Federal Ministry
for Economic Cooperation
and Development

Potsdam Institute for
Climate Impact Research

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

Climate Risk Analysis for Identifying and Weighing Adaptation Strategies in Ghana's Agricultural Sector

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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 report aims to contribute to Ghana's NDC implementation and to the objectives of the NDC Partnership.

In contribution to:

NDC
PARTNERSHIP

Climate Risk Analysis for Identifying and Weighing Adaptation Strategies in Ghana's Agricultural Sector

Lisa Murken, Christoph Gornott

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Author's contributions

Christoph Gornott and Lisa Murken coordinated and edited the overall study, with Christoph Gornott designing the study and contributing to Chapter 3, while Lisa Murken conducted expert interviews and contributed to Chapter 4. Paula Aschenbrenner performed the climate analysis in Chapter 1. Abel Chemura analysed climate impacts on crop yields and crop suitability in Ghana, leading on to Chapter 3 and contributing to Chapter 4. Fred Hattermann contributed to Chapter 6 on uncertainties. Hagen Koch and Stefan Liersch conducted the hydrological analysis for Chapter 2. Jascha Lehmann contributed to Chapter 1 on the analysis of changing climatic conditions. Felicitas Röhrig contributed to the adaptation assessment in Chapter 4. Bernhard Schauberger conducted statistical analyses on the link between weather and crop yields and contributed to Chapter 3 and Chapter 4. Amsalu W. Yalew conducted the economic analysis in Chapter 5 and contributed to Chapter 4. All authors contributed to Chapter 6 on uncertainties.

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Abstract

With climate change impacts increasingly affecting people's livelihoods and dampening economic growth perspectives, effective adaptation is essential to ensure that development goals such as food security and poverty reduction are achieved. However, often only limited information is available on climate risks, on which climate change adaptation decisions should be based. Therefore, this study provides a comprehensive climate risk analysis for Ghana at the national level, focusing on the evolving trends for temperature and precipitation, future water availability and the country´s suitability to grow crops. Different impact models are used, such as an eco-hydrological model or a semi-statistical and process-based crop yield model. The eco-hydrological model and four global climate models (GCM) are forced by the global climate scenarios RCP2.6 and RCP8.5 for this analysis. In addition, a crop suitability model is employed to identify future changes in crop suitability for maize, sorghum and groundnut in Ghana. Based on this information, adaptation strategies are selected and analysed with regard to their feasibility, cost effectiveness and aptitude for local conditions. Semi-structured expert interviews, a literature review and results from an impact analysis inform this selection and assessment. The selection was validated with partners from the Ghanaian government in line with its political priorities. Additional information regarding the economic potential for climate change adaptation is generated using a net-value-of-production approach, to evaluate the cost effectiveness of different adaptation measures under a range of cost scenarios. The overall results of the adaptation assessment are then combined in a multi-criteria assessment for the different adaptation strategies.

The results show that mean temperature in Ghana will increase considerably and robustly by mid-century, with the magnitude depending on the emission scenario. Precipitation projections, in contrast, carry large uncertainties and regional differences. Precipitation potentially slightly decreases in the South of Ghana and increases in the North in the first half of this century. Heavy precipitation events become more likely in the future, especially under the high emission scenario. Average annual water discharge under both climate scenarios increases until mid-century, whereas by the end of the century, either an increase or decrease in discharge appears possible, depending on the scenario. Areas suitable for maize, sorghum and groundnut production will shift by 2050, requiring a reorientation in some areas of Ghanaian agriculture. To cope with those impacts, the economic analysis reveals that post-harvest management can be a suitable adaptation strategy due to its high cost effectiveness. Irrigation is costly, however, it has the potential to considerably increase agricultural production. Crop insurance as a risk-transfer strategy is crucial to address climate risks that cannot be reduced. Generally, adaptation strategies should ensure local ownership, be complemented by capacity building and local extension, and, where possible, aim to combine strategies to increase effectiveness and create synergies.

Keywords: climate change adaptation, climate impacts, climate risk, agriculture, Ghana, cost-benefit analysis, multi-criteria analysis

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Next to addressing a scientific audience, this study is also meant to inform policy makers, especially with regard to climate change adaptation in Ghana. Thus, throughout this study emphasis was placed on clearly explaining the different methods and models used. Further information can be found in the supplementary material, as well as in the accompanying methods factsheet.

List of abbreviations

AMPLIFY	Agricultural Model for Production Loss Identification to Insure Failures of Yields
APSIM	Agricultural Production Systems Simulator
AYII	Area-Yield Index Insurance
CDD	Consecutive dry days
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMIP5	Coupled (climate) Model Intercomparison Project
ECMWF	European Centre for Medium-Range Weather Forecasts
FAO	Food and Agriculture Organization of the United Nations
GAIP	Ghana Agricultural Insurance Pool
GCM	Global Climate Model
GDP	Gross domestic product
GLC	Global Land Cover map
GRDC	Global Runoff Data Centre
HWSD	Harmonised World Soil Database
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace (Climate model)
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
MoFA	Ministry of Food and Agriculture – Republic of Ghana
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NVP	Net Values of Production
OECD	Organization for Economic Cooperation and Development
PET	Potential evapotranspiration
PHL	Post-harvest losses
PICS	Purdue Improved Cowpea Storage
RCP	Representative concentration pathways
RWH	Rainwater harvesting
SDGs	Sustainable Development Goals
SRTM	Shuttle Radar Topography Mission
SWIM	Soil and Water Integrated Model
VRB	Volta River Basin
WFDEI	WATCH Forcing Data methodology applied to ERA-Interim data
WII	Weather index-based insurances

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Introduction

Especially developing countries often lack adequate risk information for designing adaptation policies. This study seeks to address that gap for the case of Ghana.

While many countries recognize adaptation as an important component of their responses to climate change, little guidance on how to operationalize adaptation goals exists. 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, to date especially developing countries often lack comprehensive analyses of their projected climate risks and oftentimes have to take decisions in the absence of adequate climate risk information. Climate impact modelling plays an important role in filling this gap by enabling decision makers to design adaptation strategies and take investment decisions based on comprehensive risk assessments (Klein, Adams, Dzebo, Davis, & Siebert, 2017). This is precisely what this study seeks to provide for the context of Ghana: it combines climate impact modelling with economic and multi-criteria analyses[1], to identify the adaptation options[2] best fit for Ghana. A better understanding of projected climate impacts and of possible benefits of adaptation and risk-transfer solutions has the potential to guide, incentivize and accelerate public and private sector investments for a climate-resilient transformation. There is a lack not only of risk and impact assessments but also of accessible tools to assess costs and benefits of potential adaptation options. This can inhibit countries such as Ghana from gaining access to local and international climate finance, which is crucial for implementing their adaptation strategies. The present climate risk analysis can support actors in their access to climate finance by outlining quantified benefits of envisaged adaptation investments. Consequently, this study addresses this gap and offers advice for a wide range of actors from the public to the private sector, enabling improved decision making for climate change adaptation.

Agriculture is a critical sector for Ghana´s economy, accounting for about one fifth of the country´s GDP. Dealing with climate change is therefore of vital importance.

Due to its geographic location and economic depence on agriculture, Ghana is particularly vulnerable to climate change. Agriculture is the cornerstone of Ghana's national economy and is key to ensuring food security as well as to maintaining the trade balance. It is the main source of people's livelihoods, employment and export earnings. Cash crops such as cocoa contribute largely to the country's GDP. In 2017, cocoa production alone accounted for as much as 1.8% of Ghana's total GDP, with the total share of agriculture being 18.3% in the same year (Ghana Statistical Service, 2018). Staple crops such as maize, millet and cassava are of great importance for food security. Agriculture is also among the sectors most exposed to climate change since crop production crucially depends on water availability and suitable climatic conditions. Conversely, those factors are influenced by changes in precipitation (variability) and temperature projected under climate change. Already today, these shifts have become reality in Ghana. Stakeholders from various sectors including research, governmental counterparts of German development cooperation, development and civil society have confirmed that smallholder farmers in Ghana are increasingly challenged by climate-induced uncertainty and variability of weather, particularly in the northern regions of Ghana. The majority of smallholder farmers depend on rain-fed agriculture with only a small fraction using irrigation techniques. This reliance on rainfall further increases the sector's vulnerability to climate change. In order for Ghanaian farmers to effectively adapt to climate change, a diverse portfolio of adaptation measures is needed ranging from climate risk reduction, risk transfer mechanisms for irreducible risks and finance solutions for the enhancement and further development of agricultural production.

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[1] All methods and models used throughout this study are explained in the relevant chapters, in the supplementary material as well as in the accompanying methods factsheet.

[2] Note that throughout this study, the terms "adaptation option", "adaptation strategy" and "adaptation measure" are used interchangeably and refer to specific adaptation actions that aim to lower the impact of (projected) climate change impacts on agricultural production.

Table 1: 2013-2017 average harvest area and yield of maize, sorghum and groundnuts for each region of Ghana.

Region	Maize			Sorghum			Groundnuts		
	Area (000ha)	% of national	Yield (t/ha)	Area (000ha)	% of national	Yield (t/ha)	Area (000ha)	% of national	Yield (t/ha)
Ashanti	138	14.5	1.55	—	—	—	6	1.1	1.4
Brong Ahafo	229	24.0	1.9	1	0.5	1.23	13	2.3	1.1
Central	91	9.5	2.15	—	—	—	—	—	—
Eastern	163	17.1	2.52	—	—	—	9	1.6	1.44
Greater Accra	4	0.4	1.05	—	—	—	—	—	—
Northern	113	11.9	1.66	61	27.7	1.62	113	20.2	1.63
Upper East	46	4.8	1.46	53	24.1	0.98	287	51.3	0.8
Upper west	63	6.6	1.55	101	45.9	0.89	131	23.4	1.18
Volta	53	5.6	1.68	4	1.8	1.44	—	—	—
Western	53	5.6	1.34	—	—	—	—	—	—
National	953	100	1.68	220	100	1.23	559	100	1.26

Source: MoFA (2018).

First conclusions for the improvement and stabilisation of agricultural production in Ghana can be drawn from Ghana's recent crop production profile. Owing to the heterogeneous agro-climatic conditions in the country (see right map in Figure 1), crop harvested area, yield and production vary significantly across regions (see left map in Figure 1 for Ghana's regions). Table 1 shows the 5-year average (2013-2017) harvested area and yield for maize, sorghum and groundnut in Ghana. The table shows that there is potential for switching crops in order to better adapt to climatic conditions and climate change, based on the yield levels attained in the different areas of Ghana.

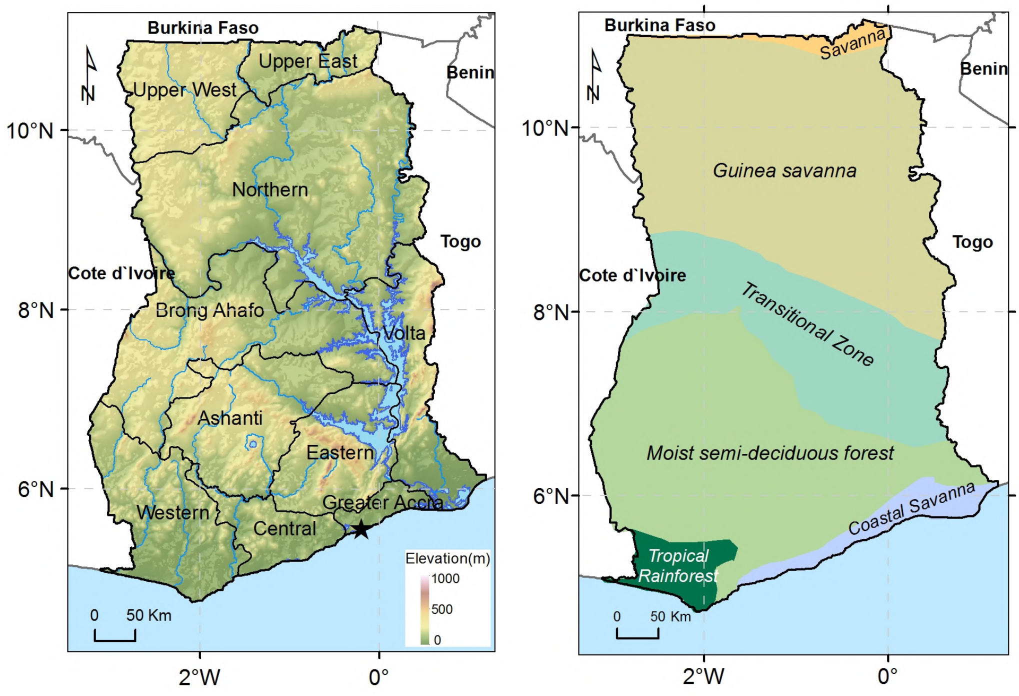

Figure 1: Map of Ghana with regions and elevation (left) and agro-ecological zones (right).

An example for this is sorghum, which is produced in the Upper West region, and maize, which is produced in the Brong Ahafo region, where the conditions for yield maximisation are not optimal, judged on the yield levels attained thus far (Table 1). In the past, the agricultural sector in Ghana has experienced positive growth, with production increasing rapidly since the 1990s (Choudhary, Christienson, Josserand, & D'Alessandro, 2016). In 2017, the agricultural sector grew by 8.4% (Ghana Statistical Service, 2018). This growth was partly due to public and private sector investments. However, these agricultural-production and related socioeconomic gains are now threatened by climate change, which poses risks to production.

The study provides an in-depth risk analysis for Ghana´s crop production, followed by a set of concrete recommendations on how to deal with these risks.

The present study provides an in-depth analysis of climate risks for Ghana's crop production, combining climate change impact assessments with recommendations for action. Chapters 1-3 look at the impact dimension of climate change in Ghana, then feeding into the action dimension in chapter 4 and 5:

- The first chapter gives an overview on future climate change impacts in Ghana, which are derived from Global Climate Model (GCM) results for two climate scenarios, namely RCP2.6 and RCP8.5. These two scenarios assume two contrasting possible future developments and were chosen as the two most extreme scenarios: while RCP2.6 describes a future mainly in line with the climate stabilisation targets defined in the Paris Agreement (staying below 2°C), RCP8.5 is associated with no attenuation of global warming and thus a substantially warmer world (a 3-5°C temperature rise by end of the century).
- Chapter 2 provides insights on the hydrological development in Ghana under climate change, with an assessment of future water availability for agriculture.
- In Chapter 3, future crop suitability under climate change is simulated for the different zones in Ghana.
- In Chapter 4, the combined insights from the climate impact analysis together with other criteria are used for identifying key adaptation strategies, aligned with the main adaptation policy documents from the Ghanaian government, in particular the NDC and the NDC Implementation and Investment Plan for the Agriculture Sector, which are useful for Ghana to reduce the impacts of climate change on its agricultural production.
- Chapter 5 presents an economic analysis of selected adaptation strategies.
- Chapter 6 critically discusses uncertainties related to the analysis and gives an outlook for future research to complement this work.
- Finally, a conclusion synthesizes the study results and key lessons. The results are meant to inform and support stakeholders from government, civil society and the private sector in effectively prioritizing and designing adaptation investments or to support effective investment decisions at individual or farmer-cooperative level.

Chapter 1 – Changing Climate Condition

1.1 Data and Method

Two scenarios were analysed - one with a temperature increase below 2 degrees (RCP2.6), the other without climate policy (RCP8.5).

To identify changes in future climatic conditions in Ghana, this chapter analyses temperature and precipitation changes under two global climate scenarios. Projected climate data was analysed to show the range of possible future climatic conditions until 2030, 2050 and 2090, thereby providing information for the near, mid-term and far future. To cover the full range of climate change projections, the climate change impacts were examined for the scenarios RCP2.6 and RCP8.5, which are the lowest and highest CO_2-emission scenarios covered by the IPCC reports. RCP2.6 represents a scenario that is likely below 2°C compared to pre-industrial temperatures (IPCC, 2014) and is thereby in line with the goals of the Paris Agreement. RCP8.5 is a high-emission scenario and refers to the scenario without climate policy.

The basis for the evaluation of the current and near-past climate is the WFDEI dataset (WATCH Forcing Data methodology applied to ERA-Interim data, the **E**uropean Centre for Medium-Range Weather Forecasts (ECMWF) **re**-**a**nalysis data) (Weedon et al., 2014). The WFDEI dataset consists of climate data which is observed on a daily basis, covering land (not above ocean) in the period 1979-2016. The simulated past and future climate data were obtained from ISI-MIP2b data (Inter-Sectoral Impact Model Intercomparison Project). The ISI-MIP was created to offer a framework for the comparison of climate impact projections in different sectors. The data are bias-corrected with the observation-based watch forcing data (Warszawski et al., 2014). Historical simulations cover the years 1861-2005 and projected simulations cover the years 2006-2100. All data sets have a spatial resolution of 0.5°x0.5°, corresponding to approximately 50kmx50km at the equator. ISI-MIP data combines data from four climate models: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M and MIROC5 (Frieler et al., 2017). The climate variables used for the analysis are daily maximum temperature, daily minimum temperature, daily mean temperature and total daily precipitation.

Observed daily data for the period 1979 to 2016 was used for projections and modelling. Four models were used, because results are usually better than with a single-model approach.

Multi-model means usually show better results than single-model results, which is why the results in the following chapters are averages from the four models. All climate data analyses are based on a 20-year average[3], meaning that the mean annual temperature in 2030 is calculated as an average from the mean temperature between 2021 and 2040. The reference for the pre-industrial time is the climate in 1880 (1871-1890), the present climate is referred to as the climate in 1995 (1986-2005) and the projected climate data is evaluated for the periods 2030 (2021-2040), 2050 (2041-2060) and 2090 (2081-2100). Days with heavy precipitation exceed the 95th percentile[4] of all wet days of a year and days with very heavy precipitation days exceed the 99th percentile. The number of rainy seasons was determined with the help of the percentage cumulative mean rainfall method, which is similar to the work done by Amekudzi et al. (2015).

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[3] Climate variables (such as temperature and precipitation) show high annual variabilities. 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.

[4] A percentile is a value below which a given percentage of observations falls. Precipitation values exceeding the 95th percentile are all values larger than 95% (considering only wet days).

RCPs - representative concentration pathways

The standard set of scenarios used in the 5th Assessment Report of the IPCC (2014) is the four pathways RCP8.5, RCP6.0, RCP4.5 and RCP2.6. Each RCP defines a specific emissions trajectory and subsequent radiative forcing. The RCPs are labelled after the additional radiative forcing level reached in the year 2100 relative to pre-industrial times (+2.6, +4.5, +6.0, and +8.5 W/m², respectively). Each RCP is consistent with a socioeconomic pathway. RCP2.6 assumes that through policy intervention, greenhouse gas emissions are reduced drastically and almost immediately, leading to a slight reduction of today's levels by 2100. The worst case scenario – RCP8.5 – assumes more or less no interventions and thus undiminished emissions (van Vuuren et al., 2011; Wayne, 2013).

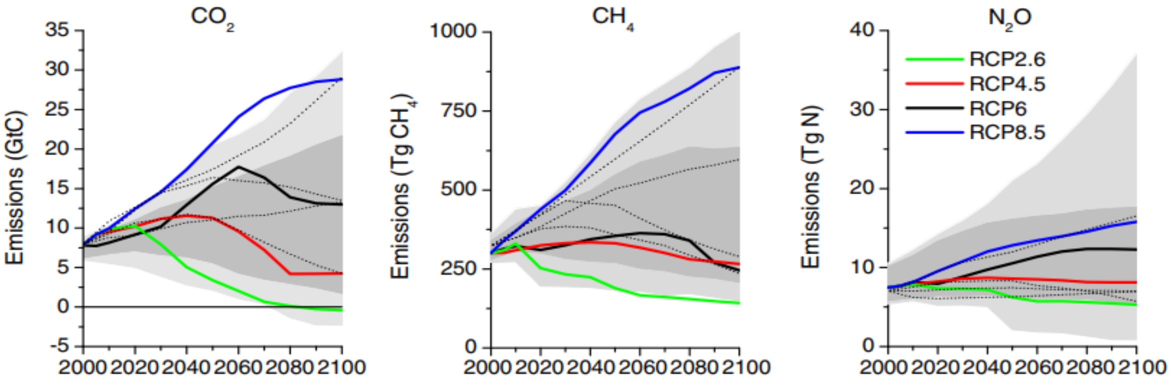

Figure 2: Emissions of main greenhouse gases across the RCPs.
Grey area indicates the 98th and 90th percentile (van Vuuren et al., 2011)

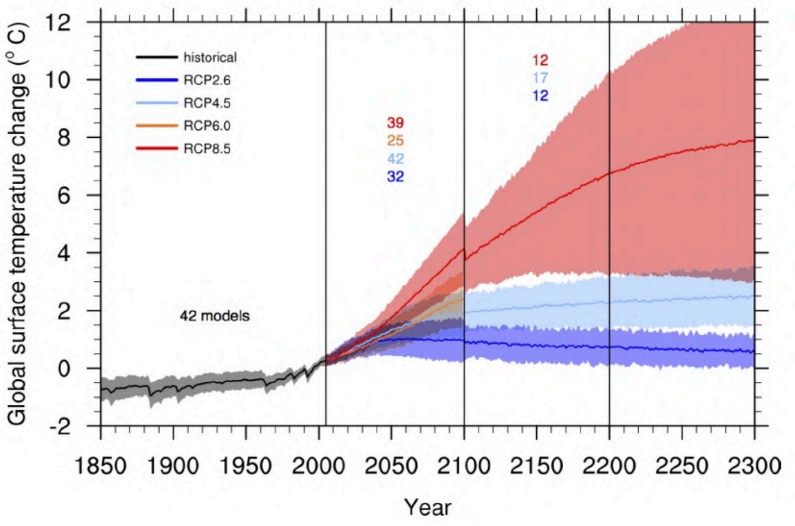

Figure 3: Multi-model global annual mean surface air temperature (relative to 1986-2005) for each RCP (IPCC, 2014).

1.2 Present Climatic Conditions

Ghana currently has two rainfall regimes: a long one in the North and two shorter ones in the South.

Ghana has a tropical climate with high mean annual temperatures in all six agro-ecological zones of Ghana (see Figure 1 for Ghana's agro-ecological zones). An agro-ecological zone is a "land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use" (FAO, 1996). The concept of agro-ecological zones facilitates the analysis of climate impacts and is used throughout this study. In Ghana, average mean annual temperature is 27.5°C with higher temperatures in the North and in the dry period. The average number of very hot days (maximum temperature above 35°C) has a variability of 0 to 200 days per year across Ghana with higher values in the North of Ghana. The average number of tropical nights (minimum temperature above 25°C) has a spatial variability of 0 to 130 days per year with higher values at the coast. Annual precipitation in Ghana ranges from 1000mm in the North to about 1800mm in the Southwest. Ghana has two rainfall regimes. The northern part has one rainy season lasting from May to October (modal rainfall regime). The south of the country has two rainy seasons lasting from April to July and from September to November (bimodal rainfall regime). Additional figures can be found in the supplementary material.

Extreme weather events under global warming in the past and future

According to the IPCC (2012), it is very likely that there has been an overall increase in the number of warm days and nights and an overall decrease in the number of cold days and nights. However, the past trend for extreme precipitation events is not that clear. Although, it is likely that more regions have experienced increases in heavy precipitation than decreases, there are strong regional and subregional differences in these trends.

The relation between future climate change and an increase in the frequency of extreme weather events is not trivial either. Confidence in projected trends of extreme events depends on region, season and type of extreme event. It is virtually certain that increases in the frequency and magnitude of warm daily temperature extremes will increase on a global scale. There is medium confidence that droughts will intensify in the 21st century in some areas and low confidence in other areas (including Ghana). It is likely that the frequency of heavy precipitation or the proportion of total precipitation from heavy precipitation will increase in tropical regions (IPCC, 2012).

1.3 Past Climate Change[5]

In the past, temperature rose on average by 0.1 degrees per decade in Ghana.

Ghana's climate in the recent past (1985-2010) was analysed using observational data. In this period, an increase in mean annual temperature of 0.1°C per decade averaged over Ghana was detected. The results show regional differences. The highest increases occurred in the South of Ghana and nearly no temperature difference was found in the East. Observed mean annual precipitation data show a negative trend for most of Ghana. The difference in mean annual precipitation has values of +3.5% to -8.0% per decade between 1985 and 2010. Heavy precipitation increased in the North and decreased in the South of Ghana while very heavy precipitation decreased in almost all parts of Ghana since the 1980s.

1.4 Projected Climate Change

Temperature is projected to rise for all four models and both scenarios in this century.

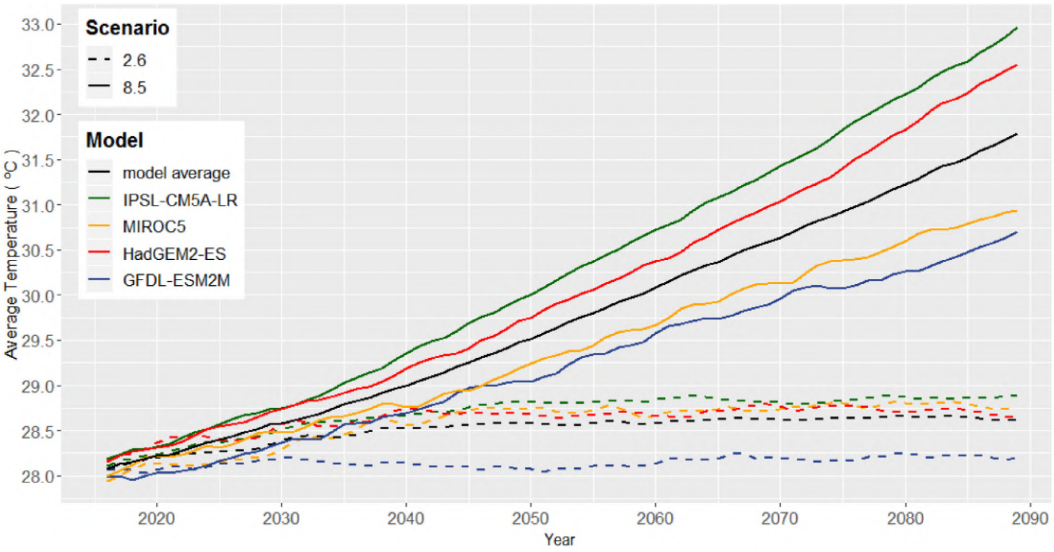

Figure 4: Projected mean annual temperature in Ghana for two emission scenarios and four global climate models.
The graph shows the smoothed increase based on a 21-year moving average.

Projections show a temperature increase in the range of 0.8 to 2.5 degrees between 1995 and 2050 in Ghana.

In all agro-ecological zones, mean annual temperature is estimated to increase between 0.8-1.3°C until 2030, 0.7-2.5°C until 2050 and 0.8-5.5°C until 2090 compared to 1995 depending on model and scenario. The greatest increase is projected for the North. Figure 4 shows the projected temperature differences in 2030, 2050 and 2090 for the different scenarios averaged for each of the four ISI-MIP models and the average over the four ISI-MIP models.

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[5] For this section see additional graphs in the supplementary material.

