et al.* (2020) found that climate effects on yields show different regional trends within Ghana. The suitability to grow different crops will either increase or decrease in the future, depending on the part of the country and subsequent differences in soil and climate. Figure 20 shows the suitability to grow the selected four different crops in north-western Ghana now and in the future under the two different emissions scenarios.

The potential to grow maize is found to be low in most parts of the UWR, except for Sissala East and West in 2005. The suitability for sorghum is moderate in the UWR and the suitability for cow peas marginal to moderate. The suitability to grow groundnuts ranges from marginal to optimal, with higher potential in the north-western part, including the Lawra district. The suitability for cow peas is also variable across the UWR, ranging from optimal areas in the central-southern and western parts to limited and marginal areas in the northern and north-eastern part of the region.

According to the analysis, the suitability to grow maize, sorghum and cow peas will slightly decrease in the future in some parts of the UWR. The suitability to grow groundnuts will remain stable or increase.

The suitability of all four crops shows slight changes in the future depending on the scenario, crop and region. While maize, sorghum and cow peas show rather a decreasing suitability, the suitability to grow groundnuts is projected to increase in some areas, especially under the high emissions scenario.

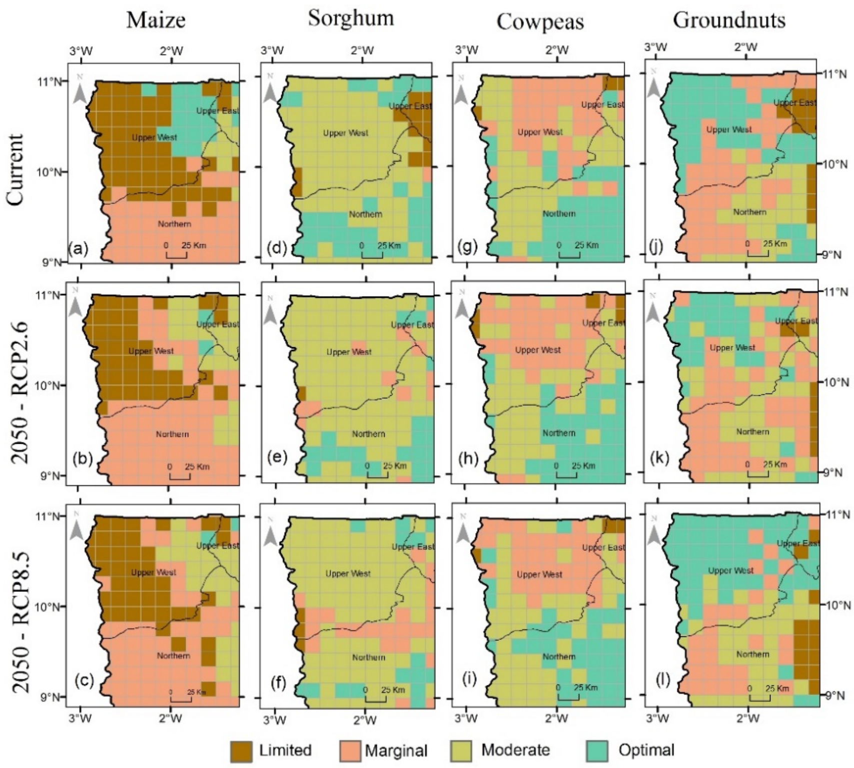


Figure 20: Modelled current (2005) and projected crop suitability for groundnuts, sorghum, maize and cow peas by 2050 (Chemura, Schauberger and Gornott, 2020).

Diets in Ghana include combinations of maize or sorghum, cow peas, groundnuts and other crops in various proportions, thus food security depends on the availability of a variety of different crops, also under climate change. Limited attention has been paid on assessing the impacts of climate change on multiple crops to provide farmers with options for diversification or crop switching. With the aim of addressing this, Figure 21 shows the potential for multiple crops based on the combined suitability of the four crops. This allows assessing the suitability of multiple cropping or intercropping strategies. The results show that under current climate conditions many areas in the central parts of the UWR have high suitability for two or more crops. This suitability for multiple crops is projected to decrease under future climatic conditions for both scenarios. The reduced potential for growing multiple crops has implications on food security as diets mainly rely on the production of two or more crops.

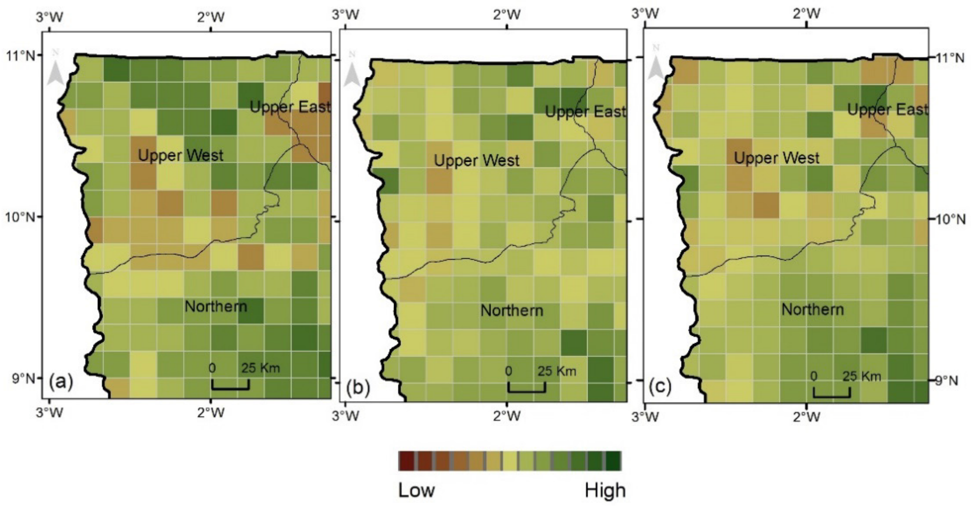


Figure 21: Modelled combined suitability for maize, sorghum, cow peas and groundnuts under Current (left), SSP1-RCP2.6 (middle) and SSP5-RCP8.5 (right) in 2050.

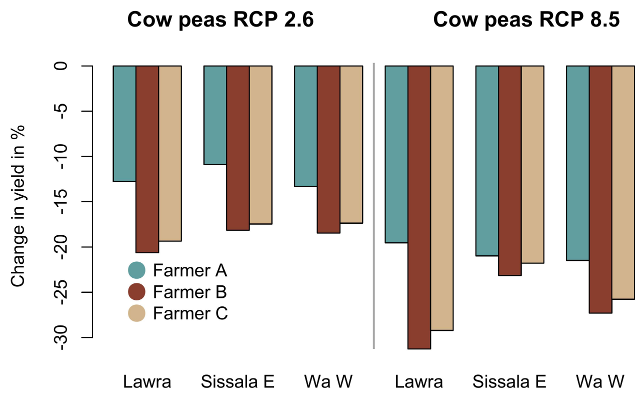
2.3.2 Crop Yields under Future Climate

The magnitude of projected yield changes is not only influenced by the future climate conditions but also by management practices of the farmer.

The results in yield projections show differences depending on the selected GCM, farmer type, emissions scenario, district and crop type. Average values that are displayed in the following graphics are MMEM.

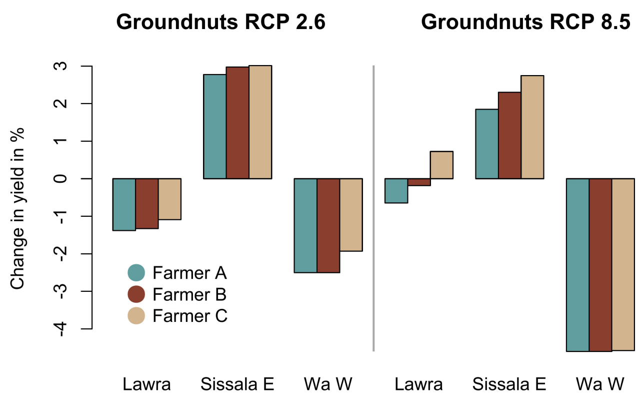
Cow peas:

Cow peas show strong decreasing trends for almost all models and under both scenarios in the three districts. Decreases are stronger under the high emissions scenario. The variances in yield projections in different districts and for different farmer types are small.



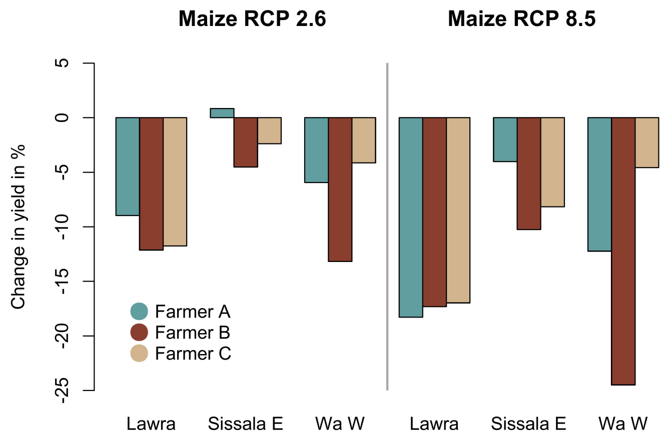
Groundnuts:

The crop models project only slight increases or decreases of groundnut yields under both scenarios and in all districts, which does not allow for a robust conclusion on any trend. The maximum range of projected yield changes is +/-10 % for any model and scenario. In Sissala East, the model median projects small increases in yields and for Lawra and Wa West small decreases.



Maize:

Maize yield is projected to decline until 2050. Declines are stronger under the high emissions scenario and for farmer B. Sissala East shows the smallest changes in maize yield but also the highest uncertainties in projections. Generally, the different models agree well on the trend shown in the figure, especially on the decrease in yield for farmer B.



Sorghum:

Farmer C is projected to have a strong decrease in sorghum yield under both emissions scenarios in all three districts and for all climate models. While farmers A and B are projected to experience a decline in yield in Lawra and Wa West, farmers A and B in Sissala East, are projected to experience only slight yield declines with a low model agreement. Differences between individual models as well as year-to-year variability are high for sorghum.

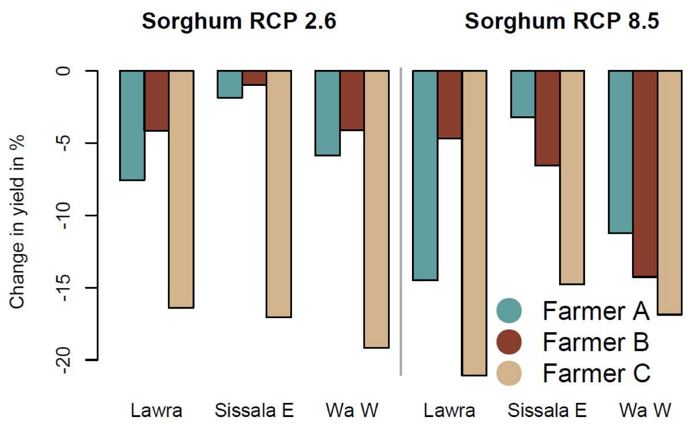


Figure 22: Projected changes in yield of maize, sorghum, groundnuts and cow peas based on multi-model median in 2050 (2041 - 2060) compared to 2014 - 2016 in the three districts Lawra, Sissala East and Wa West for the two emissions scenarios SSP1-RCP2.6 and SSP5-RCP8.5.

Yields for maize, sorghum and cow peas are projected to decrease in the future. Yields for groundnuts are projected to remain almost the same.

Since the crop yield projections do not account for CO_2 fertilisation, the actual future crop yields are expected to show higher results than Figure 22 displays. Especially groundnuts and cow peas would benefit from CO_2 fertilisation. They are so-called C3 plants, which follow a different metabolic pathway than maize and sorghum (C4 plants) and benefit more from the CO_2 fertilisation effect under higher concentration pathways. Thus, groundnuts could even show increasing yields in the future when accounting for CO_2 fertilisation.

Cow peas are highly sensitive to temperature increases in the present temperature range in the UWR. Thus, yields are expected to decline stronger under high emissions scenarios and towards the second half of this century.

For most models, the yield changes show higher values and higher model ranges under SSP5-RCP8.5 compared to SSP1-RCP2.6. The trends agree well for the two scenarios.

The projected yield changes with the APSIM model agree well with the results obtained from the suitability analysis. The projected decrease in sorghum and maize yields also agrees with two other regional crop modelling studies in northern Ghana (Adiku *et al.*, 2010; MacCarthy and Vlek, 2012). Furthermore, the crop modelling within the scope of the climate risk profile in Ghana (Roehrig and Lange, 2019) projects similar trends for maize, sorghum and groundnuts on a national level using different impact models.

Projected yield changes are higher under high future greenhouse gas-emissions than under low future emissions.

Summary Chapter 2

The crop model APSIM was used to project future yields of four important crops in the UWR. The results show that yields of groundnuts are projected to remain stable until 2050 and yields of maize, sorghum and cow peas are decreasing in case no adaptation strategies are applied. Depending on the management practices of the farmers, the projected yield changes are of higher or lower magnitude, but the trends are mainly preserved independently of the management decisions and capacities of the farmer. Decreasing yield trends in Sissala East are of smaller magnitude then for Lawra and Wa West, underlining the higher resilience of Sissala East.

Crop	District	Farmer	Future Trend [19]	Certainty[20]
Maize	Sissala E.	A, B, C	Slightly decreasing	Medium
	Wa W. & Lawra	A, B, C	Decreasing	Very high
Sorghum	all	C	Decreasing	Very high
	Sissala E.	A, B	No trend	Medium
	Wa W. & Lawra	A, B	Slightly decreasing	High
Groundnuts	all	A, B, C	No trend	Medium
Cow peas	all	A, B, C	Decreasing	High

[19] A trend in any direction of 5-10 % is characterised as „slightly de/increasing“. A trend of more than 10 % is characterised as „de/increasing“. Changes under 5 % are labelled as „no trend“. For easy readability of the table, we considered values averaged over the five models and the two emissions scenarios.

[20] The certainty level of future climate projections is determined by the percentage of models agreeing on the direction of trend (compare IPCC, 2014). >= 90 %: very high; >= 80 %: high; >= 50 %: medium; <=50 %: low

PART II - ADAPTATION

While the first part of the climate risk analysis assesses climate impacts on agricultural production in the UWR, the second part focusses on the assessment of four selected adaptation strategies.

Based on the impact analysis of the first two Chapters, the second part of this study assesses the potential of selected adaptation strategies for farmers in three districts of the UWR: Lawra, Sissala East and Wa West. As a first step, we analysed the vulnerability and adaptive capacity of different groups in the UWR looking at social characteristics such as social class, gender, migration status and age to better understand the needs of different groups in strengthening their adaptive capacities. Driven by the interest of local stakeholders and informed by the projected climate impacts on agri culture, four adaptation strategies were deemed the most commonly used and efficient for the analysis: improved seeds, Farmer Managed Natural Regeneration (FMNR), alley cropping of cashew with legumes, and irrigation (for details of the selection process see Chapter 3.3). In the subsequent Chapters, the four strategies are analysed with a specific focus on their economic potential as well as on their risk mitigation potential in the UWR. Using the multi-criteria framework, the negative and positive contributions of the adaptation strategies are analysed, for example with regard to poverty reduction, equity, climate mitigation, employment generation, health, gender equality, biodiversity and maintenance of ecosystem services. In this way, the multi-criteria framework ensures a holistic analysis of the adaptation strategies.

Chapter 3 – Designing the Adaptation Assessment

This Chapter introduces the design developed for the adaptation assessment. Based on the analysed climate impacts, we assessed the adaptation strategies with the help of ten assessment indicators. The applied analysis builds on three different pillars: a modelling approach, a literature review and expert knowledge from local partners in the UWR (Figure 23).

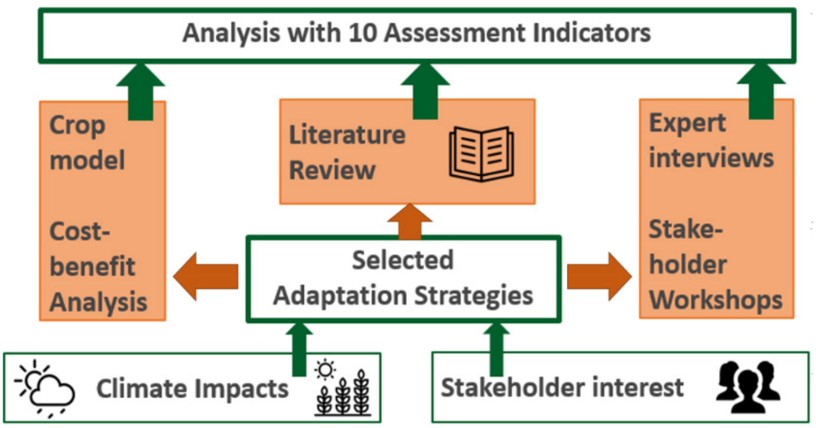


Figure 23: Design of adaptation assessment.

3.1 Collaboration with Partners

To ensure the suitability of the study results for decision makers in the UWR, we cooperated with two local partners: The University for Development Studies (UDS) and the Resilience Against Climate Change Project (REACH).

Acknowledging the limitations of doing an adaptation assessment without being on-site and having limited local knowledge, PIK sought collaboration with two partners to ensure the usability of the study results and to integrate knowledge and data from different local perspectives.

Co-creation with the University for Development Studies (UDS)

The Department of Planning in the Wa campus of the University for Development Studies (UDS) co-created the study. The researchers provided scientific support throughout the study, includeing conceptual inputs, data collection, facilitation of stakeholder engagement, literature review and conducting of interviews. Especially after March 2020, when the COVID-19 pandemic led to travel restrictions, the knowledge and research by UDS provided an invaluable resource to ensure the suitability of the study results for the UWR.

Collaboration with the Resilience Against Climate Change Project (REACH)

REACH is an EU and BMZ funded development project that is implemented by GIZ and the International Water Management Institute (IWMI) in cooperation with MoFA between 2019 - 2024. It aims to "enable a sustainable and inclusive improvement in the rural economy through the enhanced implementation of gender-sensitive climate adaptation and mitigation practices in a minimum of 200 communities within the 14 districts" (factsheet REACH) located in the north-western part of Ghana. Figure 24 demonstrates how the collaboration between REACH and the climate risk study can enrich both projects on various levels. Namely, on the one hand, this study benefits highly from the in-depth data collection that has been done within the REACH project and from the local network that REACH has built. Thus, the two workshops were conducted jointly with REACH. The climate adaptation documents as well as the matching fund of REACH, on the other hand, can profit from the comprehensive climate risk assessment. The science-based recommendations on adaptation strategies can contribute to steering the decisions within the REACH project, specifically they will feed into the development of conservation agriculture manuals and curriculum trainings.

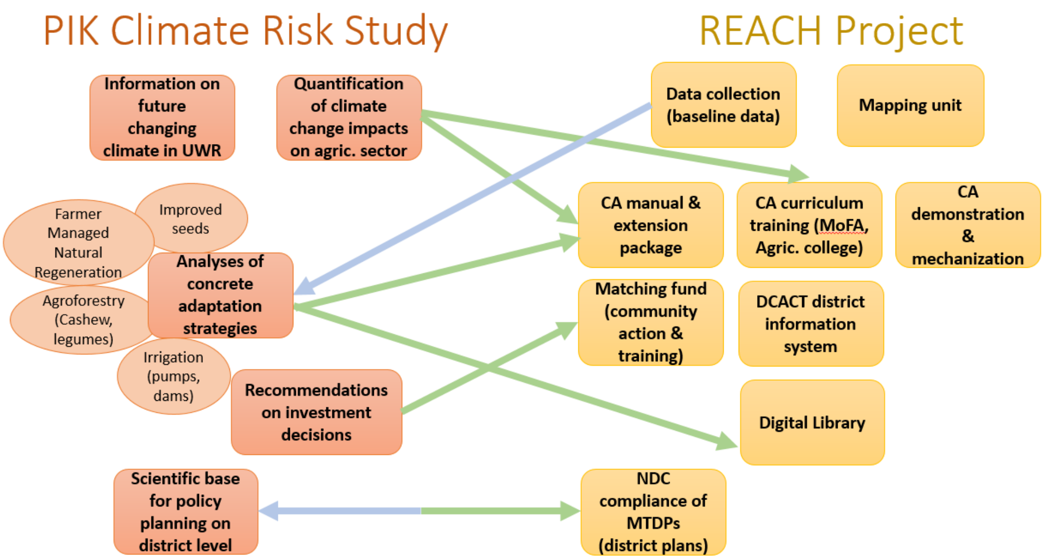


Figure 24: Synergy Mapping of Outputs of REACH project and PIK climate risk study as created on the workshop by PIK, REACH and stakeholders. Grey arrows indicate that information gathered in the course of the REACH project is integrated in the study. Green arrows indicate the planned uptake of study results by the REACH project.

