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Climate Risk Analysis for Identifying and Weighing Adaptation Strategies in Burkina Faso‘s Agricultural Sector

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A report prepared by the Potsdam Institute for Climate Impact Research (PIK) together with 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 West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), the HFFA Research GmbH and stakeholders from local and national governmental institutions, civil society, academia, the private sector, practitioners and development partners.

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Authors' contributions:

Christoph Gornott, Felicitas Röhrig, Nele Gloy and Sophie von Loeben coordinated and edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Christoph Gornott, Lisa Murken and Felicitas Röhrig designed the study approach with steering input from stakeholders. Felicitas Röhrig and Oblé Neya coordinated the stakeholder engagement process. Paula Aschenbrenner performed the climate analysis in Chapter 1. Hagen Koch, Stefan Liersch and Michael Wortmann conducted the hydrological analysis for Chapter 2. Ponraj Arumugam analysed climate impacts on crop yields and suitability for Chapter 3 and the biophysical risk assessments in Chapter 8-10, under the guidance of Abel Chemura, Bernhard Schauberger, Felicitas Röhrig and Christoph Gornott; Rahel Laudien analyzed climate impacts on crop yields with statistical methods; Abel Chemura conducted a crop suability analysis. Sophia Lüttringhaus, Juliane Kaufmann and Steffen Noleppa conducted the farm level cost-benefit analyses in Chapters 8-10. Julia Tomalka contributed Chapters 6-8. Sophia Lüttringhaus contributed Chapter 10. Sophie von Loeben contributed Chapter 9. All authors contributed to Chapter 5 on methods and Chapter 11 on uncertainties. Felicitas Röhrig, Nele Gloy, Sophie von Loeben, Lisa Murken, Julia Tomalka provided overall research support. The summary for policy makers was compiled by Léa Baek together with Nele Gloy, Sophie von Loeben and Christoph Gornott.

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Abstract

Burkina Faso has a high socio-economic dependency on agriculture, a sector which is strongly influenced by weather-related factors and increasingly challenged by the impacts of climate change. Currently, only limited information on climate risks and its impacts is available for the agricultural sector in the country. Therefore, this study aims to provide a comprehensive climate risk analysis including a thorough evaluation of four potential adaptation strategies that can guide local decision makers on adaptation planning and implementation in Burkina Faso. The impact assessment consists of several steps including climate projections based on two emissions scenarios (SSP3-RCP7.0 and SSP1-RCP2.6), hydrological modelling on water availability changes, modelling and comparison of future yields of four widely used crops (maize, sorghum, millet and cowpeas) and an assessment of livestock production under future climate conditions. Based on the projected climate change impacts on agricultural production, four different adaptation strategies ((1) Integrated soil fertility management (ISFM), (2) irrigation, (3) improved seeds and (4) climate information services (CIS)) suggested and selected by different national stakeholders were analysed regarding their potential to risk mitigation, (cost-)effectiveness and suitability for local conditions. The analyses have been further complemented by expert- and literature-based assessments, semi-structured key informant interviews and two stakeholder workshops.

The results show that the mean daily temperature is on the rise and projected to increase further by 0.6°C (2030) up to 1.1°C (2090) under SSP1-RCP2.6 and by 0.5°C (2030) up to 3.6°C (2090) under SSP3-RCP7.0 in reference to 2004, dependent on future greenhouse gas emissions. Some uncertainty exists for annual precipitation projections, with slight increases until 2050 followed by a slight decrease under SSP1-RCP2.6 and continuous increase under SSP3-RCP7.0 with high year-to-year variability. Projected impacts of climate change on yields vary between regions and show partly opposing trends. Some regions in the north show increasing yields (up to +30% in SSP1-RCP2.6 and up to +20% in SSP3-RCP7.0), while few regions in the south present decreasing yields (down to -30% in SSP1-RCP2.6 and down to -20% in SSP3-RCP7.0). Crop models show that the areas suitable for cowpeas will decrease in Burkina Faso under future climate change conditions while the suitability for maize, millet and sorghum will remain stable. Moreover, the potential to produce multiple crops will become more and more difficult, which limits farmers' diversification options. Regarding the livestock sector, it seems very likely that the grazing potential will decrease under both climate change scenarios with higher decreases under SSP1-RCP2.6 than under SSP3-RCP7.0.

All four adaptation strategies were found to be economically beneficial, can have a high potential for risk mitigation and entail different co-benefits. Particularly, ISFM can be highly recommended for smallholder farmers, resulting in very positive effects for societies and environment. Irrigation and improved seeds have a high potential to improve livelihoods especially in Northern Burkina Faso, but are also complex, costly and support-intensive adaptation strategies. Lastly, CIS can support farmers to make informed decisions and thereby reduce the impact of climate risks. Generally, a combination of different adaptation strategies can entail additional benefits and active stakeholder engagement as well as participatory approaches are needed to ensure the feasibility and long-term sustainability of adaptation strategies. The findings of this study can help to inform national and local adaptation and agricultural development planning and investments in order to strengthen the resilience of the agricultural sector and especially of smallholder farmers against a changing climate.