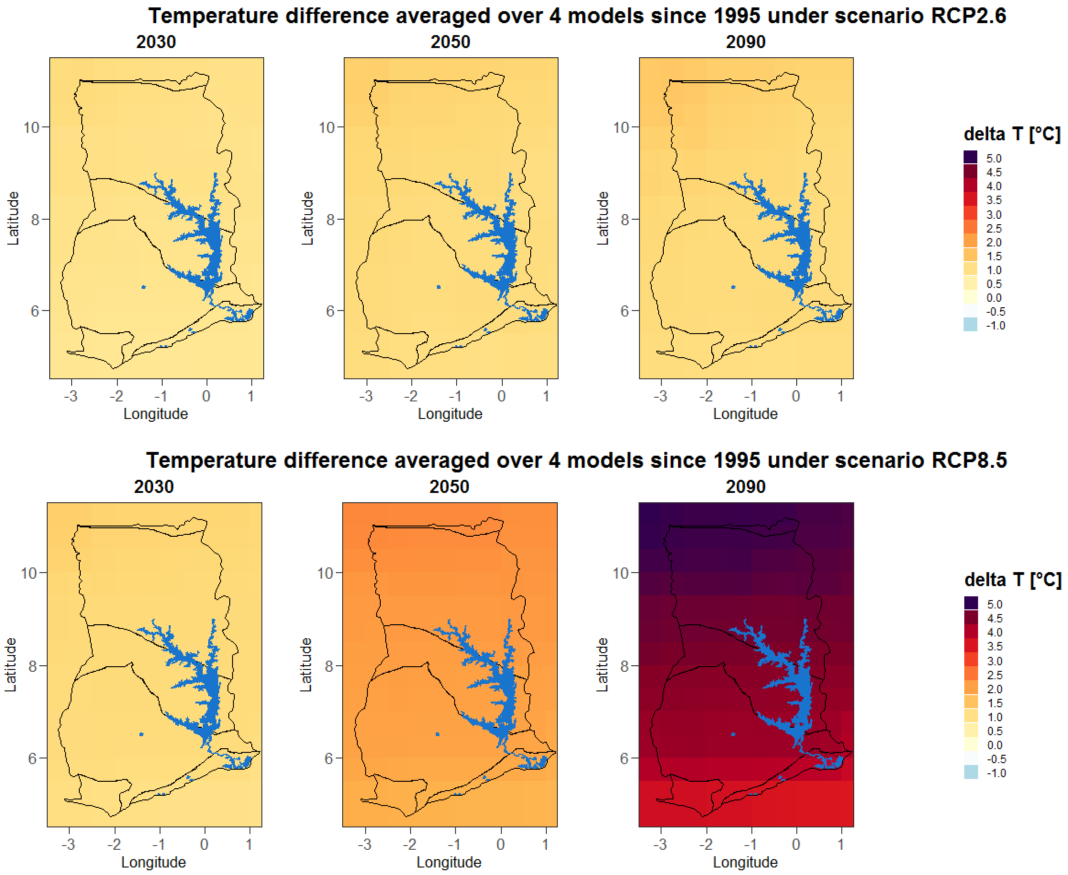

Figure 5: Temperature difference between 1995 and 2030, 2050 and 2090 under RCP2.6 and RCP8.5.

Table 2: Projected mean annual temperature and temperature difference for RCP8.5 and RCP2.6. All values in bold show the multi-model mean[6]. The values in brackets show the model range.

Year	Scenario	Temperature [°C]	Temperature difference [°C] compared to 1995	Temperature difference [°C] compared to 1880
1880	-	**26.7** [26.3-26.9]		
1995	-	**27.4**		**0.7** [0.5-1.2]
2030	2.6	**28.4** [28.2-28.6]	**0.9** [0.8-1.1]	**1.7** [1.4-2.2]
	8.5	**28.6** [28.4-28.8]	**1.1** [1.0-1.3]	**1.9** [1.6-2.4]
2050	2.6	**28.6** [28.1-28.8]	**1.1** [0.7-1.3]	**1.9** [1.6-2.5]
	8.5	**29.5** [29.0-30.0]	**2.1** [1.6-2.5]	**2.9** [2.3-3.7]
2090	2.6	**28.6** [28.2-28.9]	**1.2** [0.8-1.4]	**2.0** [1.7-2.6]
	8.5	**31.8** [30.7-33.0]	**4.3** [3.3-5.5]	**5.1** [4.0-6.7]

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[6] Small deviations of values may occur due to rounding.

By 2090 and under the scenario without climate policy, days with temperatures above 35°C are projected to occur more than 300 days per year in most regions of Ghana.

The number of tropical nights (minimum temperature not below 25°C)[7] and very hot days (maximum temperature above 35°C) is increasing for all models and all scenarios. The temperature pattern of more tropical nights around the coast and more very hot days in the North of Ghana is projected to intensify. For RCP2.6 almost no change in number of very hot days and tropical nights is projected after 2030, while the numbers for RCP8.5 are continuously increasing. Figure 6 shows that days with temperatures above 35°C will be the case more than 300 days per year in 2090 (RCP8.5) in most regions in Ghana.

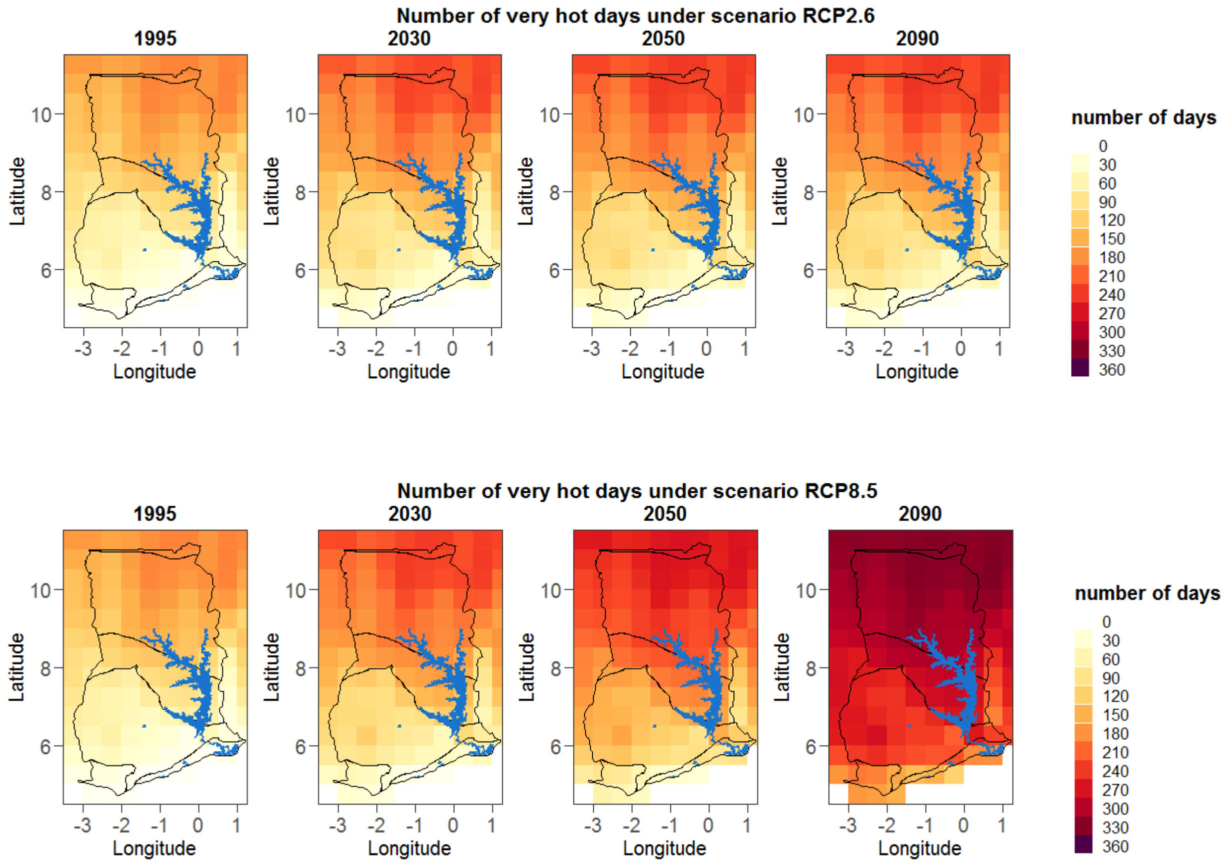

Figure 6: Average number of very hot days per year in 1995, 2030, 2050 and 2090 under scenario RCP2.6 and RCP8.5.
Results are averages over the four ISI-MIP models.

For temperature, all models and scenarios show a general agreement about future temperature changes. For precipitation, however, the models show significant differences in projected changes in Ghana, making climate projections for precipitation uncertain.

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[7] For maps visualising the changes, please refer to the supplementary material.

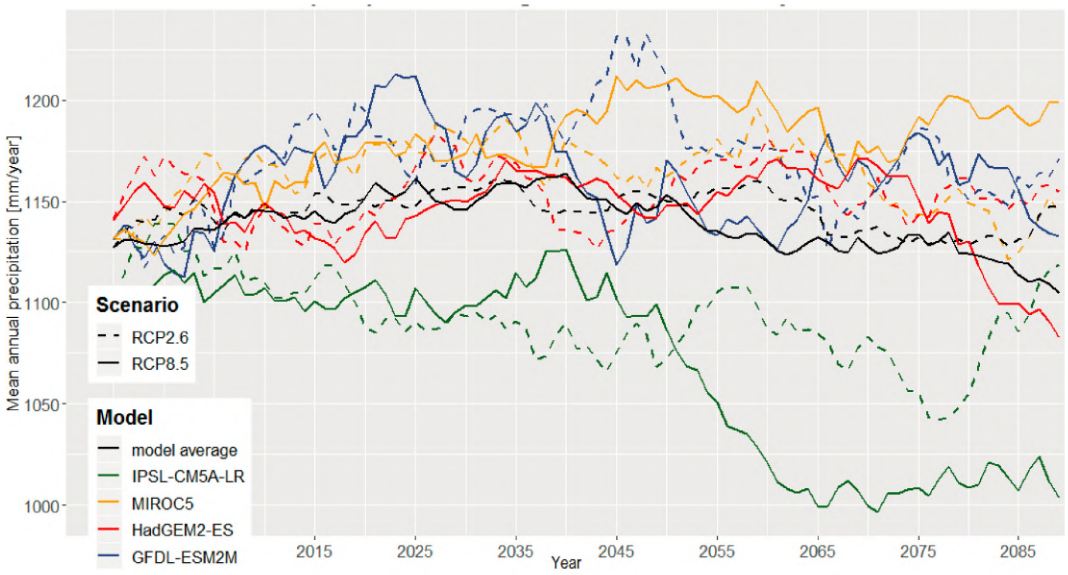

Figure 7: Projected difference in mean annual precipitation over Ghana from 1995-2090 for two scenarios and four models.

The graph shows the 21-year moving average.

> Unlike for temperature, models do not agree on the sign and magnitude of change in precipitation in Ghana under climate change.

Models do not agree on the sign and magnitude of change in precipitation. One model (IPSL-CM5A-LR) shows a drying trend, one (MIROC5) projects a slightly wetter future and two models (HadGEM2-ES and GFDL-ESM2M) do not show clear trends under RCP8.5. Generally, the high emission scenario shows a higher range of possible future precipitation and thus a higher uncertainty of prediction. Furthermore, the projections under the high emission scenario show that the future dry and wet periods are likely to become more extreme. The degree of projected change in mean annual precipitation (multi-model mean) is much smaller than the model range in all regions of Ghana. Thus, the following results have high uncertainties. Nevertheless, minor trends can be obeserved in the multi-model means and will be analysed in the following. Mean annual precipitation is projected to decrease by 1-12% in the South of Ghana until 2090. This is true for both scenarios. The multi-model projections for northern Ghana indicate an increase in precipitation in the next decades of up to 10% and a decrease at the end of this century. These trends for northern Ghana are similar for the two scenarios but are stronger for the high emission scenario RCP8.5. Due to the regional differences in projected precipitation, the impacts of climate change on agriculture also vary. This is further discussed in Chapter 3.

The projections show higher uncertanties for the second half of this century and the high emission scenario. At the end of this century, the projections for the two different scenarios show great differences (see Figure 8).

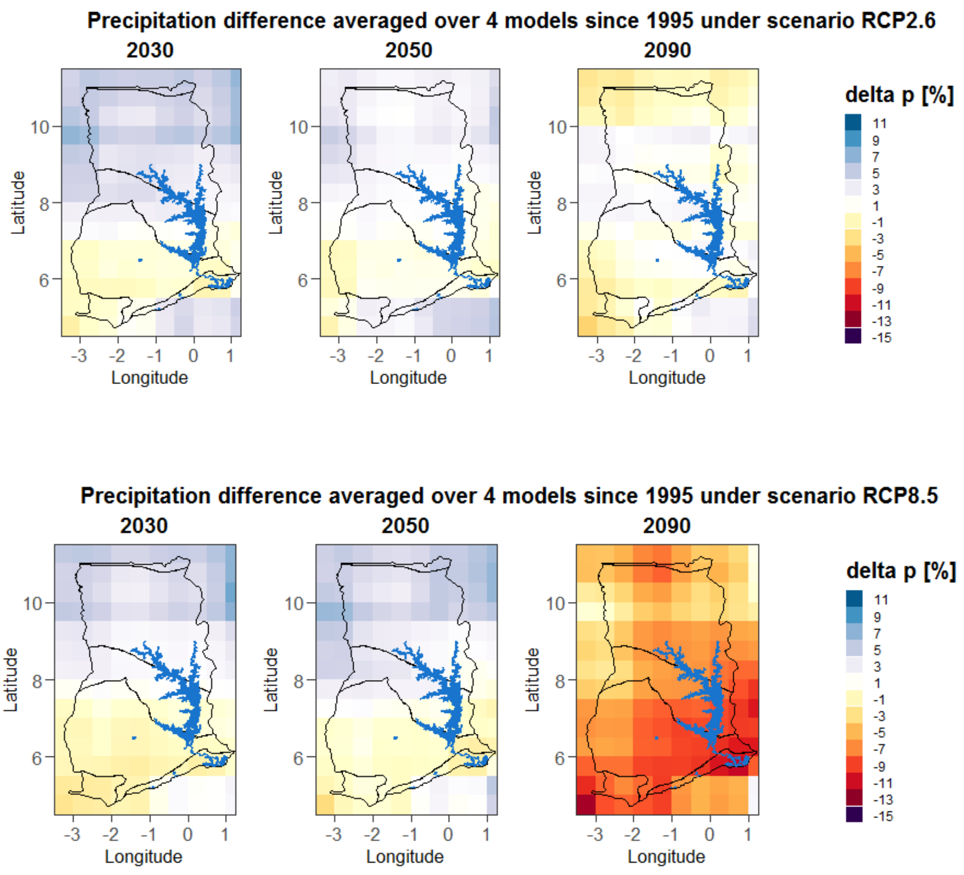

Figure 8: *Projected change in mean annual precipitation in percent between 1995, 2030, 2050 and 2090 under RCP2.6 and RCP8.5.*
Multi-model means are shown.

While projections until 2050 show only a slight increase in days with heavy precipitation for both emission scenarios, the number of days with very heavy precipitation is projected to increase substantially (see Figure 9 and 10). The projections of days with (very) heavy precipitation carry extensive uncertainties. Nevertheless, three out of four models agree on an increasing trend of very heavy precipitation. Effects of heavy precipitation events on yields are complex: they depend on crop type, stage of plant growth, local soil characteristics, number of days with heavy precipitation and dry days before the precipitation event. For crops such as groundnuts and maize, heavy precipitation can result in significant yield loss, if it occurs during flowering as the soft flowers can be completely stripped from the crop or pollen can be washed off the plant. Increasing heavy precipitation can favour epidemics, leaf fungal pathogens, leaching of nutrients, exposure of plant roots and damage of leaves (Rosenzweig et al., 2001). To arrive at concrete estimates of yield loss due to increased very heavy precipitation, further investigations need to be made for different crops.

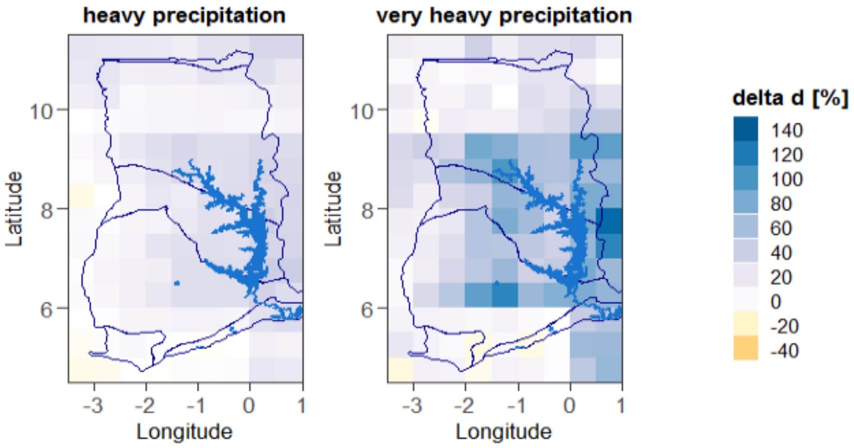

Figure 9: Change in days with heavy precipitation (exceeding 95th percentile) and very heavy precipitation (exceeding 99th percentile) under scenario RCP2.6 until 2050.

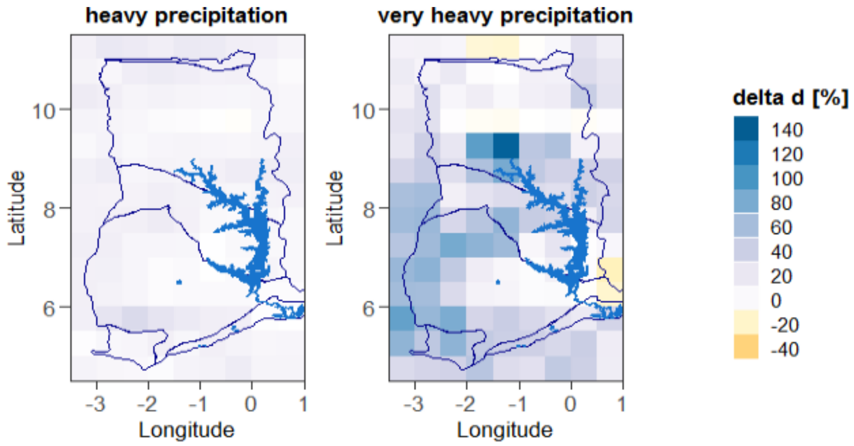

Figure 10: Change in days with heavy precipitation (exceeding 95th percentile) and very heavy precipitation (exceeding 99th percentile) under scenario RCP8.5 until 2050.

In parts of southern Ghana, projections show an earlier termination of the rainy season, which is likely to convert the current bimodal regime (two rainy seasons) to a modal one (one rainy season). In Figure 11, one can see that one of the four models projects a conversion of the rainfall regime under the high emission scenario, while no conversion is projected for any model under the low emission scenario.

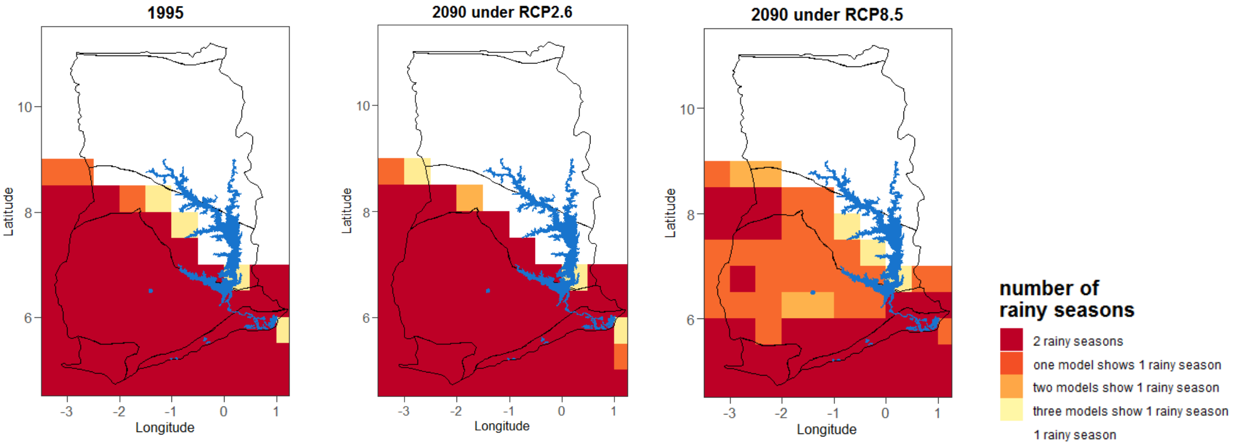

Figure 11: Simulated number of rainy seasons in 1995 and 2090 under RCP2.6 and RCP8.5.

Even though three models do not project a shift from bimodal to modal rainfall regime, they still project a change in length of rainy season. The long rainy season is projected to be shorter by 15-37 days while the short rainy season is projected to be longer by 3-22 days until 2090 under scenario RCP8.5. Projections for RCP2.6 do not show any clear trend in change of length of rainy season.

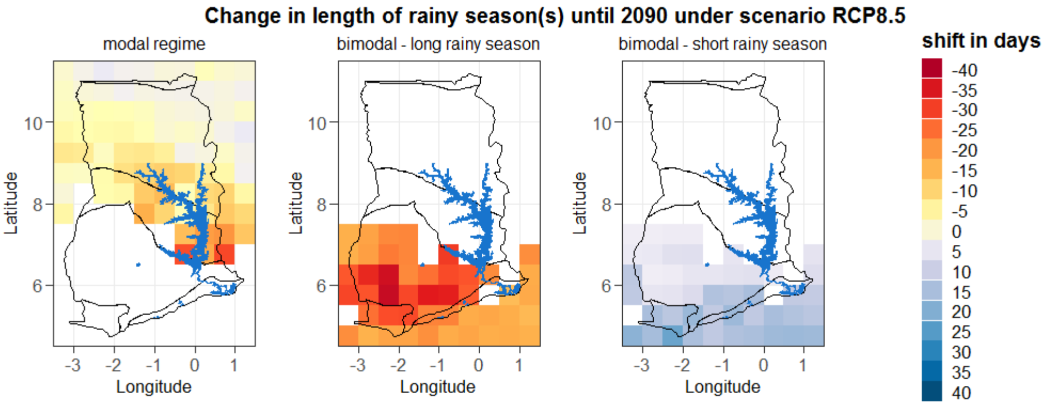

Figure 12: Change in length of rainy season(s) in days until 2090 under scenario RCP8.5. The left map displays the change in length for modal rainfall regime and the middle and right image display the change in length for the bimodal rainfall regime.

Chapter Summary

Historical and present climate

- Ghana has a tropical climate with an average mean annual temperature of 27.5°C, reaching higher temperatures in the North and in the dry period (Nov-Apr).
- Mean annual precipitation ranges from 1000mm in the North to about 1800mm in the Southwest.
- An increase in mean annual temperature of about 0.1°C per decade occurred between 1985 and 2010.
- The North exhibits one rainy season (modal rainfall regime), while there are two rainy seasons (bimodal rainfall regime) in the South.
- A negative trend for mean annual precipitation occurred in most parts of Ghana in the last decades. The difference in mean annual precipitation ranged between -8.0% and +3.5% per decade in 1985-2010.

Projected climatic changes

- Projected increase in mean annual temperature of 0.8-1.3°C until 2030, 0.7-2.5°C until 2050 and 0.8-5.5°C until 2090 compared to 1995 depending on model and scenario.
- Highest projected temperature increases in the North of Ghana. Slightly smaller projected increases in the South.
- Mean annual precipitation is projected to increase more likely in the North and decrease in the South of Ghana until 2050.
- Under the high emission scenario (RCP8.5) the multi-model mean predicts that precipitation is also decreasing in the North of Ghana at the end of this century.
- Future dry and wet periods are likely to become more extreme under the high emission scenario (RCP8.5).
- Under the high emission scenario (RCP8.5), the long rainy season in southern Ghana will become shorter, while the short rainy season will become longer. A switch from bimodal to modal rainfall regime until the end of this century is possible.
- Temperature trends are similar for all models and scenarios and, therefore, temperature projections show low uncertainties.
- Projected precipitation trends do not agree in sign and magnitude for all models and scenarios. Precipitation projections come with high uncertainties. While the multi-model mean suggests only moderate average changes, individual models predict significantly drier and wetter conditions.
- Precipitation projections show high regional differences, while temperature projections show only small regional differences.

Chapter 2 – Changing Water Availability for Agricultural Production

An eco-hydrological model (SWIM) was used to assess the impacts of climate change on water resources in Ghana.

To assess the impacts of climate change on water resources (precipitation, groundwater recharge, actual evapotranspiration and river discharge) in Ghana, the Soil and Water Integrated Model (SWIM), an eco-hydrological model developed by Krysanova et al. (2005), was used to simulate the hydrological processes in the Volta River basin (VRB). The VRB covers an area of 403,269 km² and represents about 70% of the total area of Ghana. In this study, SWIM is driven by climate input of RCP2.6 and RCP8.5 from four ISIMIP2b Global Climate Models (GCMs), described in Chapter 1.

2.1 Input Data and Hydrological Modelling

The Shuttle Radar Topography Mission (SRTM) 90m digital elevation model was used to delineate the VRB into 578 sub-basins. Soil parameters were derived from the Harmonised World Soil Database (HWSD v1.0) and data on land use/cover were derived from the Global Land Cover map (GLC2000). The hydrological model was calibrated and validated using daily discharge data at 16 gauges provided by the Global Runoff Data Centre (GRDC) and a number of time series copied from hydrological yearbooks.

Existing and planned reservoirs as well as water withdrawals for different purposes like agricultural and domestic use are not yet considered in the simulations, as data was not available. Therefore, the results presented here assume a natural hydrological system without human interference. Land use/cover is also considered to be constant without changes in future periods.

2.2 Results and Discussion

Although the hydrological model simulates discharge at any river section in the VRB, we will discuss the absolute and relative changes at the VRB outlet here. However, maps of selected hydrological components are used to visualise the spatial distribution of projected changes anywhere in the catchment.

Average annual discharge projections at the VRB outlet

Figures 13 and 14 show the projection of the 11-years moving average of the mean annual discharge for each model in the entire simulation period from 1960-2099. The grey boxes highlight the three future periods (P1 2021-2040, P2 2041-2060 and P3 2080-2099)[8] and the reference period (1986-2005). The figures show that all models simulate periods above or below their respective means in the reference period, which are indicated by the dashed lines. This corresponds to observations over the last decades with rather dry multi-year periods followed by rather wet multi-year periods. The multi-year wet or dry periods are not synchronised among the models, like for example in the beginning of P2 in RCP2.6 (see Figure 13), where the IPSL model projects a dry period below its reference mean and the GFDL model a wet period above its reference mean. Both models are clearly above their reference means at the beginning of the simulation period in the 1960s and 1970s. Such discrepancies are not an exception but

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[8] The mean for each period corresponds to the climate periods “2030”, “2050” and “2090”.

The variability of future mean discharge in 2050 is expected to be in the order of the variability in the past.

usually a rule, which makes the analysis and the interpretation of results more complex. In this example, the average of the two models would balance the two opposing trends and would show no change at all. A more meaningful message is that, according to the two models, the variability in future mean annual discharge around the year 2050 is expected to be in the order of the variability in the past.

In RCP2.6, the HadGEM and MIROC models project a wetter future where the mean annual discharge is above the mean annual discharge in the reference period (see Figure 13). The GFDL and IPSL models show future periods where the mean annual discharge is above or below the reference mean, depending on the period (see Figure 13). Based on the 11-years moving average, it seems that the dry and wet periods are not expected to be more extreme than in the past, the 3-years moving average (see Figure 7 in the Supplementary Material) changes this interpretation slightly. Some models show years with higher or lower mean annual discharges than in the reference period.

Under RCP8.5, one can expect more extreme changes in both directions than under RCP2.6. Particularly after mid-century, all models simulate periods with either relatively higher or lower mean annual discharge than simulated in the past. The 3-years moving average (see Figure 8 in the Supplementary Material) supports this statement. The future will not be either dryer or wetter but the future dry and wet periods may become more extreme and are, therefore, out of the range of events experienced in the past.