3.2 Stakeholder Engagement Process

Stakeholders from Ghanaian local and national governmental institutions, civil society, academia, the private sector, practitioners and development partners shaped the study focus actively.

To ensure the sustainability and suitability of the study approach and to deliver tailored policy advice, stakeholders from Ghanaian local and national governmental institutions, civil society, academia, the private sector, practitioners and development partners were consulted and engaged from the outset. To include the expertise of the diverse stakeholders, we followed the stakeholder engagement process displayed in Figure 25 throughout the study process.

At the kick-off workshop in Wa in February 2020, 60 participants provided feedback on the study design and actively steered the foci of the climate risk analysis, by specifying, contextualising and prioritising the adaptation strategies to be analysed in the study (see Chapter 3.3). At a further event in Accra two weeks later with participants from the national government, NGOs, academia and development cooperation, the study concept and the results of the kick-off workshop were discussed to facilitate the uptake of the study results into national policies and planning.

Between February and May, 11 experts were interviewed[21] by UDS and PIK to consult the concept of the adaptation assessment and ensure the adequate formulation of context-specific policy recommendations.

During the validation workshop, which took place in the final stage of the study completion in October 2020, the same stakeholders as at the kick-off workshop were invited to discuss the study results and to identify entry points for the application of the results. The stakeholders identified a vast amount of ongoing projects and political processes that could benefit from an integration of the study results on climate impacts and adaptation strategies.

Figure 25: Stakeholder engagement process followed throughout the study.

[21] List of interview partners can be found in the supplementary material.

3.3 Selection of Adaptation Strategies

Ensuring the relevance and suitability of the adaptation strategies to be analysed, the research team developed a process based on selection criteria combined with a stakeholder prioritization and specification. The process is described in detail in the following and visualized in Figure 26.

Nine adaptation strategies were pre-selected by the PIK research team according to three criteria:

1. The strategies have the potential to address the climate risks identified for the UWR in the impact analysis.
2. The strategies are suitable for the economic analysis (cost-benefit analysis) and the bio-physical analysis (crop models).
3. The strategies are part of relevant adaptation and climate change policy documents in Ghana[22].

The pre-selected adaptation strategies were validated regarding their relevance and completeness during the kick-off workshop. In several group sessions guided by GIZ, UDS, REACH and PIK, the workshop participants specified the adaptation strategies further for the context of the UWR and analysed opportunities and barriers for each measure. Due to the diversity of participants' knowledge and background, it was possible to conduct an extensive assessment of the adaptation strategies during the workshop. Detailed results can be found in the supplementary material and are integrated into the Chapters 5 - 8. Being informed by the climate change impact analysis done by PIK and the assessment of the suitability of each adaptation strategy by the local stakeholders, all workshop participants could select which adaptation strategies should be analysed further in the course of the study. Each stakeholder could vote for three different adaptation strategies. Finally, the selection of adaptation strategies was validated and concretized with a literature review and expert interviews. The process resulted in four concrete adaptation strategies, which are analysed in detail in the Chapters 5 - 8. These are: improved seeds, Farmer Managed Natural Regeneration (FMNR), alley cropping of cashew with legumes, and irrigation.

The four adaptation strategies analysed in this study are improved seeds, Farmer Managed Natural Regeneration (FMNR), alley cropping of cashew with legumes, and irrigation.

In policy documents, during interviews and the workshops, other relevant and promising adaptation strategies were mentioned. Also, changes and diversification of livelyhoods within and outside the agricultural sector as well as migration, were subject for discussions during the workshop. These were found to be relevant adaptation strategies and at the same time to come with their own positive and negative side-effects. Even though these strategies are not the study focus and can only partially be assessed with the methods used in this study, we want to make clear they are no less relevant for building a climate-resilient society. In the end, the four strategies that were of most interest to stakeholders and deliver at the same time meaningful results with the methods available to the research team coincided, supporting the decision to analyse the chosen four adaptation strategies in depth.

The selection of the four adaptation strategies was driven by stakeholder interest, importance for current policy processes and suitability for the biophysical and economic analysis.

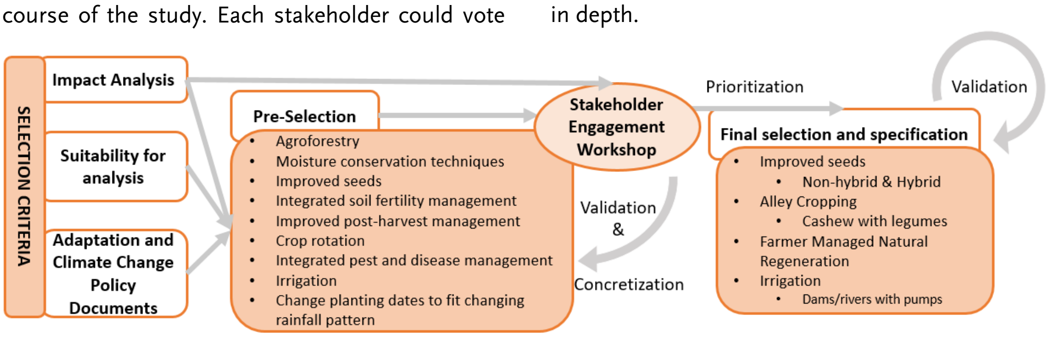


Figure 26: Selection process for the adaptation strategies to be analysed.

[22] Namely: Medium-term agriculture sector investment plan, National climate change adaptation strategy, Integrating Climate Change and Disaster Risk Reduction into National Development, Policies and Planning in Ghana (2010), Ghana's Second Communication to the UNFCCC (2011)

3.4 Adaptation Assessment Criteria

A framework of ten assessment indicators was used to evaluate the four adaptation strategies.

To account for impacts on society and environment, it is important to use complementary soft assessment methods that evaluate adaptation strategies beyond their potential for yield increases or their economic value. Based on experience from previous research, literature and discussions with stakeholders, we thus applied a framework consisting of ten assessment criteria to evaluate the four selected adaptation strategies regarding their overall suitability. The indicators allow integrating the findings into a wider context taking the biophysical, social, institutional, and economic setting into account. This approach limits negative side effects on society and the environment, due to falsely given adaptation recommendations. The four adaptation strategies were assessed qualitatively based on the following criteria:

1. **Stakeholder interest:** A crucial indicator for assessing adaptation strategies is the interest that stakeholders show in a strategy, as this determines future uptake and implementation.
2. **Risk mitigation potential:** An important assessment criterion for adaptation strategies is their potential to mitigate risks, i.e. to reduce yield losses due to climate change. This was assessed based on the crop model results.
3. **Risk gradient (risk-independent vs. risk-specific):** Adaptation strategies can be useful even in the absence of climate change and in case of uncertainty regarding future climate change impacts (risk-independent) or they can only be beneficial in case of the projected climate impacts (risk-specific). This was assessed based on the crop model results.
4. **Cost-effectiveness:** A cost-benefit analysis on farm level provides information on the costs and cost-effectiveness of the different adaptation strategies depending on the emissions scenario.
5. **Upscaling potential:** In this category, we explore how much further potential there is to apply different adaptation strategies in the UWR and beyond, especially taking into account if an upscaling bears the risks of negative outcomes.
6. **Potential co-benefits:** Many adaptation strategies do not only adjust systems to cope with climate risks but have other potential benefits. Here, this is indicated by referring to relevant Sustainable Development Goals (SDGs)[23].
7. **Potential negative outcomes:** However, some adaptation strategies may also produce undesired effects for society, climate and environment, which need to be considered for a comprehensive assessment and which are discussed within the scope of this indicator.
8. **Barriers for implementation:** Here the barriers to adopt an adaptation strategy and possible solutions are discussed.
9. **Institutional support requirements:** While all adaptation strategies benefit from an enabling environment that can be created through institutional support, the amount of support needed differs. A distinction can be made between strategies which generally require high institutional support and those that can be initiated by farmers themselves (institution-led vs. autonomous).
10. **Differential vulnerability:** Depending on social identity factors (e.g. gender, social class, social status, education, ethnicity, etc.), some farmers may face more challenges in adopting an adaptation strategy. While some adaptation strategies increase differential vulnerabilities, others reduce them.

The selection of adaptation strategies was made by the stakeholders, guaranteeing a high stakeholder interest in all four adaptation strategies. The indicators “risk mitigation potential” and “risk gradient” are covered by the bio-physical model APSIM and verified by literature. The cost-effectiveness of an adaptation strategy is assessed with a cost-benefit analysis. The other indicators are analysed with the help of ten expert interviews, consultations with extension officers, insights from the workshops and a literature review.

[23] With the exception of SDG5 on gender equality, since this is covered in indicator 10.

3.5 Crop Model-based Evaluation

A bio-physical model was used to evaluate the risk mitigation potential and the risk gradient of the selected adaptation strategies.

We used the biophysical crop model APSIM as employed in Chapter 2 to quantify the effects of different adaptation strategies on crop yield. We thereby applied adaptation strategies only on the three crops experiencing yield losses under climate change, namely maize, sorghum and cow peas (see Chapter 2). Within the crop model, it is possible to perform simulated experiments to predict and understand the effects of different agricultural practices, with enough certainty to guide the development of agricultural policies. We changed key parameters in the model as compared to the baseline settings to simulate the effect of the applied adaptation strategy under current as well as future climate conditions. Future climate is set to 2050 (averages over 2041 - 2060). Additionally, we confirmed the results with findings from literature.

There is a wide call for a clear distinction between an adaptation strategy and a business-as-usual agricultural practice. Figure 27 presents a simplified scheme of a "climate impact-neutral" agricultural practice (left side) and a "climate impact-reducing" adaptation strategy (right side) as defined by Lobell (2014). In both cases, the agricultural technology (T2) increases the yield compared to the baseline T1. The climate impact-neutral measure (left side) shows similar yield increases under current and future climatic conditions (i.e. (C-D) - (A-B) = 0). In case of the climate impact-reducing measure (right side), the yield increase is larger under future climatic conditions than under current climatic conditions (i.e. (C-D) - (A-B) > 0).

From a farmer's perspective, it is of most interest that despite climate change, the crop yields are stable or increasing, regardless of whether the characteristics of the measure are climate impact-reducing or climate impact-neutral. In this study, we focus on the farmer's perspective and thus quantify the risk mitigation potential of an adaptation strategy according to how much the yields are changing when applying the adaptation strategy under future climatic conditions (corresponds to C-D in Figure 27). This definition of risk mitigation potential does not allow a clear distinction between an improved agricultural practice and an adaptation strategy.

To provide a solid base to apply for climate funds that call for a distinction between adaptation and business-as-usual (and explicitly do not focus on development projects), we give additional information for each adaptation strategy on the effect it has under future climate compared to its effect under the current climate. Some climate adaptation finances call for adaptation strategies that have a more positive effect under future climate than under current climate (Figure 27 right schematic; (C-D) - (A-B) > 0).

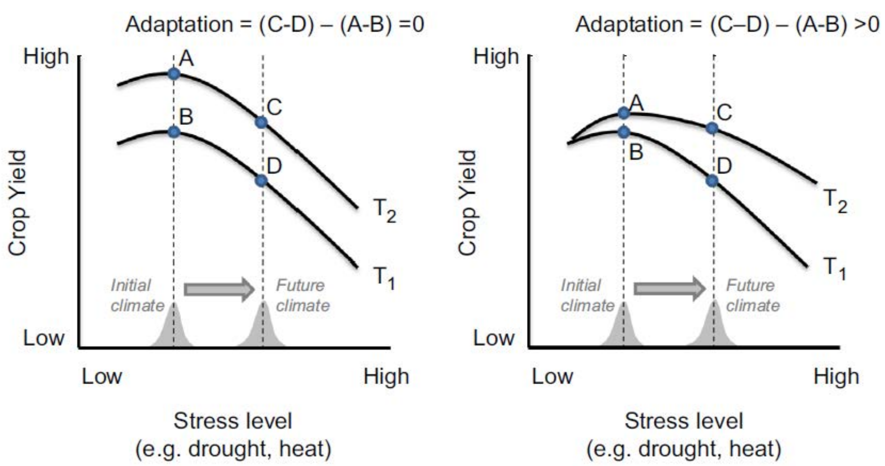


Figure 27: A schematic of the calculation of adaptation (Lobell, 2014).

3.6 Cost-Benefit Analysis

We conducted a farm level cost-benefit analysis to evaluate the cost-effectiveness of the individual adaptation strategies.

A cost-benefit analysis (CBA) is conducted to evaluate the economic costs and benefits of selected adaptation strategies at the farm level. A CBA applied in the context of adaptation examines the expected costs and benefits of implementing a specific adaptation strategy and allows to compare it with the costs and benefits of a business-as-usual production system or with alternative adaptation strategies. In this way, the analysis allows a direct comparison and helps to identify the adaptation strategy with the highest net economic benefits compared to potential alternative strategies or a business-as-usual scenario. The CBA is done by monetising all expected costs and benefits associated with implementing a specific adaptation strategy over a certain period of time. The costs of an adaptation strategy at farm level may include costs related to agricultural input, labour, tools and machinery, whereas the benefits derived from an adaptation strategy at farm level are mainly concerning yield outputs. For a CBA, the costs and benefits of adaptation strategies that are linked to different time periods are discounted at an appropriate discount rate to take into consideration the timely value of money (Boardman *et al.*, 2011). This is necessary, as we typically value current benefits (and costs) more than benefits in the (distant) future, which is integrated into the calculation using a discount rate.

Economic indicators such as the net present value (NPV), benefit-cost ratio (BCR) and the internal rate of return (IRR) are commonly used as indicators for ranking or prioritisation in CBA (Quillérou, 2019). The NPV represents the discounted net benefit. An adaptation strategy with a positive NPV is considered to be economically viable (Boardman *et al.*, 2011). When comparing among alternative scenarios, the adaptation strategy with the highest NPV would be given a preference in terms of its economic value. The benefit-cost ratio represents the ratio between the discounted benefits and costs of an adaptation strategy. An adaptation strategy with a BCR value greater than 1 is considered to be economically profitable. However, when comparing among alternative scenarios, the adaptation strategy with the highest BCR may not necessarily be the one with the highest NPV if the adaptation strategies under comparison have a different scale (Boardman *et al.*, 2011). It is, therefore, important to look at both NPV and BCR. The IRR, on the other hand, tells the discount rate at which the NPV is equal to 0 and if the IRR is greater than the discount rate the adaptation strategy is considered to be economically profitable (Boardman *et al.*, 2011).

An increase in yield resulting from the implementation of an adaptation strategy does not necessarily mean an increase in economic return to the farm household. Hence, a CBA is essential for the evaluation of adaptation strategies in terms of eventual welfare effects. Economic returns are a function of the yield productivity as well as the production costs unique to the adaptation strategy. Nevertheless, as a CBA often uses economic returns as a pure decision criterion, and in our case only at the farm level, a CBA alone might not be adequate to evaluate other environmental and social costs and benefits of an adaptation strategy. This is especially true for those costs and benefits which are difficult to quantify in monetary terms (FAO, 2018). Also, the environmental and social costs and benefits of adaptation strategies are often experienced outside of the farm. Therefore, it is important to use complementary soft assessment methods that evaluate adaptation strategies beyond their economic values as it is done in the current study for each adaptation strategy.

While several adaptation strategies could have the potential to minimize the impact of climate change, for this study we focus only on the most promising adaptation strategy for each district. We base our selection of adaptation strategy per district according to the comparative agronomic, market and commercialization advantages available in each of the districts. The three adaptation strategies that are selected for a CBA are:

1. Improved- and hybrid maize seeds in Sissala East
2. Alley cropping of cashew with legumes in Lawra as a crop switch from sorghum
3. Irrigated tomato production during the dry season in Wa West as an additional income-earning activity to compensate for the potential yield for losses from sorghum during the main cropping season

Local and regional food production is expected to remain a key determinant of food and nutrition security for rural societies in areas where food markets are not well-integrated. Therefore, climate change adaptation strategies need to consider total food production and availability of diversified foods at regional level. In the current CBA, the three selected adaptation strategies target three crops representing different dimensions of food production i.e, a staple crop, a crop with export value and a nutritionally important cash crop. Maize represents one of the major staple crops in Ghana. Cashew-ground nut production targets commercialisation as well as export value for the nation. While tomato production is an important income-earning production activity, it is also a source of high nutritional benefit to farmers themselves.

In our CBA analysis, we focus on farmer types that are considered to be representative of the farmer majority in the study areas. Thus, we used the crop model results of "Farmer type B" as specified in Chapter 2.

Scenarios and assumptions

Several scenarios are considered for each adaptation strategy. They are a combination of the production system, climate scenario (i.e., no climate change vs. SSP1-RCP2.6 vs. SSP5-RCP8.5) and potential future socio-economic scenario (i.e., positive economic development vs. low economic development). The impact of the production system under the respective climate scenario determines the expected yield, whereas the socio-economic setting has implications for the price and costs of production.

For the baseline period, the yield, costs of production and price data are derived based on information collected from the farm survey (more information is provided under each adaptation strategy). For the future alternative production systems, in the first stage, the average yield changes estimated based on the crop model simulations or literature are applied linearly from 2020 to 2040. We could not apply the crop model to all analysed crops. For tomatos, previous studies have predicted a reduction in the area suitable for tomato production in Ghana (Litskas *et al*., 2019). In line with this prediction, we considered a scenario in which yield decreases by 10 % under climate change in the period 2020 to 2040. Further, Läderach *et al.* (2011) project that the URW will become more suitable for cashew production under climate change. We applied the conservative assumption that cashew yield will remain the same. To calculate the costs of production for the future alternative production systems, first, the costs of production for the specific production system are calculated based on present farm data. In the second step, costs and prices in the future are calculated based on future socio-economic scenarios. These scenarios were adopted from a study by Claessens *et al.* (2012) which makes parametric estimations for maize in Kenya. Accordingly, under a positive economic development scenario, prices are assumed to increase by 30 % and costs to decrease by 10 % until 2040. Under a low economic development scenario, prices are assumed to remain the same and costs to increase by 10 %. Even though the parametric changes estimated by the study by Claessens *et al.* (2012) are for maize crops, we applied these estimated changes to sorghum and tomato to understand how the economic profitability of these production activities would change under a similar scenario. Similar to yield, the average changes in costs and prices are applied linearly from 2020 to 2040. For the CBA of cashew-groundnuts alley cropping, we do not apply a similar scenario in prices and costs as we consider that being an export-oriented crop the prices and costs of cashew and groundnuts might develop differently. A particularly sensitive assumption for the CBA is the discount rate - here a discount rate of 10 % is used. There are still ongoing discussions regarding the choice of discount rates in CBA. Various studies use different discount rates for adaptation strategies in agriculture. For example, discount rates between 5 - 15 % have been used by Shongwe, Masuku and Manyatsi (2013); a 5 % rate has been used by Westerberg *et al.* (2019), and other studies in sub-Saharan Africa have used discount rates in the range of 6 - 12 % (Westerberg, Doku and Damnyag, 2019). With a 10 % discount rate this study thus situates itself in the medium spectrum.

3.7 Expert-based Assessment and Literature Review

A range of additional data sources was used to complement model results and put them into perspective. These include insights from expert interviews, group work at workshops and literature review.