Keywords: climate change adaptation, climate impacts, climate risk, agriculture, livestock, Burkina Faso, biophysical modelling, cost-benefit analysis, multi-criteria assessment

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List of abbreviations

AEZ	Agro-Ecological Zone
AGRA	Alliance for the Green Revolution in Africa
AGSDS	Accelerated Growth and Sustainable Development Strategy
AIC	Akaike Information Criterion
ALR	Agrarian Land Re-organization
AMGP	African Market Garden Project
AMPLIFY	Agricultural Model for Production Loss Identification and Failures of Yields
ANAM	National Meteorological Agency
AUC	Area Under the receiver operating Curve
AZN	Association Zoramb Naagtaaba
BCR	Benefit-Cost Ratio
BMZ	German Federal Ministry for Economic Cooperation and Development
C3S	Copernicus Climate Change Service
CBA	Cost-Benefit Analysis
CFA	Communauté Financière Africaine (African Financial Community)
CGIAR	Consultative Group on International Agricultural Research
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CILSS	Permanent Interstates Committee for Drought Control in the Sahel
CIS	Climate Information Services
CMIP	Coupled Model Intercomparison Project
CWR	Crop Water Requirement
DGESS	Direction Générale des Etudes et des Statistiques Sectorielles
DGRE	Directorate General of Water Resources
DSSAT	Decision Support System for Agrotechnology Transfer
ECS	Equilibrium Climate Sensitivity
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
FAO	Food and Agriculture Organization of the United Nations
FEWS NET	Famine Early Warning Systems Network
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GLC	Global Land Cover
$GrCO_2$	Global CO_2 emissions
GRDC	Global Runoff Data Centre
HWSD	Harmonised World Soil Database
IAM	Integrated Assessment Models
ICT	Information and Communication Technologies
ICV	Improved Crop Varieties
IITA	International Institute of Tropical Agriculture
INERA	Institut de l'Environnement et de Recherches Agricoles
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISFM	Integrated Soil Fertility Management
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ITCZ	Intertropical Convergence Zone

LPJmL	Lund-Potsdam-Jena with managed Land
LUCODEB	Combating Desertification in Burkina
MAAH	Ministère de l'Agriculture et des Aménagements Hydro-agricoles
MMEM	Multi-Model Median
MRAH	Ministère des Ressources Animales et Halieutiques
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organisation
NPV	Net Present Value
OOS	Out-Of-Sample
PAGIRE	Action Plan for the Integrated Management of Water Resources
PIK	Potsdam Institute for Climate Impact Research
PSDB9	Programme Sahel Burkina
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SAP	Système d'Alerte Précoce
SDGs	Sustainable Development Goals
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
SWIM	Soil and Water Integrated Model
TLU	Tropical Livestock Unit
UNPS-BF	National Union of Seed Producers of Burkina Faso
USAID	United States Agency for Internal Development
USD	United States Dollar
WAM	West African Monsoon
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WMO	World Meteorological Organization
XGBoost	eXtreme Gradient Boosting

PART I – CLIMATE CHANGE IMPACTS

In the first part of this climate risk analysis, we look at the interplay between changing climatic conditions, water availability and agriculture in Burkina Faso. The part aims to answer two main questions: How will the climatic conditions change in the next decades? And how are these changes going to influence agricultural activities of smallholder farmers in Burkina Faso?

Introduction

While many countries increasingly recognise the importance of adaptation in a world of changing climate, there is often a lack of guidance on how to operationalise adaptation goals. 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). Due to its high dependency on climatic factors, the agricultural sector is particularly vulnerable to climate change. Extreme events and slow-onset hazards increasingly threaten agricultural production and thereby pose a serious threat to agricultural livelihoods with cascading impacts on food and nutrition security. Adaptation decisions often take place at the sub-national level, where decision-makers have to cope with a lack of locally specific data on current and projected climate risks and their impacts, as well as on costs and benefits of suitable adaptation strategies. This calls for fine-grained climate risk analyses and assessments as a foundation of risk-informed and economically sound investment decisions at local level. A better understanding of projected climate impacts on agricultural and livestock production, associated climate risks and possible adaptation benefits at both national and province level is important to guide, incentivise and accelerate public and private sector investments for climate-resilient agricultural development.

The present study provides an in-depth analysis of climate risks for selected crops and livestock systems in Burkina Faso, together with recommendations and an accompanying assessment of the feasibility, costs and benefits of four selected adaptation strategies. Burkina Faso was selected for this study due to the country's high socio-economic dependency on the agricultural sector, which is also highly exposed and vulnerable to climate change. The study seeks to provide the base for risk-informed and economically sound adaptation decisions for the agricultural sector in Burkina Faso.