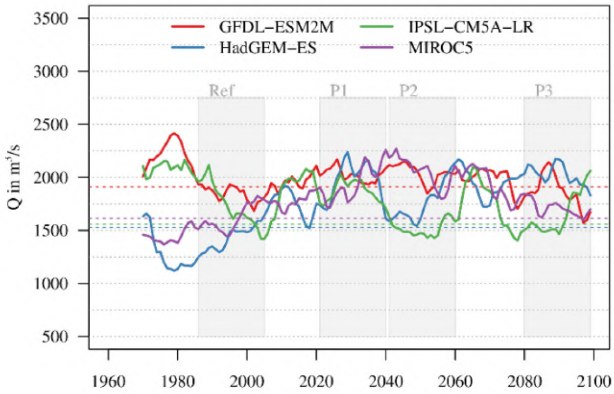


Figure 13: Annual mean discharge at the VRB outlet (11-years moving average), RCP2.6.

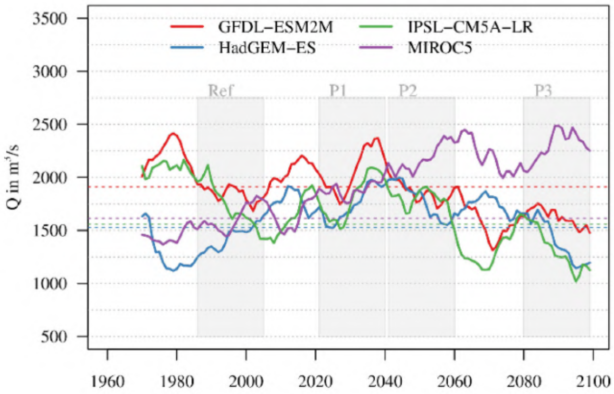


Figure 14: Annual mean discharge at the VRB outlet (11-years moving average), RCP8.5.

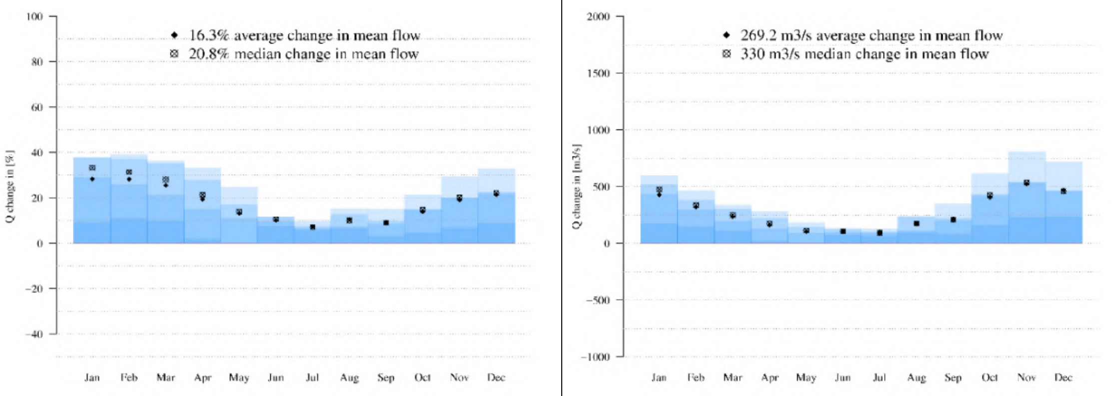
Average monthly discharge projections at the VRB outlet

In contrast to the previous section, which focused on average annual discharge changes over the entire simulation period, this section discusses average monthly changes in the three future periods at the VRB outlet. In Figures 15 and 16, each GCM simulation is represented by a semi-transparent bar, where bluish colours indicate an increase and reddish colours a decrease in monthly discharge. The more saturated the colour, the more models project the same direction of change. Monthly relative changes are shown in the left panels of Figures 15 (RCP2.6) and 16 (RCP8.5), while monthly absolute changes are shown in the right panels.

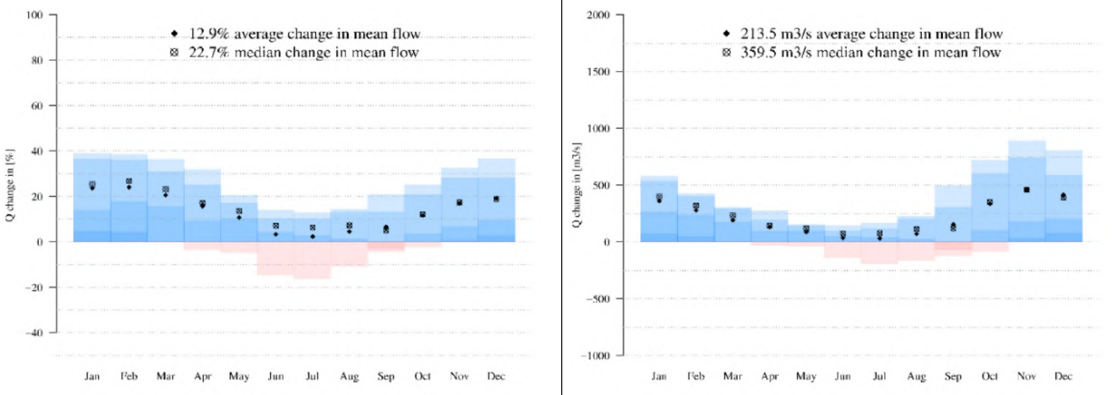
On average, the multi-model mean projects an increase of mean annual discharge in all three future periods and RCPs except at the end of the 21st century (P3) under RCP8.5. The average change in mean flows declines gradually from +16% in P1 over +13% in P2 to +11% in P3 under RCP2.6. In period P1, all four models project an increase in average monthly discharge (see Figures 15a and b). In periods P2 and P3, at least one model projects a decrease of discharge in some months between April and December (see Figures 15c-f).

The average change in mean monthly discharge under RCP8.5 for the periods P1 and P2 is comparable to the change in RCP2.6 (around +13 to +15%). However, the increase projected by the MIROC model (see Figure 14) is much more pronounced in RCP8.5 (see Figures 15c and d) than in RCP2.6 (see Figures 15c and d). The period P3 at the end of the 21st century is exceptional. MIROC is the only model that projects an increase of average monthly discharge by up to 70% in January (low flow season) and about 55% in November (high flow season), as shown in Figure 16e. The other three models project decreasing average discharge in all months by up to –15% in January and -40% in July (see Figure 16e).

a) Monthly relative changes 2021-2040 b) Monthly absolute changes 2021-2040



c) Monthly relative changes 2041-2060 d) Monthly absolute changes 2041-2060



e) Monthly relative changes 2080-2099 f) Monthly absolute changes 2080-2099

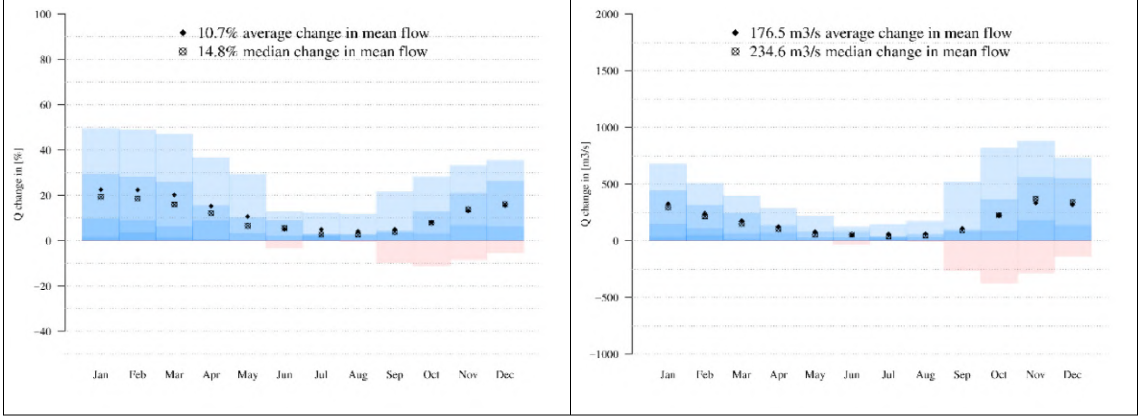
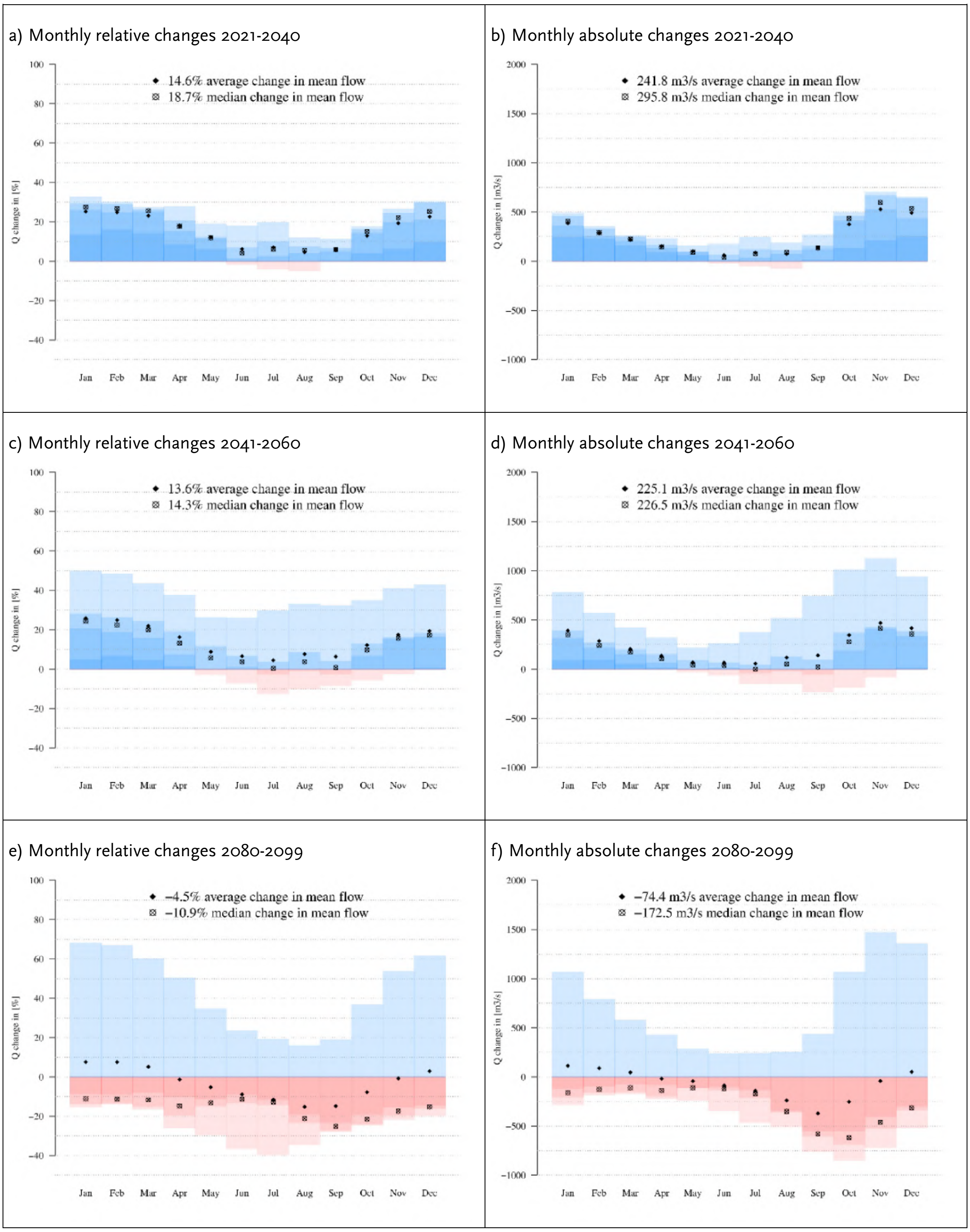


Figure 15: Relative and absolute mean monthly discharge changes at the Volta River Basin outlet between future periods and the reference period 1986-2005 (RCP2.6).



a) Monthly relative changes 2021-2040

b) Monthly absolute changes 2021-2040

c) Monthly relative changes 2041-2060

d) Monthly absolute changes 2041-2060

e) Monthly relative changes 2080-2099

f) Monthly absolute changes 2080-2099

Figure 16: Relative and absolute mean monthly discharge changes at the Volta River Basin outlet between future periods and the reference period 1986-2005 (RCP8.5).

Chapter Summary

Main changes in water availability

- The multi-model mean of average annual discharge projections suggests an increase under both RCPs by mid-century. At the end of the 21st century, the two RCPs differ, where discharge is projected to increase under RCP2.6, a decrease is projected under RCP8.5.
- The multi-model mean or median balances the projected changes suggesting that, on average, the changes might be moderate or insignificant. In fact, when the four models are analysed individually for the two RCPs and different periods, where all projections are considered as possible futures, we would rather draw the conclusion that one can expect dry and wet conditions, which have not been experienced in the past. The magnitude of change in both directions depends on the period of interest, the climate scenario (RCP) and the GCM.
- The cyclic behaviour of multi-year dry and wet periods will continue in the future.
- The selection of future periods and their length (e.g. 20 or 30 years) have an impact on the results.

Chapter 3 – Climate Impacts on Crop Production

Due to changing climate and weather patterns in combination with limitations to extend arable land area, the pressure on food production systems is likely to increase. In addition, future food production systems must feed a growing population in Ghana with a current growth rate of 2.2% (UN DESA, 2017). The demand for food rises and is likely to become increasingly land-intensive (UNDP, 2012). To cope with these challenges, it will be indispensable to increase crop yields and take measures to avoid yield loss as much as possible. This requires, however, a deeper understanding of the factors influencing crop yield variability and a quantification of their relevance under different soil and climatic conditions.

Smallholder farmers dominate Ghana´s agriculture: they contribute more than 80% of its commodities.

Agriculture in Ghana is dominated by smallholder farmers who contribute over 80% of agricultural commodities. These farmers also practice multiple cropping types where they produce a number of food and cash crops in e.g. intercropping, alley cropping or relay cropping systems[9]. There is a number of advantages to these systems in terms of reducing climatic and market uncertainties at household, community, regional and national level. Agricultural produce is aggregated by agricultural merchants at local markets for trade within and outside the country, with export currently mainly limited to cash crops. Crop choice is mainly based on subsistence food requirements with excess being sold at local markets.

Crop production in Ghana is heavily based on rain-fed smallholders systems with low input.

Ghana's agricultural sector is distributed across the various heterogeneous agro-climatic zones with a south-north gradient in precipitation and temperature. Crop production is heavily based on rain-fed smallholder agricultural systems which are generally low input. Drivers of crop yield in the country are weather variables, inherent soil fertility and use of external inputs, which is often very limited and use of rudimentary equipment is common. The relative contribution of each of these factors to yield of major crops is uncertain and varies between time and space. Consequently, the types of crops and areas planted vary between the different regions of the country. This also means that the causes, frequency and severity of weather-related climatic risks to crops will also vary among different areas, crops and years, with difference between aggregate, regional and local drivers of crop production. Generally, precipitation is limiting production in the northern regions, which have lower uni-modal rainfall, while excess water is limiting for some crops in the southern regions. Thus, challenges such as droughts and pests, e.g. the fall armyworm and variegated grasshopper, are more prevalent in the North, while flooding and waterlogging are likely to limit crops in the southern parts of the country. While non-biophysical factors such as access to markets, culture of use, methods of storage amongst others also determine ultimate crop production levels, this analysis focuses on biophysical drivers, which can be analysed employing a range of different climate impact models.

Weather influence on crop yields is difficult to detect, as there may be other decisive factors like management.

Due to the high precipitation level in Ghana and the dominance of low-input management (i.e. limited fertilizer application, little to no mechanisation, limited application of herbicides), weather influence on crop yields in Ghana is difficult to detect as it may either be low (as there is enough water and temperatures are optimal) or

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[9] Intercropping is a term used for several cultivation practices, where two or more crops are planted simultaneously on the same field. Alley cropping and relay cropping are specific forms of intercropping, with alley cropping referring to the planting of crops and trees on the same field, whereas relay cropping means growing two or more crops on the same field, but with different planting dates. The planting of the second crop normally occurs after the first one has completed its growth.

shaded by other limiting factors[10]. To test this weather influence on the Ghanaian crop production, we applied two established crop yield simulation models: AMPLIFY (Gornott and Wechsung 2016; Schauberger et al. 2017) and the process-based crop model APSIM (Agricultural Production Systems sIMulator) (Holzworth et al., 2014). Both models confirmed that there are important drivers besides climatic influence.

The results for AMPLIFY and APSIM are shortly discussed here and both convey the same conclusion. Exogenous variables in the AMPLIFY model are different weather indices measured during the growing season. The model quality is measured by reproduction of the observed yield time series on national level, with an additional out-of-sample quality test. Input data are district-level maize yields from 1993 to 2017, provided by the Ghanaian Ministry of Agriculture and pooled in a panel to increase statistical power. Weather data are derived from ERA-Interim (Dee et al., 2011) except precipitation which is extracted from CHIRPS (Funk et al., 2015). For APSIM, maize yield was simulated from 2005 to 2017 for 27 districts, which had complete maize yield records for the time period and for which reliable management data could be applied. The out-of-sample explained variance (as the most reliable indicator for model performance; see Figure 17) is 0.26 and the estimation explained variance is 0.56 for AMPLIFY. This means that 56% of the year-to-year yield variability can be explained by weather factors. Thus, the weather effect is not negligible, but the results are sensitive to choice of parameters, spatial aggregation and input data. Reasons for the comparably low performance of the statistical model in comparison to other countries (Schauberger et al., 2017) are discussed in Chapter 6.

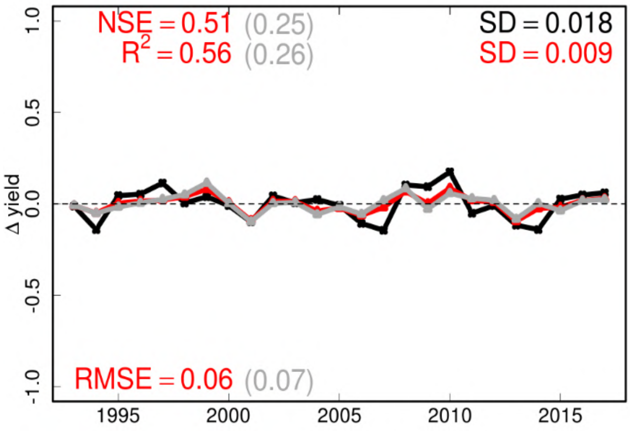

Figure 17: Time series of maize yields in Ghana, as de-trended anomalies between 1993 and 2017.
Black lines are observed yield anomalies, red lines are modeled yields estimated with the full observed data set and grey lines are modeled yields estimated out-of-sample. NSE, R^2 and RMSE indicate model performance, once for the full model (red) and once for the out-of-sample model (grey). SD denotes standard deviation for observed (black) and modeled yields (red).

The results for biophysical modelling using APSIM show that the model could explain only a third of the variance in yield between 2005 and 2017 in Ghana. There was model underestimation of observed maize for many districts and years (PBIAS = -8.9), indicating that there are other factors influencing yield variability in space and time apart from weather and management used in the modelling (see Figure 18). At the same time, a low model performance may also point to the quality of the input and validation data used. The model was, however, able to represent high and low production areas and is in line with other APSIM applications for Ghana (MacCarthy et al. 2015; Tachie-Obeng et al. 2013).

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[10] A rise in application rates of fertilizer (NPK) and herbicides is assumed to strongly benefit crops, since these factors are currently often limiting. Possible downsides of an increasing fertilizer use are the risk of eutrophication of water resources in particular due to leaching under heavy rains, and a surge in N2O emissions from the soil, which is a potent greenhouse gas. Regarding herbicides, it is obvious that excess or untimely usage may create resistant plants, damage insects or other plant species and favour monocultures with all their known problems (susceptibility to diseases, low biodiversity, compounding of risks, etc.).

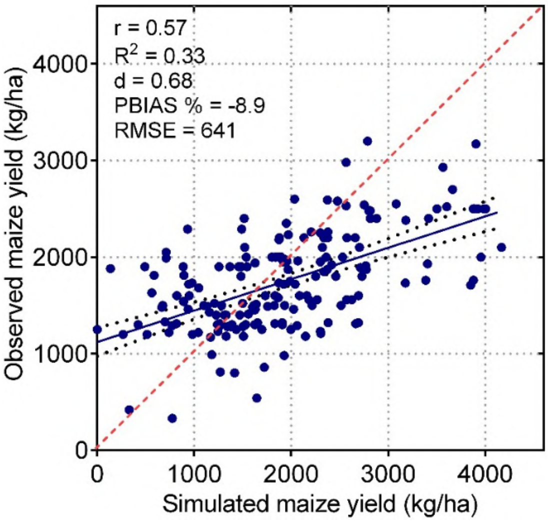

Figure 18: A comparison of modelled vs. observed maize yield for the period 2005 to 2016 for 27 districts using APSIM.
The red line is the 1:1 line while the dotted black lines are the 95% confidence intervals.

3.1 Climate Change Impacts on Crop Suitability in Ghana

Suitability models capture the production potential for crops under changing climatic conditions.

Since weather impacts on maize in Ghana explain only one influence on yield variability, a different approach is taken to assess possible impacts of climate change on crop production using an ensemble suitability model. Suitability models capture the production potential for agricultural crops since crop production tends to be influenced by the weather signal and as such can be explained by dominant biophysical parameters such as weather and soils (Hummel et al., 2018; Moat et al., 2017). The understanding that biophysical parameters are important in determining suitability or production potential of a crop now and under projected climate change is valid for tropical countries such as Ghana, as crop genetics and cropping systems are not expected to significantly change in the medium term. Since the results are spatially explicit, 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. Methods and results of this analysis are described in the following sections and in the supplementary material.

We used machine-learning ensemble crop suitability modelling to evaluate the suitability of sorghum, maize, groundnuts and cassava under current and projected climate change. These crops were selected based on their importance with regard to harvested area for agriculture in Ghana, availability of yield data as well as the capacity of the crop models for these crops. From 2006-2008, on more than a quarter of the harvested area in Ghana, cocoa beans were harvested, followed by cassava (*Manihot esculenta*) with 12.6%, maize (*Zea mays*) with 12.1%, groundnuts (*Arachis Hypogaea*) with 7.4% and sorghum (*Sorghum bicolor*) with 5.3% (MoFA, 2011a). Cocoa is a cash crop and was, therefore, not the focus of this study, which concentrates on staple crops and climate change impacts on food security. Consequently, the crops evaluated in this study are maize, groundnuts, sorghum and cassava.

The variables used from the suitability modelling were obtained from daily weather data for the current and projected climatic conditions. These variables could be divided into three; (1) conditions of the sowing months for major crops for North and South, (2) conditions of the growing season for North and South and (3) the condition of the entire agricultural season without distinction of region. As such we determined the sum rainfall and mean temperatures for the sowing months, which were end of March to end of April for the South's major season and end of May to end of June for the northern parts with unimodal rainfall. Consequently, the growing season for the South was considered as end of March to end of July for the bimodal rainfall in the southern parts of Ghana and end of May to end of September for the unimodal rainfall in the northern parts. The March to September rainfall and temperature variables did not separate between the North and South (see supplementary material).

Groundnuts, sorghum, maize and cassava were analysed.

In the following, some key characteristics of the selected crops are provided, which are relevant for the suitability modelling and give an indication on their cultivation: Groundnut is an annual legume that 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 production of peanut butter and edible oils. Groundnut has a growing period of 90-140 days with sensitivity to rainfall or hail from flowering onwards. Sorghum is an annual grass species cultivated for its grain. The crop takes 90-120 days to mature with the grain being used for food and the stover for feed. Sorghum is adapted to warm days and night temperatures above 22°C throughout the growing season. Maize is a vigorous annual grass and grain crop that can reach up to 2m in height. The grains are widely used as food in Africa and many parts of the world. The growing period for maize depends on local conditions and can vary between 70 and 210 days. Cassava is an erect shrub with upright woody stems. The cassava leaves and fleshy elongated tuberous roots or rhizomes are used mainly as food. The average growing period for cassava is 180-270 days.

3.2 Model Scaled Determinants of Crop Potential in Ghana

Precipitation influences the potential for maize, groundnut, cassava and sorghum production more than temperature-based factors.

Using the contribution of each factor to the model fit and its effect on the fit when excluded (Altmann, Toloşi, Sander, & Lengauer, 2010), we established the relative contribution of each variable used in the model to the suitability of each crop. The results show that rainfall factors influence the potential for maize, groundnut and cassava production in Ghana more than the temperature-based factors, which were ranked as the most important in determining sorghum suitability. The rainfall factors explained up to 90% of the suitability of cassava, up to 60% of the suitability of groundnuts, 77% for maize and 51% of the suitability of sorghum (see Figure 19). The total sum of rainfall received throughout the growing season is most important in determining the suitability of cassava (50%) and groundnuts (34%), while for maize, the total precipitation in the sowing months is the most important factor (25%) (see Figure 19). The mean temperature was not identified to be important for all three crops, but the diurnal temperature range explains 30% of the suitability for sorghum in Ghana, while being the second most important factor for the suitability for maize (25%). Although the overall contribution was low, organic carbon was found to be relevant for sorghum (5%) and cassava (3%) with a 2% contribution of suitability for groundnuts and maize.

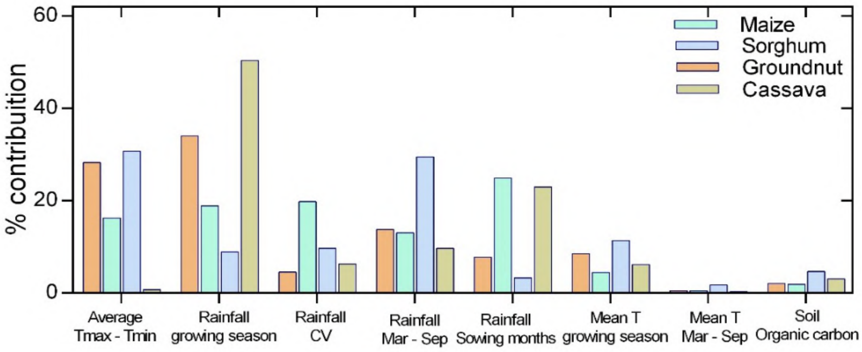

Figure 19: Importance of variables for suitability of groundnuts, maize and sorghum in Ghana[11].

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[11] CV = Coefficient of variation; The growing season and sowing months differ between the regions in Ghana, more information on this can be found in the supplementary material. The period from March to September covers all growing seasons for all crops analysed.

3.3 Current and Projected Climate Impacts on Agricultural Production in Ghana

> Suitability is the ability of a site to sustain the entire production cycle of a crop from establishment to harvesting and achieving current production levels at current production costs with the provided biophysical parameters.

From the models, we established the suitability of each crop for the current and the projected climatic conditions in Ghana around mid-century (2050). We used suitability models to determine the current and future production potential of maize, sorghum groundnuts and cassava in Ghana. Suitability models for agricultural crops are based on the understanding that crops are produced in areas where they are climatically suitable or where at least the management can complement climatic factors to enable successful crop production (Evangelista, Young, & Burnett, 2013). Suitability is the ability of a site to sustain the entire production cycle of a crop from establishment to harvesting and achieving current production levels at current production costs with the provided biophysical parameters. The models were run using the RCP2.6 scenario (based on the 1.5-2° warming) and RCP8.5 (without-climate-policy scenario). The projected changes in suitability of groundnuts, maize, sorghum and cassava produced from the suitability models are shown in Figure 20.

Groundnuts

> The northern parts of Ghana are projected to become more suitable for producing groundnuts, regardless of the scenario. However, the overall suitability for groundnuts decreases due to climate change.