We conducted a systematic literature review for each of the four adaptation strategies in which we screened empirical as well as modelling studies for the ten assessment criteria.

In addition to the literature review, we conducted ten expert interviews with eleven experts[24] working in the three analysed districts as well as on regional level in the UWR. Experts were representatives from the district and regional governments and NGOs. The majority is associated with MoFA in the positions of extension officer, (deputy) director of agriculture on district or regional level or officer in charge of Women in Agriculture. Nine interviews were conducted in person in the three districts or in Wa. One expert was interviewed by telephone since the risk situation due to COVID-19 did not allow travelling at the time of research. The representation of female to male experts was two to nine. The interviews were semi-structured and designed to add to the information found in literature as well as to close existing information gaps. Therefore, the questions were adapted to each interview situation and within the course of the study development. The interviews concentrateed on (1) the general challenges of smallholder farmers in the UWR and (2) the assessment of the four selected adaptation strategies. We screened the interviews for information on the ten assessment criteria.

The evaluation with assessment criteria was also informed by ten local expert interviews and a thorough literature review.

[24] The individual experts are listed in the supplementary material.

Chapter 4 – Differential Vulnerability in the Upper West Region

Climate change effects not only happen in the context of a geographically complex landscape but also of a complex social landscape where people and groups are situated within broader socio-cultural, political and economic relations (Djoudi *et al.*, 2016). Thus, people around the world and within a country are differently affected by climate change and are not equally equipped to combat climate risks, even when facing the same climatic stressors (Thomas *et al.*, 2019). While smallholder farmers belong to one of the most vulnerable groups in the face of climate change, they are not a homogeneous group. Chapter 2 already showed that yield changes under climate change differ for the different farmers A, B and C and are dependent on the access of the farmer to resources like technical equipment and fertilizer. Additionally, deeply rooted agricultural practices, many of which have a long history and are an integral part of local cultures, render some people and groups more (dis)advantaged than others in facing climate risks (Carr and Thompson, 2014; Nyantakyi-Frimpong, 2019). Therefore, we introduce the concept of differential vulnerabilities meaning that the vulnerability of people is differently shaped by several socio-demographic variables. The term "vulnerability" is understood according to the IPCC AR4 (2007) as a function of exposure, sensitivity and adaptive capacity. Consequently, the (non-)ability of farmers to adapt is already included in the term "vulnerability" in the following. Many studies have confirmed differential vulnerabilities of people depending on characteristics like gender, location, social class, ethnicity, migrant status, marital status, age and health status (Padgham *et al.*, 2015; Baptiste and Kinlocke, 2016; Lawson *et al.*, 2019; Nyantakyi-Frimpong, 2019). On the basis of existing literature and insights from expert interviews (see Chapter 3.7), we will examine the vulnerability of smallholder farmers in the UWR while taking multiple social characteristics into account.

Socio-demographic variables like gender, location, social class, ethnicity, migration status, marital status, age and health status are shaping the vulnerability of farmers to climate change and their adaptive capacities.

4.1 History of Vulnerability in the UWR

The dominant ethnic group in the UWR is Mole-Dagbani, accounting for 73 % of the population. While the Mole-Dagbani[25] are also the main ethnic group in the districts Lawra and Wa West, Sissala East is mainly home to the Grusi[26]. The different ethnic groups in the region as well as elsewhere in Ghana can be described as patriarchal, including patrilineal inheritance (Ghana Statistical Service, 2018; REACH, 2020). Chieftaincy is a significant aspect of the culture of the different ethnic groups in the region. The current chieftainship is the result of complex interactions of colonialism, the interests of British indirect rule and the insertion of a local political agency. The commodification of land both during colonial times and beyond gave chiefs even more power, especially regarding land tenure (MacGaffey, 2013; Yaro, 2010; REACH, 2020). Patriarchy and Chieftaincy largely shape the power relations within the communities.

[25] The Mole-Dagbani consist of a range of groups inhabiting large parts of West Africa. They include the Dagomba, Kusasi, Mamprusi, Nanumba, Dagarte (Dagaba), Lobi and Wali (Wala). The Dagarte (Dagaba), Wali (Wala) and the Lobi are those with their traditional home in the Upper West.

[26] The Grusi are inhabiting northern Ghana,and areas of Burkina Faso and Togo. They largely consist of the Kasena, Sisala, Mo, Vagala and the Birifor.

The higher vulnerability of northern Ghana compared to southern Ghana is determined by climatic factors and by a structural and developmental divide between the regions.

The UWR falls within the southern fringe of the West African Sahel region with historical and present high climate variability and exposure to droughts and floods (see Chapter 1). Northern Ghana faces less favourable climatic conditions for agricultural production (e.g. only one rainy season, less annual precipitation) than southern Ghana. However, the higher vulnerability of the north is not only determined by climatic factors, but by a structural and developmental divide between the two regions. The beginning of this divide can be traced to colonial policies that disadvantaged the northern regions and encouraged migration from north to south due to labour requirements (Flange, 1979; Nyantakyi-Frimpong and Bezner-Kerr, 2015; M. H. Ahmed *et al.*, 2016; Lawson *et al.*, 2019). The current structural inequality is, for example, well reflected in the literacy rates, which is about 79 % for the whole country, but only 46.2 % in the UWR (REACH, 2020).

Additional pressure in the northern region comes from increasing land degradation. Rapid population growth and high poverty rates have pushed an intensification of unsustainable agricultural practices (e.g. bush burning, incorrect fertiliser and pesticide use, overgrazing) as well as alternative livelihoods such as cutting of trees for charcoal production and small-scale illegal mining. The results are degradation of forests and natural vegetation cover, the decline in soil fertility, increasing soil erosion and loss of biodiversity, which also influence the microclimate and further increase vulnerability of the local communities (A. Ahmed, Lawson, Mensah, Gordon, & Padgham, 2016, Expert 3 & 4).

An expert interview in Wa West demonstrates how land degradation is affecting smallholder farmers' livelihoods and how the location of the farm on infertile land especially becomes a problem when it comes together with poor or no access to finances, poor access to extension services and poor infrastructure:

"The way the land is no more fertile, so before a farmer does any meaningful farming and to get something good to get home for the family, they need to apply fertiliser to the land that they cultivate, and the fertiliser is not really gotten. They have to get the money and go and buy from the market. Sometimes the Ministry of Agriculture is coming to help." (Expert interview 1, Wa West)

Additionally, climate change interacts with land degradation posing additional challenges for the farmers through:

- more intense precipitation events and wind increase soil erosion through aeolian processes and surface run-off on degraded lands,
- due to the reduced water holding capacity and increased compaction of the soils in degraded land, the negative effects of dry spells and floods are increasing (de la Paix *et al.*, 2013; A. Ahmed *et al.*, 2016).

Expert 3 elaborates on the impact of land degradation on biodiversity, livelihoods and the microclimate and the increasing negative effects in case of climatic changes.

"Weather as it was in those days, where the power was restored in chiefs to control environmental issues as well as other community issues and those who were born before independence, keep their version of the story as the climate issue at that time [before independence] was very favourable, because there was no bush burning, indiscriminate tree cutting was forbidden, there was no careless fishing (...) and even to tell whether the season was up or not they had migratory birds. The arrival of the migratory birds before the rains told them that the season was about to start. So they had to start preparing their farms and when the rains began they could tell if during the year they will have heavy rains or floods or just moderate rains depending on the level at which some particular birds wove their nets along the river bed." (Expert interview 3, Lawra)

Within the UWR, smallholder farmers in Sissala East and Sissala West are on average less vulnerable due to a better microclimate as the region is more forested, holds relatively better soils and has better coverage of extension services and higher food production compared to the rest of the north-western region (Derbile, 2014, expert interviews 6 & 7 & 8). This will be further enhanced by the differential climate impacts on crop yields. As shown in Chapter 2, projected yield decreases are higher in Lawra and Wa West than in Sissala East. Furthermore, Sissala East has a higher proportion of commercial crop farmers including a higher availability of tractors, higher household income levels and a lower livestock density (REACH, 2020) shaping the resilience of the Sissala farmers.

This already indicates that while (changing) climatic conditions (see Chapter 1) present a mainly similar climatic setting for all people and groups in the UWR, the vulnerabilities and decision-making possibilities of the different groups and individuals are dependent on other factors. In the following, we will look at four identities (social class, gender, migration status, age) and their intersection with other socio-demographic variables as important factors that influence vulnerability and food insecurity.

4.2 Different Identities and their Influence on Vulnerability

Vulnerability regarding climate change is circumscribed by low access to resources, which include and go beyond the availability of capital, access to credit and liquid assets and include e.g. secured land tenure, extension services, food stores, migration support, durable infrastructure, transportation, education, alternative housing, insurance, early warning systems, climate information, and social information and communication networks (Cinner *et al.,* 2018, expert interviews 2, 6, 7 & 8). The current political emphasis on agricultural intensification and liberalisation of the agricultural sector has favoured large-scale developments and thus has reinforced marginalisation of smallholder farmers and social inequalities in semi-arid Ghana (Nyantakyi-Frimpong and Bezner-Kerr, 2015). In addition, this marginalisation hits some social groups and individuals in a different and more intense way than others, leading to the fact that a smallholder farmers' social identity is often a determinant for its level of vulnerability to climate change.

4.2.1 Economic Inequality (Social Class)

In Chapter 2 different farmer types where introduced depending on their access to the amount of fertilizer and technical equipment (e.g. tractors). Thereby, we were able to show that yield changes under future climate conditions are partially dependent on the farmer type. Nevertheless, the dependency of yield changes on the farmer type is not definite but varies with crop and location.

The economic resources of farmers determine their adaptive capacity to climate change.

An indicator ranking based on literature and expert interviews in northern Ghana by Abdul-Razak and Kruse (2017) revealed that economic resources, determined by diverse sources of income, remittances and access to credit, seem to be the most relevant factor for smallholder farmer's adaptive capacity. However, these economic resources depend on various factors that are inherently linked to social class, such as land tenure and extension services.

Regarding the first factor, land tenure, it is to note that Ghana has a pluralistic system of land tenure. About 80 % of the land is held as trust land by the stool/skin[27] in accordance with customary law, while 10 % is held by the central government for public development purposes (Bob-Milliar, 2009). The lands held in trust by the traditional authorities in the UWR belong to various clans and families, who determine access and ownership according to long-standing norms but also new terms of land commercialisation. For rural communities, households and individuals largely depend on long-standing traditional norms and practices to access lands for farming. Long or reliable tenure arrangements create a more conducive environment for farmers to invest in adaptation strategies or sustainable farming practices than short tenure or less reliable tenure arrangements (Abdul-Razak and Kruse, 2017), making secure land tenure a crucial determinant of adaptive capacity.

Second, extension services play an important role for farmers regarding access to information and

[27] Means that it is held by the Kings/Queens/Chiefs. The stool refers to the Kings/Queens/Chiefs who sit on stools as a symbol of their authority. The Skin refers to those Kings/Queens/Chiefs who sit on animal skins to symbolise their authority.

assets, especially under changing climatic conditions and increasing land degradation. Extension services are not available to all farmers, especially not to those with poor road access to their homes (expert interviews 3, 7 & 8). The subsequent unequal access to information and assets shapes unequal opportunities to adapt.

"He [extension officer] is not able to cover all the farmers in reasonable time. Before he gets to your end, you are already behind time. And here we have only one rainy season. So once the season is missed you are lost for an entire year. And, of course, the season now is becoming a bit shorter and unpredictable." (Expert interview 7, Wa)

4.2.2 Gender

The lower adaptive capacity of female farmers is shaped by gender disparities in wage, employment, decision-making power, tenure security and access to assets and finances.

On average, women in northern Ghana have higher rates of poverty due to gender disparities in wage and employment, less decision-making power, higher land tenure insecurities, less access to finances, new technologies, climate information and extension services, as well as higher household burdens (A. Ahmed *et al.,* 2016; Bugri, 2008; Naab & Koranteng, 2012; Padgham *et al.,* 2015), thus increasing their vulnerability to climate change impacts and restricting their adaptive capacities with regard to agricultural activities.

First of all, those disparities between men and women are due to cultural norms, restricting women as well as men in their selection of work. For example, norms discourage women's ownership of livestock resulting in a situation where women have a very small share of livestock. In addition, gendered social norms play a role in the decision to migrate and make it easier for men to choose to migrate to places with more favourable climatic conditions. Nevertheless, the number of young female migrants from northern Ghana has increased in recent years (Padgham *et al.*, 2015). Next to cultural norms, higher wage rates of men make it easier for them to choose livelihoods besides subsistence farming. Although a considerable number of women choose alternative (and more diverse) livelihoods, mostly they earn far less for the work they are doing than men.

Second, rooted in the patriarchal system that characterises northern Ghana, decision-making power is mainly in the hands of men. This encourages interventions, such as public investments, regarding agricultural value chains where men have a competitive advantage and hinders women's access to new technologies and information. Thus, shaping gendered adaptation opportunities (A. Ahmed *et al.*, 2016; F.A.O, 2018) and making it harder for women to cope with negative climate impacts. In addition, 85 % of all extension officers are male (Mabaya *et.al*, 2017), which can lead to a service focusing on the needs of male and to structural disadvantages for female farmers in access to information, seeds and fertiliser.

Access to land is one of the most important factors shaping gender inequality, whereby ownership through inheritance is the most determining cause for the inequality in land ownership in northern Ghana (A. Ahmed *et al.*, 2016). The patriarchal system of inheritance ensures that only men can inherit the lands of their fathers, while women may inherit portions from their deceased husbands. This concentrates control and access to land in the hands of men. Only 9.8 % of agricultural land in Ghana is owned by individual women farmers whereas 83.1 % is owned and used by their male counterparts (REACH, 2020).

The importance of the question of access to land also became clear during the expert interviews that were held in the three districts. Being asked about general challenges of smallholder farmers in the UWR and not explicitly about gender inequality, male as well as female interviewed experts mentioned that women face additional challenges, especially regarding access to fertile land (expert interviews 1, 3, 7 & 8).

"A man can farm. A woman, too, can farm. But before a woman farms, she will have to acquire the land. And the land is always in the hands of the men, whom you call the landowners. So the women have to go and beg for the land." (Expert interview 1, Wa West)

Several experts raised the concern that due to the insecure land rights for most women, the women farmers are discouraged to invest in their land, use new technologies, put adaptation strategies in place and apply sustainable agricultural practices. They reported that some landowners claimed their land back from women after seeing that the soil fertility of the land increased, which discourages women even further from improving the land.

These examples show that identifying gender inequalities and associated different vulnerabilities and adaptive capacities is important in order to understand how climate change vulnerability emerges and how to target those patterns in an efficient way. However, the rigid victimisation of women and the sole men-versus-women dichotomy makes it impossible to meet the highly specific needs of particular groups of women or men and does not address the power imbalances responsible for the differential vulnerabilities in the first place (Arora-Jonsson, 2011; Djoudi *et al.*, 2016; Lawson *et al.*, 2019).

Literature about climate change and gender has often encouraged a generalised belief in women's vulnerability, forgetting that men can also be highly vulnerable to climate change, not at least through predominant ideals of masculinity (Arora-Jonsson, 2011; Nyantakyi-Frimpong, 2019). While drawing attention to the challenges that women are facing through structural inequalities, presenting women as a homogeneous, victimised and passive group has to be replaced by an overall call for power balance. This has to start with gender-equitable access to all resources and decision-making power.

"Gender is not only about women, or neither is it about men. It is a combined work." (Expert interview 1, Wa West)

4.2.3 Migration Status

Nomadic pastoralists are differently affected by climate change than sedentary farmers. This can but does not have to run along ethnic lines. The main concern of migrants, especially of pastoralists of the Fulani tribe, relates to access to rangeland and agricultural land (Padgham *et al.*, 2015). The UWR has been a major Fulani destination in Ghana. In some communities, sedentary farmers and Fulani herdsmen live peacefully together and profit from each other's expertise. After harvest, herders are free to use the fields on the passing by and farmers profit from the manure left behind. In other communities, the competition for land resources between Fulani herders and crop farmers and the destruction of farmland has been an ongoing source of conflicts.

In addition to high competition for fertile land, changing climatic conditions force Fulani herders to move further away in search of suitable pasture and water resources. The long distances and different environmental conditions pose risks to reduced milk output, the spread of diseases and loss of weight to the livestock (Padgham *et al.*, 2015; Napogbong, Ahmed and Derbile, 2020). The change of precipitation patterns and the resulting difference in routes of the nomadic pastoralists can also lead to conflicts. Pastoralists are forced to leave established relationships with farmers on previous routes behind and have to form relationships with unknown farmers along new routes. Trust and cooperative relations have yet to be built. The relationship is challenged by farmers who view Fulani identity as non-Ghanaian and constructed prejudices like the widespread perception that chiefs sell lands indiscriminately to Fulani herders (Kuusaana & Bukari, 2015, expert interview 3).

Changing climate conditions can force herdsmen to leave their established roots in search for pasture and water. This can further fuel the existing conflict between Fulani herders and sedentary farmers.

Interviewed experts (all not migrating pastoralists) brought in another perspective. Since Fulani herders have mostly no secured land tenure, bush-burning and destruction of farmlands by livestock are incentivised, reducing agricultural production of sedentary farmers and fuelling the conflicts between Fulani herders and farmers (Padgham *et al.*, 2015, expert interviews 3, 7 & 8). Regional and national governments have largely excluded Fulani from socio-political participation (Bukari and Schareika, 2015) and failed to sufficiently include Fulani herders' perspective and indigenous knowledge into national and regional policies so far (Napogbong, Ahmed and Derbile, 2020). The current conflict and subsequent unsustainable land practices lead to insecure livelihoods of nomadic as well as sedentary communities and at the same time lead to land degradation minimizing yields of sedentary farmers. Expert 3 called to create and maintain pastoral corridors, detect rangelands for herders and clarify land tenure rights to mitigate conflicts, land degradation and secure livelihoods.

4.2.4 Age

Low access of the youth to land and decision making power drive young people further to migrate south.

In Ghana, the farmer population is overall ageing, with a current average age of 55 years (Naamwintome and Bagson, 2013). Limitations in land access, poor perception of people involved in agriculture and low decision-making power of the youth are the main barriers for young people to get involved in agriculture and main drivers for youth to migrate south (Naamwintome and Bagson, 2013; Padgham *et al.*, 2015; Kidido, Bugri and Kasanga, 2017). Youth migration has several downsides: Elderly people might be left alone and physically not capable of managing their farms, traditional knowledge gets lost and modernisation of farms is slowed down (Mba, 2004; A. Ahmed *et al.*, 2016). Naamwintome & Bagson (2013) call for governmental and family interventions to ensure accessibility of land, labour force/bullocks and farm inputs to youth in order to mitigate migration and youth unemployment.

4.3 Intersectionality

Looking at a single part of the identity of a person falls short in explaining vulnerability and adaptive capacity. An intersectional approach recognizes that the vulnerability of people is shaped by the intersecting different social characteristics they inherit.

It was shown that social characteristics like social class, gender, migration status and age influence the vulnerability of farmers in the UWR. An intersectional approach recognises that the experiences people make are shaped by the different identities they inherit. At the same time, intersectionality moves beyond looking at a single part of the identity of a person to explain their vulnerability but looks at the different intersecting characteristics of the person. The following two examples show that looking solely at one identity cannot explain the adaptive capacity and level of vulnerability of a person.

Nyantakyi-Frimpong (2019) did intensive fieldwork in the UWR focusing on the intersection between health status, gender, religion, age, marital status and poverty and resulting effects on individual vulnerabilities. An example from this fieldwork shows how intersectionality comes into play: In the case of a drought, a married woman, a widow and a woman married to the chief are differently affected by extreme weather events and have a different capacity to recover. While resources are unevenly distributed between men and women, a married woman and especially a woman married to the chief has better access to inputs like drought-resilient seeds and irrigation facilities and thus is less vulnerable in case of a drought.