The study area

Burkina Faso is a semi-arid landlocked country in Western Africa, bordering Mali to the west and north, Niger to the northeast, Benin to the southeast and Ghana, Togo and Côte d'Ivoire to the south. Located in the Sahel, it is highly vulnerable to climate change due to a combination of naturally high levels of climate variability, high reliance on rain-fed agriculture, and limited economic and institutional capacity to cope with and adapt to climate variability and change. The region has experienced a decline of rainfall resulting in a series of severe natural disaster such as droughts since the late 1960s, leading to severe famines with detrimental socio-economic impacts. Climate trends indicate a general ongoing shift to a drier climate linked to rising global tropical sea surface temperatures, which will likely further increase the frequency and intensity of droughts in the region (Traore & Owiyo, 2013). The need for reliable information on climate trends, related impacts on agricultural production and food security as well as on suitable adaptation options becomes increasingly important in this context.

Figure 1: Map of Burkina Faso with administrative regions.

The situation is further aggravated by one of the highest population growth rates globally with nearly 3% (Plecher, 2020), which will lead to a doubling in population within 25 years adding a massive increase in food demands under climate change. All West African countries are currently net importers of cereals, indicating that the current production is insufficient to meet domestic demands (FAOSTAT, 2020). The existing trends in West African agriculture indicate that shortages are expected even without the adverse effects of climate change (Gerland et al., 2014; Ray et al., 2013).

Agriculture plays an important role for Burkina Faso's economy and the population's food and nutrition security. Overall, 80–90% of the population is engaged in smallholder farming and heavily relies on agriculture for food security and livelihoods (FAO, 2014). Many rural households in the country are also heavily dependent on livestock, as they live below the poverty line and face major constraints in producing or buying food to meet a satisfactory intake of calories and proteins (Sanfo & Gérard, 2012). Livestock in Burkina Faso, like in other sub-Saharan African countries, is equal to wealth for the rural population and, since historical times, holds great cultural value. As there are different forms of livestock keeping, such as sedentary farming and transhumance, chapter 4 will provide an excursion on their potential conflicts and the general security situation in Burkina Faso in face of the climate change.

The study approach

The need for scientific evidence regarding climate change includes more information on climate impacts as well as accessible information on the costs and benefits of potential adaptation strategies. Consequently, the study combines a model-based climate impact assessment with an economic and a multi-criteria analysis to evaluate adaptation strategies under different emissions scenarios. We thereby consider one GHG concentration pathway scenario (hereafter also referred to as emissions scenario) following strong mitigation being in line with the Paris Agreement (SSP1-RCP2.6), and one scenario without climate policy (SSP3-RCP7.0). The study thereby models the whole chain from the impact dimension of climate changes for the agriculture, water and livestock sectors, to an action dimension assessing specific adaptation options and policy recommendations, as well as a discussion on uncertainty of results (Figure 2).

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

Although this study focuses primarily on the crop agricultural sector, it provides an accompanying analysis on the water and livestock sectors. The hydrological analysis focuses on modelling future water availability for agricultural production, assessing both river discharge and groundwater recharge for irrigation. The assessment of climate impacts on livestock production analyses future grazing potential in the country, an indicator for livestock carrying capacity and future fodder availability. In addition, the results provide important insights that are relevant for other economic sectors as well, including forestry, energy, health and infrastructure. These findings are intended to support national and local policy makers, development actors, the private sector and farmers to inform long-term planning and investment. In addition to this in-depth scientific report, there is also an executive summary, as well as a policy brief available that give a condensed overview of the findings relevant for high-level policy making at national and local level. A complementary climate risk profile for Burkina Faso provides a snapshot overview on key climate risks to other sectors such as health, water, biodiversity and infrastructure. The profile and related information can be found on the project website www.agrica.de.

In order to ensure alignment of the study focus with national goals and priorities, a wide range of local experts and stakeholders have been involved throughout the study process via stakeholder workshops, farmer surveys and expert discussions. Close collaboration with the local partner institute, the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) allowed us to get continuous validation of our focus and results. The study is organized as follows: The first four chapters cover the impact dimension of climate change in Burkina Faso, whereas the following chapters 5 to 10 focus on the action (or adaptation) dimension.

- Chapter 1 provides an overview of past and projected future climatic changes in Burkina Faso focusing on changing temperature and precipitation regimes in the country. All future projected climate impacts are based on outputs of ten Global Climate Models under two future climate scenarios, a low-emissions scenario (SSP1-RCP2.6) and a high-emissions scenario (SSP3-RCP7.0).
- Chapter 2 analyses changing water availability for agricultural production, looking at both river discharge and groundwater level availability for irrigation.