The results show that there is high potential for the production of groundnuts in Ghana, particularly in the Northern Region, Brong Ahafo, Volta and part of the Ashanti region. Production potential, however, is very low in the southern parts and in the Upper West Region under current climatic conditions. The models show that the suitability for groundnuts will decrease in the central parts of the country but increase in the Upper West Region under both the RCP2.6 and RCP8.5 (see Figure 20). At national level, the proportion of the total area in the country modelled suitable for groundnut is 56% under current climatic conditions (see Figure 20). Under future climatic conditions, the area suitable for groundnuts will be 60% of the country under RCP2.6 scenario and 58% under RCP8.5 with a notable northwards shift in suitability in the medium term (see Figure 20). Overall, the impacts of climate change on suitability of groundnuts in Ghana show that the total suitable area will not change considerably (net gain in suitability of 2% under RCP2.6 and 4% under RCP8.5, see Figure 19) but the geography of suitability will shift. The higher gain under RCP8.5 can be explained by the fact that this scenario projects precipitation increases (see also Figure 6, Chapter 1) compared to current conditions, even though coupled with higher warming. Despite this increased warming, the additional precipitation is still useful for crop production and leads to more favourable conditions than under RCP2.6 (see Chapter 1).

Interestingly, the northern parts of Ghana will become more suitable for groundnut production under both scenarios (see Figure 20), while parts of Volta, Eastern, Ashanti and Brong Ahafo will become marginal for groundnut production. The increased suitability for groundnuts in the North is explained by both the projected increases in precipitation in some parts of the North until 2050 (see Chapter 1) and the fact that groundnuts are a grain legume, whose harvested parts grow below ground and, thus, are partly shaded by soil from direct effects of warming. Groundnut viability is closely related to rainfall patterns, particularly the amount of precipitation in the growing season due to the less extensive root system, with increasing precipitation directly increasing suitability (Van Duivenbooden, Abdoussalam, & Mohamed, 2002).

Sorghum

> Climate change is expected to have limited impact on the production of sorghum, because it is a tolerant crop even under marginal conditions.

The northern half of Ghana is currently suitable for sorghum production and this will remain so under projected climate change, with changes in production potential for sorghum in the central parts of the country. The northern parts of the country will remain suitable, while the southern parts of the country will remain unsuitable in the medium term. At national level, the proportion modelled suitable for sorghum is 55% under current climatic conditions (see Figure 20). Under future climatic conditions, the high sorghum potential areas will be 54% of the country area under RCP2.6 and a fall to 49% under RCP8.5 (see Figure 20). Concurrently, 5.1% of the area that is currently suitable for sorghum production will become unsuitable under RCP2.6 scenario and 9.3% under RCP8.5 scenario. Increases of suitability of 2.9% of the current area are projected under RCP2.6 and 4.4% under the RCP8.5 scenarios. We, therefore, predict net losses of suitability for sorghum of 2% under RCP2.6 and around 5% under RCP8.5 scenarios (see Figure 20). The results confirm that sorghum is a more tolerant crop under marginal conditions in Ghana, as compared to the other crops. The limited impacts of climate change on sorghum suitability are explained by its heterotic mechanisms from its phenotypic plasticity enhanced by its adventitious and high density rooting systems. These allow for dehydration avoidance to deal with increased heat and water stress in sorghum coupled with lower soil fertility demands than those for maize and groundnuts (Blum, A. 2004, Kebede et al. 2001). Thus, the results show that sorghum remains a high potential crop in the northern parts of Ghana under a changed climate, which is encouraging as sorghum is already a major food crop in the northern parts of Ghana. However, wholesale adoption of sorghum in the suitable areas can also create other problems such as increased requirements for milling of the crop especially given that sorghum requires more post-harvesting processing compared to maize.

Maize

Suitability for maize production will be considerably lower than today: net losses are expected.

The suitability of maize production in Ghana is variable and dependent on site conditions. There is a higher chance of successful cropping under current conditions in the transition zone and the Guinea Savanna belt, particularly in the Upper West Region. However, in the Upper West region decreases in suitability are projected under both the RCP2.6 and the RCP8.5 scenario, leading to only marginal maize production in this area by 2050. The models also indicate that parts of northern Ghana will remain or become unsuitable for maize production by 2050 (see Figure 20). The proportion of the country modelled as suitable for maize is 71% under current climatic conditions. Under projected climatic conditions, high potential maize areas will be 54% of the country under RCP2.6 and 60% under RCP8.5 in the medium term. These major shifts in suitability will happen mainly in the Northern Region, Upper West Region and in parts of Ashanti regions. The area that will become marginal for maize production is much higher than the area that will become suitable under climate change, indicating large net losses in maize suitability in Ghana under climate change, and the largest of all the four crops (see Figure 21 below). The great loss in area suitable for maize is due to the large number of crop stages of maize that are influenced by climatic conditions. Therefore, maize is more sensitive to weather variables than many other crops (Reynolds, 2010).

Cassava

Suitability for cassava will decrease at country level in the medium term, with gains in the North and losses in other regions.

The suitability models show that the southern parts of Ghana will be largely suitable for cassava with projected shifts in the transitional zone under both RCP2.6 and RCP8.5. The shifts of areas turning more suitable or marginal for cassava are most remarkable under the RCP8.5 scenario. The most affected regions by these changes will be the Northern Region and the Brong Ahafo region (see Figure 20). The Upper West Region and the Upper East Region of Ghana will remain marginal for cassava, while the western, Ashanti, eastern, central and Volta region will remain suitable for cassava under a changing climate.

At national level, the suitability models indicated that under current climatic conditions, 62% of the country is suitable for cassava production. Climate projections indicate that the suitability for cassava will decrease to 57% under both RCP2.6 and RCP8.5 with associated changes in the geography of the areas that are suitable. Interestingly, under RCP8.5, greater losses of suitable area will also come with higher gains in suitability in different areas in the Northern Region of Ghana, indicating that as some areas become marginal, some areas are becoming suitable. Compared to maize, cassava will be suitable in more areas under climate change. This can be explained by the fact that tuber production can be delayed depending on the weather conditions over a range of between 6 to 24 months.

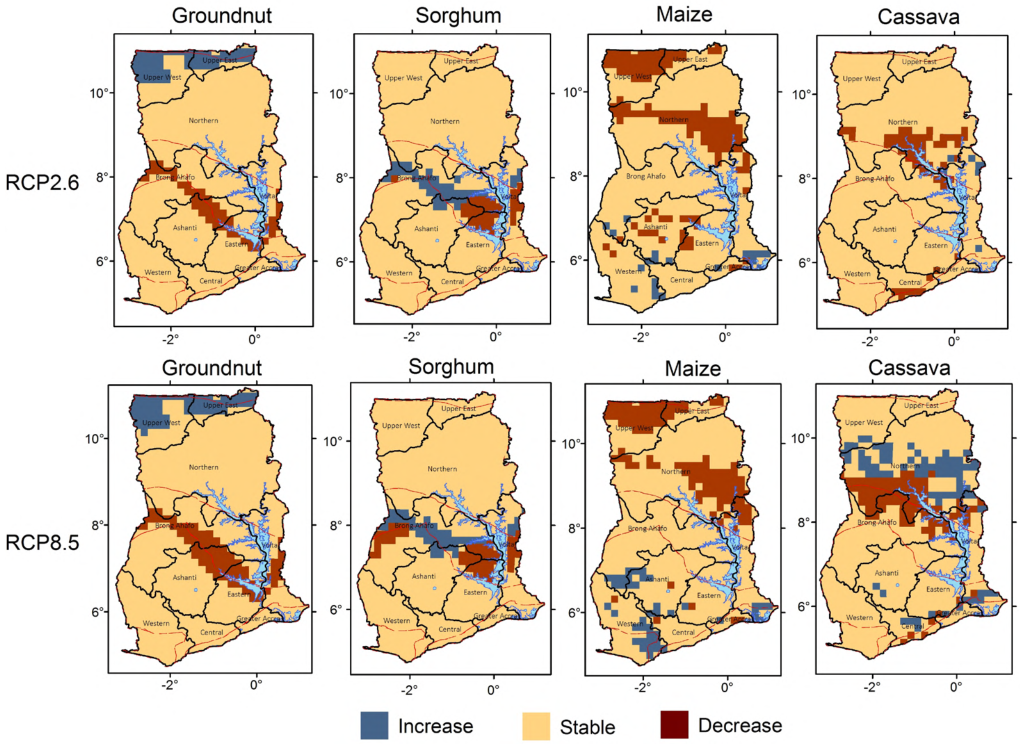

Figure 20: Modelled current and projected crop suitability for groundnuts, sorghum, maize and cassava by 2050.

The yellow colour shows areas with no change, blue areas will have improved suitability, while red areas will have decreased suitability of the crop (the red lines indicate the approximate boundaries of the six agro-ecological zones).

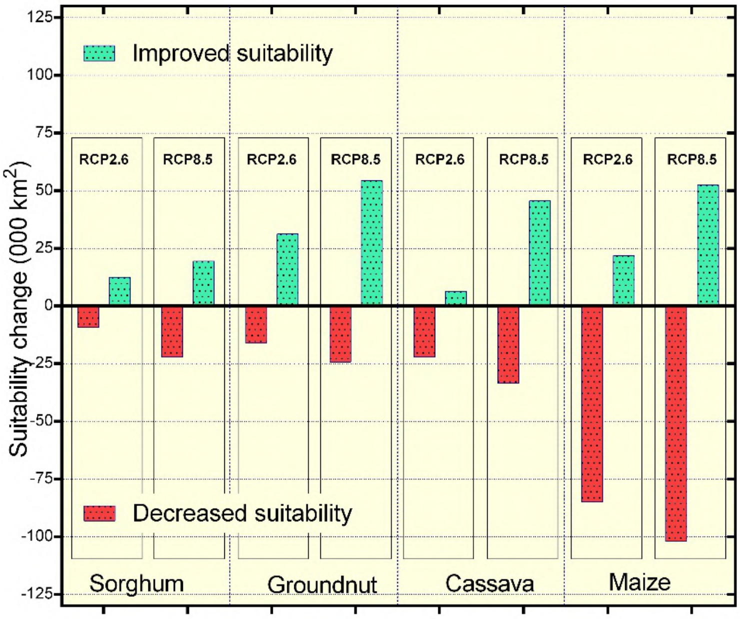

Figure 21: Projected changes in suitability of groundnuts, maize and sorghum in Ghana under emission scenarios RCP2.6 and RCP8.5.

Suitability of multiple crops

The suitability of each pixel for multiple crops was evaluated by determining the number of crops that have been considered suitable for that pixel (50km*50km resolution). Under current climatic conditions, 21% of the country is suitable for production of cassava, groundnut, maize and sorghum, especially in the central parts of the country. A greater proportion of the country (41%) is suitable for producing two different crops under current climatic conditions (see Figure 22), with a further 21% suitable to support three different crops (of the ones analysed). Only 16% of the country is suitable for production of only one crop and just 1% is considered suitable for neither of the crops. Using the climate projections, the results show that the area that will be suitable for all of the four crops will decrease by 5% under RCP2.6 and by 18.4% under RCP8.5 (see Figure 22). The results show that the area suitable for three of the four crops will decrease by 9% under RCP2.6 and increase by 3% under RCP8.5 in Ghana.

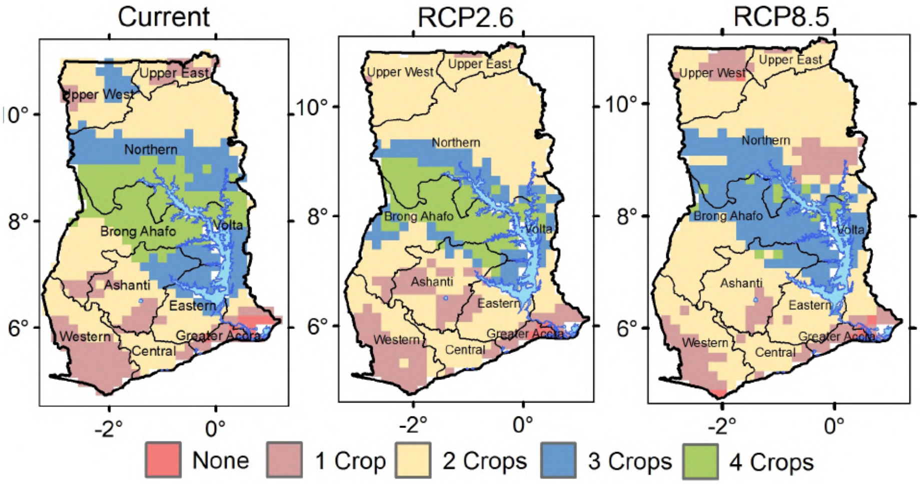

Figure 22: Projected changes in suitability for multiple crops under (a) current climatic conditions and emissions scenarios (b) RCP2.6 and (c) RCP8.5.

By mid-century sorghum and groundnuts are best produced in the North and maize in the South-West, while cassava remains largely unaffected by climate change.

From a farming perspective, the suitability of an area to produce three or four different crops is desirable, as this means more choice with regard to crop selection and the possibility to change cropping patterns. Under both RCP2.6 and RCP8.5, the area suitable for production of two crops will increase by 15% and 16% respectively, gaining from the decreases in suitability from areas suitable for growing three or four of the crops, as suitability for multiple crops diminishes (see Figure 23). The area that is suitable for one crop and none of the crops will decrease indicating that the projected changes in climate will make some areas more suitable for crops, albeit small. Sorghum and groundnuts will be the two crops suitable in most parts of the northern areas while in the southern parts, maize will become the only suitable crop under both scenarios (see Figure 22).

With regard to specific crop combinations, the largest area of the country is currently suitable for the production of a combination of cassava and maize (53%), followed by groundnut and sorghum (47%) and then groundnut and maize (41%). The combination of cassava and sorghum is the least suitable combination of crops, as only 22% of the country area are suitable for this combined production (see Figure 23). Under projected climatic conditions, the area suitable for all combinations will decrease under both RCP2.6 and RCP8.5 scenarios as compared to current conditions. Under RCP2.6, the greatest losses will be in the combination of groundnut and maize (14%), driven by decreases in suitability of maize production in the northern parts of Ghana. Under RCP8.5, the largest losses in crop combination suitability involve sorghum with 8% combined losses for sorghum and cassava and 5% combined losses for sorghum and maize.

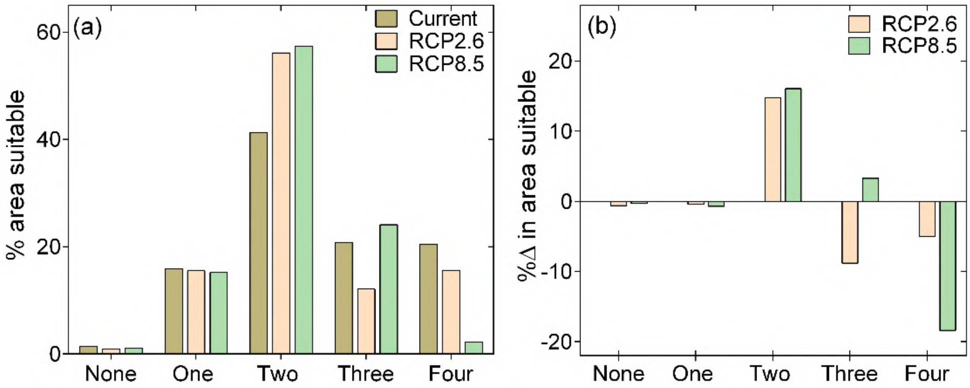

Figure 23: Impacts of climate change on (a) percentage of area suitable for multiple crops and (b) projected changes in area suitable for multiple crops under current, RCP2.6 and RCP8.5 climatic scenarios in Ghana.

Future crop suitability

The overall outcomes of the suitability modelling show that the impacts of climate change are site- and crop-specific, as determined by both the bioclimatic factors that influence crop viability and the specific characteristics of crops. Shifts in crop suitability have been identified as a key impact of climate change, spurring a need for adequate adaptation measures in the identified areas and/or for food transfer policies, which distribute food between the areas that will become suitable and those that will become marginal for a particular crop (Rippke et al., 2016; Travis, 2016). After considering other socioeconomic factors such as experiential learning in crop production, already existing technologies for crop production and culinary preferences, by 2050, it should be possible to grow sorghum and groundnuts in the northern areas, which will either become or remain suitable. Concurrently, maize can be produced in the south-western parts of the country where suitability will increase in response to changes in weather patterns, especially precipitation quantity and trends. Cassava production will remain largely unaffected by the changing climatic conditions except in a few regions. The ability of many regions to produce multiple crops in intercropping systems, alley cropping or rotations will be severely limited by climate change, as fewer combinations of crops are possible. In addition, interventions and implementation of adaptation measures such as irrigation or improved crop varieties should focus on areas that were predicted to become marginal, as the changes in suitability are indicators of climate impacts. This becomes even more important when investment resources are scarce and need to be targeted for maximum impact.

3.4 Yield Response Estimates and Main Determinants in Ghana

As the findings and discussion above reveal, standard crop models deliver highly uncertain results on future crop yields in Ghana, which can partly be explained by data quality. Existing literature confirms this, containing a wide range of crop yield response projections for Ghana (see Table 3):

Table 3: Literature results on crop yield projections in Ghana (maize and sorghum).

Crop	Region	Reference	Time frame	Key message	Deduced yield change by 2050
Maize	Whole Ghana	Shi & Tao 2014	1961-2010	Yield increases with increasing precipitation, decreases with increasing temperature	Decrease by 5-10% for 1°C of warming (RCP 2.6)
Maize	Whole Ghana	Challinor et al. 2015	Unspecified	Yield response to temperature depends on spatial scale of analysis	Decrease by 10% for 1°C of warming (RCP 2.6)
Maize	Whole Ghana	Arndt et al. 2015[12]	2045-2050	Yield changes only very slightly	Increase by 1%
Maize	Central Ghana	Srivastava et al. 2017	2030/2080 averaged here	Yield increases, mainly due to CO_2 and less water stress	Increase by ca. 30%
Sorghum	Whole Ghana	Arndt et al. 2015[13]	2045-2050	Yield changes only very slightly	Increase by 2%

The results show a wide span of yield changes from 10 to + 30% (for maize, under different emission scenarios), using different methods, time frames and data. Most studies model maize, with only one study found for sorghum and no results found for cassava and groundnut.

Management methods may have a larger influence on crop yields than climate change.

Considerable uncertainty on yield responses and future crop yields in Ghana thus prevail and no positive or negative impacts can be concluded. It seems that, in Ghana, changes in management are going to have a much larger influence on crop yields in the next decades than climate, for instance changes in cropping intensity and crop rotation patterns, as also suggested by the studies listed in Table 3. Other factors affecting crop yields are adaptive capacity of farmers, their economic situation (e.g. fertiliser buying power) and the water demand by other sectors (in case of irrigation). However, as most studies analyse the national level, climatic effects on yield may also be confounded by regionally distinct changes, which cancel each other out in a national average as a result of different directions of the effect. The suitability analysis suggests the same pattern, with both increases and decreases in suitability for crops projected, depending on the area.

Crop suitability models, as employed here, are better suited to detect spatially explicit projected changes in the suitability of farmland for specific crops. They are advanced, compared to the existing literature. Thus, we conclude that adaptation strategies should rather be fit to regions projected to become less suitable for producing certain crops, than based on overall crop yield response projections, given their high uncertainty and the potentially limited influence of weather. However, for policy decisions, we generally recommend to assume rather worst case scenarios when considering future climate impacts on crop yields, as the majority of potential adaptation strategies will be no-regret measures and be effective even in the absence of large climate impacts. In addition, as Chapter 1 and 2 have shown, extreme weather events such as droughts and river flash floods are likely to increase in the future, which also require appropriate adaptation responses in the agricultural sector. Adaptation strategies for improved management and climate risk reduction should have high potential to increase yields and thus to make farming systems in Ghana more resilient to climate shocks.

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[12] SRES scenarios, averaged here.

[13] SRES scenarios, averaged here.

Chapter Summary

Climate change impacts on crop suitability

- The impacts of climate change are site- and crop-specific, as determined by both the bioclimatic factors that influence crop viability and the specific characteristics of the crops.
- A key impact of climate change will be shifts in crop suitability.
- By 2050, sorghum and groundnuts could be grown in the northern areas that will either become or remain suitable. Maize production could be increased in the southwestern parts of the country, where suitability will rise in response to changes in weather patterns, especially precipitation quantities and trends. Cassava could be grown in all parts of Ghana, except for the lower and middle northern region, as well as southern parts of the Central Region.
- In addition to the impacts of climate change on individual crops, suitability for multiple cropping will also be reduced by climate change. In regions where formerly multiple crops could be cultivated, climate change now restricts the potential for crops that could be cultivated.

Chapter 4 – Assessment of Adaptation Strategies for Ghana

With the first three chapters providing important information on the impact dimension of climate change in Ghana, the subsequent analysis focuses on the action dimension, which is needed to translate the climate risk findings into effective adaptation strategies. Adaptation strategies can broadly be defined as measures which facilitate the adjustment of human or physical systems to expected or actual climate change and its effects. A multitude of different adaptation strategies exists, of which only a few can be treated in this study, with a specific focus on the agricultural sector.

4.1 Methodology

Adaptation options for Ghana were assessed based on a multi-criteria analysis.

In order to identify and assess the feasibility and suitability of different adaptation strategies for Ghana's agricultural sector, a multi-criteria analysis was conducted for selecting the most promising adaptation strategies. We developed a simple framework for assessing agricultural adaptation strategies for the context of Ghana. The framework builds on the country-specific climate risks as modelled and analysed above, as well as on country-specific measurement and adaptation information to analyse a list of criteria (see Figure 24).

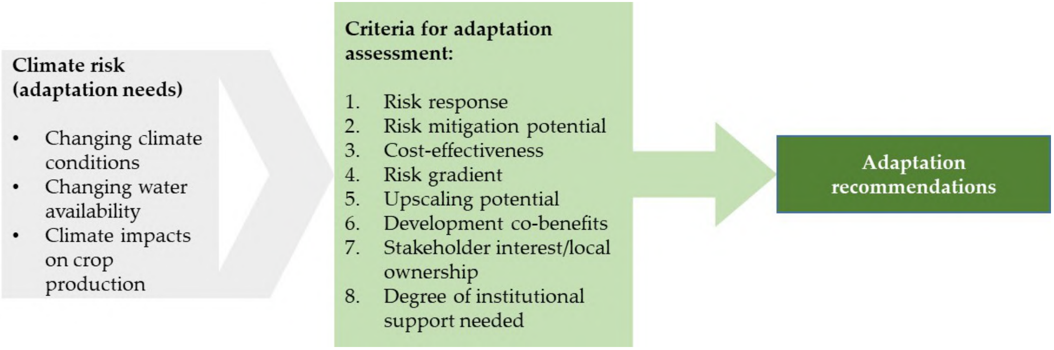

Figure 24: Adaptation assessment framework.

Biophysical, economic, social and institutional indicators were applied.

This framework builds on the impact analysis and integrates the findings into the wider context, using biophysical, economic, social and institutional indicators to derive a comprehensive picture of the suitability of adaptation options. The assessment is informed by economic and biophysical modelling, academic literature, case studies and expert judgement, which served as a starting point for the selection of appropriate adaptation strategies. Relevant policy documents, including Ghana's NDC Implementation and Investment Plan for the agricultural sector and input from government partners such as the Ghanaian Ministry of Food and Agriculture (MoFA), were also consulted for selecting the adaptation strategies to be studied. Based on a country-specific risk profile and country-specific adaptation information, adaptation recommendations are formulated. A focus is placed on assessing the performance of adaptation measures with regard to cost-effectively mitigating climate risk, based on biophysical impact models and economic models.

The biophysical impacts have been presented and analysed in Chapter 1-3, whereas the cost-benefit analysis follows in Chapter 5. The biophysical adaptation analysis of climate risk mitigation potential forms section 4.4 of this chapter. With climate models projecting a considerable increase in temperatures in Ghana and a decline in precipitation for the south of Ghana (see Chapter 1), changes in water availability and evapotranspiration have to be considered for selection of appropriate adaptation strategies. In addition, the projected increase in climate extremes and the changes in suitability of areas for different crops (Chapter 3) need to be taken into account.

As a further component of the climate risk analysis, the exposure of the agricultural sector to climate impacts was assessed mainly via qualitative interviews as well as different crop importance rankings. The country-specific adaptation information comes from modelling assessments and a literature review, in addition to interview content.

Next to quantitative indicators, interviews with experts were conducted and key policy documents consulted.

For the qualitative analysis, 16 semi-structured expert interviews with a total of 20 researchers, NGO workers and private sector representatives were conducted. In addition, a stakeholder workshop was held with governmental counterparts of German development cooperation, informing the subsequent assessment[14]. The interviews were transcribed, coded and analysed using thematic analysis following the Attride-Stirling model (Attride-Stirling, 2001), to identify key themes and perceptions of experts on a range of issues such as adaptation barriers, climate vulnerability and exposure in Ghana and specific adaptation strategies. In addition, key policy documents were consulted such as the Ghana National Climate Change Adaptation Strategy, the Ghana National Climate Change Policy and Ghana's Nationally Determined Contribution (NDC).

4.2 Adaptation in Ghana

Exposure and vulnerability in Ghana's agricultural sector

Maize, groundnut, cassava and sorghum were selected according to a crop importance ranking and according to modelling feasibility.

In order to select suitable adaptation strategies, the target population, location and the key crops in Ghana needed to be identified. In addition to the interviews, literature and stakeholder consultation, a crop importance ranking, based on selected quantitative indicators, supported the analysis, in order to identify which crops should primarily be addressed with adaptation strategies. The crop importance ranking for the whole of Ghana showed cassava, yam and cocoa to be the most important crops based on indicators linked to economic importance, nutrition and production[15]. The methodology employed for this ranking was developed by the International Centre for Tropical Agriculture (CIAT). For this study, maize, groundnut, cassava and sorghum were selected as crops to be assessed, based on their importance ranking, their potential for improving food security of the most vulnerable populations, the current harvested area of the staple crops as well as the focus of this study on food crops (see Chapter 3). The expert interviews revealed specific interest in those four crops and their contribution to smallholder farmers' diets and livelihoods especially in the climate vulnerable north of Ghana is high. This links with the interest of both experts and the stakeholders at the workshop to target the most vulnerable parts of the population, notably smallholder farmers and especially those concentrated in northern Ghana. While important for Ghanaian agriculture, yam and cocoa are difficult to model with existing crop models. An expansion into this field would, however, be a useful addition for future assessments.

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[14] For additional details on the interview partners as well as a sample interview topic guide, please refer to the supplementary material.

[15] Please refer to the supplementary material for the full results.

Stakeholder engagement and interest

Stakeholder workshops in Accra and continuous stakeholder engagement informed the study and validated results.

Figure 25 describes the stakeholder engagement process followed for this study: A first stakeholder workshop was held in Accra, Ghana in September 2018, to kick off the study. The majority of participants came from Ghanaian ministries involved in the development of the Ghanaian NDC Implementation and Investment Plan, as part of the interministerial technical working group responsible for developing the agricultural NDC Implementation and Investment Plan. This included representatives from the Ministries for Agriculture and Environment as well as from Ghana's Environmental Protection Agency (EPA). After presenting the study approach and preliminary findings, a discussion took place, facilitated by GIZ, on the selection of adaptation strategies and the alignment of the study with the Ghanaian government's interests and needs.

Figure 25: Stakeholder engagement process followed throughout the study.

On a general level, it was concluded that all adaptation strategies identified by the research team are relevant and of general interest for the Ghanaian context, with a specific interest in the priority areas of Ghana's NDC, namely conservation agriculture, post-harvest management and increased fisheries and livestock productivity. Bold approaches were also called for with transformative potential for the agricultural sector – here irrigation upscaling and improved crop varieties were highlighted. The final selection of adaptation strategies by the study team, after analysis of the interviews and further criteria, was validated with the kick-off workshop participants via email. In March 2019, the study findings were presented and discussed at a validation workshop in Accra. Valuable feedback from this workshop informed the final study and specifically fed into the policy recommendations.

The adaptation measures selected for analysis within this study are: Crop insurance, post-harvest management, irrigation, rainwater harvesting and small-scale irrigation and improved crop varieties.