In another study conducted in semi-arid Ghana, Lawson (2019) demonstrates that not every female smallholder famer struggles with tenure insecurity. Comparing farmers who were born in the area to migrant women farmers; older farmers to younger farmers, and married women (especially with sons) to single women or widows, the former always have better access to land. Thus, while inequalities between women and men indeed influence vulnerability to climate change, other social identities and circumstances may be equally or even more important than their gender group (Nyantakyi-Frimpong, 2019). Gender intersects with other identities, roles and responsibilities to influence adaptation strategies and barriers to climate change adaptation. Socio-demographic factors like age, marital and residential status also affect the power and decision-making of women in northern Ghana (Lawson *et al.*, 2019).

Social inequalities are systemic and arise on a multidimensional base. The examples above show how focusing on one single characteristic cannot explain vulnerability on an individual level. Ignoring the intersection between different social characteristics, climate adaptation strategies in agriculture may not be conducive for most vulnerable groups and might aggravate rather than diminish existing injustices. Any effort to tackle differential vulnerabilities requires an understanding of why they exist and an examination of power structures and social difference (Djoudi *et al.*, 2016; Thomas *et al.*, 2019).

This chapter has shown how structural inequalities and asymmetries of power among different social groups heavily influence the severity with which climate risks impact different groups (Padgham *et al.*, 2015) and also influence the adaptive capacities of those groups. We argue that adaptation planning has to include the perspective on differential vulnerabilities to increase the adaptive capacity of a whole community. Including groups in decision-making processes that have been disadvantaged up to date and thus, integrating diverse knowledge and resources, does not only increase the adaptive capacity of disadvantaged groups but leads to a better resilience of all groups. It has been highlighted that the various constraints and opportunities that different groups face are shaped by a wide range of intersecting social identities coming with specific responsibilities, roles and power which are subject to continuous changes (Carr, 2008). Key factors found to combat differential vulnerabilities are to ensure equal access to land, assets and decision-making power for disadvantageed groups. A critical intersectional approach has to be applied in adaptation planning to tackle the differential vulnerabilities in the UWR that are constructed by the complex social and political power dynamics, especially concerning those key factors.

In the subsequent analysis of the four adaptation strategies, we will therefore also focus on differential vulnerabilities, meaning that we will elaborate on the ability of different groups to benefit from the measure. Furthermore, we will also provide some insights on how the adaptation strategies can be implemented to decrease differential vulnerabilities rather than reinforce them.

Chapter 5 – Improved Seeds

For a more productive use of land, water, nutrients, and other resources farmers can apply genetically improved crops that enable higher yields, increased resistances and tolerances to abiotic and biotic stress factors and thus can be an adaptation to changing climatic conditions. Farmers can adopt these new technologies created by breeding in the form of improved seeds[28], which can be one measure within the farming system to contribute to climate change adaptation (Mbow *et al.*, 2019; WRR, 2019). In order to maximise potential breeding-induced benefits, it is necessary to harness the vast local and global genetic material available and to include landraces[29], wild relatives of crops, and orphaned and neglected crops (e.g., millet, beans, cassava) in breeding programs (WRR, 2019; Searchinger, 2014) in search for desired traits such as increased resistance to biotic stressors or heat tolerance.

In Ghana, crops that particularly benefit from breeding programs are yam, maize, rice, cassava, sweet potato, cow peas, plantain, groundnuts and soybean (Bennett-Lartey, S. O. & Oteng-Yeboah, 2008). Advantages of improved varieties that are often stated by farmers in northern Ghana are drought tolerance, short duration to maturity and high yield quality and quantity (Dapilah & Nielsen, 2020).

Local NGOs, financed by donor-funded projects, first distributed improved varieties in the region in the 1980s (Dapilah & Nielsen, 2020). The adoption of improved varieties as a climate change adaptation strategy has increased since the 2000s (Dapilah & Nielsen, 2020).

In Ghana, most farmers use farmer-saved seeds that they acquire from their own production or buy at local markets (Pardoe, Kloos and Assogba, 2016) in the informal seed sector. According to Catherine Ragasa *et al.* (2013), 61 % of the maize area was planted with modern varieties, but only 15 % with certified seeds. In Ghana, the average age of a variety (starting with its release date) is as long as 23 years, which means that the system is either producing varieties that do not fit farmers' needs or that new varieties and corresponding knowledge are not adequately disseminated to farmers (Catherine Ragasa *et al.*, 2013). Extension officers interviewed suggest that 70 - 80 % of farmers currently use improved seeds and that most of the seeds are obtained from the food markets and vendors. This is, however, not to suggest that farmers use these seeds in large proportions. The interviewed extension officers estimated that between 20 - 40 % of all seeds grown by farmers are improved seeds. These low uptake rates mainly origin in often high costs of seeds and inputs as well as bad experiences that have been made partially due to poor seed quality or mismanagement. The remaining seeds are landraces. Highest uptake rates can be found in the Sissala districts.

> The uptake rate of improved seeds is currently low in the UWR, whereby within the three analysed districts, Sissala East shows the highest use of improved seeds.

Hybrid[30] varieties, a sub-category of improved varieties, can improve farmers' livelihoods due to yield superiorities compared to other varieties (Kante *et al.*, 2019). Most available hybrid varieties are maize varieties. Studies carried out in Tanzania and Kenya found that the recycling of hybrid maize seeds for three to six years was economically beneficial for smallholder farmers even though yields decreased due to the inbreeding depression (Nkonya and Mwangi, 2005; Japhether *et al.*, 2006). To sustain and increase the efficient recycling of hybrid seeds, hybrids with reduced inbreeding depression should be bred and farmers should be advised on how to best select seeds to reduce the yield depression of hybrids over generations.

Improved seeds can help in closing the high yield gap in the UWR. This means reducing the gap between the yields achievable under comprehensive

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28 Definition of improved varieties (Access to Seeds Index 2020) : A new variety of a plant species which produces higher yields, higher quality or provides better resistance to plant pests and diseases while minimising the pressure on the natural environment.

29 Other terms for these are ancestral, farmers', folk, indigenous or traditional varieties. In contrast to improved varieties, landraces are varieties that were not bred in formal breeding processes but evolved from farmers' selection.

30 Definition of F1 Hybrid (Access to Seeds Index 2020): Hybrid of two homozygous parent lines. The F1 hybrid combines desired traits of both parent lines and has a uniform phenotype.

management and the actual farm yields achieved by an average Ghanaian farmer. Plant breeding has increased the genetic yield maximum of the plants – and still has the potential to increase it further. Additionally, plant breeding can create varieties that produce high yields under various environments and limited input use (Voss-Fels *et al.*, 2019) and thus can contribute to the resilience of smallholder farmers. Also, new traits facilitating crop production (e.g., dwarf varieties or short cycle seeds) have helped farmers to achieve higher yields. For example, the crops "late millet" (Zea) and sorghum are rather long maturing crops whose production is difficult when the length of the rainy season shortens (Derbile, Jarawura, & Dombo, 2016) or have an unreliable length as is the case in northern Ghana. In the UWR, farmers replace these long-maturing crops with maize, but new varieties could prevent such crop switches and sustain the more drought-resilient and culturally embedded staple crops. For instance, one approach is to plant crops earlier to take advantage of the first precipitation events as plants will then be sturdier when heavy precipitation occurs. However, such plants have to withstand longer rain breaks as well (Pardoe, Kloos and Assogba, 2016).

5.1 Crop-Model-based Evaluation

Risk mitigation potential

Plant breeding aims at stabilising and improving crop performance under various conditions, including the adaptation to climate change impacts on agriculture. Increased drought and heat tolerance are, for example, achieved by creating crops with larger root systems (IPCC, 2019). This improves the water uptake of the plants, as these can reach lower water reservoirs and thereby draw water from a larger area. Further, also more nutrients can be absorbed. Plant breeding can optimise the life cycle of plants under new climatic conditions, which ultimately results in higher and more stable yields. Depending on a region's climate, the growing period of a variety can also be shortened to avoid water stress events during crucial stages of plant growth or to allow for several harvests per year.

Farmers in northern Ghana brought forward that improved crops were able to withstand droughts, high temperatures and dry spells and that the use of improved seeds leads to a significant yield improvement (Fagariba, Song and Baoro, 2018). Under future climatic conditions with rising temperatures, higher potential evapotranspiration, possibly stronger and more frequent heavy precipitation events and continuously high variability in the length of the rainy season and dry spells (compare Chapter 1), suitable improved varieties can stabilise yields and mitigate climate risks for farmers. A diversification of different improved varieties and landraces, as a way of tapping into the merits of each, can further decrease risks. Many farmers already apply this strategy in the UWR. For example, while specific improved seeds are drought resistant, most local landraces are more disease resistant. The extent to which the risk mitigation potential of the improved seeds can be exploited also depends on general plant care and soil and weather conditions.

We evaluated the yield responses under a future climate of one sorghum, one cow peas and two maize improved varieties (one of them hybrid and one not) as exemplary varieties using the crop-model APSIM. All varieties are specified in the table below. Dependent on the farmers' capacities we applied three different management practices in APSIM. This is reflected in farmer type A, B and C as defined in Chapter 2.

Table 2: Characteristics of applied improved varieties.

Improved variety	Short name	Variety used in APSIM
Maize hybrid variety "Dorke"	Maize HV	Dorke
Maize improved variety "ObatanB"	Maize iV	Changed parameters of ObatanB
Sorghum improved variety "Pan606"	Sorghum iV	Pan606
Cow peas improved variety "Banjo"	Cow peas iV	Banjo

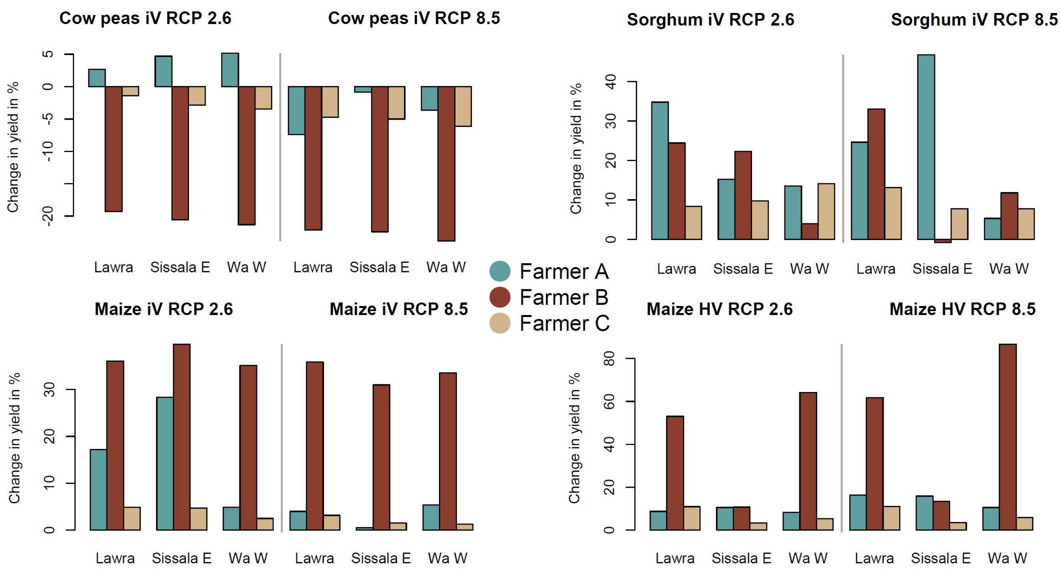

Figure 28: Projected changes in yield based on multi-model median in 2050 (2041 - 2060) when applying sorghum improved variety (iV), cow peas improved variety and two maize varieties (one of them hybrid (HV)), compared to used landraces. Results are displayed for the three districts Lawra, Sissala East and Wa West and the two emissions scenarios SSP1-RCP2.6 and SSP5-RCP8.5.

With the exception of the cow peas variety, all improved varieties lead to small to high increases in yield depending on the district and the farmer type (8). For both maize varieties, the average farmer B can experience the highest yield increases. For farmer A, the inputs are the main limiting factor, making improved varieties only very efficient if combined with other improved management practices. Farmer C had the chance to put effective management practices into place, which gives only limited room for further yield increases when applying improved seeds. The high differences in yield increases between the different districts and farmer types emphasise the high dependency on the success of the adaptation strategy on soil characteristics and management decisions. However, these results are only exemplary and cannot allow conclusions for all improved varieties. The lower yields that are simulated for the improved cow peas variety compared to the applied landrace demonstrates that improved seeds have to be carefully selected, also in accordance with local soil and climatic conditions as well as crop management possibilities.

Applying improved seeds can significantly increase agricultural production. The positive effects highly depend on the variety, its suitability for local soil and weather conditions, the cultural acceptance of the product and the input need of the seed.

Risk gradient

The yield changes for sorghum and the two maize varieties show similar trends under current climate as well as under the two different emissions scenarios, making these three improved varieties a risk-independent adaptation strategy. This is certainly not the case for all improved varieties since many varieties are bred for specific climatic conditions and are thus risk specific.

5.2 Cost-Benefit Analysis

Cost-effectiveness

The cost-effectiveness of improved seeds depends on its costs as well as on the costs for accompanying learning and restructuring measures of agronomic processes. The costs for improved seeds can vary greatly from farmer to farmer depending on their market access. Farmers' financial possibilities can inhibit the adoption of improved seeds due to initial investments that are needed to buy seeds and adopt agricultural practices. The adaptation strategy cannot be equally taken up by all groups due to the high requirements in access to information and financial services, which is not equally available for all farmers but depends on social characteristics like gender and social class (more information can be found under the assessment criterion "differential vulnerabilities").

Expert interviews revealed that farmers in Sissala East are more commercially oriented than in the other two districts. Therefore, the potential to adopt improved seeds is expected to be relatively high in Sissala East. Commercial farmers are likely not only to buy improved/hybrid seeds but also other necessary accompanying packages such as fertiliser inputs which might be expensive for subsistence/relatively poor households. Therefore, this adaption strategy primarily targets those farmers who would be able to buy improved seeds as well as other input packages. However, provided that enabling environments such as credit services are made available to larger populations of farmers, this adaptation strategy can also be adopted by farmers who are facing financial constraints.

The CBA of improved maize is done using detailed farm level production and economic data collected from the Sissala East district. The data is collected from three farms that are currently using landraces and improved seeds (hybrids and non-hybrids) [31]. Farmers were asked to provide detailed information on costs of production, yield and market prices. The production costs accounted for in our CBA analysis include input costs such as seed, fertiliser and herbicide. Other production costs include rent of tractors, rent of sheller and costs of labour required for land preparation, sowing, fertiliser application, harvesting, weeding and shelling activities. There exist various land use and rental arrangements in Ghana which include varying customary arrangements and other ways of accessing land through monetary and non-monetary arrangements such as sharecropping and fixed cash rental (Zackaria 2013; Bugri and Yeboah 2017). Due to these various forms of practiced land arrangements, the current study does not take the value of land into account in the CBA analysis. The unit of analysis is an acre of land since this is the commonly used unit in the UWR.

Results

Key outcome of the cost-benefit analysis is that using the chosen improved seeds is economically beneficial.

Table 3 presents the NPV, BCR and IRR of the various climate change scenarios. In all of the scenarios, the NPV is positive, the BCR is greater than 1 and the IRR is greater than the discount rate. Depending on the future scenario under analysis, the NPV reaches between 8373 and 13298 GH¢; with a BCR value in the range 1.8 - 2.4. This suggests that maize production would still be economically viable in all considered future scenarios. When comparing the different climate and socio-economic scenarios, the no adaptation scenario always showed lower NPV than the two adaptation scenarios. This suggests that there would be a possibility to minimize the impact of climate change through both adaptation strategies. Among the two adaptation strategies, the non-hybrid seeds seem to provide a higher NPV (9863- 13298 GH¢) compared to the hybrid seed with NPV in the range of 9485-12,082 GH¢. This is mainly due to the different yields projected by the two varieties applied in APSIM. Thus, this does not allow any general conclusion that non-hybrid varieties are economically more profitable than hybrid varieties.

[31] The interviewed farmers are listed in the supplementary material.

Table 3: CBA results of hybrid and improved maize in Sissala East.

Period	Current	Future: No CC		Future: RCP 2,6						Future: RCP 8,5					
Scenario	Baseline	No climate change		No adaptation		Hybrid		Improved		No adaptation		Hybrid		Improved	
Socio-economic	Baseline	Positive	Low	Positive	Low	Positive	Low	Positive	Low	Positive	Low	Positive	Low	Positive	Low
NPV (GH¢ acre^{-1})	8,698	11,108	8,373	11,249	8,734	12,082	9,485	13,298	10,526	10,620	8,193	12,082	9,488	12,528	9,863
BCR	1.89	2.17	1.83	2.18	1.86	2.29	1.95	2.41	2.05	2.12	1.81	2.29	1.95	2.33	1.98
IRR	81	87	80	85	81	85	81	80	76	84	80	85	81	79	75

5.3 Assessment based on Literature and Expert Interviews

Upscaling potential

As the level of adoption of improved seeds is very low, i.e. the level of usage is low, there is a large upscaling potential regarding the number of farmers that adopt new varieties, but also regarding the number of crops where farmers can switch to improved seeds. Currently, the demand of farmers for improved varieties is low as these are often costly and negative experiences have been made with F1 hybrids and replanting these, i.e. F2 hybrids.

These are some possibilities for upscaling:

- Breeding and multiplication of sturdy and high-yielding varieties, that farmers have access to (i.e. they can purchase and afford them) and knowledge about (extension services, participatory breeding/ farmer-breeder-collaborations),
- Extension services or cooperatives can make seeds accessible to farmers and show them in field trials,
- A formal Ghanaian seed system could be structured and build to breed according to farmers' needs. It should process the seeds, multiply them sufficiently and further ensure seed quality with registration and certification so that the seeds are beneficial and healthy,
- An empirical study investigated the factors that drive households to use new technologies such as the adoption of new seeds in the face of climate change (Etwire *et al.*, 2013). Their study suggests that targeting females, improving extension services, and raising awareness of climate change impacts promote the adoption of climate-related innovations.

Potential co-benefits

Improved seeds cannot only mitigate climate risks but have a range of other benefits that influence each other.

Through stable and increased yields, improved seeds can increase the household income by moving smallholder farmers beyond auto-consumption, so that they can sell products on the market. Also, improved seeds can improve or change the product quality in such a manner that it better meets demand and can be sold at markets (e.g. longer storage time, uniform shape).

Breeding has improved the quantity and quality of crop production. As yields increase, food security can be improved through greater availability of food.

Plant breeding can stabilise or even increase the micronutrient content of crops under unfavourable climate change conditions. This is done, for example, by reducing the sensitivity of crops to atmospheric CO_2, since research has shown that increased CO_2 levels reduce the micronutrient content of crops (Mbow *et al.*, 2019). Consequently, breeding can improve food security and global health by providing inputs that ensure high-quality food production under climate change conditions. New maize varieties in Ghana produce e.g. high quality protein that makes them more favourable than older varieties (CIMMYT; IITA, 2013).

Improved seeds can enhance living conditions in rural communities and, hence, decrease rural exodus.

In addition to climate change adaptation, improved seeds can contribute to climate change mitigation when they increase land productivity through improved yields and, hence, reduce land-use changes that are e.g. created through slash-and-burn agriculture devastating high-biodiversity and high-GHG tropical forests. Additionally, some improved seeds show better nutrient efficiency leading to less fertiliser use, the production of which requires a lot of energy and the use of which leads to the emission of the greenhouse gas nitrous oxide.

Less environmental impacts can occur with improved seeds through improved production systems (e.g. water- and nutrient-efficient varieties).

Potential negative outcomes

Focusing on improved seeds can lead to the loss of traditional landraces and accompanying local knowledge (Derbile, Jarawura and Dombo, 2016) and cultural customs. Landraces already experience genetic erosion (Bennett-Lartey & Oteng-Yeboah, 2008) driving an additional loss of biodiversity. A focus on improved crops and their better performance must be accompanied by ex- and in-situ conservation programs to avoid genetic erosion and conserve genetic resources for future needs.

Least input agriculture is the most common form of farming in the UWR. Many new and early maturing crop varieties cannot adapt to least input agriculture (Derbile *et al.,* 2016).

Investment costs in improved seeds and their inputs are higher than traditional farming practices. When the harvest is (partially) lost due to inadequate farming practices, extreme weather events, fall armyworms or bush fires, farmers might be left indebted.

Increasing use of improved seeds and their inputs make farmers dependent on the supply and on commercially oriented companies. The unreliable seed market, insufficient supply to rural areas and legislative changes restrict continuous access. Community-based seed systems and supply can buffer this dependency.

Institutional support requirements

Implementing a reliable and suitable seed system requires the involvement of many stakeholders which makes it an institution-led strategy. To allow farmers to make well-informed decisions about which seeds to use, the appropriate conditions have to be given. This includes the availability of inputs, suitable seeds, demonstration sites, credit systems and extension services. These factors need to be ensured and provided for accessible prices (Fosu-Mensah, Vlek and MacCarthy, 2012; Fagariba, Song and Baoro, 2018). Public institutions can support this by strengthening and supporting research and development, the private seed sector, cataloguing and testing of varieties, certification, breeding and multiplication laws and the development of credit systems, knowledge platforms and apps. Mabaya *et al.* (2017) specifically call for investments in the quantity and quality of extension services in Ghana, as this would promote the adoption of improved seeds and good farming practices.

Institutional support is needed for the development and use of improved seeds meeting the requirements of local agro-ecologies under current and future climate.

After the several attempts, a new bill protecting the rights of breeders has just passed into law at the end of 2020 (Press release, Parliament of Ghana, 2020). The 'Plant Variety Protection Bill' has the aim to 'establish a legal framework to protect the rights of plant breeders of new varieties of plants or plant groupings and to promote the breeding of new varieties of plants aimed at improving the quantity, quality, cost of food, fuel, fibre and raw materials for industry' (Press release, PFAC July, 2020). Meanwhile, several civil society organisations, notably the Civil Society Food Sovereignty Platform in Ghana, led by the Peasant Farmers Association of Ghana, oppose the bill asserting that it is harmful to Ghana's development. They highlight several concerns including the bill's hostility to farmers traditional knowledge and exchanging seeds of so-called 'protected varieties', arguing that especially smallholder farmers will be put out of business, while the bill is heavily tilted in favour of the largest global seed companies. It is also asserted that the bill will undermine biodiversity and food sovereignty in the country as seeds will not necessarily be grown to suit local conditions. In addition, the bill is said to contain clauses that will further erode Ghana's sovereignty as a Republic, as for example, it seeks to limit the country from regulating the production, certification and marketing of any material of a variety or its importation or exportation. The platform of organisations, therefore, advocates for a Farmers' bill that promotes and protects the rights of farmers in general, particularly smallholder farmers, promotes local development of improved seeds, and protects Ghana's sovereignty as a Republic (Press release, PFAC July, 2020).

Barriers for implementation

Many factors constrain the adoption of improved seeds. Improved varieties do not always match farmers' and consumers' needs due to a new taste, different agronomic or cooking qualities, shorter storage capacities or a different size or colour (Pardoe *et al.*, 2016). The supply of the required seeds and fertiliser may be unstable (Pardoe *et al.*, 2016), especially in remote areas. Inadequate seed distribution systems lead to unavailability, long travels or high prices of improved seeds and their required inputs (Bennett-Lartey and Oteng-Yeboah, 2008). Especially at the beginning of the rainy season when seeds and new inputs must be bought, the availability of financial means for the more costly improved seeds is limited (Pardoe *et al.*, 2016). A farmers' cooperative or the easy accessibility of microcredits could help to overcome this shortage. Additionally, some farmers did not achieve the desired yields due to mismanagement or inadequate seeds. In return, the trust in seed vendors is low. Stakeholders are thus calling for community-based seed systems to regain trust and accelerate the uptake of improved seeds (discussions at inception workshop, 2020). Dapilah and Nielsen (2020) show that climatic barriers, such as the increased occurrence of extreme weather events, additionally hinder the adoption of adaptation strategies. Extreme events devastate agricultural production and can leave farmers, who previously invested in improved seeds, indebted.

The use of improved seeds is hindered by high input costs, lacking trust of farmers and unreliable access to inputs, credits and information.

Only a few companies in Ghana produce and process seeds (Access to Seeds Index, 2019). Breeding is a capital-intensive sector and inadequate funding and training for breeding programs is a major constraint. Unclear policy guidelines for crop multiplication, crop improvement and commercial production put additional constraints on breeding programs (Bennett-Lartey and Oteng-Yeboah, 2008). Research on all crops (incl. wild relatives and landraces) has to be supported by governments and NGOs.

Currently, access to information about improved seeds and improved technologies is limited, while the support mechanisms to promote capacity development are poor (Mapfumo et al., 2013). Out of the 17 seed companies included in the Access to Seeds Index in Ghana, only two accompany their sales with extension services (Access to Seeds Index, 2019). According to Ghana's national seed plan (2015), the ratio of extension workers to farmers is 1:1.500 and thereby considerably lower than in other African countries (Mabaya *et al.*, 2017). This was also confirmed by many experts who called for better coverage of extension services as well as better training for extension officers (Expert interviews 7 & 8).

Extension officers emphasise that farmers are hesitant to use hybrid seeds as their re-use is limited. This goes against the traditional seed system approach which they have long known and used. Non-hybrid improved varieties, on the other hand, are seen as generally more friendly as the harvested seed can be re-used without a strong yield decline in subsequent crop cycles.

Differential vulnerability

Our crop model analysis shows that especially farmers with average access to inputs and technology can profit from yield increases with improved varieties (Chapter 5.1). Farmers with little access to finances are largely excluded from the more expensive use of improved seeds and the needed inputs. The efficient use of improved seeds requires access to a broad range of services including credits, demonstration sites, extension services, supply of inputs and seeds. Access to these services is not provided equally to all groups. Gender, education, literacy, spoken languages, financial means, migration status and location highly influence the access and, thus, the ability to adopt improved seeds. For example, 85 % of all extension officers are male (Mabaya *et.al*, 2017), leading to a structural disadvantage for female farmers. If active measures are taken to balance the unequal access to services, the use of improved seeds can reduce structural inequalities instead of further enhancing them. Depending on the introduction of improved seed innovations, groups that have not been active decision-makers or practitioners beforehand can be integrated into agricultural production due to new crop characteristics or learning events.

Chapter 6 – Agroforestry: Farmer Managed Natural Regeneration

Agroforestry is a complex field of interventions, comprising many different specific practices. The World Agroforestry Centre (ICRAF) offers one possible definition (ICRAF, 2019):

"Agroforestry is the interaction of agriculture and trees, including the agricultural use of trees. This comprises trees on farms and in agricultural landscapes, farming in forests and along forest margins and tree-crop production, including cocoa, coffee, rubber and oil palm."

ICRAF thus distinguishes between diverse types of agroforestry strategies. For this study, we analyse two very different forms of agroforestry: "Farmer Managed Natural Regeneration" (FMNR) and "Alley cropping". Each form has individual objectives, benefits and barriers, which will be further discussed in the next two chapters.

Whereas the concept of agroforestry often implies the planting of tree seedlings, the key distinction of FMNR is the absence of planting (Weston *et al.*, 2015). In FMNR systems, farmers use pruning to encourage the growth of trees and shrubs that regenerate naturally in their fields. The standard practice is that continuous grazing by livestock, regular burning and/or regular harvesting for fuelwood result in shrubs never attaining tree stature. FMNR practice, on the contrary, consists of selecting the most vital stems and protecting the remaining branches from livestock, fire and competing vegetation. Tree growth can be turned into a valuable resource without jeopardising but enhancing crop yields. FMNR is thereby a low-cost land restoration technique that can combat land degradation, having various benefits for farmers, biodiversity, soil and climate (Francis, Weston and Birch, 2015; Westerberg, Doku and Damnyag, 2019). FMNR is a practice found everywhere in the Sahel and particularly in Niger, where it was practised on 50 % of farmlands in 2004. Practices only differ in magnitude and tree density (Francis, Weston and Birch, 2015).

6.1 Crop-Model-based Evaluation

Risk mitigation potential

We quantified the effect of FMNR systems on crop production of maize, sorghum and cow peas under future climatic conditions, by simulating the shading in APSIM. The effect is simulated by reducing the solar radiation in meteorological files, with respective effects of this radiation reduction on temperature modelled through fitting a random forest model between radiation and temperature. Dependent on the farmers' capacities we applied three different management practices on the crops in APSIM. This is reflected in farmer type A, B and C as defined in Chapter 2.

Microclimate amelioration with the help of trees can increase growth and production of understory crops, especially during periods of adverse weather, such as droughts. However, excessive shading can also have negative effects on plant photosynthetic potential, adversely affect growth and yields. We simulated the effect of shading on the microclimate by the use of machine learning to predict the effect of 10 % shade on temperature from long-term weather data. Agroforestry can also lead to higher soil organic carbon content and can reduce soil erosion by stabilising the soil, especially on slopes and after heavy precipitation events. In addition, trees produce timber and non-timber products, which can be used for household consumption or for sale on the market. This additional value is contributing to livelihood diversification and thus the climate resilience of the farmers.

The results show that 10 % shading does increase the yields of maize and sorghum with different magnitudes depending on farmer type, district and emissions scenario. Cow peas, on the contrary, show lower yields under shading in the future. The different results in the districts can be explained by slightly differing climatic conditions and differing soil fertility. When increasing the shading in APSIM, the positive results of shading become smaller or negative. A higher density of trees or growing canopy covers and, thus, excessive shading can lead to negative effects on crop yields. Good management of the FMNR system (e.g. thinning of the forest canopy and eliminating some trees) is necessary to benefit from the highest yield increases.

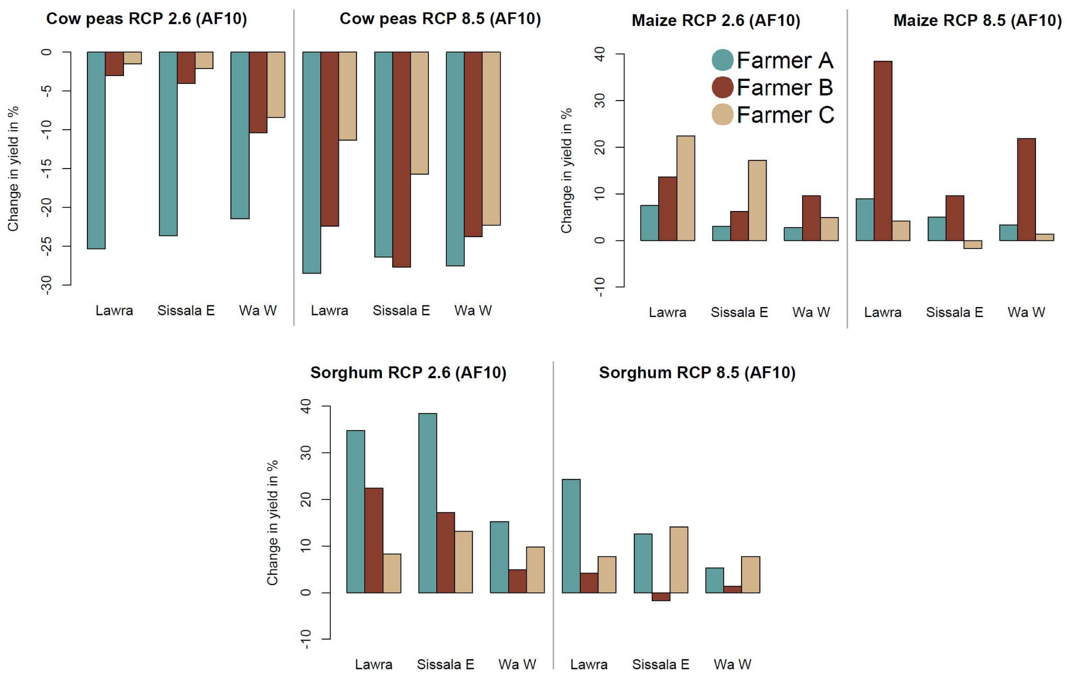

Figure 29: Projected changes in yield of maize, sorghum and cow peas based on multi-model median in 2050 (2041 - 2060) with adaptation strategy FMNR applied by agroforestry with shading of 10 %(AF10) compared to results without adaptation strategy in 2050 (2041 - 2060). Results are displayed for the three districts Lawra, Sissala East and Wa West and the two emissions scenarios SSP1-RCP2.6 and SSP5-RCP8.5.

The capability of FMNR systems to reduce negative effects of extreme precipitation events plays an even more important role under future climate change with increased risk of heavy precipitation events under the high emissions scenario (compare Chapter 1). Nevertheless, the benefits of FMNR are diverse and determined by complex interactions between trees, crops, soil, climate and management practices. The chosen simplification to simulate FMNR systems under future climatic conditions cannot explore the whole system behaviour under changing climatic conditions (e.g. tree growth might be different under temperature changes, which cannot be covered by the crop model).

In support with these findings, studies by Haglund *et al.* (2011), Place & Binam (2013) and Westerberg et al. (2019) also found strong crop yield increases under FMNR in different parts of the Sahel.

FMNR systems can increase yields of staple crops like maize and sorghum and reduce yield losses due to heavy precipitation events.

Risk gradient

The shading has a positive effect on sorghum and maize under the current climate and under a future climate under both emissions scenarios. This makes increased shading through FMNR a rather risk-independent adaptation strategy, even though the magnitude of this positive effect also depends on the climatic conditions and can increase under higher temperatures.

6.2 Assessment based on Literature and Expert Interviews

Cost-effectiveness

The Economics of Land Degradation (ELD) Initiative conducted a CBA based on the impact of interventions led by the Center for Indigenous Knowledge and Organisation Development (CIKOD) in the Lawra district (Westerberg, Doku and Damnyag, 2019). Due to the very detailed and comprehensive CBA done by Westerberg *et al.* (2019) in the study area, the results of this CBA are used here to show the cost-effectiveness of FMNR and to avoid duplicating research efforts.

A FMNR scenario, where farmers have a high tree density (13 trees per acre) is compared to a non-FMNR scenario with an average tree density of five trees per acre. With a discount rate of 5 % and a time frame of 20 years, farmers applying FMNR are found to be significantly more profitable than conventional farmers. This especially holds true for farmers applying additional strategies such as crop rotation (compare Table 4). Even under crop rotation only a smaller share (one fourth) of the increased NPV comes from higher crop income while a bigger part (three fourth) comes from higher forest incomes. The CBA was conducted under current climatic conditions and does not account for effects of climate change on yield. Our models showed that shading of crops through FMNR shows similar benefits under future and current climatic conditions, allowing for the conclusion that FMNR systems allow similar levels of crop income increases in the future.

Furthermore, other studies from Binam *et al.* (2015), Haglund *et al.* (2011), Rinaudo (2012), and Weston *et al.,* 2015 show the beneficial effect of FMNR systems on farmers' incomes.

Table 4: CBA of FMNR.

Scenario	Non-FMNR	FMNR	FMND & crop rotation
NPV (GHS/acre)	1,518	1,813	2,304
BCR	-	3.3	3.8
IRR	-	23 %	33 %

Upscaling potential

While conventional tree-planting requires seedling nurseries, transport, special tools and supplementary watering, FMNR requires no special inputs and is easily learned (Weston *et al.*, 2015). The high uptake of the FMNR practice in many parts of the Sahel region (Francis, Weston and Birch, 2015) and the success story of FMNR uptake in the neighbouring Upper East Region (Baxter, 2018b) gives hope to a high upscaling potential in the UWR. The absence of severe potential negative outcomes does not put any constraints on upscaling. Once ongoing, a successful, sustainable and holistic FMNR program appears to be self-sustaining and expanding as adopters see and experience the benefits of FMNR and become promoters themselves (Francis, Weston and Birch, 2015).

Potential co-benefits

FMNR cannot only mitigate climate risks but has a range of other social, environmental and economic benefits that are highly interconnected and are thus influencing each other.

Farming systems including FMNR have shown to be more profitable and bring additional income from timber and non-timber products as well as increased livestock production at different times of the year (Rinaudo, 2012; Place and Binam, 2013; Francis, Weston and Birch, 2015; Westerberg, Doku and Damnyag, 2019). Westerberg *et al.* (2019) state that adopting FMNR in association with crop rotations, farmers can earn an additional four GHS from the enhanced forest and crop produce for every GHS invested.

Farmers using FMNR in the UWR have shown to be more food secure since they can harvest a wide range of on-farm forest products during the dry season when it is most necessary to combat hunger. FMNR contributes to improve nutrition and calorie intake (e.g. from dawadawa seeds, ebony and mango fruits) (Binam *et al.*, 2015; Westerberg, Doku and Damnyag, 2019). Yield losses from storms, heavy precipitation events, droughts and pests can be reduced (Brown *et al.*, 2011; Westerberg, Doku and Damnyag, 2019). Westerberg *et al.* (2019) showed that farmers can increase the productivity of their cropland by a minimum of 83 % within five years. Also livestock production can profit from FMNR systems due to increased fodder availability and can in return increase food security.

FMNR can enhance rural livelihoods (Haglund *et al.*, 2011), and have psycho-social benefits (Weston *et al.*, 2015). The systems lead to health improvements, either directly through reduced wind speeds, airborne dust and provided cooling shade or indirectly through a stabilised income. Diverse food sources from forest products and access to medicinal plants also contribute to good health and well-being (Baxter, 2018b).

Higher tree density can support to cover bioenergy demand for cooking (Cunningham and Abasse, 2005).

The increased labour requirements for FMNR systems can create jobs in the region. The increased land productivity and decreased fertiliser need make it profitable for the farmer to move financial resources to hired labour (Westerberg, Doku and Damnyag, 2019).

Enhanced living conditions, social cohesion through whole-of-community approaches and higher generated income in rural communities through FMNR (Weston *et al.*, 2015; Westerberg, Doku and Damnyag, 2019) can decrease rural exodus. The interaction between tree planting and land rights is complex and based on customary arrangements. In some cases, planting trees on a farm can enhance farmers' land rights and tenure security (Lambrecht and Asare, 2015).

Regenerating trees contributes to climate resilience as well as to climate change mitigation by capturing carbon dioxide from the atmosphere in the trees and soil (Expert interviews 1, 7 & 8, Bayala *et al.*, 2020). Additionally, the micro-climate of the region is improved by higher tree density.

FMNR systems can combat land degradation by increasing soil moisture, soil carbon, fertility and decreasing erosion. They can, additionally, protect and increase biodiversity (Weston *et al.*, 2015; Westerberg, Doku and Damnyag, 2019; Bayala *et al.*, 2020). Once trees are mature, bush fires can be hindered (Expert interview 2). Households responded that FMNR systems on communal land improve social cohesion, which in return increases the common task to mitigate bush burning (Westerberg, Doku and Damnyag, 2019). For livestock, greater tree density can supplement grass fodder (Place *et al.*, 2009).

FMNR has various benefits as it is cost-effective, combats land degradation, contributes to climate mitigation, food security, livelihood diversification and social cohesion.

Potential negative outcomes

The literature review revealed only one potential negative outcome. Some tree species impact soil fertility unfavourably, such as the neem tree (Azadirachta indica), although it is a ready source of lumber for construction and fuelwood (Westerberg, Doku and Damnyag, 2019).

Barriers for implementation

Main barriers to adopt FMNR practices that were stated by farmers in the region are a lack of equipment (pruning knife, pickaxe, safety clothing, etc.), increased labour costs, destruction of small trees by wild animals, illegal tree cutting, bush burning, and the fear of expulsion due to weak tenure rights (Westerberg, Doku and Damnyag, 2019). Under insecure or informal tenure systems, such as sharecropping and lease-holdings, farmers are hesitant to make long-term investments in increasing the tree density on the farm (Damnyag *et al.*, 2012). Policies to make forest management sustainable and less vulnerable because of insecure land tenure are a prerequisite for increasing the scale of FMNR (Baxter, 2018a). Furthermore, the dispersed trees on the fields make it difficult to use heavy machinery which discourages farmers who are dependent on such for their crop production.