Feasibility of adaptation options: barriers to adaptation

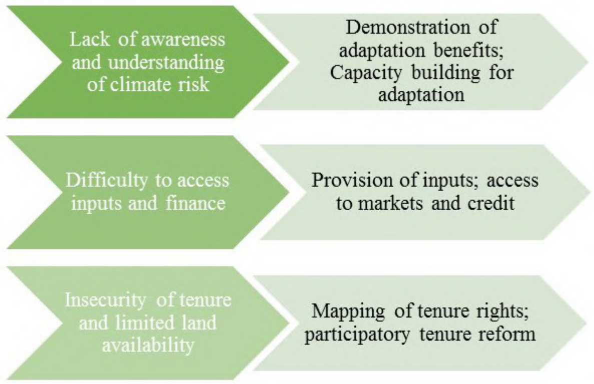
Interviewees named three key barriers to adaptation: lack of risk awareness, limited finance and insecure land tenure.

From the expert interviews, a number of important themes emerged which should guide adaptation in Ghana (see Figure 26): Interviewees identified three main barriers including (1) a lack of awareness and understanding of climate risk, (2) difficulty to access inputs and finance for adaptation as well as in some cases (3) insecurity of tenure and land availability. In order to overcome these barriers, a number of key themes were mentioned by stakeholders such as the need for demonstrating adaptation benefits. This underlines the need for the present study, which evaluates the benefits of adaptation solutions for

Ghana, specifically with regard to their economic benefits. Capacity and the means to implement adaptation strategies also play an important role: Capacity building, education and information on climate change adaptation should thus be given priority, as this crucially determines uptake of adaptation strategies and correct implementation. Providing inputs and improving access to credit and markets is important for scaling up adaptation activities. Tenure insecurity can discourage investment into land among farmers, since farmers with uncertain land occupation may lose benefits from adaptation in case of future eviction. Land rights systems in Ghana are very complex. Customary or informal tenure systems predominate, sometimes overlapping with formal, statutory land rights. In customary systems, farmers typically do not hold official titles over the land, making them vulnerable to outside claims. Adaptation strategies should thus consider tenure factors and participatory mapping exercises. In addition, governmental reforms can be useful in order to ensure that adaptation benefits can be seized by farmers.

Local and indigenous knowledge should be seized.

Regarding the design of adaptation strategies, it was repeatedly noted that combinations of strategies may be most effective and bring better results than stand-alone interventions. Local and indigenous knowledge should be seized, as good solutions already exist for some challenges, which have been developed and tested locally. This links with the often voiced call for local ownership: Interviewees across all groups highlighted that adaptation actions need to be rooted at the grassroots level, with proximity to beneficiaries and participatory consultation being key factors for successful implementation. Ultimately, most informants, however, also agreed that adaptation should be brought to scale in order to be impactful.



Adaptation design:

1. Combinations of adaptation strategies
2. Seize local and indigenous knowledge
3. Importance of local ownership: participatory consultations
4. Upscaling of strategies

Figure 26: Barriers and potential solutions to adaptation in Ghana[16].

4.3 Adaptation Assessment Criteria

The adaptation needs as identified based on the impact assessment in Chapter 1-3 and the adaptation interests by Ghanaian stakeholders as outlined above are now matched with specific agricultural adaptation strategies. For some strategies, the process-based crop model APSIM and the crop suitability models introduced in Chapter 3 were used to assess the strategies' risk mitigation potential. For the other adaptation strategies assessed in this study, the biophysical crop models could not be employed, which is why a holistic assessment based on literature and the qualitative interviews was conducted.

For each strategy, its inherent nature is presented first and then further specified with measurement, modelling and implementation information, where available. Chapter 5 adds further economic evaluation to selected strategies, for final assessment. The following characteristics of adaptation strategies are considered here:

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[16] This figure shows key themes identified from the expert interviews conducted.

1) **Risk response (risk mitigation vs. risk sharing or transfer):** Adaptation measures can either reduce climate risk (for instance better water management) or share/transfer risk among groups, to lessen the burden on individuals (e.g. insurances). This distinction is important as climate risk can be reduced to only some extent, but climate risk which is not manageable needs other mechanisms to transfer that risk, for instance crop insurance.
2) **Risk mitigation potential:** An important assessment criterion for adaptation measures is their potential to mitigate risk, i.e. to reduce yield losses due to climate change. Where possible, this was assessed based on adaptation evaluation within the impact models.
3) **Cost effectiveness:** Although absolute costs depend on the scope of applying identified adaptation strategies (e.g. scale and size), information on the costs and cost effectiveness of different adaptation strategies based on scenarios are included in the assessment (see Chapter 5).
4) **Risk gradient (no-regret vs. risk-specific):** Closely linked to the question of cost effectiveness, adaptation strategies can be useful even in the absence of climate change ("no-regret"), for instance when they increase production, or they can be risk-specific, where their implementation is only sensible when a risk is actually present (e.g. insurances).
5) **Upscaling potential:** This category considers in how far different adaptation strategies can be upscaled from a micro to a macro level, covering many farmers.
6) **Development co-benefits:** Most adaptation strategies do not only adjust systems to cope with climate risk, but have the potential to contribute to other development benefits as well, or may conflict with them, which can lead to maladaptation. Here, this is indicated by referring to relevant Sustainable Development Goals (SDGs), which can also be addressed by specific strategies.
7) **Stakeholder interest/local ownership:** Another indicator for selecting adaptation strategies is the interest that relevant stakeholders (e.g. from government, academia, civil society and the private sector) show in a measure, as this is crucial for future uptake and implementation.
8) **Degree of institutional support needed (institution-led vs. autonomous):** While most adaptation strategies can be initiated and implemented by different actors, a distinction can be made between strategies which require institutional support and those that can be initiated by farmers themselves.

Most adaptation strategies can offer co-benefits, e.g. for mitigation.

Regarding indicator 6) on development co-benefits, a number of potential co-benefits exist for different adaptation strategies. For instance, all five adaptation strategies discussed in this study can contribute to climate change mitigation efforts (SDG13), in addition to their adaptation benefits. With enhanced efficiency of input use and increased productivity, additional GHG emissions, otherwise caused by further agricultural expansion, can be avoided, thus providing important mitigation co-benefits. Furthermore, oftentimes soil quality is enhanced as a result of adaptation strategies, which improves carbon storage capacities of soil. However, this of course depends on the local context and the concrete design and implementation of the adaptation measure. When shifting cropping patterns or increasing fertilizer use for instance, the positive effect for mitigation may be reversed. This needs to be considered in the design of responsible and sustainable adaptation strategies.

In addition to mitigation aspects, other potential development co-benefits can include contributing to the achievement of SDG1 (no poverty), SDG2 (zero hunger), SDG3 (good health and wellbeing), SDG8 (decent work and economic growth), SDG11 (sustainable cities and communities) and SDG16 (peace, justice and strong institutions), among others, even if the potential link is indirect in some cases: Increased agricultural production and more resilient agricultural systems can contribute to lower poverty rates, improved food security indicators, better health (notably through improved nutrition), economic growth with a stronger agricultural sector, less demographic pressure on cities because of more income perspectives in rural areas and less conflict potential due to higher overall development and food security.

Potential resource conflicts and conflicts of target can, however, occur with irrigation: Here, agriculture may compete with other sectors such as household consumption for water, which might negatively affect the achievement of SDG6 (clean water and sanitation). Diverting water for irrigation can also conflict with renewable energy generation

(SDG7 for affordable and clean energy) such as hydropower. This is also relevant for the context of Ghana, where new hydropower capacity has recently been added with the Bui Dam Hydroelectric Power project on the Black Volta (Government of Ghana, 2014).

As regards indicator 7) on stakeholder interest, all adaptation measures discussed below have sparked great interest among the stakeholders we consulted for this study. In the following, the respective adaptation measures and their assessment according to the above criteria are presented.

4.4 Model-based Evaluation of Adaptation Strategies

In the following model-based analysis, the potential of specific adaptation strategies is assessed for reducing climate risk for crops in Ghana's agricultural sector, at different spatial scales: utilizing improved crop varieties, applying manure, delaying the sowing date and enhancing soil organic carbon. First, the process-based crop model ASPIM is used to evaluate the strategies in three selected districts, then the crop suitability models as introduced in Chapter 3 are utilized.

4.4.1 Process-based Evaluation of Adaptation Strategies

Using a process-based crop model (APSIM), we evaluated four adaptation measures for maize: improved varieties, application of manure, delayed sowing and enhancing soil organic carbon.

Although APSIM as a process-based crop model seems to have limitations to capture the year-to-year yield variability in the whole of Ghana (see discussion in Chapter 6 on possible reasons), it does provide robust results for selected districts. These were West Akim (moist semi-deciduous forest zone in the Eastern Region), Akatsi (coastal savanna and moist semi-deciduous forest zone in the Volta Region) and Nkwata (Guinea savanna in the Volta Region). With the help of APSIM, three adaptation measures were evaluated to understand their potential for cushioning farmers from the impacts of climate change, using maize as a sample crop. Maize was chosen as sample crop, because according to the crop modelling results, it will experience the highest yield losses under climate change, as compared to other crops analysed for Ghana (see Figure 21, Chapter 3). The adaptation measures employed here were the use of two improved varieties (one hypothetical (ObatanB) and one current variety (Dorke)), the increased use of organic manures and, finally, delayed sowing to avoid insufficient water supply in the beginning of the growing season (Lana et al., 2017) in the three districts. To evaluate these measures, climate impacts in the three districts were compared between no adaptation and either one of the three measures.

The greatest maize yield losses without adaptation are likely to occur in Nkwata (8.1% loss under RCP2.6 and 10.8% loss under RCP8.5). West Akim is projected to also have yield losses of 6.2% under RCP2.6 and 8.4% under RCP8.5 of current levels under climate change, while Akatsi sees positive yield improvement under climate change of 4.8% under RCP2.6 and 4% under RCP8.5. These results concur with the results of the suitability models that the impacts of climate change on crop potential are not similar between different sites in Ghana. These variations are explained by the projections showing that precipitation in the southern parts of the country will decrease, while in some parts of the North increases in precipitation are expected (see Chapter 1).

The overall most promising adaptation strategy is using different maize varieties, although the impact of the adaptation measure depends on the district and the scenario.

We evaluated the yield response of two maize varieties under climate change. The results show that the Dorke variety will improve maize yield by 30.2% compared to the current yield levels under RCP2.6 in Nkwata and by 15.9% under RCP8.5 while having only a limited effect of about 1% yield increase in the other two districts (see Table 4). In all districts and scenarios, manure application is not very effective in cushioning maize production from the impacts of climate change. Delaying the sowing period by two weeks from the current farm calendar had also a positive effect on reducing the impacts of climate change, particularly in Nkwata. Overall, the impact of the adaptation measure depends on the district and the scenario, but using the improved varieties proved to be the most promising climate change adaptation strategy based on its impact on yields, particularly for the northern district of Nkwata, followed by late sowing.

Table 4: Impact of agronomic adaptation measures on maize yield under climate change for three districts in Ghana (average yield projection for 2050 compared to 2006 baseline).

Emission Scenario	District	No adaptation	Improved variety		Manure	Late sowing
			Dorke	ObatanB		
RCP2.6	West Akim	-6.2	0.8	-0.3	3.4	-3.2
	Nkwata	-8.1	30.2	22.7	-5.4	0.1
	Akatsi	4.8	1.0	5.0	4.8	5.5
RCP8.5	West Akim	-8.4	0.2	4.2	5.2	3.1
	Nkwata	-10.8	15.9	13.5	7.2	9.4
	Akatsi	4.0	4.3	7.1	0.6	8.7

4.4.2 Evaluation of Adaptation Strategies in Influencing Crop Suitability

We evaluated two adaptation options and their combinations. These were shifting the growing season by 14 and 28 days and increasing the soil organic carbon layer by 10%. Thus, the evaluated adaptation measures were a two weeks (2W) forward shift of the growing season, a four weeks (4W) forward shift of the growing season, increasing soil organic carbon by 10% (10%OC), a 2W forward shift combined with a 10% increase in organic carbon content (2W10%OC) and a 4W forward shift and 10% increase in soil organic carbon content (4W10%OC). We evaluated these measures by comparing the effect of these adjustments on current and future crop suitability.

The most promising adaptation measure for cassava in Ghana is shifting the growing season by four weeks in combination with a 10% increase in soil organic carbon, which produces an increase in area suitable of 8% (see Figure 27). For groundnut, these adaptation measures will reduce the projected increases in area suitable for groundnuts. The results indicate that the effect of the adaptation measures are crop-specific, shifting the growing season by two weeks for instance reduces groundnut suitability, but increases suitability for maize and sorghum (see Figure 27). Overall, the most promising adaptation measure for all crops was shifting the growing season by four weeks, with the average area suitable across crops increasing by 2.9% under RCP2.6 and by 4.8% under RCP8.5.

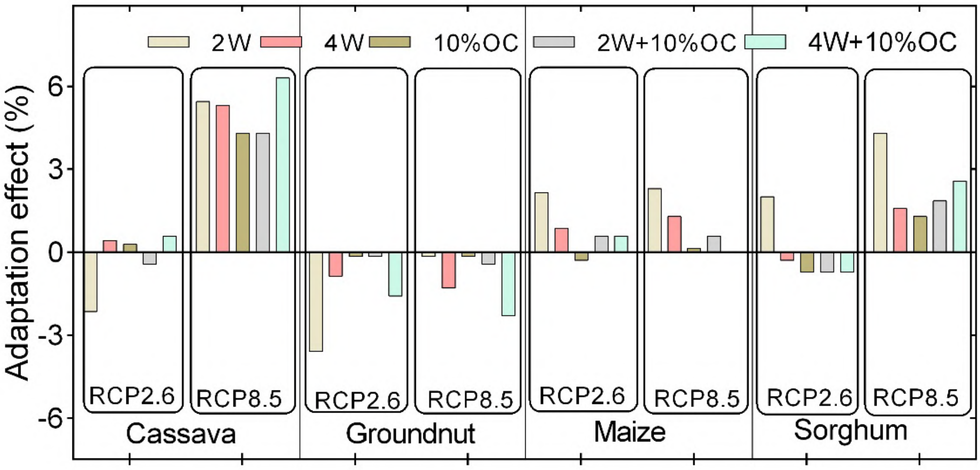

Figure 27: Projected effects of different adaptation options on crop suitability for cassava, groundnut, maize and sorghum under RCP2.6 and RCP8.5.

The adaptation options analysed are: a two-week shift in the growing season (beige), a four-week shift in the growing season (red), increasing soil organic carbon by 10% (brown), a combination of shifting the growing season by two weeks and increasing soil organic carbon by 10% (grey) and a combination of shifting the growing season by four weeks and enhancing soil organic carbon by 10% (mint).

4.5 Specific Adaptation Strategies in the Ghanaian Context

The needs of local communities are important in deciding which adaptation strategies are adequate.

In addition to the specific adaptation strategies analysed in the previous section, many different adaptation strategies can be useful and the local context and communities' needs are key for ultimately deciding on the strategies to pursue. The following list of strategies is thus meant as an indication only, for which adaptation measures may provide a useful start and hold potential at a wider scale.

Crop insurance

While most adaptation strategies seek to minimize risks stemming from climate change, not all risks can be eliminated. Weather perils such as droughts, storms or erratic precipitation represent so-called systemic risks that go beyond the farmers' coping ability. Thus, mechanisms are needed that distribute residual risks to avoid that certain groups or individuals lose their livelihoods. One such risk transfer solution is crop insurance, which allows farmers to insure their crop yields against weather-induced losses. While insurance usually is based on indemnity assessment, this model is problematic for smallholder farmers due to the high transaction costs which insurance schemes usually entail. Thus, a more suitable approach for smallholder farmers are weather index-based insurances (WII), a scheme that uses a weather index, such as precipitation, to determine a payout. Alternative index-based insurance schemes can also be useful, such as area-yield index insurance[17].

Many smallholder farmers cannot afford insurance and may need government subsidies.

As regards the level of implementation and stakeholders needed, insurance solutions are necessarily institution-led adaptation strategies, since they cannot be set up autonomously by individual farmers or beneficiaries. As regards the target audience, crop insurance can benefit any parts of the population, depending on the design of the insurance scheme. Although it may be easier for larger farms to afford insurance and coverage of larger units is also more convenient for insurers to handle, government support and the setting up of WII schemes can help make insurance affordable. It is then more accessible also for the most vulnerable parts of the population, namely smallholder farmers. However, it is difficult to offer self-sustaining insurance schemes for smallholder farmers. The need for affordability may require continued subsidies by the government or third parties, which can hamper the development of insurance products for the most vulnerable. Here new solutions are needed to address the trade-off between affordability for smallholder farmers and the insurance industry's profit. Generally, insurance schemes are rather costly adaptation strategies (see also Chapter 5), at least when considering the overall costs and with progressing climate change increasing the overall risk to the agricultural sector. However, insurance schemes have an important role to play for securing livelihoods: They can stabilize farm incomes and can prove to be very cost-effective for farmers when a hazard occurs. Insurance schemes can be rather easily scaled up. In fact, they depend on large coverage for becoming operational and they provide potential opportunities for the private sector to be engaged, with private insurers holding large expertise in this sector.

In Ghana area-yield index insurance has shown the biggest potential for insuring yield losses.

For Ghana, a number of specifications can be made to this general adaptation profile: According to the Ghana Agricultural Insurance Pool (GAIP), area-yield index insurance (AYII) as an alternative to WII has shown the biggest potential for smallholder farmers in Ghana as of yet [Interview 16, 23.10.2018]. GAIP is a pioneer in implementing AYII in Ghana, insuring since 2011 successfully some 3000 – 4000 smallholder farmers' cereal crops[18] on over 18,000 acres of land. In 2017, GAIP made payouts to nearly half its insured parties.

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[17] An area yield index insurance scheme defines the compensation based on the realized average yield of an area. A payout occurs if the realized average yield for the area is less than the insured yield, which is based on a percentage of the average yield for the area. The individual yield attained by the farmer is thus not taken into account, which lowers the costs for such an insurance scheme.

[18] The main insured crops are: maize, sorghum, millet and groundnut.

However, AYII may increase moral hazard by providing index coverage to farmers, with the index capturing all relevant factors to determine yield, including management. Nevertheless, these schemes allow identifying the weather-related part and thus, moral hazard among farmers is not an important issue as only weather-related yield losses are covered. Regarding adverse selection, the AYII scheme offers the advantage to rather easily scale up insurance coverage. This can counter adverse selection, as more insurance holders are included. Another common problem for insurance schemes is basis risk, which occurs when insurance payouts incorrectly are not triggered by events or when payouts are triggered in the absence of events. With index insurance, this risk can never be fully eliminated, but with better data quality and fine spatial resolution, basis risks can be reduced.

Despite good prospects, farmers' interest in insurance remains limited.

Although AYII is a promising development, farmers' uptake of AYII in Ghana remains limited. Balmalssaka et al. (2016), who examined the willingness of farmers in northern Ghana to participate in insurance schemes, found access to credit as well as education and experience with insurance to be important factors determining farmers' engagement with crop insurance (Balmalssaka et al., 2016). In fact, 41% of farmers in their study "viewed insurance as unnecessary and additional burden" (ibid., p. 1263) and were unwilling to participate. Similarly, experts interviewed pointed out a lack of information and capacity building on the topic, high premiums, which are unaffordable for poor farmers, and distrust in abstract insurance systems as key challenges for insurance uptake. This indicates the need for additional incentives or financial support for taking out insurance, underlined also by Aidoo et al. (2014) who determined farmers' willingness to pay for crop insurance in one municipality in Ghana. He concluded there was a need for government subsidies to implement it in the country (Aidoo et al., 2014). While subsidies are one strategy, experts also suggested to bundle insurance with inputs, where possible, to increase uptake. This might be a promising strategy as some studies found that Ghanaian farmers who participated in WII would increase investments in farm inputs by 13% (Karlan et al., 2012) or in fertilizer use by some 30% (Haruna et al., 2017). The large majority of stakeholders consulted see WII as an important and promising avenue for the future, partly recommending, however, to also look into alternative risk-sharing strategies, such as local savings associations. In any case, due to the complexity of the topic, it is necessary to offer complementary capacity building measures to avoid unintended consequences, such as overuse of fertilizer.

In the following, a potential design for an index-based insurance scheme for Ghana is laid out. Chapter 5 provides further insights on the costs of insurance via an economic analysis.

Potential design of an index-insurance scheme based on weather input only

Since standard procedures for capturing weather signals in crop yields are not well applicable for maize in Ghana (see Chapter 3), an index insurance based on a decision tree is presented here. The decision tree serves two purposes: first, forecasting expected losses already during the growing season and, second, deriving a weather-based insurance index. This is valid for the northern part of Ghana (i.e. the savannah zone); results in the South are analogous but skipped due to limited space. Decision trees are models that split a given data base into subsets so that correlations with one or several predictive variables (e.g. temperature or potential evapotranspiration) are maximized within the subsets. We applied model-based trees as detailed in Zeileis et al. (2008). The resulting data splits are intuitive, easy to understand and have the advantage of being based on observable quantities during the season, e.g. number of days without rain. The result for maize in the savannah zone is presented in Figure 28. The growing season is assumed as May 01 to September 30, in accordance with Adu et al. (2014), and a "yield loss" event occurs if yield is 30% or lower of the long-term average per district. The weather-based insurance index derived from the decision tree analysis could be defined as follows: If the number of consecutive days without rain in July is below the long-term average per district, there is no payout as losses are likely to be small. In the other case (i.e. July was dryer than on average), payout depends on two further factors. First, if potential evapotranspiration (PET, a combined proxy for temperature and radiation) in September is lower than the long-term district average, payout occurs if the total precipitation during the growing season was lower than average. If PET is higher than average, payout is granted if the minimum temperature in July was below average. In sum, insurance payout mainly depends on weather conditions in July and

September. There are two further sub cases in each of the two leaves under “PET 9” that grant payout in particular cases which are not detailed here. The overall accuracy of this scheme is that 51% of occurred losses are correctly detected (and hence a payout is triggered), while 49% of payouts are unfounded i.e. no loss actually occurred. This is, in sum, not a very efficient insurance scheme. But the potential of this approach is not yet fully exhausted such that we will continue to improve the accuracy.

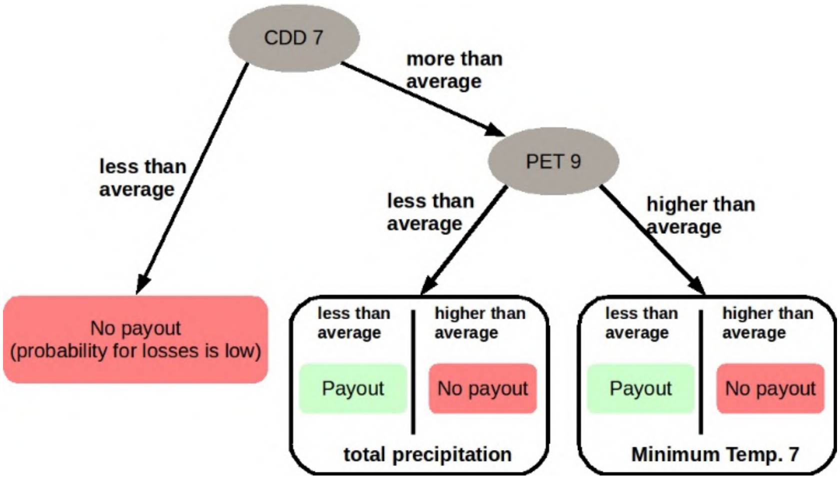

Figure 28: Decision tree for loss forecasting and insurance payouts.
Payout is granted if the probability (log odds) for yield loss is higher than 0.5. Abbreviations: CDD = Consecutive Dry Days (i.e. subsequent days without rain), PET = Potential Evapotranspiration, Temp. = temperature, and 7 or 9 denoting July or September, respectively.

In sum, crop insurance in Ghana has the for upscaling and is useful for climate risk transfer, which cannot be mitigated. However, complementation with additional measures for risk reduction is needed.

Post-harvest management

Effective post-harvest management is particularly important in times of climate change.

Effective post-harvest management is crucial to avoid food loss along the value chain. Investments in scaling technologies for improved post-harvest management have high potential for reducing crop losses, also and especially under climate change. With climate change altering growing and harvesting seasons, post-harvest management is crucial to cope with increased uncertainty. It is a risk-reducing strategy that lowers the vulnerability of crop production to climate impacts. Next to main staple crops such as maize and beans, post-harvest loss (PHL) of easily perishable horticulture crops could be avoided. Numerous effective and low-cost technologies exist that can prevent or reduce PHL. While some larger interventions would need government support, we classify post-harvest management as an autonomous strategy, where farmers themselves can invest in better small-scale storage and improve their harvest handling. Furthermore, post-harvest management can also provide interesting development co-benefits. Especially climate change mitigation co-benefits are valuable, albeit indirect, since by increasing the net agricultural output, post-harvest management lowers the need for farmland expansion, thus reducing the deforestation rate.

Ghana’s NDC lists post-harvest management as a priority for adapting agriculture to climate change.

Ghana’s NDC Implementation and Investment plan lists post-harvest management as a priority for adapting agriculture to climate change, with interviews confirming wide-spread interest in such strategies. Every year, post-harvest losses significantly reduce the amount of food available for human consumption in Ghana. For example, recent estimates suggest a PHL for total annual maize yield in Ghana of between 14% (Mutungi and Affognon, 2013) to 30% (Opit, G.P., Campbell, J., Arthur, F., Armstrong, P., Osekre, E., Washburn, S., Baban, O., McNeill, S., Mbata, G., Ayobami, I., Reddy, 2014; Baoua et al., 2018), of 7% for groundnuts, 31% for yam and 34% for cassava (Mutungi and Affognon, 2013). However, in Ghana adoption of post-harvest management technologies has been limited due to a number of constraints such as lack of knowledge and information, limited or no access to credit and behavioural preferences for present consumption over future income (Baoua et al., 2014; Carlotta Ridolfi, 2018). Even where public spaces for harvest storage exist, accessing such facilities may be difficult in rural areas, as experts cautioned.

Consequently, capacity building and decentral post-harvest management approaches are needed. In addition, experts recommend investment in the full value chain, including processing capacities for value addition, to ensure income gains for rural smallholders. A concrete post-harvest technology with promising results in the context of maize production in Ghana have been so-called PICS bags (Purdue Improved Cowpea Storage): simple and affordable yet effective hermetic storage bags originally developed for storing cowpea. Piloted with maize in 12 sites across Ghana, Burkina Faso and Benin, they have proven to reduce insect and rodent infestation of stored grains by 95-100%, while maintaining quality and germination potential of the seeds (Baoua et al., 2014; Opit et al., 2014). Also, weight of grain remained constant in PICS bags over a 6.5 month storage period, compared to a 21% reduction in standard woven bags, while insect damage remained the same as in the beginning, compared to a 60% increase in standard woven bags (Baoua et al., 2014). PICS bags have the additional advantage of being locally produced and are already embedded in a rather well-established distribution network, thus displaying strong potential for further upscaling and adoption (ibid.). Private sector actors could be engaged in the provision and distribution of PICS bags, potentially with government support to improve targeting of the most vulnerable communities. However, PICS bags alone are not enough. Farmers should also be trained and supported in conducting baseline assessments of insect pest populations and aflatoxin levels in maize and learn effective methods of ecological and integrated pest management even before harvest. Other promising examples of climate smart PHL management technologies include the utilisation of moisture meters, solar dryers or small affordable plastic or metal silos (Opit et al., 2014).

Generally, there appears to be considerable potential to further upscale improved post-harvest management across Ghana. Furthermore, as the economic analysis in Chapter 5 confirms, most post-harvest management measures are rather low cost interventions, with most intervention types being “no regret” strategies because even in the absence of climate change, the improvement in crop handling will lead to lower crop losses and higher agricultural output, being economically sensible.

Overall, post-harvest management strategies have considerable potential in Ghana and, being a low-cost and often no-regret strategy, can be recommended for wider implementation.