Institutional support requirements

Although farmers and entire communities can implement FMNR practises autonomously, institutional support is also needed. Many current national policy and development priorities in Ghana promote FMNR through commitments to reduce land degradation and fire as well as promote sustainable woodland management. Nevertheless, FMNR runs contrary to the way that North Ghanaian agriculture has developed in recent decades. Policies and programs have mainly focused on conventional farming techniques and mechanisation, encouraging extensive use of fertiliser and machinery (Westerberg, Doku and Damnyag, 2019).

While extension services fall under the responsibility of MoFA, activities related to FMNR (i.e. pruning, thinning, grafting, fire management, etc.) fall under the Forestry Services Division and Wildlife Division of the Forestry Commission (FSD & WD of FC) and thus woodland management techniques are not automatically covered by extension services. Westerberg *et al.* (2019) therefore express the urgent need to ensure harmonisation between the activities and mandates of MoFA and FSD & WD of FC.

To ensure a wide-spread implementation of FMNR systems, it is necessary that institutions or communities mediate whole-of-community agreements and regulations. This decreases the risk of setbacks due to tree cutting, bush burning and destruction by livestock (Francis, Weston and Birch, 2015).

Differential vulnerability

Besides some constraints to access information and equipment to establish FMNR systems, access to secured tenure, which is influenced by gender, social class, migration status or age, is the main factor in creating different possibilities in the uptake of FMNR.

Through promoting FMNR practices as whole-of-community engagements, all farmers, regardless of gender or age, are encouraged to participate (Baxter, 2018b). Whole-of-community approaches paired with reforms of the tenure system can also make the benefits of FMNR accessible to people who have difficulties to access other adaptation strategies. FMNR, thus, has the potential to decrease differential vulnerabilities. FMNR is especially useful for farmers without heavy machinery since the machinery is difficult to use on farms with dispersed trees. Gender wise, FMNR can improve women's livelihood through more efficient production and collection of firewood and forest products like shea nuts. Through promoting gender inclusiveness, FMNR provides a platform for women to share their knowledge and experiences as well as to be empowered and in return take on increasingly important roles in agricultural production and community decision making (Francis, Weston and Birch, 2015).

FMNR is one of the most easily accessible adaptation strategies and has the potential to decrease differential vulnerabilities.

Chapter 7 – Agroforestry: Cashew Plantation with Legumes

Alley cropping is a farming practice where shrubs or trees are grown in alternate rows with food crops. It is one subcategory of agroforestry. Under good management practices this can result in higher yields and better soil conditions while the farmer can additionally profit from the produce of the trees. Alley cropping in Ghana is most commonly done with cashew or mango trees. Cashew cultivation was introduced in Ghana in the 1960s and over the decades, it has contributed to the livelihood improvement of farmers and their households (Evans *et al.,* 2014). Cashew farming has been popular in the southern part of the country, but by now is also gradually spreading to the northern parts, largely due to NGO and development cooperation efforts. The 2010 census reported that only 1.9 % of farmers in the UWR were engaged in tree planting, mainly cashew and mango. Researchers have noted a rising number of households engaged in cashew farming over the past years with a concentration in the Sawla-Tuna-Kalba areas in the Savannah region south of the UWR (Evans *et al.,* 2014). In these areas and in the zone along the Black Volta in the UWR are particularly noted as falling within the 'cashew belt' - an area with well-drained, light to medium textureed and deep soils which are conducive to cashew cultivation (Dedzoe, Senayah and Asiamah, 2001). Extension officers point to the existence of only few cashew plantations in the UWR. It has been reported that farmers plant few of these trees on their farms to benefit from their shade, fruits and nuts. The gradual integration of cashew into farms can be seen as a positive step towards a more effective agroforestry approach. The adoption of cashew as a cash crop brings valuable income to farmers. It allows for alley cropping practices by integrating different kinds of food crops. Depending on the spacing between the trees, the intercropping can be permanent or only in the first years of tree planting before the canopies are closing. Most commonly, legumes including groundnuts, soybeans, bambara beans, and cow peas are used for intercropping to benefit from their ability to fix substantial amounts of nitrogen in the soil. (Antwi-Agyei *et al.,* 2014, Expert interviews 9 & 11). The cropping method serves as a good extra source of income until the trees start fruiting and as a natural fertilising method for the farmers (Expert interview 1). Legumes increase soil fertility by increasing the carbon stock in the soil, thereby boosting the yield of the cashew crop. The soil fertility is also enhanced by the ability of the legumees to retain the soil moisture by reducing evapotranspiration.

Cashew plantations are currently sparsely spread over the UWR. Cashew plantations can bring valuable income to local farmers and allow for intercropping of legumes.

7.1 Crop-Model-based Evaluation

Risk mitigation potential

Farmers in the Sissala East district report positive gains from the cropping of legumes with cashew trees (Fagariba, Song and Baoro, 2018). Extension officers confirm similar results in the Sawla-Tuna-Kalba district. According to Dedzoe (2001), most areas in Lawra, Sissala East and Wa West have suitable but not perfect soil and precipitation characteristics to grow cashew. A study by CIAT (2014) used the MAXENT software, based on the maximum-entropy approach for modelling species niches and distributions, to simulate current and future suitability for cashew production in Ghana. The study results project a strong increase in the suitability of cashew production in the UWR until

2050. Suitability is shifting from marginal/good to good/very good in all parts of the UWR with high model agreement (Läderach, 2011).

The suitability to grow groundnuts and cashew is projected to remain stable or to increase under future climate change conditions in the UWR.

Also, the suitability to grow groundnuts in the UWR is projected to remain stable or increase under future climate change conditions (see Chapter 2). Thus, alley cropping of cashew intercropped with groundnuts is promising since cashew as well as groundnuts are belonging to the few crops where no yield declines are expected under climate change.

The effect of cashew trees on groundnuts yields is complex. Competition for water and light between trees and the crops leads to a decrease of yields after a certain tree density and tree maturity.

Risk gradient

The cashew-groundnuts production can also be applied in the absence of climate change. Nevertheless, it is likely that the production even increases under future climatic conditions, since the suitability to grow cashew in the UWR might increase.

7.2 Cost-Benefit Analysis

Cost-effectiveness

"If you plant cashew an acre, it's better than farming three acres of maize because there is more profit in cashew than even in cocoa." (Expert interview 10, Sissala East)

The stakeholders and interviewed experts repeatedly mentioned the high economic potential of cashew plantations. The Cost-Benefit Analysis (CBA) of producing cashew and groundnuts using alley cropping as an alternative to sorghum production leads to the same conclusion. The CBA was conducted using detailed farm level production and economic data collected from the Lawra and the Sawla-Tuna-Kalba district. The data was collected from three farms that are currently producing cashew intercropped with groundnuts and three farmers that are producing sorghum[32]. The farmers were selected in consultation with stakeholders to be representatives of an average farm in the area. The interviewed farmers were asked to provide detailed information on costs of production, yield and market prices for the two crops. The production costs of cashew-groundnuts production, accounted in our CBA analysis, include costs of equipment, input costs such as seeds, seedlings and manure. Other production costs included costs of labour required for all the activities from land clearing to harvesting and drying. Similarly, the costs and benefits of sorghum production were estimated by accounting for the costs of equipment, inputs and labour requirements. The unit of analysis is an acre of land. The value of land is not taken into consideration for both cashew-groundnuts and sorghum production.

[32] The interviewed farmers are listed in the supplementary material.

Results

Table 5 presents the NPV, BCR and IRR of the various scenarios. Some of the scenarios of sorghum production show negative NPVs, others show a positive but low NPV. Similarly, the BCR of sorghum production under climate change and under the low economic setting are below 1, suggesting that sorghum production will become economically unprofitable under these scenarios. In most of the scenarios, the IRR also does not justify sorghum production as economically viable. Whereas, the NPV value of cashew-groundnuts reaches 15,289 GH¢ and the BCR and IRR values all suggest economic viability. Therefore, it would be economically beneficial to switch to cashew-ground nut production as the economic returns are higher under future conditions. Taking into consideration that cashew production allows for the commercialisation of several by-products like wood, cashew fruit and products from beekeeping, cashew plantations become even more profitable.

Cashew plantations intercropped with legumes have a great economic potential, particularly when the whole product chain is utilised (i.e. combined with beekeeping, using cashew apple and nut as well as intercropped legume).

Table 5: CBA results of shifting from sorghum production to producing cashew and groundnuts.

Period	Current	Future: No climate change		Future: SSP1-RCP2.6		Future: SSP5-RCP8.5		Future: climate change
Scenario	Baseline	No climate change (sorghum)		No adaptation (sorghum)		No adaptation (sorghum)		Adaptation (cashew-groundnuts)
Socio-economic	Baseline	Positive	Low	Positive	Low	Positive	Low	Baseline
NPV (GH¢ acre^{-1})	48	748	-129	2,327	1,184	2,250	1,120	15,290
BCR	1.01	1.15	0.98	1.45	1.21	1.4	1.2	2.64
IRR	1	10	-4	17	11	17	10	194

7.3 Assessment based on Literature and Expert Interviews

Upscaling potential

Several factors underpin the upscaling potential of this adaptation strategy. These include the general suitability of the UWR and large areas beyond for cashew and legumes, the general success of early farmers, the high income possibilities, the increasing market for cashew (Expert interview 9), the positive projections of cashew and groundnuts under climate change conditions (Chapter 2 and 7.1) and the drive by NGOs and government to support cashew farming (Expert interviews 9 & 10). Cashew has the advantage to be a low-input crop, which requires only small irrigation efforts after maturing and no use of pesticides (Expert interviews 7 & 8).

A study by the African Cashew Initiative has shown that pollination initiatives like beekeeping can raise cashew yields enormously. Yields have increased in study locations in Ghana by an average of 116.7 % where beekeeping was integrated (African Cashew Initiative, 2013). Furthermore, beekeeping can bring additional income to farmers through the sale of honey,

Cashew plantations have a great potential in the UWR. Nevertheless, extensive implementation of cashew production comes with several negative side effects. Small-scale cashew production that is integrated on the farm might thus be more suitable.

beeswax and propolis (Evans, Mariwah and Antwi, 2014). The fresh cashew fruit (cashew apple) is currently underutilised or wasted. It has great potential to be processed into a variety of snacks and food, with high economic and nutritional value (Ackah *et al.*, 2020). Using the whole cashew chain needs careful planning, experience and investments to in return bring high revenues. Additionally, extensive cashew planting harbours the risk of negative outcomes on nature and society, which have to be considered carefully when upscaling cashew plantations.

Potential co-benefits

Alley cropping with cashew and groundnuts can mitigate climate risks and provide a range of other benefits that are highly interconnected and are thus influencing each other.

As a valuable cash crop, cashew brings additional income to households. Income from cashew plantation is highest shortly before the rainy season when it is most needed for farmers. Selling the by-products (e.g. cashew apple juice, fruit as feed for livestock) can create additional income (Evans, Mariwah and Antwi, 2014). Opportunities to engage in beekeeping are growing under cashew production, which comes with a favourable impact of further income from honey, beeswax and propolis.

Stable annual income from cashew can contribute to no hunger in the communities. The intercropping of groundnuts can provide rich nutrients and proteins already in the first years of planting.

Stable annual income from cashew can contribute to increased living standards and better health conditions. Cashew is rich in fibre, heart-healthy fats, and plant protein and are a good source of copper, magnesium, and manganese. Using the cashew for own consumption can help diversify food sources (also through by-products like honey and cashew apple) and thus contribute to SDG 3.

According to Evans et.al (2014), increased cashew production has enabled farmers to pay for their children's education.

Higher income opportunities due to cashew plantations can enhance living conditions in rural communities and can decrease rural exodus.

Planting cashew trees contributes to climate resilience as well as to climate change mitigation by capturing carbon dioxide from the atmosphere (Expert interviews 1, 7 & 8). Additionally, the micro-climate of the region is improved by tree planting. These benefits apply only in case the plantations are established on bare land and no former trees are cut to create space for the plantations.

Cashew trees can increase soil quality by higher soil moisture and decreased erosion (Expert interviews 6, 7 & 8). Intercropping with groundnuts can fix nitrogen in the soil (Expert 1). Once trees are mature, bush fires are hindered (Expert 2).

Potential negative outcomes

The extended use of land for cashew plantations can increase food insecurity since less land is cultivated with food crops. Reduced engagement in multiple land uses by focusing on cashew plantation does not only reduce biodiversity but also increases the risk of crop failure. Given the concern about increased food insecurity, some community chiefs in the Brong-Ahafo region (in central Ghana) call for people to stop the expansion of cashew and instead reserve a portion of their land for food crops. Increasing the planting distance between cashew trees to around 30 meters to allow for enough space for growing food crops has proven to be a reliable alternative to dense cashew plantations (Evans, Mariwah and Antwi, 2014). Also trimming is key to ensure profiting from the intercropped legume. Learning from regions further south in Ghana or in Burkina Faso, where cashew cultivation is already more common than in the UWR, and adopting strategies like increased planting distance can reduce the negative outcomes greatly.

Temudo and Abrantes (2014) state that farmers are concerned about their weak bargaining position in negotiating fair prices with export companies and intermediaries. Greater integration into the global economy through the cash crop cashew exposes rural actors to multiple risks and inequalities, such as the uneven effects of global economic trade, rises in food prices, hunger and food insecurity and growing competition for land. Evans *et al.* (2014) state that with stronger farmer associations and cooperatives cashew farmers have a chance of benefitting from greater integration into the global economy, through strengthened bargaining positions.

Another potential negative outcome is that the high workload and costs to establish a plantation might leave farmers indebted in case of a destruction of plantations, for instance due to bush fires or cattle intrusion (Temudo and Abrantes, 2014, Expert interview 10). The high investment costs and knowledge required makes it difficult for most farmers to profit from the adaptation strategy. Extensive cashew production has the risk of increasing existing inequalities (see assessment criterion "differential vulnerabilities").

Cashew plantations are not yet very common in the UWR. Varieties that are brought in might not be suitable for the local weather and soil conditions and a careful selection and pre-testing is therefore required (Expert interview 11).

Furthermore, sometimes, old and resilient forests are cut to provide space for cashew plantations (Expert interview 2), taking away the benefits of the forests for the communities and for climate change mitigation.

Barriers for implementation

Access to land seems to be a great challenge as many farmers face tenure insecurity, which hinders investment in any kind of agroforestry. This is enforced by complex socio-cultural norms, which keep non-land-owning farmers from planting commercial trees as they usually require long gestation periods. More so, the flexibility of the usufruct arrangements means landowners could take back their lands at any time (Expert interview 6). Additionally, the allocation of land used for food crops is very challenging for smallholder farmers in the first years when there is still no income from cashew and only part of the land can be used for intercropping (Expert interview 2). This situation could be improved by using new varieties that start fruiting earlier and are just coming in (Expert interview 9). Also intercropping of legumes with high distances between trees can bridge the years without income to some extent (Expert interview 1).

Further constraints include water scarcity to water young seedlings in the dry season, bush fires and cattle stampedes. In the first years, young cashew trees need good care to be protected from fire and cattle (Expert interviews 7, 8 & 10). Lack of knowledge, training, loans and interest is further hindering the adoption of cashew (Expert interview 3, Evans Mariwah and Antwi, 2014) and might also be a reason for the currently small cashew production in the UWR.

After harvesting, barriers include insufficient storage facilities, lack of vehicles and costs of transporting produce to markets where fair prices can be received (Evans, Mariwah and Antwi, 2014).

Institutional support requirements

Public institutions incentivise cashew production in northern Ghana. MoFA is providing seedlings for farmers for free in increasing numbers (Expert interviews 7, 8, 9 & 10) to keep investment costs low. Training and demonstration sites provide the necessary information and meet local interest. Institutional support can help to benefit from the whole cashew value chain, including the promotion of beekeeping, fruit juice production and cashew processing. To ensure guaranteed and stable cashew prices, farmers and the Cashew Growers Association call for governmental regulations of the sale prices in the same way as it is done for cocoa (Evans, Mariwah and Antwi, 2014).

While in the Brong Ahafo Region in southern Ghana, cashew production is widely spread due to the support of NGOs and MoFA, cashew production in the UWR can still be incentivised. Since cashew plantations have various potential negative outcomes, institutional incentives have to be carefully set to profit from the many benefits and reduce negative outcomes. Incentivising small-scale cashew plantations or planting few cashew trees on a farm combined with exploring the whole cashew production chain are promising solutions to minimize potential negative effects.

Differential vulnerability

High investment costs and low profit in the first years only allow farmers who have the financial means or access to credit to go into cashew production. Gender wise, the cultivation of cashew has largely remained a male-dominated activity (Fagariba, 2018, Expert 10). This mainly relates to land tenure systems, which are patrilineal in nature and lead to unequal distribution of land ownership. Women are mostly engaged in the collection of nuts which is labour-intensive, yet less rewarding (Evans 2014; Fagariba, 2018). The need to have secure land rights to grow cashew is not only a constraint for most women farmers but also for some male farmers. Access to land is not only determined by gender but also by, for example, social class, migration status and age.

Temudo and Abrantes (2014) put forward that rising privatisation and commodification of land due to increased cashew production already show negative social and environmental consequences. Evidence from a case study suggests that the expansion of cashew plantations is leading to increased land disputes and conflicts, with wealthier farmers being able to intrude into the land of poorer farmers. The shift towards cashew cultivation, thus, tends to be intensifying existing gender and generational inequalities in access to land and food insecurity. Furthermore, extensive cashew production leads to reduced land availability to grow food crops. The subsequent food insecurity is likely to have the greatest impacts on women and young people, further marginalising their usufruct land rights (Evans, Mariwah and Antwi, 2014).

These negative effects can also be reduced by applying small-scale cashew plantations or planting few cashew trees on a farm. In addition, community owned cashew plantations can bring enormous benefits while reducing negative effects.

Chapter 8 – Irrigation

The agricultural sector in the UWR is heavily dependent on water from precipitation. Since precipitation is increasingly erratic, irrigation can help farmers to adapt to these changing conditions and to pursue agricultural production under conditions which would otherwise be too dry. The FAO distinguishes between three types of irrigation: surface irrigation, where water flows over the land; sprinkler irrigation, where water is sprayed under pressure over the land; and drip irrigation, where water is directly brought to the plant (FAO, 2001). Even though irrigation is not widely implemented in Ghana yet, political as well as scientific interest in irrigation is high: A literature search with the database Scopus returned 366 results on the terms "irrigation" and "Ghana", most of which were published after 2007. Publications from the last ten years further show a clear focus on small-scale irrigation as linked to climate change, exploring irrigation in the context of climate adaptation and in comparison to other adaptation strategies (Laube, Schraven and Awo, 2012; Ndamani and Watanabe, 2016; Fagariba, Song and Baoro, 2018). A significant portion of studies has also explored linkages between irrigation and its effects on poverty reduction and food security (Swamikannu and Berger, 2009; Owusu, Namara and Kuwornu, 2011; Amankwah and Ocloo, 2012; Kuwornu and Owusu, 2012; Dogkubong Dinye and Ayitio, 2013; Adam, Alhassan and Akolgo, 2016; Balana *et al.*, 2020).

Ghana has abundant water resources from precipitation. However, actual levels differ across regions. The north has a unimodal precipitation regime with only one rainy season from May to September (compare Chapter 1) and even during the wet season, precipitation is not evenly distributed but concentrated in few heavy precipitation events. Hence, irrigation can lengthen the agricultural production season and allow for year-round farming, especially in the UWR (Appiah-Nkansah, 2009). Thereby two main irrigation adaptation strategies can be useful. First, supplying water needed during the rainy season and, therefore, mitigating the impact of dry spells on staple crops, and secondly, compensating crop failures in the rainy season by cultivating irrigated high-value cash crops during the dry season.