Irrigation

In areas short of precipitation, irrigation can be a key strategy to enable plant growth and increase yields. Water can be drawn from different sources, such as groundwater, surface water and in some countries even desalinated seawater, to enable a better growth of plants. While irrigation is not by default an institution-led adaptation strategy, but can also be initiated and implemented by farmers themselves, for larger irrigation installations, technical agencies and extension officers play an important role. In Ghana, irrigation is often driven by institutions, which to date are mainly governments and development corporations, but could also be private sector actors in the future, for instance as part of outgrower schemes. Irrigation can be a no-regret strategy, depending on the costs of installing and maintaining irrigation systems. However, as the analysis in Chapter 5 shows, irrigation in Ghana as of yet is costly, making the suitability of irrigation dependent on climate risk. Irrigation can reduce risk by decreasing the vulnerability of farming systems.

Generally, the upscaling potential of irrigation depends on water availability (e.g. in the form of groundwater resources) and on the need for irrigation in the first place. Where precipitation is sufficient to water crops, additional irrigation is not needed. As regards development co-benefits, while – like all other measures assessed here – also irrigation offers considerable co-benefits e.g. with regard to food security, improved nutrition and poverty reduction, it may also conflict with some development goals. Those include notably other water usages: Agriculture is the main water user in many countries. More irrigation water would lower the availability of water for households and with regard to energy security could conflict with hydropower development.

Irrigation is not widely implemented in Ghana, mainly because the necessary infrastructure is lacking and investments would be needed.

As of yet, irrigation is not widely spread in Ghana, with only an estimated 1.6% of the area with a respective potential actually being irrigated (Mendes, Paglietti & Jackson, 2014), mostly for rice and horticulture cultivation (Namara et al., 2011)[19]. But this figure may underestimate the actual irrigation share, as unconventional, autonomous and private schemes are likely not included in the calculation (Namara et al., 2010)[20]. Using a multi-criteria evaluation technique, Worqlul et al. (2019) calculate that about 9% of Ghana is suitable for irrigation, mainly in the southwestern part of the country. Under climate change (RCP4.5) they project that by 2050, 9.5% of this land will have become unsuitable, with 17% in 2070. Nonetheless, it is estimated that an increase in irrigation could be useful (see e.g. Akudugu, Nyamadi & Dittoh, 2016): Although Ghana is a relatively water-abundant country, precipitation varies considerably both temporally and spatially. Irrigation could thus enhance water availability and agricultural production in certain areas such as in the Southwest, especially during the dry season (Mendes, Paglietti & Jackson, 2014). We thus assume a medium upscaling potential for irrigation in Ghana. But so far, the necessary infrastructure is lacking and substantive investment would be required.

Stakeholders in Ghana have shown considerable interest in irrigation, especially due to the low uptake so far and the enormous potential irrigation holds for increasing yields in areas where precipitation is insufficient or unreliable. Additional irrigation would particularly benefit production of rice, vegetables, sugar and palm oil, where the local market would absorb increased production (ibid., 2014). Since rice consumption is increasing in Ghana, with much of the demand satisfied by imports, production intensification of rice could particularly benefit Ghana's agricultural sector (Namara et al., 2011). The main barriers to irrigation uptake in Ghana have been the high costs of most irrigation systems and the limited access to credit, especially for smallholder farmers in Ghana. Experts also cautioned that there is a lack of extension officers who can train farmers on irrigation. So not only are infrastructure investments needed but also improved capacity building and maintenance of existing systems. Although public extension services technically cover the full country, in reality they often provide limited information on informal irrigation systems used by smallholder farmers. High power costs also play into irrigation costs, other barriers include higher labor requirements of some irrigation systems and lack of inputs needed. In some areas, water availability is limited, although this is not a major issue in Ghana, where average precipitation is sufficient. Namara et al. (2011) estimate that irrigation costs are higher in Ghana as compared to other countries, which they see, among others, due to insufficient local expertise and use of unnecessarily costly inputs. Chapter 5 provides more information on the costs of different irrigation systems in the context of Ghana.

Improving irrigation capacity in Ghana also requires better training of farmers and better maintenance of existing systems.

While irrigation has the potential to increase agricultural production, it is also a costly strategy, often requiring institutional support for implementation and maintenance.

Rainwater harvesting and small-scale irrigation

Rainwater harvesting is a promising practice for reducing irrigation costs based on groundwater.

Rainwater harvesting (RWH) allows storing irrigation water for critical times in the growing period of otherwise rain-fed crops. It is also a promising practice for reducing costs for irrigation uptake as its installation is considerably cheaper than building groundwater irrigation infrastructure. Depending on the concrete design, RWH strategies can be institution-led for large-scale projects or autonomously implemented, when smaller structures are built and maintained by farmers themselves.

Like irrigation, RWH reduces risk and is often a no-regret measure, being cost-effective and thus sensible to implement even in the absence of

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[19] As of 2016, about 21% of Ghana's total land area was arable land, which amounts to about 4,700,000 hectares (World Bank, 2019).

[20] Irrigation potential and investment are assessed and facilitated by the public Ghana Irrigation Development Authority (GIDA).

climate change. However, since additional rainwater is collected and no water is diverted from existing sources, RWH can be associated with more development co-benefits than irrigation as water-user conflicts are lessened. Like irrigation, the strategy is estimated to hold medium upscaling potential, although this depends again on the need for additional agricultural water and here also the capacity to disseminate knowledge and motivate uptake of the strategy.

In Ghana, limited evidence on the use and potential of RWH for small-scale irrigation systems exists. Even though Ghana has abundant water resources for irrigation, its uptake is very low. RWH can provide a cost-efficient alternative to irrigation installment and is notably a strategy with usage potential at different scales. It is particularly well suited to be coupled with farm-level horticulture production, either for additional income from vegetable sales or satisfying changing demands in household consumption (for Sub-Saharan Africa as a whole, see e.g. OECD & FAO, 2016). This could also yield nutritional and thus health benefits, with vegetables enriching otherwise staple-based diets in Ghana. A combination with conservation agriculture techniques can be particularly useful, with further improvements in soil water storage capacity enhancing the water use efficiency of RWH. It has also shown potential to increase cereal crop yields, such as maize, e.g. in a South African trial designed as in-field harvesting and coupled with conservation agriculture (Botha, Anderson and Van Staden, 2015).

In an assessment study of RWH potential for maize across rain-fed Africa, Lebel et al. (2015) find that "RWH can bridge up to 40% of the yield gaps attributable to water deficits under current conditions and 31% under future (2050s) climatic conditions during the main growing season for maize" (Lebel et al., 2015, p. 4803).

Women could especially benefit from rainwater harvesting, because it saves them time and can open up new farming opportunities.

In addition, RWH has the potential to deliver gender co-benefits. Since it is usually women who are in charge of fetching water and who engage in backyard vegetable farming, collecting rainwater could save women time, making time for other activities and enabling additional farming activities. Furthermore, RWH can both benefit the most vulnerable communities, with small-scale structures being relatively simple to construct, while at the same time, they can be brought to scale with larger installations, linked to the expansion of irrigation schemes. However, it is not clear whether private sector investment could be attracted for this purpose, potentially when linked to outgrower schemes. In Ghana, several stakeholders interviewed have shown interest in RWH, specifically community, NGO and development actors have voiced this support. This is even more noteworthy as RWH is a rather specific adaptation strategy, which in interviews was not prompted for specifically, but was singled out by a number of interviewees.

RWH is a promising adaptation strategy meeting local interest in Ghana. It can be implemented by farmers autonomously and decrease dependency on precipitation.

Improved crop varieties

Breeding improved crop varieties can increase resilience to climate change and raise yields. But it is costly and requires time.

Smallholder farmers in the global South mostly use traditional crop varieties, which can be vulnerable to climate impacts such as droughts, floods or also diseases. In order to improve the resilience of crops to climatic shocks and to raise yields, improved crop varieties are bred from traditional varieties. The process of breeding is lengthy and costly, but once better varieties are released and used, they can substantially improve agricultural yields and resilience, depending on their specific characteristics. As such, breeding improved varieties is an institution-led approach, since it requires resources and time, which smallholder farmers most often do not have. Since they are designed to specifically address climatic risks, they reduce risk and, at least in the case of high yielding varieties, are often no-regret strategies.

We estimate that improved crop varieties have a medium upscaling potential in Ghana: While their use is restricted to the respective agro-ecologies and sometimes local environments they were developed for, some varieties have also proven successful on a larger scale. However, the focus of this study is on locally adapted breeding and improving existing varieties, which usually caters to specific areas and target beneficiaries. Improved crop varieties can offer a number of interesting development co-benefits, especially linked to increased agricultural production and income. However, they are expensive to develop, while a multitude of factors will determine prices of the seeds, such as demand, scale of adoption, and – for farmers – potential government subsidies.

A number of improved crop varieties already exist in Ghana or are being developed, for instance for maize, rice, cassava and cocoa. Sought-after properties are drought-resistance, flood-resistance and achievement of high yields.

The interviews with experts revealed that new crop varieties are thought to have the potential to significantly transform agriculture in Ghana. Many interviewees across NGOs, development cooperation and academia voiced a specific interest in better crop varieties and deemed them necessary for increasing yields, while also stressing that more research is needed in this field. A number of improved crop varieties already exist or are being developed, for instance for maize, rice, cassava and cocoa, with sought-after properties being drought resistance, flood resistance and achievement of high yields. Maize appears to be the focus of breeding efforts in Ghana, as several publications (e.g. Alhassan, Salifu & Adebanji, 2016; Danso-Abbeam et al., 2017) and the number of active breeders for maize (10 out of 26) confirm (Mabaya et al., 2017).

However, in the North of Ghana, recent research showed that only about 20% of farmers use improved seeds, which is even less than the estimated 25% of farmers who use improved seeds in Sub-Saharan Africa in general (Innovations for Poverty Action, 2018). Despite efforts by the Ghanaian government to increase the availability of improved seeds, which even includes a seeds law for this purpose, a number of challenges for more improved varieties remain: insufficient consultation of smallholder farmers and involvement of private seed companies in prioritizing seeds for breeding and improved seed production, difficulty to ensure high quality of improved seeds and a weak public extension system (Poku, Birner & Gupta, 2018). At the individual level, factors such as education, extension and membership in a farmer-based organisation were shown to be key for higher uptake of improved varieties, in this case maize (Danso-Abbeam et al., 2017). Another barrier for the uptake of improved seeds is the rather high cost of breeding: Smallholder farmers with low income may only be able to utilise improved varieties when they are available for free. Keeping those challenges in mind, improved crop varieties do hold potential for larger uptake across Ghana, once they are developed and as long as they fit the respective agro-ecological conditions. As with all other adaptation strategies, the expected improved agricultural output of improved seeds would decrease the pressure on land and thus avoid further deforestation and release of CO_2.

Although improved crop varieties individually have high potential for increasing yields, their lengthy and costly breeding process, among others, makes them a rather complex adaptation strategy.

While the strategies listed here were found to be the most promising ones based on the selection criteria given above, a number of other strategies deserve further attention. Due to space constraints, more detailed information on climate services, conservation agriculture and agroforestry in the Ghanaian context are given in the supplementary material.

Chapter Summary

General results

- Main barriers to adaptation in Ghana:
  (1) a lack of awareness and understanding of climate risk
  (2) difficulty to access inputs and finance for adaptation as well as in some cases
  (3) insecurity of tenure and land availability
- Key solutions to overcome those barriers: Demonstration of (economic) adaptation benefits; capacity building; access to markets and credit; provision of and access to inputs; participatory tenure reform and mapping of tenure rights
- Design elements needed for effective adaptation: combination of adaptation strategies; use of local and indigenous knowledge; participatory consultations; upscaling of strategies

Biophysical evaluation of adaptation strategies

- Adaptation strategies should be focused on areas that are predicted to become marginal.
- The impact of adaptation strategies depends on the district and the scenario.
- Improved varieties proved to be the most promising climate change adaptation strategy based on its impact on yields, particularly for the northern district of Nkwata.
- The second most promising strategy was late sowing, while manure application showed no significant effect.

Specific adaptation strategies

- Crop insurance is a promising strategy for transferring climate risk. There is high interest in Ghana and demand-based roll-out of insurance pilots can be recommended. However, careful design is crucial to ensure affordability and financial sustainability.
- Post-harvest management has the potential to substantially reduce production losses, decentralised solutions exist for small-scale implementation. Implementation of improved post-harvest management strategies can be recommended across the country as a low-hanging fruit, since better post-harvest management can increase agricultural production considerably.
- Irrigation could be upscaled, with limited uptake so far. However, this may incur high costs and technically challenging installation and maintenance. As a climate change adaptation strategy, the case for irrigation depends on the climate scenario, with the North of Ghana projected to see less rainfall under future climate change. However, as a measure to intensify agricultural production and enable multiple harvests, irrigation can also be considered useful today, where water is available for agricultural use.
- Rainwater harvesting and small-scale irrigation are a good alternative for action at smallholder level, with simple installation techniques proving less difficult to implement, maintain and refinance as compared to large-scale irrigation systems.
- Improved crop varieties are seen as a transformative tool for buffering climate impacts in Ghanaian agriculture. Breeding is costly and time intensive, but where improved varieties already exist, they can contribute importantly to a higher agricultural output.

Chapter 5 – Economics of Adaptation to Climate Change

5.1 Introduction

Two ways of climate impacts were modelled: yield per ha and the change in area suitability for crop growth.

This section presents the economic aspects of climate change and links biophysical production of crops to economic values of crops for different scenarios (see Figure 29). It presents five scenarios, namely: the benchmark scenario (BAS), the climate change scenario (CC), an irrigation scenario (IRR), a post-harvest management scenario (PHM) and a crop insurance scenario (INS). A scenario for improved crop varieties was not included because of lack of data for quantifying breeding costs and benefits. Some of the parameters in Figure 29 below will be relevant only when representation of a specific scenario is needed. Otherwise, their value will be zero.[21] For example, insurance premium and share of insured area are needed only when we deal with the insurance scenario. Because of this, we have conducted a comparative static analysis. Specifically, we compare the net values of crop production (NVP) among the scenarios. The net value of production is the gross value of production (which is the product of quantity of production and product prices) minus the costs of inputs used in producing and supplying the product. In this study, only costs associated with irrigation, insurance, and post-harvest management are included. All economic values reported here are based on 2010 prices. The reference scenario for climate change impacts is the benchmark scenario (BAS). For all adaptation scenarios (IRR, PHM and INS), the climate change impact scenario (CC) is the reference scenario. This is because the rationale for adaptation measures is to dampen the economic consequences of climate change.

In the following, we present our analysis for three levels: national, regional, and district as decisions are made at different levels of government. The discussion in this section is intended to provide a first impression of the likely costs of climate change and costs of selected adaptation strategies.

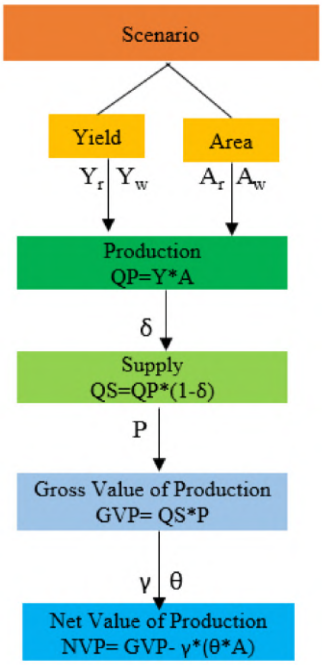

Figure 29: Conceptual framework for the economic analysis.[22]

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[21] The parameters are collected from the empirical literature on Ghana whenever possible, on developing countries otherwise.

[22] Source: Authors' illustration. The average crop yield (A) and area harvested (A) at a given geographic scale can be irrigated (Y_w, A_w) or rain-fed (Y_r, A_r). However, we could not find reliable information allowing us to split the yield and area harvested between irrigated and harvested for each crop at each scale. Therefore, for area harvested we simply used the national average irrigated cropland which is minuscule, whereas for yield, we merely assumed that irrigated yield is 20% higher than rain-fed yield. All parameters shown, i.e., crop yield (Y_r, Y_w), area harvested (A_r, A_w), post-harvest loss (δ in %), prices (P in $), crop insurance premiums (γ in $), and proportion of total harvested area in the geographic area under insurance coverage (θ in %) are in principle scenario-, crop-, location-, and geography-specific. However, the quality of data available used is not always adequate.

5.2 Benchmark (Base) Scenario

Our benchmark (BAS) scenario represents the average values of the 2009-2011 period, for which baseline data was available, as summarised in Table 5. The regional analysis in this report focuses on the Northern Region because the Nationally Determined Contributions (NDCs) of Ghana focus on this region. In addition to this, the Northern Region is highly susceptible to climate change impacts revealing the insufficient adaptive capacity in the region. As a case study, we focused on the Savelugu-Nanton district in the Northern Region, partly because the district has better crop yield and area data (SRID-MOFA, 2018) and partly because single-crop farming is very important in this district (GSS, 2010).

Among the three crops, maize is the most important crop in Ghana, whereas it is groundnuts in the Northern Region and the Savelugu-Nanton district, as can be seen in Table 5.

Table 5: Summary of benchmark data.

Level	Geographic Area	Crop Type	Area (000 ha)	Yield (t/ha)	Production (000 tons)	Producer Price ($/ton)	PHL (%)
National	Ghana	Maize	990	1.74	1726	385	18
	Ghana	Sorghum	254	1.26	320	481	12
	Ghana	Groundnuts	351	1.45	508	804	15
Regional	Northern Region	Maize	112	1.66	186	385	18
	Northern Region	Sorghum	70	1.80	125	481	12
	Northern Region	Groundnuts	125	1.78	222	804	15
District	Savelugu-Nanton	Maize	98	1.61	16	385	18
	Savelugu-Nanton	Sorghum	3	1.60	5	481	12
	Savelugu-Nanton	Groundnuts	11	2.38	27	804	15

Source: CountrySTAT (2014), SRID-MOFA (2018), APHLIS (2018).

5.3 Climate Change Scenario

We modelled impacts of climate change as changes in crop yields or area suitability. The impacts here refer to the changes in anticipated (counterfactual) yield and area suitability (in the 2040s) relative to the present (actual) yield and area suitability (in 2010s), in alignment with the time periods analysed in Chapter 3. The exercise involves imposing these anticipated changes on the current crop production system. There are two channels through which climate change influences crop production: by affecting the yield per ha (impact channel one) and/or changing area suitability for crop growth (channel two, variant to the yield impacts). Both of the channels are modelled: For the yield impact channel, we assumed a 5% rain-fed crop yield loss in maize, sorghum and groundnuts at all of the three geographic scales which will be called yield-based impacts scenario (Y-CC). In the variant impact channel, we assumed a 5% decline in area suitability for each crop. Those assumptions are best estimates based on the impact model results from Chapters 1, 2 and 3, after triangulation with other sources, such as listed in Table 3 in Chapter 3. Such marginal land, whose suitability to grow crops is reduced due to climate change, could sustain a maximum of 50% benchmark yields. The remaining portion of land could still maintain its benchmark yield even under climate change. We call this an area-based impacts scenario (A-CC). The results under the climate change scenarios represent the costs of climate change or the costs of inaction.

Table 6: Net values of crop production under climate change (in million $).

Crop/Scenario	Ghana			Northern Region			Savelugu-Nanton District		
	BAS	Y-CC	A-CC	BAS	Y-CC	A-CC	BAS	Y-CC	A-CC
Maize	544	518	531	59	56	57	5	5	5
Sorghum	135	129	132	53	50	52	2	2	2
Groundnuts	347	330	338	152	145	148	19	18	18

The presumed impact scenarios imply costs of climate change from the three cereal crops in Ghana to be up to $51 million (in the Y-CC case) and about $25 million (in the A-CC case). More than 53% of these economic costs are caused by impacts on maize, followed by 33% caused by impacts on groundnuts. The economic costs may reach up to $13 million in the Northern Region. In this region, groundnuts account for the majority of the economic impacts. Likewise, due to the importance of groundnuts in the district, about 72% of the economic impacts in the Savelugu-Nanton district can be attributed to the impacts in the groundnuts production. The sum of the economic impacts in the Savelugu-Nanton district is about $1 million (in the Y-CC case) and $0.64 million (in the A-CC case). These figures are equivalent to a 4.9% and 2.5% decline of the net value of each crop in the district.

5.4 Irrigation Scenario

Increasing the share of irrigated land to make up for yield losses due to climate change is rather costly.

For the yield-based impact scenario (Y-CC), we considered an irrigation scenario that would offset the average yield loss due to climate change by 50%, by increasing the share of irrigated land. We calculated and found this goal requires at least 10% of each crop's harvested area to be irrigated. Whereas for the area-based impacts scenario (A-CC), we defined that the goal of irrigation as adaptation is to irrigate the whole marginal land, which becomes less suitable for farming due to climatic changes. The adaptive effect of irrigation is equal to the difference in yield of the irrigated area over rain-fed yield under the benchmark scenario (which was taken to be 20%). Then, we calculated the total costs of irrigation of the aforementioned cropland sizes with a range of unit costs of different irrigation types.[23] The unit cost of irrigation ($/ha/year) range is very wide, as it spans between 22 and $1,790/ha/year. This is due to the range of irrigation types analysed: Table 7 provides an overview of the five different irrigation types, which form the basis for the cost scenarios. Type 1 refers to renting irrigation services, which can be the cheapest option (see minimum price). Type 2 is small-scale irrigation, for which the highest minimum and maximum prices were found. Seasonal shallow wells (Type 3) and permanent shallow wells (Type 4) require groundwater to be pumped for irrigation, whereas Type 5, surface water pumping, relies on surface water availability.

Table 7: Summary of irrigation unit cost scenarios ($/ha/year).

TYPE	DESCRIPTION	MIN	MAX
1	Renting irrigation services	22	110
2	Small-scale irrigation	271	1790
3	Seasonal shallow wells	129	478
4	Permanent shallow wells	239	614
5	Surface water pumping	68	68

Source: Namara et al. (2011), Mendes et al. (2014).

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[23] In cases where our sources give only the investment costs, we assume the investment time horizon to be 10 years with a 5% discounting rate.

Table 8 summarises the total costs of irrigation. In Ghana, the costs of irrigation for adaptation may range from $3.6 to $290.6 million per annum (in Y-CC) and from $1.75 to $142.75 million per annum (in A-CC), for combined irrigation of maize, sorghum and groundnut and depending on the type of irrigation as well as the unit cost. In the Northern Region, under the maximum costs scenario, the total cost of irrigation may go beyond $55 million (in the Y-CC case) and $27 million (in the A-CC case). In the Savelugu-Nanton district, irrigation against yield-based impacts may cost about $5.432 thousands to $4.42 million per annum.

Table 8: Costs of irrigation under the two climate change impact scenarios (in million $).

Region	Crop	1Min	1Max	2Min	2Max	3Min	3Max	4Min	4Max	5Min	5Max
IRR-Y-CC											
Ghana	Maize	2.22	11.08	27.34	180.34	13.00	48.16	24.11	61.89	6.93	6.93
Ghana	Sorghum	0.57	2.85	7.03	46.36	3.34	12.38	6.20	15.91	1.78	1.78
Ghana	Groundnuts	0.79	3.93	9.69	63.94	4.61	17.08	8.55	21.94	2.46	2.46
Northern	Maize	0.25	1.25	3.09	20.39	1.47	5.44	2.73	7.00	0.78	0.78
Northern	Sorghum	0.16	0.78	1.92	12.67	0.91	3.38	1.69	4.35	0.49	0.49
Northern	Groundnuts	0.28	1.40	3.46	22.80	1.64	6.09	3.05	7.83	0.88	0.88
Savelugu-Nanton	Maize	0.02	0.11	0.27	1.78	0.13	0.48	0.24	0.61	0.07	0.07
Savelugu-Nanton	Sorghum	0.01	0.03	0.08	0.56	0.04	0.15	0.07	0.19	0.02	0.02
Savelugu-Nanton	Groundnuts	0.03	0.13	0.32	2.08	0.15	0.56	0.28	0.71	0.08	0.08
IRR-A-CC											
Ghana	Maize	1.09	5.44	13.43	88.58	6.38	23.66	11.84	30.40	3.41	3.41
Ghana	Sorghum	0.28	1.40	3.45	22.77	1.64	6.08	3.04	7.81	0.88	0.88
Ghana	Groundnuts	0.39	1.93	4.76	31.40	2.26	8.39	4.20	10.78	1.21	1.21
Northern	Maize	0.12	0.62	1.52	10.01	0.72	2.67	1.34	3.44	0.39	0.39
Northern	Sorghum	0.08	0.38	0.94	6.22	0.45	1.66	0.83	2.14	0.24	0.24
Northern	Groundnuts	0.14	0.69	1.70	11.20	0.81	2.99	1.50	3.84	0.43	0.43
Savelugu-Nanton	Maize	0.01	0.05	0.13	0.88	0.06	0.23	0.12	0.30	0.03	0.03
Savelugu-Nanton	Sorghum	0.00	0.02	0.04	0.27	0.02	0.07	0.04	0.09	0.01	0.01
Savelugu-Nanton	Groundnut	0.01	0.06	0.15	1.02	0.07	0.27	0.14	0.35	0.04	0.04

Table 8 shows the costs of the five different irrigation scenarios for each crop and each level of analysis, with minimum and maximum values given for each scenario (see Table 7 for minimum and maximum costs of the different irrigation scenarios, as reported in the literature). Both the yield-based (Y-CC) and the area-based (A-CC) costs are given.

Comparing the NVP of crops under the climate change and the irrigation scenario indicates that not every irrigation scenario is worth undertaking. Figure 30 shows the net value of maize production in Ghana under climate change in the yield impact scenario, without climate change and with selected irrigation scenarios. Without climate change, in the BAS scenario, maize production in Ghana would have a NVP of $545 million, with climate change and no adaptation (Y-CC), this would fall to $518 million. Thus, every scenario which leads to a NVP above $518 million is cost-effective, as it increases the NVP of maize production, while the overall costs (see Table 9), do not lead to a lower NVP. In Figure 30, the thin orange line indicates which scenarios are cost-effective and which are not. Note that full adaptation via irrigation was not modelled, but rather an attainment of 50% reduction of losses was aimed for. Thus, no scenario can logically reach a NVP above $531.22 million, which is exactly the no-cost irrigation scenario (IRR-NO). This accounts for irrigation without costs, which could occur from the farmer perspective when government or donors decide to bear the costs of irrigation implementation. Furthermore, the scenarios are rather conservative and may underestimate the full benefits of irrigation as they do not account for the option of multiple harvests in one year under irrigation.

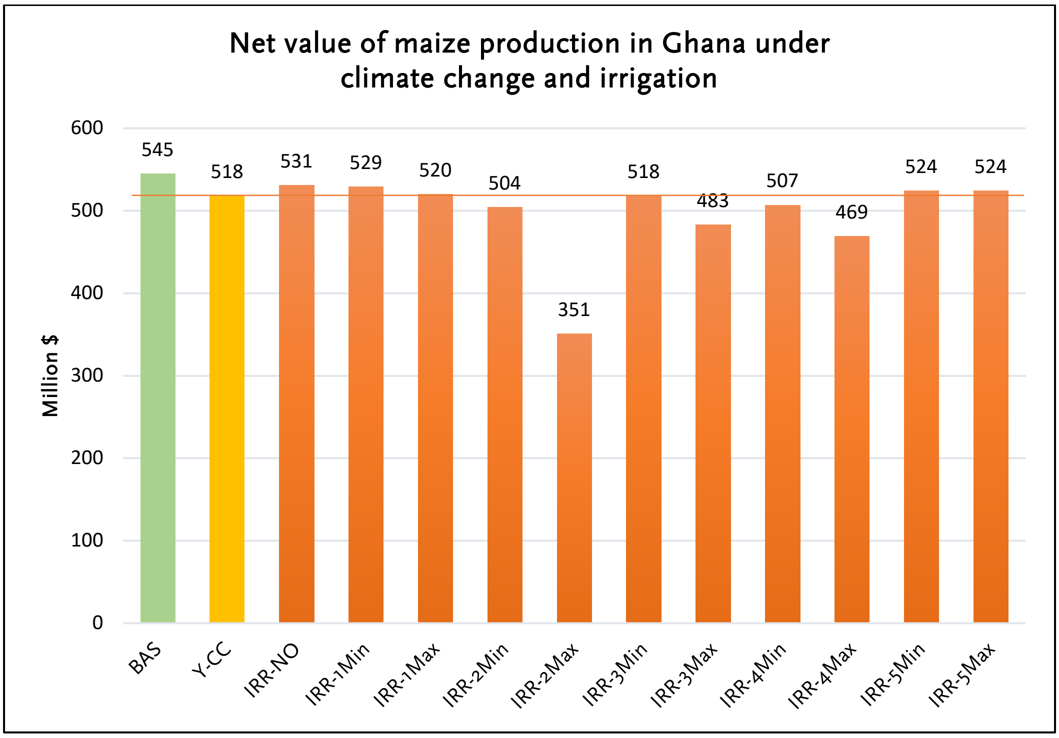

Figure 30: Net value of maize production in Ghana under different irrigation scenarios (in million $), compared to no adaptation and no climate change.