> Irrigation can especially be beneficial in northern Ghana, where the rainy season is short and dry spells are common.

Although the northern part of the country is relatively dry, it is nevertheless endowed with sufficient water resources to expand on irrigation. In terms of surface water, the UWR is connected to the Volta river system with the Black Volta flowing along the western border of Ghana. Other, albeit smaller and intermittent rivers are the Kulpawn, which originnates close to the northern border, flowing south-east and feeding into the White Volta around 100 km north of Tamale, and the Sissili, which originates in Burkina Faso and feeds into the Kulpawn. Lawra and Wa West profit from the Black Volta flowing directly through the district. The Black Volta is the only natural water body that does not dry out during the dry season, which is why most irrigation schemes have constructed dams and reservoirs to store water from various rivers, or boreholes to tap on groundwater (Appiah-Nkansah, 2009). Groundwater can be found in most locations at less than 10m from the surface, usually allowing for hand pumping (Appiah-Nkansah, 2009). Agricultural production in close proximity to water bodies has led to the silting of many streams in the UWR, which is why these bodies need to be desilted in order to make water available for irrigation and other uses (MoFA, 2020).

Irrigation systems in Ghana vary with regard to their ownership (e.g. by the government, community or private owners), initiator, source of water, operating body, size and other factors, such as technologies or energy sources used (Namara *et al.*, 2011). Overall, irrigation systems can be classified into two types, namely conventional ones initiated by the Ghanaian government or NGOs and emerging ones which are developed and operated by private entrepreneurs (Namara *et al.*, 2011). The first type of irrigation system has been largely funded by foreign donors and international organisations, such as the FAO and World Bank (Namara *et al.*, 2011). In the UWR, irrigation farming is not yet widely used[33], with the majority of facilities being operated by farmers themselves or members of the local Water Users Association (WUA) (Appiah-Nkansah, 2009). Facilities typically consist of a reservoir surrounded by a dam, which helps to collect surface runoff during the wet season (Appiah-Nkansah, 2009). In most cases, irrigation systems are designed in a way that the water from the reservoir is diverted directly to the cropland via open concrete canals and in some cases via non-concrete farm ditches (Appiah-Nkansah, 2009). Sissala East has only one dam and irrigation water is diverted mostly via subsurface conduits and stored in tanks which are evenly distributed at the irrigation site (Appiah-Nkansah, 2009). In the Lawra and Wa West district, farmers draw water from the Black Volta, mostly using pumps to flood their fields (Expert interview 4). The Wa West district has two dams at Siiru and Baleofili. However, these are dysfunctional allowing for just bucket watering and the use of pumps to cover only a small area. Besides government-initiated projects, there are also informal small-scale farmer-led irrigation systems in the UWR (Dakpalah, Anornu and Ofosu, 2018).

Irrigation is not yet widely used in the UWR and is mostly applied as dry-season irrigation of vegetables. Nevertheless, scientific and political interest is high.

In the UWR, irrigation farming is mostly an off-season engagement (December - March). It involves rice and vegetable cultivation, the latter including tomatoes, cabbage, pumpkin leaves, bean leaves, lettuce, watermelon, okra, pepper and garden eggs (Namara *et al.*, 2011, Expert interview 10). The irrigation of tomatoes is the most extensive and practised under all types of irrigation technologies. It has been the main contributor to the upscaling of irrigation development in the basin over the past two decades (Ofosu *et al.*, 2010).

Overall, the number of dams and dugouts is limited (Ndamani and Watanabe, 2015). A 2011 study counted a total of 84 small-scale dams and 54 dugouts in the UWR (Namara *et al.*, 2011). These infrastructures are not sufficient in order to serve the study area's population of 233,139 (Ghana Statistical Services, 2019). Many of the dams have not been renovated for years and are either not in operation or operating below capacity (Savannah Accelerated Development Authority, 2016). A study of major problems regarding irrigation in the UWR found that nine out of 12 study sites had collapsed or have poorly maintained canal networks, some of which were broken or choked with weeds and mud (Appiah-Nkansah, 2009). For example, at the irrigation scheme in Kokoligu, cropland was also used for grazing cattle, which is why many of the irrigation pipes had holes or were broken, leading to water wastage and affecting crop production (Dakpalah, Anornu and Ofosu, 2018). In mid-2019, the Ghanaian media reported that MoFA commissioned the construction of seven small-scale irrigation dams in the UWR (Business Ghana, 2019). These dams were expected to be completed within eight months and under the government's 'One Village One Dam' (IVID) - policy which was launched in 2018 to enhance dry season farming in northern Ghana (Business Ghana, 2019). In the study area, Degri in Wa West is the only beneficiary community (Business Ghana, 2019). Communication with MoFA stuff members revealed that the dam constructions are delayed. Additionally, concerns about the suitability of the dams to provide water for irrigation year around are rising due to the size of the dams and the lack of canals or other necessary infrastructure.

33 A map of existing water sources like dams, rivers and bore wholes in the Upper West Region can be found in the supplementary material. The map additionally displays the dams that are planned to be built by the EU Agriculture Development Programme (which REACH is part of).

8.1 Crop-Model-based Evaluation

Risk mitigation potential

Irrigation is a promising strategy to cope with erratic precipitation in the UWR now and in the future and thus can reduce climate risks. Climate change leads to increased evapotranspiration and uncertain and highly variable precipitation amounts, number of dry spells and length of the rainy season in the region (compare Chapter 1). This creates additional uncertainty regarding the already variable water availability for rain-fed agriculture. Irrigation, however, can help smallholder farmers to compensate for the negative impacts of erratic and insufficient precipitation sums: In the rainy season, irrigation can mitigate the impact of dry spells, while in the dry season, this strategy can compensate for crop failures from the rainy season through the cultivation of high-value cash crops (Namara *et al.*, 2011). In this way, irrigation can help to significantly stabilise agricultural production and food security year-round.

Various studies in northern Ghana have found positive links between irrigation and agricultural production, in addition to welfare levels:

Table 6: Collection of studies that found positive links of irrigation on agricultural production and well-being.

Region	Reference	Time frame	Key message	Yield/Income/ Expenditure change
Upper East Region	Adam, Al-hassan & Akolgo, 2016	2012/13 cropping season	Access to irrigation has a positive impact on farm household income.	The mean annual income of irrigation farmers was USD 4,164 compared to USD 1,314 for non-irrigation farmers.
Tolon-Kumbungu (Northern Region)	Kuwornu & Owusu, 2012	2011 (estim.)	Access to irrigation has a positive impact on yields	Access to irrigation technology increased cropping intensity by 73.6 % for rice, 32.1 % for pepper and 33.3 % for okra.
			Access to irrigation reduces food shortages during the rainy season (food shortages are concentrated between May and August).	Irrigation households suffered from food shortages during the rainy season for 1 day/week. For non-irrigation households, this number was more than 2.
Upper East Region	Laube, Schraven & Awo, 2011	2008	Access to irrigation has a positive effect on household wealth.	The average wealth of irrigation households was almost twice as high as that for non-irrigation households.
			Access to irrigation reduces seasonal migration.	31 % of irrigation households and 41 % of non-irrigation households had members seasonally migrating.

Beyond that, our analysis based on the bio-physical crop model APSIM also shows a positive influence of irrigation on crop yields during the rainy season. Under the climatic conditions expected in 2050, crop yields are increasing under irrigation, independent of the three crop types, districts and emissions scenarios applied in the crop model. We simulated the effect of irrigating sorghum, maize and cow peas during the rainy season by including the automatic irrigation module in the crop model. The model configures an irrigation schedule according to a soil moisture threshold, which is dependent on the specific soil properties. Even though the models simulate a quasi-ideal irrigation schedule that is difficult to obtain in reality, the results nevertheless show the potential that irrigation holds for coping with climate impacts, such as dry spells during the rainy season or variability of the onset and cessation of the rainy season, and for ultimately increasing yields in northern Ghana.

The bio-physical analysis shows that irrigation can increase crop yields by up to 75 %.

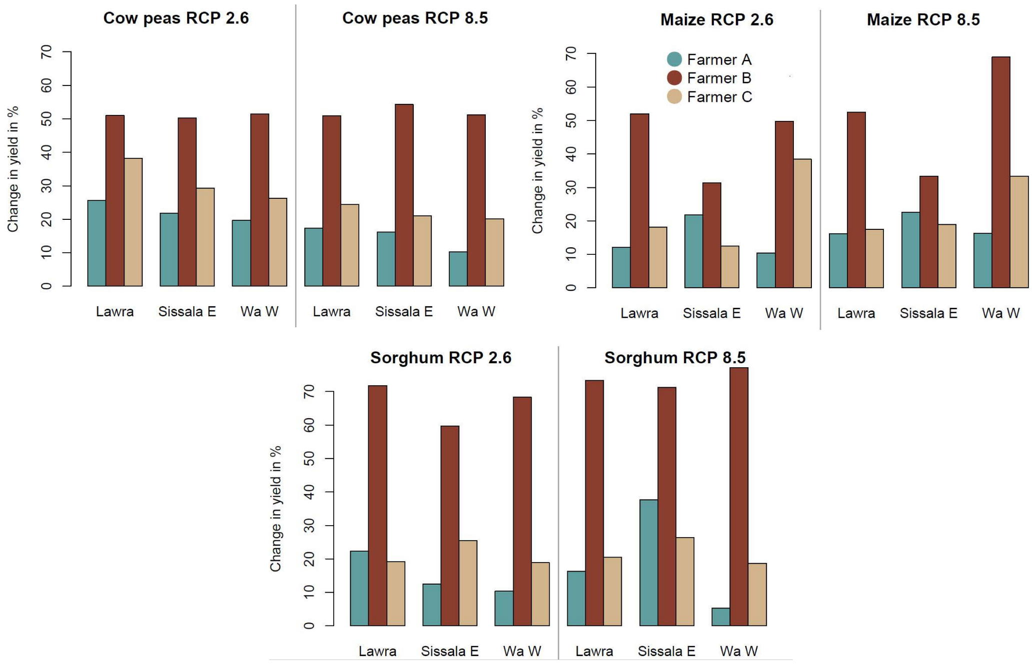

Figure 30: Projected changes in yields of maize, sorghum and cow peas based on the multi-model median in 2050 (2041 - 2060) with adaptation strategy irrigation compared to results without adaptation strategy in 2050 (2041 - 2060). Results are displayed for the three districts Lawra, Sissala East and Wa West and the two emissions scenarios SSP1-RCP2.6 and SSP5-RCP8.5.

The degree of yield increases from irrigation depends on the type of farmer. When irrigating, Farmer B[34] experiences the highest increases in crop yields between 30 - 75 %. This type of farmer already uses improved inputs and practices, which do not reach their potential due to limited water availability. For farmer A, the inputs are the main limiting factor, making irrigation only efficient if combined with other improved management practices. Farmer C already had the chance to put effective management practices into place, which gives only limited room for further yield increases when applying irrigation. Thus, farmer A and C can benefit from yield increases of only 10 - 35 % (Figure 30).

Irrigating staple crops during the rainy season in the UWR is not common, mainly due to the high investment and maintenance costs for larger fields. Nevertheless, our crop model analysis shows that there is a high potential in irrigation during the rainy season with yield increases of up to 75 %.

Dry season irrigation of high value crops, like vegetables, is much more common in the UWR than irrigating staple crops during the rainy season. Due to the limitations to model vegetable growth in APSIM, we based the crop model assessment on the four chosen staple crops. For the following economical and interview-based analysis we focus more on the interest of stakeholders in dry season irrigation.

34 Farmer types are specified in Chapter 2.

Risk gradient

Independently of the chosen model or emissions scenario, irrigation increases the yields for all three crops. The yield increases are of similar magnitude under current and future climatic conditions. Since precipitation amounts are projected to be of similar magnitude in the future, the irrigation potential is projected to remain stable. Nevertheless, irrigation is a risk-dependent adaptation strategy, since it is especially needed in case of increaseing dry spells and can only be applied if water resources are sufficiently recharged through precipitation.

8.2 Cost-Benefit Analysis

Stakeholders and interviewed experts stated that especially dry-season irrigation of high-value cash crops is highly profitable in the UWR (Expert interviews 5 & 10). In the Wa West district, this adaptation strategy can benefit from the relative advantage of sufficient water availability for irrigation as well as from the proximity to a large urban market. In terms of current water availability, the potential to use the Black Volta River for irrigation is high in Wa West and not yet fully used (Expert interview 8). With regard to market access, the Wa West district is located close to Wa, which is the capital of the Wa municipality district and the UWR. Vegetables such as tomato are perishable crops and cannot be stored for a long period. This is why market proximity is a major factor in sustaining economic profitability for farmers. As the demand for vegetables is generally high in urban areas, the proximity of Wa West to markets in Wa is an advantage to be benefited from.

In the current period, even though irrigated tomato production has a high potential as an income source, many farmers are not involved in this production activity. Some expert based estimations show that only about 14.5 acres of land are cultivated by tomato during the dry season in the Wa West district. The coverage of other dry season vegetable productions is also minimal. Therefore, we assume that the majority of farmers are not involved in larger-scale irrigated vegetable production during the dry season. We consider this as the reference for the current period. In the CBA, we evaluate whether producing tomato is profitable under future climate and socio-economic conditions to generate additional income during the dry season. Apart from Wa West, irrigation potential is existing in the Lawra and Sissala East districts as well. In Lawra, the Black Volta is a potential source of water, while in Sissala East, groundwater is the most recommended water source, according to research carried out by REACH.

The CBA of irrigated tomato production was conducted using detailed production and economic data collected from the Wa West district. The data was collected from three farms that are currently producing tomato using pump irrigation[35] from accessible rivers or dams. Similar to the data collection method for the other adaptation strategies, farmers were asked to provide detailed information on costs of production, yield and market prices of tomato production. The production costs accounted for in our irrigated tomato CBA included input costs such as seeds, fertiliser, pesticide and fuel. Other production costs included rent of tractors, costs of tools and costs of labour required for land preparation, nursery, planting, fertiliser application, harvesting, weeding and other activities. The costs of other tools such as rope and stake needed for tomato production are also taken into consideration. The unit of analysis is again one acre of land. The value of land is not considered in the costs of production.

[35] The interviewed farmers are listed in the supplementary material.

Results

Table 6 presents the NPV, BCR and IRR of the various scenarios of irrigated tomato production. In all the scenarios, the NPV is positive reaching between 18,197 to 26,727 GH¢ depending on the scenario. The BCR is greater than 1 and IRR is greater than the discount rate in all cases. This suggests that tomato production would be economically viable in all the considered scenarios. However, under a low socio-economic future scenario, the profitability will be lower than under current conditions. Whereas, the profitability will be relatively higher under a positive future socio-economic scenario. Furthermore, due to the 10 % decrease in yield that we considered under climate change, the corresponding scenarios under climate change are slightly less profitable. The conclusion is even when there will be a mild decrease in yield due to limited water availability or heat stress under climate change, dry season tomato production as an additional income generating activity could still be economically justifiable.

While irrigation is a cost intensive adaptation measure, the high economic return oftentimes justifies the investment costs.

Table 7: CBA results of irrigated tomatoes in Wa West.

Period	Current	Future: No climate change		Future: Climate change	
Scenario	Baseline	No climate change		Climate change	
Socio-economic	Baseline	Positive	Low	Positive	Low
NPV (GH¢ $acre^{-1}$)	20,736	26,727	19,922	24,710	18,197
BCR	1.82	2.09	1.76	2.01	1.70
IRR	64	69	63	67	61

8.3 Assessment based on Literature and Expert Interviews

Upscaling potential

According to the FAO, Ghana has an irrigation potential of around 4.7 million acre (FAO, 2020). However, in 2010, less than 2 % of the total cultivatable land of 39 million acre and less than 4 % of the total cultivated land of 19.4 million acre were actually irrigated (Global Yield Gap Atlas, 2020; FAO, 2020). These numbers reflect the situation in the study area, where, according to MoFA, less than 3 % of farming households are engaged in any form of irrigation.

According to Dakpalah *et al.* (2018), the UWR has enough land for agricultural production and sufficient water resources in order to expand on irrigation development (Dakpalah, Anornu and Ofosu, 2018).

Hydrological projections done within the study of Murken *et al.* (2019) show that only moderate changes of average discharge are expected in the UWR in the future due to climate change[36]. Nevertheless, high year-to-year variability of water discharge now and in the future limit the potential of irrigation substantially.

One component of the EU Agriculture Development Programme (EU GAP) will be investing in irrigation schemes based on dams, boreholes and the utilisation of water from the Black Volta River. It will, thereby, supply at least 200 communities in 14 districts with dams, water pumping stations and boreholes under the management of Agence Française de Développement (AFD) (REACH, 2020). This can provide many farmers in the UWR with the opportunity to engage in irrigation.

[36] One graph displaying the future projected discharge in the Black Volta River in Wa West can be found in the Supplementary Material.

Potential co-benefits

If developed in a planned and equitable manner, irrigation has the potential to contribute towards achieving several SDGs.

Irrigated dry-season gardening can create important income opportunities in the off-season and can reduce rural to urban migration.

Irrigation allows for the cultivation of non-traditional, high-value crops such as vegetables that can be sold on the market. Market-oriented production can help to increase farmer household incomes, thereby reduce poverty, and enable farmers to pay for books and school fees and purchase much-needed household items including cooking utensils, clothes or bicycles (Swamikannu and Berger, 2009; Amankwah and Ocloo, 2012; Dakpalah, Anornu and Ofosu, 2018).

Access to irrigation in the UWR can help farmers to grow high-value crops for household consumption and for sale at the market in the dry season. This is also the period when widespread hunger is most common.

Irrigation allows for the diversification and stabilisation of consumed food. In this way, farmers can improve their food security and dietary diversity. Stable income year-round from selling irrigated crops additionally contributes to well-being and good health.

Irrigation can provide additional income and job opportunities in the dry season for farmers. Depending on the type of technology, irrigation development requires also labour for the construction of irrigation facilities and their operation and maintenance (Swamikannu and Berger, 2009). Hence, especially larger-scale irrigation facilities can create employment opportunities, particularly for non-farming households in the region. They can also promote local agro-enterprises and contribute to overall economic growth and stability (Dogkubong Dinye and Ayitio, 2013; Dittoh, Lefore and Ayantunde, 2014).

Rural exodus rates can be reduced by providing job opportunities and income in the dry season. This is particularly important for the region's youth who often choose to migrate to urban areas in southern Ghana and search for employment, especially during the dry season, when food stocks in northern farmer households run low [2], [7, expert interview 5]. For example, the Tono irrigation scheme in the Upper East Region engages an average of 1,380 young people every season, which has helped to reduce migration rates (Dogkubong Dinye and Ayitio, 2013).

Potential negative outcomes

However, irrigation can also produce undesired effects and maladaptive outcomes. According to an analysis by Appiah-Nkansah, the lack of farmer participation, the low sense of ownership regarding public irrigation facilities and the unwillingness to pay for their operation and maintenance have led to poor operation and maintenance of facilities, which can be ascribed to a lack of knowledge and skills on the farmer side as well as inadequate supervision and extension services (Appiah-Nkansah, 2009). Regarding the environment, the expansion of irrigation can increase energy needs and lead to higher GHG emissions from agriculture (Zou *et al.*, 2013), conflicting with SDG13 on climate action. It can also incentivise the cultivation of riskier and more demanding crops, lowering agricultural resilience levels. Irrigation can lead to overexploitation of available water resources and thereby harm the environment and conflict with alternative water uses, e.g. for domestic use (Laube, Schraven and Awo, 2012). Uncontrolled upstream abstractions of water can cause shortages further downstream, which is why irrigation development should be planned in an equitable manner (Dakpalah, Anornu and Ofosu, 2018).

Institutional support requirements

Autonomous irrigation or farmer-led irrigation comes with high investments and is thus rare in the UWR. In order to realise the potential underlying irrigation development, institutional support is required in different domains, especially with regard to providing technical equipment, training and access to credit and markets (Owusu, Namara and Kuwornu, 2011; Ndamani and Watanabe, 2015, Expert interviews 7 & 8). According to Dakpalah, Anornu and Ofosu, the government, especially MoFA, along with development agencies, district assemblies and WUAs are considered as key institutions in promoting and facilitating irrigation development (Appiah-Nkansah, 2009; Dakpalah, Anornu and Ofosu, 2018). Farming communities should be involved in irrigation development and manage facilities jointly to develop a stronger sense of ownership, which will help to ensure maintenance and operation of facilities (Appiah-Nkansah, 2009). Full ownership and funding on the side of donors or the government can have a negative effect on the sense of ownership and responsibility of irrigation beneficiaries (Appiah-Nkansah, 2009). Conversely, the regular collection of a user fee can increase user commitment and ensure maintenance and timely repairs of canals. Such is, for example, the case at the Tiwii and Nyimati irrigation facilities which, compared to others, have well organised WUAs and well-maintained canal networks. Hence, Appiah-Nkansah recommends that beneficiary households either pay a small fee or contribute labour for the facility's maintenance and operation (Appiah-Nkansah, 2009). Local embedding of irrigation development and involvement of farmer communities can also help to create opportunities for sharing of land, labour and knowledge (Laube, Schraven and Awo, 2012).

Barriers for implementation

Depending on the irrigation facility, medium to high institutional, technical and financial support is required which comes with many barriers ranging from a lack of engineers and machinery to maintenance costs (Expert interviews 1, 2 & 5). Furthermore, finding a suitable spot for an irrigation facility is oftentimes challenging. Rivers drying out in some months of the year and low groundwater tables in some regions put constraints on setting up irrigation facilities. Since irrigated farming is not common in all parts of the UWR, farmers have too little information on the correct use of irrigation facilities. This can lead to loss of water, pest infestations, leaching of fertiliser and high maintenance costs of the irrigation facilities (Expert interviews 1, 6, 7 & 8).

> The high investment and maintenance costs of irrigation facilities call for institutional support to set up facilities. Irrigation facilities are only recommended in areas where access to water is cost effective.

Differential vulnerability

The construction and maintenance of irrigation facilities come with high investment costs, thus allowing only a few farmers to benefit from autonomous farmer-led irrigation. Governmental and community irrigation facilities can provide the facilities for a wider range of farmers. Nevertheless, gender, migration status and the location of the farmer still largely influence the access to irrigation facilities. While access to irrigation can help to empower women, it can also exclude them. Theis *et al.* note a gender gap in long-term adoption of irrigation technology (Theis *et al.*, 2018): Even where mechanised irrigation technology was available, it was often operated by men, while women used labour-intensive technologies such as buckets and watering cans, with the rationale being technological complexity or physical requirements. Irrigation development could help to improve the lives of women, since especially women are engaged in dry season vegetable gardening (Expert interview 1). Provided that women are given equal access to public and private irrigation facilities, training, credits and technological equipment, irrigation facilities have the potential to promote gender equality.

Chapter 9 – Uncertainties

The results presented in this study are subject to a number of uncertainties and limitations, which need to be thoroughly considered for a correct interpretation as well as for drawing policy implications and recommendations. Known uncertainties are transparently displayed in the results. Due to the high importance of understanding these uncertainties, this Chapter presents and discusses the uncertainties attached to the different types of analyses in this study in detail.

9.1 Climate Model Data

The performance of global GCMs has improved over the past decades. Nevertheless, some uncertainties surround the model projections. Future projections of temperature are more certain than of precipitation.

A climate model is a computer model, simulating the state and change rate of different Earth components, for example atmosphere, land surface, vegetation, ocean, sea ice, aerosols and carbon cycle (von Storch, 2005). The development of climate models has made vast improvements in recent decades, but climate models still display substantial biases in simulating the current climate. To remove the biases in the climate simulations thereby making the models suitable for our crop model analysis, climate data is statistically processed (bias-adjustment) with the help of observational climate data sets. 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, the step is necessary and suitable to obtain realistic simulations of climate impacts (Teutschbein and Seibert, 2012; Chen *et al.*, 2013). We analysed the performance of each individual to represent the current climate to ensure that none of the models shows extraordinary strong biases. Working with a climate model ensemble can additionally support reducing the biases that individual models show. 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 West Africa, the data sets have strong biases, especially on a fine-gridded scale.

The analysis of future climate in this report is based on five bias-adjusted GCMs produced within the ISIMIP3b project.

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 five chosen models show similar patterns as the whole CMIP5 model ensemble used in the IPCC AR5 (Niang *et al.*, 2014) and thus we can assume that the models are suitable to cover the range of possible future precipitation in the UWR. Furthermore, the five models cover a wide range of climate sensitivity[37] with equilibrium climate sensitivity (ECS)[38] values of 1.53-5.41K (Nijsse, Cox and Williamson, 2020). The two models UKESM1-0-LL and IPSL-CM6A-LR have a ECS higher than 4.5K, which is, according to various studies, very unlikely (Nijsse, Cox and Williamson, 2020). This means that the displayed

[37] The climate sensitivity of a model influences the future model projections. It describes how much the Earth's temperature changes after an alteration in the climate system, for instance, a changing CO_2 concentration.

[38] Equilibrium climate sensitivity (ECS) is an estimate of the eventual steady-state global warming after a doubling of CO_2 concentration in the atmosphere (Nijsse, Cox and Williamson, 2020).

temperature increase from the two models UKESM1-0-LL and IPSL-CM6A-LR show unlikely high future temperatures under increasing greenhouse gas concentrations. With 3.14K, the ECS of the multi-model median is well in the likely range and, thus, places our results also within the likely range.

9.2 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 (Folberth *et al.*, 2012; Rosenzweig *et al.*, 2014; Ewert *et al.*, 2015). 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 (Van Wart *et al.*, 2013), especially if highly localised weather data is needed as it is for this district study. Specific to our analysis, three main challenges occurred: First, the model input data may contain errors. This holds true for weather, soil and yield data. On the weather side, all past climate data sets carry uncertainties. Regarding the yield database, we applied preprocessing filters. Yet, this cannot exclude biases, which eventually result in unstable models. Second, specific to this case study, the short time series of only three years of crop yield and management data makes it difficult to estimate climatic impacts on crop yields. Third, the model design could be flawed, and a more apt formulation could better capture observed yield variation, in particular extreme losses. However, both model types (statistical and process-based) have often been applied (Schauberger, Gornott and Wechsung, 2017) and are unlikely to be inapt in general.

Quality and availability of data of weather, soil and yield are major constraints for crop modelling.

9.3 Cost-Benefit Analysis

The cost-benefit analysis (CBA) was conducted to evaluate the economic costs and benefits at the farm level of the four selected adaptation strategies. The CBA considered a representative farmer by taking average yields, costs and prices as it is done in many standard CBAs. Such CBAs are 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. Additionally, the number of three farmers for the data collection is likely not sufficient to exclude biases.

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 also translated into the analysis.

The number of farmers selected for data collection, future yield projections and assumptions about future economic development bring some uncertainties to the CBA results.

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 rural Ghana, 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.

9.4 Expert-based Assessment

To ensure the integration of local knowledge we conducted ten expert interviews with eleven experts working on regional and district level in the UWR. The assessment based on expert interviews suffers from a couple of limitations. The number of eleven experts interviewed is not sufficient to cover all perspectives, especially considering that the selection of experts was biased. While experts from different positions, districts and ages seem to have built a diverse expert cluster, from a gender perspective, women were underrepresented with a ratio of 2/11. The underrepresentation of women also holds true for the entire stakeholder group that was present at the workshops. Furthermore, we did not manage to include the perspective of pastoralists and Fulani herdsmen into the stakeholder group. Even though the limited number of women, pastoralists and Fulani herdsmen as decision-makers in the UWR put limitations on creating a balanced stakeholder group, our efforts to get closer to this aim have to intensify.

The travel restrictions after March 2020 due to COVID-19 made it more difficult to interview experts. Nevertheless, the cooperation with the UDS and, thus, having a Wa-based researcher, allowed for a continuation with only minor constraints. The applied analysis of interviews does not allow for stand-alone conclusions, since the expert interviews were, from the beginning, designed to only support the literature-based and model-based analyses.

> A more diverse group of stakeholders and interviewed experts regarding gender and migration status would benefit future studies.

Chapter 10 – Discussion & Recommendations

This study provides a comprehensive climate risk analysis for the three districts Lawra, Sissala East and Wa West located in the Upper West Region (UWR) in the north-western part of Ghana. The study aims at providing localised information on current and future climate risks for the agricultural sector to decision-makers in the UWR and beyond that can guide suitable adaptation planning and implementation in the region. For this we modelled the impact chain from a changing climate to resulting impacts on crop production and subsequent economic consequences for the three selected districts. We analysed the influence of socio-demographic variables like gender, age, and migration status on vulnerability to climate change to high-light the subsequent distinct needs of disproportionally affected people and groups in facing climate risks. The results then feed into an action dimension to assess different adaptation strategies. Based on the projected climate change impacts and expressed stakeholder interests, we assessed four adaptation strategies: improved seeds, alley cropping of cashew plantation with legumes, farmer-managed natural regeneration, and irrigation with regard to their risk reduction potential, their cost-effectiveness, and other socio-economic evaluation criteria, such as stakeholder interest and development co-benefits. Finally, the uncertainties attached to the results were critically discussed. Based on this, policy recommendations are given in this chapter following a short summary and discussion of the results.

Climate change reinforces the challenging conditions that smallholder farmers are facing in the UWR. Already today, variable climatic conditions are influencing the agricultural sector and climate risks are projected to become even higher in the future. Mean annual temperature is rising and projected to increase by approximately 1.1 - 1.9 °C until 2050 compared to 2005 depending on future greenhouse gas emissions. Mean annual precipitation sums as well as heavy precipitation events might increase under continuously high emissions. Only small changes are projected under low future emissions. The year-to-year variability of precipitation sums and dry spells within the rainy season is projected to remain high. We could not detect any clear changing trend in the onset of the rainy season.

Although our crop model analysis carries some uncertainties, the climate impacts in the next decades appear to have mainly negative influences on crop yields in the UWR. Maize, sorghum and cow peas yields are projected to decrease with high certainty between 1 and 30 % dependent on crop type, farmer type and districts. Groundnuts yields are projected to remain almost stable with only slightly positive or negative changes in the individual districts. When accounting for CO_2 fertilisation, groundnuts production could even benefit from climate change. Land degradation can further accelerate negative yield trends. On average, yield losses are projected to be lower in Sissala East than in Wa West and Lawra. The already higher vulnerability of farmers in the latter two districts compared to farmers in Sissala East, due to different micro climates and past economical developments, might thus further diverge in the future.

The actual climate risks that disproportionally affect people and groups face is not only shaped by the district but by a wide range of intersecting social characteristics like gender, age, social class and migrant status coming with specific needs, experiences and knowledge. Ignoring these different social characteristics and the intersection between them might aggravate rather than diminish existing inequalities. Adaptation planning therefore has to consider this differential vulnerability by considering the specific needs of disadvantaged people and groups and foster their participation in the planning process. Empowering all farmers to participate in political planning processes will ensure the inclusion of all (traditional) knowledge and skills into adaptation. Not only will participation of disproportionally affected people and groups lead to improved outcomes in adaptation, but it is also an important prerequisite for an increase of the adaptive capacity of a whole community.

Well designed and implemented adaptation strategies can balance present and future yield losses and have various positive social, economic and environmental co-benefits while also contributing to combating land degradation.

Generally, there is no "one fits all" adaptation strategy, since the most suitable adaptation varies with farmer and location. A combination of multiple adaptation strategies can often be an option to tap into the merits of more than one strategy. Nevertheless, this still needs further careful assessment to avoid conflicting effects (e.g. combining improved seeds with agroforestry might hamper the expected yield increase).

While all four adaptation strategies were found to be economically beneficial, they all bring different co-benefits, but also have potential negative outcomes.

Applying **improved seeds** can significantly increase agricultural production and contribute to stabilising yields under changing climatic conditions. Especially farmers with average access to inputs and technology can profit from yield increases with improved varieties. The outcome of using improved seeds, however, largely depends on the seed type, including its suitability for local soil and weather conditions, the cultural acceptance of the product, its continuous availability and the input need of the seed. While some improved varieties are high-yielding under current and various possible future climates, other varieties are risk-specific and only bring high benefits under specific weather conditions. For the moment, the uptake rate of improved seeds is still low in the UWR. To use the full potential of improved seeds, institutional support is required to enable the development of seeds meeting the requirements of local agro-ecologies. Community-based seed systems can further regain farmers' trust in improved varieties.

The agroforestry measure **cashew plantations intercropped with legumes** has great economic potential, particularly when the whole production chain is utilised (i.e. combined with beekeeping, using cashew apple and nut as well as intercropped legume). Alley cropping of cashew intercropped with groundnuts is promising since cashew, same as groundnuts, belongs to the few crops that might even benefit from climate change. Despite these promising effects, this strategy also comes with various potential negative effects, as extensive implementation of cashew plantation can lead to biodiversity loss, food insecurity and increasing social inequalities with implications on a global and regional scale. Carefully set institutional incentives are needed, that particularly support small-scale cashew plantations, which bear fewer risks of negative outcomes for communities.

Farmer Managed Natural Regeneration (FMNR) systems can increase and stabilise yields of staple crops like maize and sorghum and at the same time have various positive effects on the environment and communities. FMNR systems can combat land degradation, protect from the impacts of heavy precipitation events and contribute to climate change mitigation. Furthermore, farmers using FMNR have shown to have higher incomes and better access to nutritious food. In most cases, FMNR is applied as a community engagement, which increases social cohesion, decreases rural exodus and hinders human-induced bush burning. FMNR systems are targeted towards smallholder farmers without heavy machinery since the high density of trees limits the use of machinery. The upscaling potential of FMNR in the UWR is large and a wide uptake for smallholder farmers is recommended since no severe potential negative outcomes can be expected. The little requirements needed to implement FMNR make it an easily accessible adaptation strategy that has the potential to also benefit the most vulnerable groups.

Irrigation can mitigate climate risks in the UWR by on the one hand supplying water needed during the rainy season and, therefore, mitigating the impact of dry spells on staple crops, and on the other hand compensating crop failures in the rainy season by cultivating irrigated high-value cash crops during the dry season. While both forms require high investments, maintenance costs and technical knowledge, especially the former is cost-intensive due to the vast land used for staple crops, making dry-season irrigation the preferred option. No major change in water availability for irrigation can be expected due to climate change. Dry-season irrigation has the potential to considerably strengthen the livelihoods of farmers, especially female farmers, by creating income opportunities in the dry season, if equal access is ensured. In return, opportunities to use irrigation facilities can reduce rural migration. We recommend to upscale dry-season irrigation in areas where easy access to water makes it a profitable strategy without risking overexploitation of water resources.

Overall, these four adaptation strategies were found to be beneficial under the current climate as well as under a range of future climatic conditions including emissions uncertainties.

However, **three main barriers** are hindering the uptake of all four analysed adaptation strategies:

1. **Land tenure insecurities** discourage or even inhibit investments in adaptation strategies and can especially constitute a factor fostering social inequalities.
2. **Access to credits and inputs** is unreliable and not accessible to all farmers.
3. Farmers have **too little information on the benefits and implementation** of individual adaptation strategies.

These barriers to adopting adaptation strategies are present beyond the farm level and are outside the control of the farmers. Hence, a farm level decision for adaptation strategies will be effective only if supported by public institutions that enable change while at the same time supporting local ownership. To tackle these barriers, institutions shall guide a participatory tenure reform, ensure equal access to credits, inputs and high-quality extension service for groups who do not yet benefit from it and establish demonstration sites to showcase adaptation strategies. Providing the most vulnerable people and groups with information and access to finances and inputs can limit the risk of certain adaptation strategies to increase differential vulnerabilities and leads to more effective adaptation.

From a climate impact perspective, the presented results on these adaptation strategies can be upscaled to neighbouring districts and regions in northern Ghana, since the adaptation strategies show positive results under a wide range of future climatic conditions.

To build up a climate resilient society in the UWR, many more adaptation strategies can be involved which are not analysed here. Also changes in livelihoods including finding jobs outside of agriculture or migrating could be part of it.

Policy Recommendations

Based on the analysis of the four selected adaptation strategies, the following recommendations can be given:

- **Incentivise the development and use of improved seeds meeting the requirements of local agro-ecologies under current and future climate conditions**. The use of improved seeds has a great potential to increase yields in the UWR. Thus far, this potential is little explored. More research in local seed breeding including farmers' participation and local knowledge needs to be done. To allow a wide range of farmers to benefit from improved seeds, access to fertiliser, credit and markets are a prerequisite. To regain farmers' trust in seeds, stakeholders called for community-based seed systems.
- **Incentivise small-scale cashew plantations that explore the whole production chain.** Cashew plantations have great economic potential, particularly when they are combined with intercropped legumes, beekeeping and use of the cashew apple. The various potential negative effects on societies and biodiversity call for a careful incentivisation to profit from the economic benefits while reducing negative outcomes. To ensure guaranteed and stable cashew prices, governmental regulations of the sale prices are recommended by the Cashew Growers Association.
- **Support the wide upscaling of FMNR systems on community and household level.** FMNR has various benefits as it is cost-effective, regenerates soils, can be easily applied by a huge variety of farmers and highly contributes to improved and diversified livelihoods. The low requirements for input and technical equipment combined with a low risk of negative outcomes put no restrictions on the upscaling of FMNR in the context of smallholder farming communities.
- **Facilitate the development and maintenance of dams, rivers and boreholes for dry-season irrigation in areas where it is economically useful**. Irrigated cash crops during the dry season have a high economic potential, can mitigate migration and diversify diets. To benefit from irrigation, high investments in equipment and maintenance are needed, ownership should be created and access to markets for selling cash crops are a

prerequisite. The risk of overexploiting water resources and possible negative effects on biodiversity have to be carefully evaluated on the site. This makes it a highly beneficial but also costly, complex and support-intensive strategy.

Additionally, some key aspects help to build up an enabling environment for adaptation planning on district and farm level in the UWR:

- **Tenure security** encourages farmers to invest in adaptation strategies that need long-term planning. Government-led tenure reforms can be useful, designed and implemented at regional and district level. For effective formulation and implementation of such reforms, a thorough understanding of the causes of tenure insecurity as well as of community dynamics related to land tenure is needed.
- **Extension officers** should be well trained and informed by climate risks and the most suitable adaptation strategies. State-of-the-art scientific and local knowledge on climate change adaptation should be integrated into extension manuals.
- There is a **need to scale up extension services**, to ensure access for every farming household and across all social groups.
- **Adaptation planning on local level** and through a **multi-stakeholder involvement** process including farmers and community leaders, ensures the acceptability and success of the implemented adaptation strategies.
- **Limiting land degradation and the over-exploitation of natural resources** has to be a priority in the process of adaptation planning to ensure sustainable and long-term solutions under a changing climate.
- **Demonstration sites** for different adaptation strategies can gain the trust of farmers and trigger individual adaptation planning.
- Exploring the potential of **combining different adaptation strategies** can support tapping into the merit of more than one strategy.
- **Local priorities as well as natural and societal conditions** have to guide the selection of suitable adaptation strategies in the communities since none of the adaptation strategies fits to all farmers.
- **Reliable access to quality inputs and markets** is key to implementing most adaptation strategies.
- **Access to credits** enables low- as well as high-investment adaptation strategies. It can help to bridge the gap between making the adaptation investment and the point in time where the adaptation strategy becomes profitable.
- **Synergies and linkages with national plans** regarding climate change (e.g. NAPs, NDCs) and agriculture (e.g. Agricultural Sector Investment Plan, Planting for Food and Jobs) can foster the implementation of adaptation strategies.
- **Equal access to decision-making power, assets and land** can increase the adaptive capacity of the most vulnerable groups as well as the whole community. Ensuring the participation of disproportionately affected people and groups in political planning processes, where their knowledge can be integrated, contributes to effective adaptation and can mitigate the reinforcement of existing differential vulnerabilities.

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