Irrigation is only worthwhile if the costs for installation and maintenance are low.

Relating the overall scenario costs back to the unit costs of the five irrigation scenarios indicates that it may be worth to undertake irrigation only if the unit costs of irrigation remain below $110 (in the Y-CC scenario) and $25 (in the A-CC scenario). Otherwise, the irrigation scenarios seem costly when compared to the climate change impact scenarios without adaptation. Figure 30 shows the comparison of scenarios for maize in the whole of Ghana under the yield-impact scenario. Table 9 below gives the full results for all regions, crops and also the area-based impact scenario. More comparative bar plots for all scenarios can be found in the supplementary materials.

Table 9: Net value of crop production with different irrigation schemes (in million $).

	GHANA			NORTHERN			SAVELUGU-NANTON		
SCENARIO	Maize	Sorghum	Groundnuts	Maize	Sorghum	Groundnuts	Maize	Sorghum	Groundnuts
IRR-Y-CC									
BAS	545	135	347	59	53	152	4.97	2.06	18.58
CC	518	129	330	56	50	145	4.72	1.96	17.66
IRR-NO[24]	531	132	339	57	52	148	4.84	2.01	18.12
IRR-1Min	529	132	338	57	52	148	4.82	2.01	18.09
IRR-1Max	520	129	335	56	51	147	4.73	1.98	17.99
IRR-2Min	504	125	329	54	50	145	4.57	1.93	17.80
IRR-2Max	351	86	275	37	39	125	3.06	1.46	16.04
IRR-3Min	518	129	334	56	51	147	4.71	1.97	17.97
IRR-3Max	483	120	321	52	48	142	4.36	1.86	17.56
IRR-4Min	507	126	330	54	50	145	4.60	1.94	17.84
IRR-4Max	469	116	317	50	47	140	4.23	1.82	17.41
IRR-5Min	524	130	336	56	51	147	4.77	1.99	18.04
IRR-5Max	524	130	336	56	51	147	4.77	1.99	18.04
IRR-A-CC									
BAS	545	135	347	59	53	152	4.97	2.06	18.58
CC	531	132	338	57	52	148	4.84	2.01	18.12
IRR-NO	534	133	340	57	52	149	4.87	2.02	18.21
IRR-1Min	533	133	340	57	52	149	4.85	2.02	18.20
IRR-1Max	528	131	338	57	52	148	4.81	2.01	18.15
IRR-2Min	520	129	335	56	51	147	4.73	1.98	18.06
IRR-2Max	445	110	309	47	46	138	3.99	1.75	17.19
IRR-3Min	528	131	338	57	52	148	4.80	2.00	18.14
IRR-3Max	510	127	332	55	50	146	4.63	1.95	17.94
IRR-4Min	522	130	336	56	51	148	4.75	1.99	18.07
IRR-4Max	504	125	329	54	50	145	4.57	1.93	17.86
IRR-5Min	531	132	339	57	52	149	4.83	2.01	18.17
IRR-5Max	531	132	339	57	52	149	4.83	2.01	18.17

5.5 Post-harvest Management

Post-harvest management can offset a portion of crops lost due to climate change. Under most scenarios, post-harvest management is a no-regret strategy.

The objective of PHM is to increase the actual supply of agricultural products and hence to offset the economic impacts of climate change. Unlike the irrigation scenario, PHM is not meant to dampen climate-change induced yield losses. Rather it is meant to offset a portion of crop output lost due to climate change. It is worth mentioning that potential increases in post-harvest loss due to climate change are not considered in this analysis as this could not be captured with the impact models. However, climate change is expected to increase post-harvest losses via a rise in pest infestations under hotter and wetter conditions in the future. We arbitrarily assumed a post-harvest management scenario which aims to halve the average post-harvest loss rates given in Table 10. Achieving this objective under the PHM scenario would ensure a higher crop supply as compared to crop supply under climate change by 10%, 6% and 8% for maize, sorghum and groundnuts,

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[24] NO refers to a zero-cost irrigation scenario. This means that no costs occur for farmers for implementing irrigation, to reflect the option that governments or other donors pay the full costs of an irrigation installation and maintenance.

respectively. The objective would require nearly 51% of the total crop production under climate change to be stored with PICS bags – the post-harvest technology presumed in this study.[25]

Table 10: Costs of post-harvest management (in million $).

		PHM-Y-CC			PHM-A-CC		
AREA	CROP	MIN	MID	MAX	MIN	MID	MAX
Ghana	Maize	8.43	16.86	33.73	8.65	17.30	34.61
Ghana	Sorghum	1.59	3.17	6.35	1.63	3.26	6.51
Ghana	Groundnuts	2.50	4.99	9.98	2.56	5.12	10.24
Northern	Maize	0.91	1.82	3.63	0.93	1.86	3.73
Northern	Sorghum	0.62	1.24	2.49	0.64	1.28	2.55
Northern	Groundnuts	1.09	2.19	4.37	1.12	2.24	4.49
Savelugu-Nanton	Maize	0.08	0.15	0.31	0.08	0.16	0.32
Savelugu-Nanton	Sorghum	0.02	0.05	0.10	0.02	0.05	0.10
Savelugu-Nanton	Groundnuts	0.13	0.27	0.53	0.14	0.27	0.55

Depending on the unit cost (1 million t capacity size PICS bag)[26] and the climate change impact type, the total costs of buying PICS bags sufficient to fulfil this goal may require about $13 to 51 million in Ghana, about $2.6 to 11.0 million in the Northern Region and $0.24 to $0.96 million in the district of Savelugu-Nanton.

Figure 31 shows how the NVP for maize production in Ghana under the three PHM scenarios (with low, medium and high unit prices for PICS bags) compares to maize production without adaptation under the yield-impact scenario (Y-CC) and the baseline scenario (BAS) without climate change. As the figure shows, all three PHM scenarios are cost-effective, since they produce higher NPVs than the no-adaptation (CC) scenario.

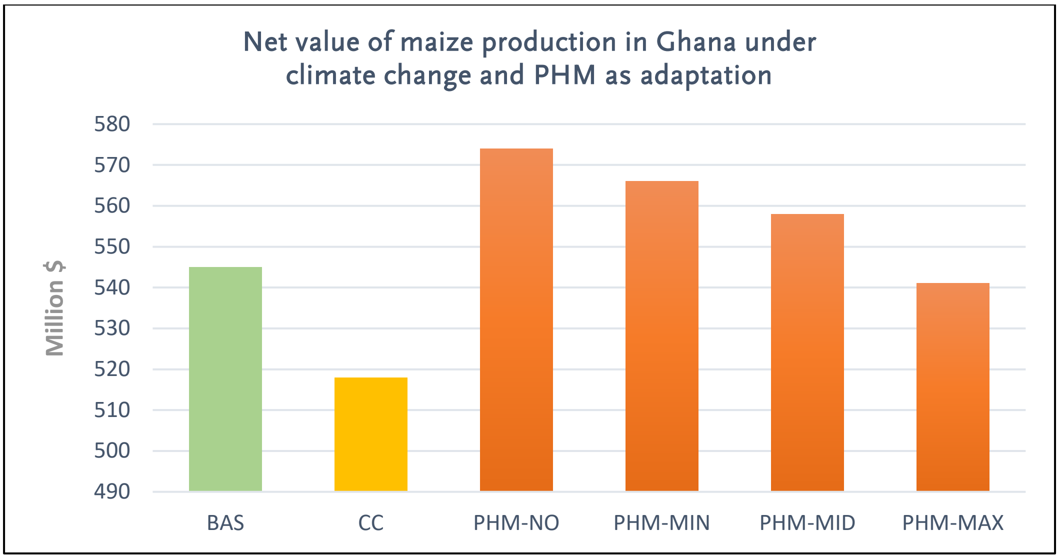

Figure 31: Net value of maize production in Ghana with different PHM scenarios, compared to no adaptation and no climate change (in million $).

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[25] PICS bags are found to be quite effective to limit the post-harvest loss to 0.3-0.5% of cereal crops (Jones et al., 2011; Baral et al., 2018).

[26] The unit costs are maximum (MAX, $40/PICS), medium (MID, $20/PICS), and minimum (MIN, $10/PICS) (Jones et al., 2011; Baral et al., 2018).

Thus, the NVP with applying a post-harvest management strategy (under all cost scenarios) is larger than the NVP under climate change without adaptation. Depending on the crop type and the unit cost of PICS bag, the NVP of crops with post-harvest management is larger than the NVP under climate change by approximately 2% to 9% at all the three geographic scales we considered (see Table 11). Thus, the expected economic benefits from using PICS bags are considerable. Figure 31 presents the results for maize in the whole of Ghana, results for other crops and scales can be found in the table below and in the supplementary material.

Table 11: Net value of crop production with post-harvest management (in million $).

AREA	CROP	BAS	CC	PHM-NO	PHM-MIN	PHM-MID	PHM-MAX
PHM-Y-CC							
Ghana	Maize	545	518	574	566	558	541
Ghana	Sorghum	135	129	138	136	134	131
Ghana	Groundnut	347	330	359	356	354	349
Northern	Maize	59	56	62	61	60	58
Northern	Sorghum	53	50	54	53	53	51
Northern	Groundnut	152	145	157	156	155	153
Savelugu-Nanton	Maize	4.97	4.72	5.24	5.16	5.08	4.93
Savelugu-Nanton	Sorghum	2.06	1.96	2.09	2.07	2.05	2.00
Savelugu-Nanton	Groundnut	18.58	17.66	19.21	19.08	18.95	18.68
PHM-A-CC							
Ghana	Maize	545	531	589	581	572	555
Ghana	Sorghum	135	132	141	139	138	135
Ghana	Groundnut	347	338	368	366	363	358
Northern	Maize	59	57	63	63	62	60
Northern	Sorghum	53	52	55	55	54	53
Northern	Groundnut	152	148	161	160	159	157
Savelugu-Nanton	Maize	4.97	4.84	5.37	5.29	5.21	5.06
Savelugu-Nanton	Sorghum	2.06	2.01	2.15	2.12	2.10	2.05
Savelugu-Nanton	Groundnut	18.58	18.12	19.72	19.58	19.44	19.17

In many of the crop-impact-cost scenarios (see Table 11), post-harvest technologies can thus effectively compensate for the economic losses due to climate change. As one would expect, the offsets will increase as the PICS bags get cheaper, which indicates that development interventions subsidizing the prices of PICS bags may be helpful to adapt to climate change as well as to achieve food security.

5.6 Crop Insurance

Crop insurance does not reduce risk, but transfers it to the insurance provider.

The insurance type in this section refers to Area-Yield Index Insurance (AYII). Our crop insurance as adaptation strategy represents a scenario in which 10% of the total harvested area of a specific crop is covered with crop insurance, which is in line with previous experience regarding crop insurance in Ghana.[27] For area-based impacts, it is only the portion of the crop area that became less suitable due to climate change (which we assumed to be 5% as discussed earlier) that is supposed to be under insurance coverage. Because we assume climate change is the sole cause of the yield changes, farmers can claim insurance payouts for any level of yield changes. The benefits of insurance, for the crop activities, will be the payouts (the maximum being the sum insured) by the insurers for the lost value of production due to climate change. We use a premium ($10.4/ha/year) and premium rate of 6% from GAIP [Interview 16, 23 October 2018], which thus implies that the sum insured is about $173/ha/year.

Table 12: Total insurance premiums, claims and sum insured (in million $).

AREA	CROP	INS-Y-CC			INS-A-CC		
		PREMIUM	CLAIM	SUM INSURED	PREMIUM	CLAIM	SUM INSURED
Ghana	Maize	1.029	3.314	17.156	0.515	16.610	8.578
Ghana	Sorghum	0.265	0.768	4.410	0.132	3.849	2.205
Ghana	Groundnuts	0.365	2.037	6.082	0.182	10.211	3.041
Northern	Maize	0.116	0.357	1.939	0.058	1.788	0.970
Northern	Sorghum	0.072	0.301	1.205	0.036	1.509	0.603
Northern	Groundnuts	0.130	0.892	2.169	0.065	4.473	1.085
Savelugu-Nanton	Maize	0.010	0.030	0.170	0.005	0.151	0.085
Savelugu-Nanton	Sorghum	0.003	0.012	0.053	0.002	0.059	0.026
Savelugu-Nanton	Groundnuts	0.012	0.109	0.198	0.006	0.547	0.099

Crop insurance as a risk-transfer strategy does not reduce climate risk, as opposed to irrigation and post-harvest management. It is meant to protect farmers from high economic losses from extreme events and thus plays an important role in addressing climate risk. However, the net value of production with crop insurance is not higher than the NVP under climate change without crop insurance. Instead, depending on premium rates and overall costs, the NVP over several years may be even lower than the NVP without crop insurance under climate change, when the insurance costs are priced in. This is because insurance schemes will oftentimes incur high transaction costs, thus the sum of premiums payed is higher than the sum of insurance payouts. However, it is not the purpose of an insurance to reduce risk but rather to transfer or share it. While this does not improve overall production, it smooths out yield losses and thus supports farmers individually, who otherwise may have lost large parts of their income. That being said, the results indicate that the current premium rates (6%) may not be adequate to cover the total damages (or claims) if climate change impacts become larger (see Table 12). The total sum of discounted crop insurance premiums, assuming 10 years of term, are given in Table 13. Depending on the climate change impact scenario and the discounting rate[28], the discounted sum of premiums (in million $) range between 0.085 and

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[27] This may be a conservative estimate but previous experiences show that the uptake of crop insurance in Ghana has been low (Nunoo and Acheampong, 2014; Mensah et al., 2016).

[28] A discount rate is a parameter used to discount a stream of payments, receipts or costs occurring over time back to their respective present values. Discount rates (or discounting future values) are needed as a dollar received today is considered more valuable than one received in the future.

0.205 in the Savelugu-Nanton district, between 1.08 and 2.6 in the Northern Region, and between 5.6 and 13.5 in Ghana as a whole. The amounts signal the market potential for private insurance companies, which have already expressed an overwhelming interest.

Table 13: Total discounted insurance premiums for 10 years term (in million $).

		INS-Y-CC			INS-A-CC		
AREA	CROP	r=5%	r=7%	r=10%	r=5%	r=7%	r=10%
Ghana	Maize	8.346	7.736	6.957	4.173	3.868	3.479
Ghana	Sorghum	2.145	1.988	1.788	1.073	0.994	0.894
Ghana	Groundnuts	2.959	2.743	2.467	1.479	1.371	1.233
Northern	Maize	0.943	0.874	0.786	0.472	0.437	0.393
Northern	Sorghum	0.586	0.543	0.489	0.293	0.272	0.244
Northern	Groundnuts	1.055	0.978	0.880	0.528	0.489	0.440
Savelugu-Nanton	Maize	0.083	0.076	0.069	0.041	0.038	0.034
Savelugu-Nanton	Sorghum	0.026	0.024	0.021	0.013	0.012	0.011
Savelugu-Nanton	Groundnuts	0.096	0.089	0.080	0.048	0.045	0.040

Chapter Summary

Irrigation

- About half of the irrigation schemes analysed may be too costly, especially compared to the post-harvest management and crop insurance strategies, at least when disregarding benefits from more frequent harvests. The net value of prodution of the different irrigation options ranges from 351 million $ to 531 million $, as compared to a NVP of 518 million $ in the no action scenario (with climate change). Thus, development of low-cost irrigation infrastructure or financial incentives for investing in irrigation could be useful.
- As a non-monetary benefit, which was not quantified in this analysis, investment in irrigation helps to increase the diversity (e.g. cereals, pulses and vegetables) and frequency (more than once in a year) of production, both of which reduce disguised unemployment in agriculture and increase overall agricultural production.

Post-harvest Management

- Post-harvest technologies can effectively offset the economic losses due to climate change in most scenarios (which for the three cereal crops in Ghana range from about $25 million to up to $51 million).
- PICS bags are a particularly interesting strategy for small-scale post-harvest management, which is already tested in parts of Ghana. Development or government interventions subsidising the prices of PICS bags can be helpful to incentivise the uptake of PICS bags, while the high cost effectiveness of this strategy can convince farmers to continuously take up this adaptation practice. If subsidies are used, an exit strategy is needed to ensure the sustainability of the measure.

Crop Insurance

- Even though the crop insurance schemes may help to recover part of the net value of production that would have been lost due to climate change, at the current premium rates, the total sum insured (which determines the maximum possible payout) may be inadequate to cover the claims as the damages get bigger.
- Uptake of crop insurance could encourage farmers to invest more into productive resources, including labour or adaptation strategies. This could specifically be achieved by lowering the premiums for farmers who invest in adaptation strategies, for instance using improved seeds. It could thus help to reduce disguised unemployment and the tendency to migrate and improve the overall production.
- Moreover, the insurance payouts would compensate for crop output or income lost due to climate change and thus relieve agricultural households from using their savings (which would reduce private and national savings) or selling assets (hence would reduce private capital and wealth), and borrowing (thus would increase household expenditure at later stages related to interest payments) to cope with climate change impacts.
- Crop insurance also helps households to maintain their consumption during climate-related shocks. Consequently, repercussions of crop failures on nutrition and health as well as school drop-outs can be minimised.

Recommendations for Adaptation Strategies

Based on the joint analysis in chapters 3, 4 and 5, recommendations for wider uptake of the adaptation strategies analysed can be given, with regard to their suitability for implementation and wider promotion in Ghana. Table 14 summarises the (potential) performance of the five strategies against the evaluation criteria:

Table 14: Performance of adaptation measures against assessment criteria[29].

Criteria	Crop insurance	Post-harvest management	Irrigation	RWH	Improved varieties
1	Risk transfer	Risk reduction	Risk reduction	Risk reduction	Risk reduction
2	No risk mitigation	High	(Medium)	(Medium)	High
3	High costs	Cost-effective	High costs	(Low costs)	High costs
4	Risk-specific	No-regret	(Risk-specific)	(Risk-specific)	(Risk-specific)
5	High	High	Medium	(Medium)	(Medium)
6	Medium	High	(Low-medium)	High	Medium
7	High	High	High	High	High
8	Institution-led	All levels	All levels	All levels	Institution-led

Colour legend:

🟩	Positive
🟨	Medium
🟧	Negative
🟦	Neutral

Assessment criteria:

1) Risk response
2) Risk mitigation potential
3) Cost effectiveness
4) No-regret vs. risk-specific
5) Upscaling potential
6) Development co-benefits
7) Stakeholder interest/local ownership
8) Degree of institutional support needed

Post-harvest management is the most promising adaptation strategy across Ghana.

All those assessments have uncertainty attached, depending on scenario, location and context of implementation. Therefore, this table should by no means be seen as a definite assessment but rather as an expert assessment based on the best available data for the case of Ghana. Nonetheless, it allows for some interesting comparison across different measures and can serve as an indicative guideline on the suitability of the respective adaptation measures in Ghana.

Post-harvest management is recommended for wider implementation across Ghana, as most indicators show high potential for upscaling and attainment of adaptation goals. Crop insurance is particularly well-suited for upscaling and, as a risk-transfer strategy, crucial for complementing risk-reduction measures, which equally can be

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[29] Brackets indicate particular uncertainty with regard to the effect, depending on scenario.

recommended for uptake in the whole of Ghana. Rainwater harvesting is a low-cost strategy with potential for autonomous uptake and additional agricultural production. Both improved crop varieties and irrigation are rather costly strategies, requiring much institutional support. Their implementation feasibility and suitability varies according to location in Ghana, irrigation is generally only recommended for areas suffering from insufficient or highly variable precipitation levels but can offer improved agricultural production levels in dry areas, if other water use interests can be reconciled with water demand for irrigation. Improved crop varieties are judged to have better prospects for transforming agriculture, also given the mostly sufficient precipitation levels in Ghana. However, improved seeds always need to cater to the requirements of local agro-ecologies, thus they cannot be recommended for the whole of Ghana. Employing multiple adaptation strategies can be useful, especially the combination of risk-reducing and risk-transferring strategies is promising. Risk-reduction measures like irrigation and improved crop varieties are important for addressing risk that can be mitigated, whereas risk-transfer strategies such as insurance are needed for managing risk that cannot be reduced.

This evaluation is only to be viewed as a careful expert assessment based on the above criteria and analyses and can by no means replace a thorough analysis for specific project design and local implementation planning. It gives an indication of the overall feasibility and suitability of the selected adaptation strategies in Ghana. Actual selection of adaptation strategies, however, should always be based on specific needs and interests of local communities. Chapter 5 provides information on the cost effectiveness of three of the strategies. Such information is crucial for deciding on investment strategies at the national level, which, in line with Ghana’s NDC Implementation and Investment Plan, indicate that small-scale post-harvest management interventions, smart index insurances and low-cost irrigation options can be particularly beneficial.

Chapter 6 – Outlook and Uncertainties

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

6.1 Climate Model Data

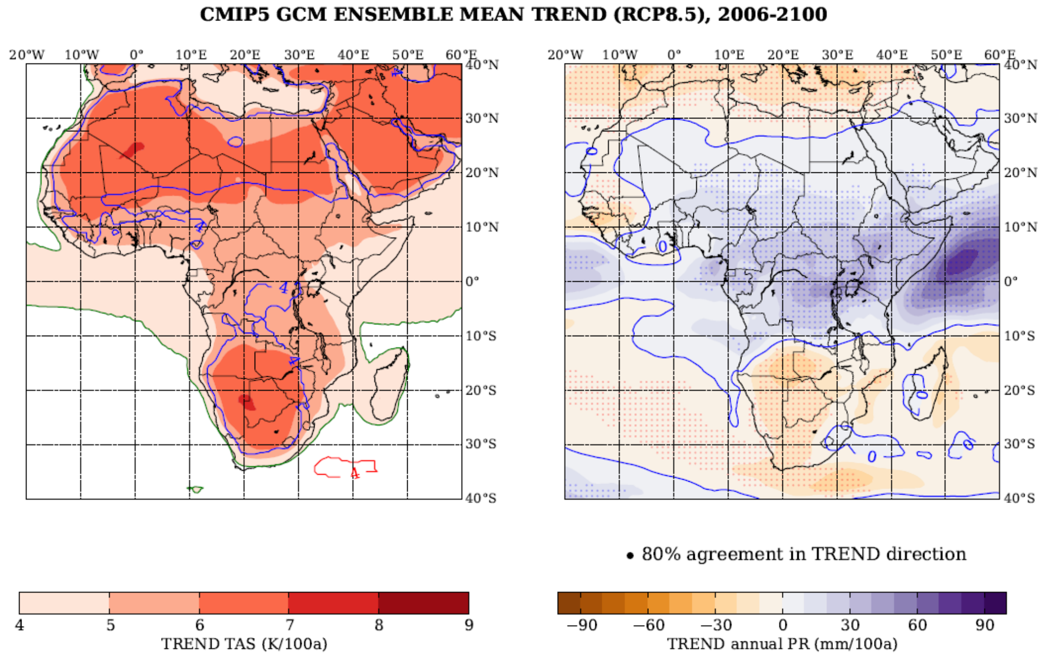

Figure 32: Left map: Mean trend in near-surface air temperature (TAS) in Kelvin. Right map: Mean trend in annual precipitatio.
Both trends are shown until end of this century under RCP8.5 climate scenario conditions (2010-2099), using linear regression of the annual sums of 18 CMIP5 global climate model results. Shaded areas indicate where at least 80 % of the model ensemble agrees in the direction of the trend. Data processed at PIK.

The hydrological cycle is sensitive to climate variability and changes.

The hydrological cycle is an essential part of the climate system and, therefore, very sensitive to climate variability and changes. Sometimes, even small variations in climate lead to significant changes in hydrological processes. When analysing the most recent climate scenario data as delivered by the Coupled (climate) Model Intercomparison Project (CMIP5, Taylor et al. 2012) for RCP8.5 (van Vuuren et al. 2011), the results show that precipitation increases with relatively high climate model agreement in the tropical parts of Africa and decreases with high model agreement in subtropical regions (see Figure 32). Our target area is located in a region where most GCMs agree on an increase in precipitation, however, the model agreement is below 80%. In this study, we make use of the climate data provided in the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). For general conclusions, it is important to cover the range of climate model outputs in the impact assessment, namely applying wet and dry climate projections for the target region. The upper panel in Figure 33 illustrates that the selected models used in this study (coloured boxes) nicely cover the entire CMIP5 model spread (black crosses), with wet and dry projections considered. The lower panel in Figure 33 shows the annual development of precipitation (as deviations from the long-term mean 1971-2000). The graph explains why in Figure 14 (see Chapter 2) we see an increase in river flow in the Volta until mid-end of the century and afterwards a decrease (as an average over all projections under RCP8.5 climate). The results look similar under RCP2.6 but less extreme.

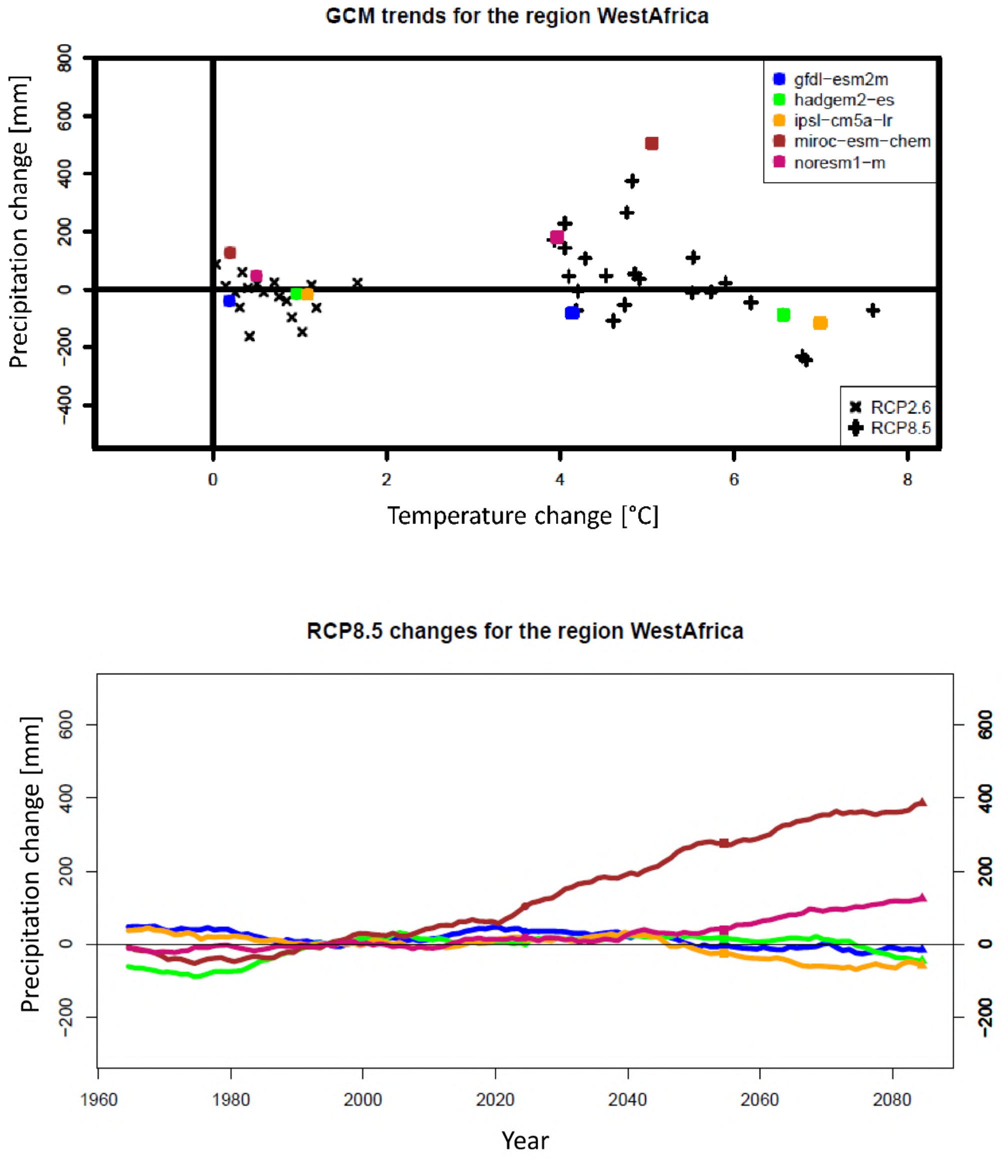

Figure 33: Model spread in temperature and precipitation change until the end of this century.
Top: Changes given compared to the period 1971-2000 for RCP2.6 and RCP8.5 (CMIP5 models used in this study are highlighted by coloured boxes. Bottom: Annual precipitation development compared to the mean values of the period 1971-2000.

6.2 Hydrological Model

Spatial distribution of projected water balance variables

The maps in Figure 34 show the two most extremely diverging examples of water discharge (analysed in Chapter 2), where the MIROC model projects a wet and the IPSL a dry future under RCP8.5 in the period P3. Where average precipitation declines in the IPSL model (up to -25% in the South of Ghana and slightly positive in the very North-west), the MIROC model projects an increase of up to 15% in northern Ghana. Higher temperatures are projected by both models and lead to higher potential evapotranspiration. Where the actual evapotranspiration (ETa) is declining by up to -15% due to a lack of available water in the IPSL model, ETa is more likely to increase in the MIROC model. From open water surfaces the ETa increases in both models up to 10%. Runoff (surface runoff + lateral flow) is decreasing in the IPSL model by up to -50% in the entire country, whereas the increased precipitation in the MIROC model leads to higher runoff generation. The SWIM model simulates no significant changes in groundwater recharge in large parts of the VRB but a generally decreasing trend when driven by the IPSL model and an increasing trend when driven by MIROC.

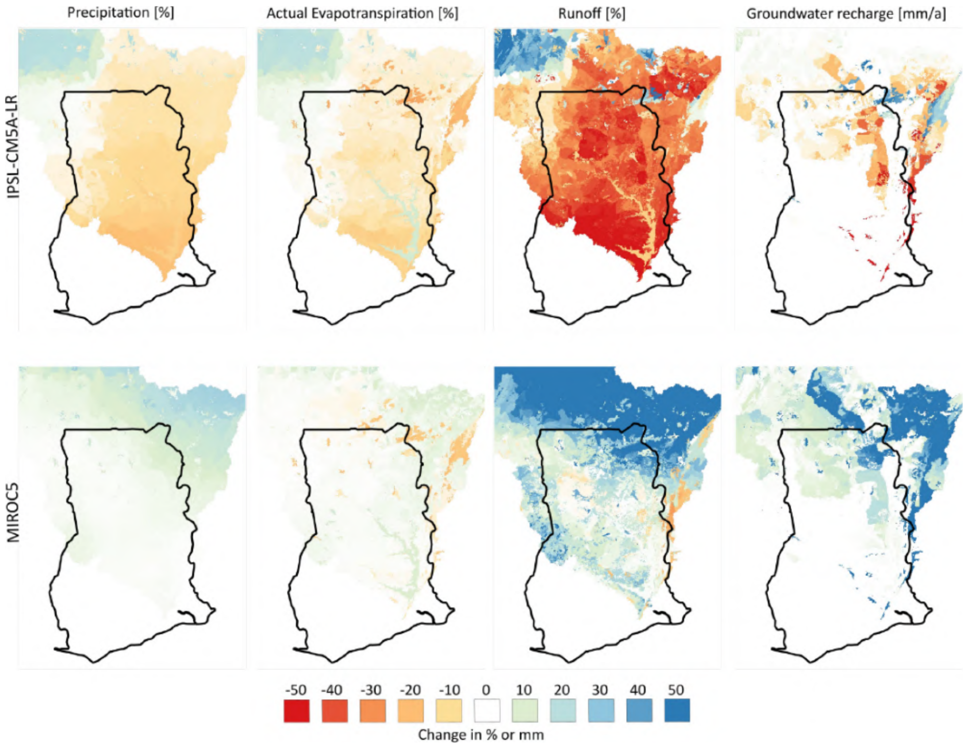

Figure 34: Projection of different water balance variables from the IPSL model (top row) and the MIROC model (bottom row) under RCP8.5 in the far future (2080-2099).

There are many sources of uncertainty for hydrological impact assessments, with climate model output considered the largest uncertainty factor.

Many studies indicate that climate model output is the largest source of uncertainty in hydrological impact assessments (see e.g. Vetter et al., 2015, Vetter et al., 2017). This is true also for West Africa, see for example the river scale comparison in Hattermann et al. 2018. However, a number of data related issues add to the impact uncertainty:

- Availability of observed discharge data in terms of the number of stations, available periods and the many gaps in the time series are limiting hydrological model calibration and validation.
- Climate data for the entire VRB are needed for the parametrisation of SWIM. Therefore, (gridded) global climate data sets were used in the calibration of SWIM, where precipitation (spatial and temporal) distribution is uncertain, verification of these data using observed data would be necessary.
- Lack of information on water resources management (irrigation and reservoir management and parameterisation)
- It would be also good to conduct additional quality checks of the input data (soil parameterisation including for instance an adaptation of soil depth, land use/cover parameterisation includeing for instance a validation on vegetation cycles etc.).

All the factors mentioned above increase the uncertainty related to input and output data quality but we are confident that the general trends analysed and the key messages reported in this study would not change substantially under optimal conditions.

6.3 Crop Models

Crop modelling

Crop models are often limited by a lack of high-quality data.

Crop models can be used to project crop yield impacts of changing climatic conditions. This can support farmers' decisions to stabilise and enhance crop yields and cope with uncertain climatic conditions in the future. Crop models are widely used to project these impacts – beyond the observed range of yield and weather variability – of climate change on future yields (Ewert et al., 2015; Folberth, Gaiser, Abbaspour, Schulin, & Yang, 2012; Rosenzweig et al., 2014). Notwithstanding, crop models also have limitations with regard to projecting yield impacts in future periods. These limitations are, for instance, the lack of high-quality input and reference data such as growing season dates or information on fertiliser applications (Müller et al., 2016) but also the quality of soil data contributes to uncertain yield assessments (Folberth et al., 2016). Moreover, in regions with low weather station density, fragmented and imprecise weather data contributes to the assessment uncertainty (Van Wart, Kersebaum, Peng, Milner, & Cassman, 2013).

Weather parameters are not the only factors explaining trends in crop yields.

Specific to our analysis, three main challenges occurred: First, the model input data may contain errors. This holds for both weather and district-level yields. On the weather side, we used the most reliable data in this region (based on re-analysis models and satellite observations) where only few measurement stations on the ground are available. Regarding the yield database we applied pre-processing filters to ensure that only districts without obviously unorthodox time series were studied (for example, districts with constant yield time series were removed). Yet, both measures cannot exclude bias, which eventually results in unstable models. Second, the model design could be flawed and a more apt formulation could better capture observed yield variation, in particular extreme losses. However, the current literature on crop yields in West Africa does not provide a basis for that assumption, since there is no established, statistically robust correlation of yields with weather under similar growing conditions as in Ghana. Moreover, both model types (statistical and process-based) have often been applied (Schauberger et al., 2017) and are unlikely to be inapt in general. Third, as a tropical country, Ghana receives relatively high precipitation to enable crop production and farmers have adopted a multitude of techniques to cope with erratic rainfall patterns. Weather parameters may, therefore, not be the dominant factors explaining trends in crop production.

Suitability modelling

Uncertainties regarding suitability models stem for instance from uncertainty attached to climate data.

There are also caveats when interpreting results from the crop suitability model. First, long-term crop production trends are considered without potential non-linear effects of extreme years. Second, a positive change in suitability does not necessarily translate into better production as the change may still be below the threshold required to meet a certain production target. Third, the ISIMIP data used for projection can introduce further uncertainties due to the rather large spatial resolution of ~50 km. Fourth, current suitability is also based on modelled weather data as it attempts to allocate weather conditions for each pixel. Finally, the suitability models are driven by climate data, which in itself has its uncertainties. Future projections of crop production suitability are produced by combining suitability models with projections based on general circulation models (GCMs) that describe potential future conditions. These different GCMs rely on different parameters and incorporate different functions to portray the dynamics of atmospheric circulation, ocean effects or feedbacks between the land surface and the atmosphere and, therefore, are prone to disagreements/errors that will be propagated in the modelling. Lastly, the modelling is driven by data inputs and, therefore, it is sensitive to the quality and quantity of the underlying sample data. For crop suitability, the models rely on pseudo-absences because there can be no “true” absence for crops as they are introduced and produced by people. Thus said, a model with both presence and absence data, as for naturally-occurring species, has a better fit than that using presence-only data, as for crops.

6.4 Qualitative Assessment of Adaptation Strategies

A number of limitations have to be considered for the qualitative approach followed in Chapter 4: First, the sample size for the expert interviews could be increased. Also, interviews were only conducted in Accra and via Skype with representatives from northern Ghana. Systematic interviews and focus groups in all key agricultural regions in Ghana could yield additional insights, which was not possible for this study due to time constraints. Second, adaptation strategies were studied at a rather general level, with most of them having many different concrete manifestations. Evaluation of specific measures from the onset could have led to more targeted and practical information from experts, however, such an approach was difficult to pursue considering regional differences and the macro-level departure of this study. For future research, it would be useful to also engage with local communities, for instance via focus groups, to gather experiences and assessments from the ultimate beneficiaries of the interventions planned, smallholder farmers. In addition, the indicator on upscaling could be assessed more comprehensively. For this study, qualitative insights from experts interviewed across the non-profit, private and development sector were used to give an indication on the potential to implement adaptation strategies on a wider scale. This could, however, be evaluated more systematically with a composite indicator combining spatial, market and feasibility criteria.

Future additions to adaptation analysis could include livestock strategies.

So far, only relevant adaptation strategies for the crop sector have been considered in this assessment. Livestock, however, is also of great importance, especially in Ghana’s Northern Region. Further research could thus investigate to which extent livestock adaptation strategies hold potential to cope with climate impacts, with a focus on making livestock systems more sustainable and reducing their carbon footprint. Moreover, there are also positive synergies in a combined livestock crop system, which is also not considered in this study.

6.5 Economic Analysis of Climate Change Adaptation

For Chapter 5, limitations of the analysis notably refer to the assumptions taken for the economic analysis. Limited data availability also impacted the results of this chapter, where the literature had to be consulted to fill data gaps. Uncertainties were not accounted for – for example of climate change impacts, adaptive effects and unit costs of adaptation strategies – to the fullest range. The analysis is also limited to the effects due to changes in mean climatic conditions, and does not consider inter-annual variability, which is supposed to increase with climate change. As such, the results shall be interpreted only as indicative.

The results would likely not change considerably with better data or less model uncertainty.

Overall, the range of uncertainties and limitations discussed in Chapter 6 calls for cautious interpretation of results and explains the context in which the scientific results should be seen. The main constraint for all analyses conducted as part of this study was limited availability and quality of data, which is a common challenge for research. However, the applied methods and data are based on the current state of research and theses methods are tested in several applications around the world. Thus, we are confident that our assessment of the results would not change considerably with better data availability or less model uncertainty. The overall trends should likely remain the same.

As regards the scale of the current analysis, the study mainly addresses decision makers at national and regional level, who can benefit from the findings for policy planning and project design. The findings are also valuable for agricultural extension officers and farmer advisory, who can sensitise farmers on expected climatic risks to their farming systems and possible adaptation options. The approach employed in this study as such is replicable at different scales and can also be used at more local scales to generate more spatially explicit results on local climate risk and performance of adaptation measures. For this, downscaled climate data are needed, which would require new model training and additional simulation rounds.

Conclusion

While some uncertainty surrounds our results, risks to Ghana's agricultural sector from climate change appear high. Considerable impacts are projected especially on water availability but also plant growth and crop suitability. In addition, the results show large spatial variability.

> Higher temperatures, differing precipitation and hydrological extremes are projected to alter farming opportunities in Ghana.

Mean annual temperature is projected to increase by 0.8-1.3°C until 2030, 0.7-2.5°C until 2050 and 0.8-5.5°C until 2090 compared to 1995, depending on model and scenario and with the highest temperature increases projected for the North of Ghana. As regards average precipitation, this is more likely to increase in the North and decrease in the South of Ghana until 2050. Under the high emission scenario, most models predict that precipitation is also decreasing in the North of Ghana until 2090. The precipitation projections carry high uncertainties, thus the magnitude as well as sign of precipitation change will possibly be different. Consequently, adaptation measures have to fit to a wide range of possible future precipitation amounts. What is key for agriculture: The bimodal rainfall regime in Ghana's South could become a unimodal rainfall regime by the end of the century, thus importantly altering farming opportunities. Water discharge is projected to generally increase by 2050, while by the end of the century, either an increase or decrease is possible, depending on the climate scenario. While the multi-model mean and medians suggest only moderate average changes in water runoff, individual model results give reason to conclude that significant dry and wet conditions may occur in the future. The characteristic cyclic behaviour with alternating dry and wet periods is projected to continue in the future.

As regards agricultural production, crop yields in Ghana are influenced by weather and non-weather factors. In line with this, crop models employed for this study confirm that maize yields are sensitive to non-weather influences like agronomic management practices, while the weather influence seems to be lower because of sufficient precipitation in most parts of the country. This demonstrates a high potential to increase and stabilise low crop yields through improved management and thus allows farmers to cope with climate change and enhance their food security situation by changing management practices. Crop suitability models found that the impacts of climate change are site- and crop-specific, as determined by both the bioclimatic factors that influence crop viability and the specific characteristics of the crops. An important effect of climate change will be shifts in crop suitability, which will necessitate adequate adaptation measures in the areas identified and may spur a need for food transfer policies. Three adaptation strategies in three selected districts (Nkwata, Akatsi and West Akim) were evaluated to assess their potential to buffer climate change impacts on crops: Manure application has the potential to create a small buffer for maize production under climate change and a delay in the sowing period by two weeks was also found to bring positive results, especially for reducing the most severe climate change impacts projected to occur in Nkwata district. Improved maize varieties were also evaluated. This measure showed particularly high potential to increase maize yields, especially in the Northern district of Nkwata.

Based on those impact results as well as additional considerations related to co-benefits, stakeholder interest and experience as well as upscaling potential among others, the following adaptation strategies were found to hold particular potential for implementation in Ghana: weather index insurance, post-harvest management, irrigation, rainwater harvesting and improved crop varieties. This list is not exhaustive, and combinations of strategies may be useful to increase effectiveness. Furthermore, improved capacity building, upscaling of local extension efforts and education on climate risks were found to be crucial components of a successful climate change adaptation strategy for Ghana.

The economic analysis of several adaptation strategies showed that crop insurance strategies and improved post-harvest management are promising avenues for adaptation in Ghana. The results, however, also indicate that the current premium rates in Ghana (6%) may not be adequate as the damages (or claims) get bigger due to higher climate change impacts. Regarding post-harvest management, PICS bags for micro-level storage of crops can increase the NVP by at least 6% in many of the cases, as compared to the NVP attained without post-harvest management under climate change. Irrigation was shown to be costly, the comparison of the NVP of crops under the climate change and the irrigation scenario indicates that not every irrigation scenario is worth undertaking. It may be worth to undertake irrigation only if the unit costs of irrigation (per ha per year) remain below $110 (in the Y-CC scenario) and $25 (in the A-CC scenario).

Proposed actionable recommendations for Ghanaian policy makers

Building on the findings of the study, Ghanaian policy makers could design risk-informed and evidence-based adaptation strategies and investment plans. The policy recommendations and study findings should not be seen as stand-alone recommendations but can be used to further advance existing policy processes in the field of agriculture and climate change adaptation in Ghana, as also requested by stakeholders. Most prominently, they can feed into the review of Ghana's Nationally Determined Contribution (NDC) as well as into its NDC Implementation and Investment Plan. First results of the study already informed the first draft of the NDC Implementation and Investment Plan for the agricultural sector. The full study can now provide a sound evidence base for Ghana's climate change adaptation process, particularly for the formulation of Ghana's National Adaptation Plan (NAP), which is currently under way.

General guidance for adaptation design in Ghana:

- **Combine and align risk-transfer mechanisms, such as crop insurance schemes, with no-regret adaptation strategies to effectively address the projected increase in weather variability and extremes.** This is important in order to provide comprehensive solutions for coping with climate risk and to tailor strategies to the type and extent of risk. Where risk can be reduced with low-cost measures that would pay even in the absence of climate change (no-regret measures), as they enhance agricultural production (e.g. irrigation systems), such strategies should be implemented. For low-frequency, high-impact climatic events where risk cannot be mitigated cost-effectively, risk-transfer mechanisms such as crop insurance are needed.

- **Seize the full range of adaptation options available: Generally, many different adaptation strategies hold potential for successful implementation in Ghana.** In addition to their potential to address climate risk, the local interest and consequently ownership of strategies is also key. Additionally, long-term sustainability of adaptation measures and behavioural changes that ensure sustained adaptation need to be considered.

- **Plan for adaptation at regional or local levels but inform national-scale planning from regional and district levels.** Climate change vulnerabilities and most suitable adaptation strategies are locally specific and there are large differences in crop response to climate change across Ghana. Weather patterns also change differently in distinct agro-ecological and geographic zones. In combination with differential local vulnerability patterns, adaptation should be planned at the lowest possible level, while ensuring national coordination and mainstreaming.

- **Expand capacity building on climate change adaptation (e.g. with regard to proper installation and maintenance of adaptation infrastructure, selection and use of suitable farm inputs and on diversification) and improve public extension services.** For all adaptation strategies, more capacity building and increased investment in extension could enhance effectiveness. Especially for more complex adaptation strategies, such as irrigation and weather index insurance, increasing farmers' understanding and knowledge on the strategies could incentivise increased and improved implementation and uptake. Agricultural extension officers should also be further sensitised to climate risk, to enhance their training of farmers.

- **Research findings need to be communicated effectively to reach farmers and local decision makers.** This may include translating findings into local languages and using alternative distribution channels with rural outreach, such as radio stations, mobile phone services or NGOs with local representation.

- **Seize local and indigenous knowledge wherever possible as this can deliver important additional benefits for successful implementation.** Indigenous knowledge is best adapted to local contexts and through careful observations over time has acquired a precious body of evidence for identifying patterns and systemic changes in the environment.
- **Adaptation planning in Ghana should not be limited to technologies but also consider shifting existing practices and management choices.** Based on the crop suitability analysis, which projects changing crop suitability patterns for four major crops across Ghana, farmers could be encouraged to shift their cropping patterns according to suitability changes.

Recommendations for specific adaptation strategies, whose primary addressees are political decision makers, but can also guide autonomous adaptation decisions of farmers and farmer cooperatives[30]:

1. **Invest in improved post-harvest management systems.** Improved post-harvest management, for instance in the form of PICS bags, is a cost-effective way of reducing agricultural production losses, even representing a no-regret strategy in most cost scenarios. Scaling-up efforts in the distribution and use of PICS bags could compensate crop production losses due to climate change and thus improve farmer income. Existing networks in Ghana can facilitate the upscaling of this strategy. Investing in improved post-harvest management technologies will directly contribute to achieving Ghana's goals on reducing post-harvest losses, as formulated in Ghana's "Multi-sectoral implementation plan for Ghana's Nationally Determined Contributions to the Paris Agreement".

2. **Ensure affordability and financial sustainability of crop insurance products, for instance via well-designed subsidy systems and bundling of insurance products with agricultural inputs: Index-based insurance has a role to play in buffering farmers' crop yield losses.** For climate risk above a threshold where risk reduction technologies are cost-effective, risk-transfer mechanisms such as crop insurance are vital for sustaining agricultural livelihoods. However, current premium rates in Ghana may be too low for cost efficiency of insurance. Yet, low premium rates make insurance affordable also for smallholder farmers. Support for affordable and cost-efficient insurance schemes could come from both government and private-sector side. Bundling insurance with agricultural inputs such as fertiliser or improved seeds could increase uptake of insurance.

3. **Facilitate setting up of rainwater harvesting structures for small-scale irrigation.** Such structures allow storing irrigation water for critical times in the growing period of otherwise rain-fed crops. With rainwater harvesting installations being considerably cheaper than building other irrigation infrastructure, they offer comparative advantages especially with regard to incentivising autonomous uptake by farmers.

4. **Increase investment in local breeding of improved crop varieties and improve dissemination of improved seeds.** Stakeholders in Ghana showed high interest in improved crop varieties. Indeed, case studies for some Ghanaian districts highlighted the value of improved maize varieties for increasing crop yields and thus reducing crop losses caused by climate change. However, for improved seeds to show their full potential and given the long time span needed for developing suitable varieties, more investment in local breeding and facilitation for farmers to access those seeds is needed.

5. **Improve water management, especially in the North of Ghana, and explore potential for irrigation upscaling**. Irrigation may become increasingly important in the medium to long term, with hydrological models projecting drier conditions in Ghana by end of the century under a high emissions scenario. Seasonal droughts may also become more severe over time, necessitating improved water management to sustain agricultural production. Adaptation decision makers and farmers could invest in farm-level rainwater harvesting structures for low-cost and small-scale irrigation options, particularly for vegetable production. While irrigation has the potential to increase yields, especially in drier parts of Ghana, such as the North and the Southwest, which is

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[30] The adaptation strategies are presented in random order, no ranking is intended.

projected to become drier, it remains a rather costly adaptation strategy to date. More research on low-cost irrigation systems is thus needed, for instance in combination with rainwater harvesting structures. Yet, the possibility to intensify production and harvest several times a year can offer important economic benefits, which make irrigation an interesting strategy to consider.

The analysis and stakeholder engagement also revealed several key factors, which are important for creating an enabling environment for adaptation in Ghana's agricultural sector:

- Access to markets and inputs is key, barriers for adopting new technologies, farming methods and for marketing agricultural production should be lowered.

- Tenure security may facilitate the adoption and implementation of adaptation strategies. In the absence of such institutional clarity, support with clarification and dispute settlement is needed.

- Strong institutions and governance structures are important for enabling and implementing adaptation.

- Adaptation incentive structures need to be understood and carefully activated to improve autonomous uptake of adaptation measures.

- Mainstreaming of adaptation strategies into development work will maximise synergies, increase efficiency of resource use and enhance effectiveness of adaptation.

- Access to information and education is crucial for successful implementation of adaptation strategies, dissemination of knowledge and extension efforts need to be ensured.

Synergies with existing climate adaptation policies:

- Ghana's Nationally Determined Contribution (NDC), Republic of Ghana, September 2015: Ghana aims to achieve its long-term adaptation goal via 7 priority adaptation policy actions, as listed in its NDC. One priority sector with three policy programmes is agriculture and food security, the natural entry point for this study. Here the results can notably be used to implement priority 3: promote innovations in post-harvest storage and food processing and forest products in 43 administrative districts. For this, the government of Ghana lists investments needs of $1,270 million, for which the economic analysis in this study as well as the climate risk analysis provides important information. The climate risk information is also useful for further developing the other two priorities within the agricultural sector, namely conservation agriculture and livestock and fishery production.

- While the study is tailored to the agricultural sector for the full impact chain analysis, it cuts across sectors and can also benefit further programme and project development in the other adaptation sectors prioritised in Ghana's NDC, such as Energy, Water, Gender, Health, Forestry, Transport and Disaster Risk Reduction.

- Ghana National Climate Change Master Plan Action Programmes for Implementation: 2015–2020, Ministry of Environment, Science, Technology and Innovation, Republic of Ghana, 2015: As regards Ghana's National Climate Change Master Plan, the climate risk study for the agricultural sector can especially support the achievement of "Policy Focus Area 1: Develop climate-resilient agriculture and food security systems". Here, the study provides evidence on the feasibility and effectiveness of programmes 1.2, 1.5, 1.6 and 1.7: Development and Promotion of Climate-resilient Cropping Systems; Support to Water Conservation and Irrigation Systems; Risk Transfer and Alternative Livelihood Systems (including insurance schemes) and Improved Post-harvest Management. The study also strengthens calls for programme 1.1 on institutional capacity development for research and dissemination. Synergies with other policy focus areas also exist, for instance with policy focus area 3 on increasing resilience of vulnerable communities to climate-related risks. Here, the study can be used to substantiate programme 3.5 on financial support and insurance schemes.

- Ghana National Climate Change Policy, Ministry of Environment, Science, Technology and Innovation, Republic of Ghana, 2013: Agriculture and food security is identified as one thematic area for effective adaptation. Within this, especially the "Focus Area 1: Develop Climate-resilient Agriculture and Food Security Systems" links well with this climate risk study. As challenges for a resilient agricultural sector the policy identifies "insecure land tenure" and "crop failure due to weather variability and unpredictability" (Ghana National Climate Change Policy, p. 61), among others, which have also been highlighted in this study. In addition, a number of adaptation options are prioritised that are also recommended as part of this study, most notably programme areas 5, 6 and 7: "P5. Support to water conservation and irrigation systems; P6. Risk transfer and alternative livelihood systems; P7. Improved post-harvest management" (Ghana National Climate Change Policy, p.63).

- National Climate Change Adaptation Strategy, November 2012: Ghana's national climate change adaptation strategy lists a number of strategies that should be pursued to enhance its adaptive capacity and to build resilience of the society and ecosystems, the overall aim of the policy document. This climate risk study will be particularly helpful for further defining measures to achieve strategies within the agricultural sector, such as linked to new technologies, cultivation of crops and post-harvest management. Other strategy areas such as health, early warning, energy, livelihoods and particularly water and land use can benefit especially.

Generally, since agriculture is the backbone of Ghana's economy and a key income source especially for the most vulnerable, rural populations, all adaptation measures tailored to agriculture can also benefit other adaptation and development initiatives. Multiple synergies between this study and issue areas such as water availability, better health, improved value chains etc. may exist, underlining the importance of agriculture as a priority area for adaptation, while at the same time showing the many additional benefits that investment in adaptation in the agricultural sector can provide.

In addition, the climate risk analysis is relevant beyond the agricultural sector, as other sectors, such as energy, transport, infrastructure, water and health are equally affected by changing climatic conditions and changing water availability. The study can thus be used as input for planning also in those issue areas which will notably be important in the process of implementing the abovementioned NDC priority actions. The climate risk projections and derived investment cases for adaptation offer quantified estimates for economic benefits from adaptation and can be used to incentivise investments. Within Ghanaian development policy planning, this study can serve as guidance and evidence base for further substantiating efforts in Ghana – also in line with Ghana's Long-Term Development Plan and the Agenda 2063 of the African Union – to advance the achievement of the SDGs, notably SDG13 on climate change and SDG2 on zero hunger.

> This climate risk analysis is relevant beyond the agricultural sector, as other sectors such as energy, transport, infrastructure, water and health are equally affected by changing climate conditions and changing water availability.

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