- Chapter 3 presents a comprehensive overview of climate impacts on crop production, ranging from weather influence on crop yields, changes in crop suitability under climate change and projected yield impacts of climate change on crop production.
- Chapter 4 assesses climate impacts on livestock production by analysing both a trend in livestock numbers and projected grazing potential and associated fodder availability in the country under climate change.
- Chapter 5 introduces the action component of the study and presents the methods and approaches used for the evaluation of the adaptation strategies, starting with the multi-criteria assessment, then the biophysical evaluation and the cost-benefit analysis.
- Chapter 6 provides an overview of the adaptive capacity in Burkina Faso and presents the assessment framework for selecting and evaluating adaptation recommendations for the agricultural sector, including biophysical, economic and soft-assessment indicators.
- Chapters 7 – 10 assess selected adaptation strategies. Chapter 7 looks at climate information services, chapter 8 at irrigation, chapter 9 at integrated soil fertility management and chapter 10 at use of improved crop varieties.
- Chapter 11 discusses sources of uncertainty and presents limitations of the study to facilitate interpretation of results.
- Chapter 12 concludes with a synthesis the study results and derives policy recommendations. The results are meant to inform and support local and national government authorities, non-profit, and private sector stakeholders in prioritizing and designing their adaptation investments to increase the resilience of smallholder farmers under climate change.

Chapter 1 – Changing climatic conditions

To identify changes in future climatic conditions in Burkina Faso, this chapter analyses several indicators concerning temperature and precipitation under two global emissions scenarios, scenario SSP1-RCP2.6 and scenario SSP3-RCP7.0, which are low and high GHG concentration pathway scenarios covered in the Intergovernmental Panel on Climate Change (IPCC) reports (details in box 1). SSP1-RCP2.6 represents a scenario that remains globally below 2°C above pre-industrial temperatures (IPCC, 2014) and is thereby in line with the goals of the Paris Agreement. RCP7.0 is a high emissions scenario and refers to the "without climate policy" scenario. Projected climate data were analysed to show the range of possible future climatic conditions by 2030, 2050 and 2090 and thus inform decision makers and implementers on the mid- and long-term future climate conditions.

First, the drivers of the current climate in West Africa and more specifically in Burkina Faso are presented in the subsequent section. This is followed by the description of data and methods and an outline of the current climate conditions. On this basis, past as well as future climate trends of mean annual climate variables, extreme weather events as well as seasonal shifts have been analysed.

1.1 What drives Burkina Faso's climate?

Depending on the source, Burkina Faso can be divided into five agro-ecological zones (AEZ) (Figure 3), which also define the agricultural production in the country: the arid/Sahel zone to the north, the semi-arid/Sudan savannah and the northern Guinea savannah spanning the central part of the country, and the southern Guinea savannah and derived savannah to the south. It should be noted that there are different classifications of AEZ in Burkina Faso, for instance, Burkina Faso can be also divided into four major agro-ecological zones which are based on the natural vegetation and land cover map by Fontès and Guinko (1995), which also define the agricultural production in the country (Saydou, 2012). The zones in the North are characterised by semi-arid steppe and shrubby savannahs. The mean annual precipitation amount is of less than 400mm in the Sahelian zone mainly distributed over approx. five months during the summer.

Figure 3: Topographical map of Burkina Faso with agro-ecological zones (AEZ), adapted from International Institute of Tropical Agriculture.

Largely covered by grasslands and shrubs, dry and degraded soils lead to low levels of agricultural production, especially in the North. Millet and livestock production dominate in this region, which is also among the poorest in the country (FEWS NET, 2017; USDA, 2011). The annual precipitation amounts gradually increase towards the South, where the climate is also becoming increasingly humid and tropical. With increasingly fertile soils, crop production in this belt is dominated by sorghum and groundnuts (FEWS NET, 2017; Konate et al., 2020). Lastly, the Southern part of the country receives up to 1100mm of precipitation per year and is considered the country's crop basket. With fertile soils and relatively abundant water supply, cotton, maize and rice are predominantly produced in this region (Saydou, 2012; USDA, 2011).

The climate in Burkina Faso is mostly dominated by high temperatures and variable precipitation. Precipitation increases from north to south and is linked to the migration of the Intertropical Convergence Zone (ITCZ) and thus the formation of the West African Monsoon (WAM). The atmospheric and oceanic processes influencing the WAM are complex and sensitive to external forcing. Following the migration of the sun's zenith, the WAM develops around March and brings precipitation to the south of Burkina Faso at the end of March and to the north at the end of June (Figure 4). The WAM is mainly driven by the temperature gradient between the ocean and the land surface. The high temperatures over the Sahara in boreal summer create a heat low which drives the moist air from the Atlantic Ocean inland towards the Sahel and thereby brings precipitation inland (Herzschuh et al., 2014; Minka & Ayo, 2014).

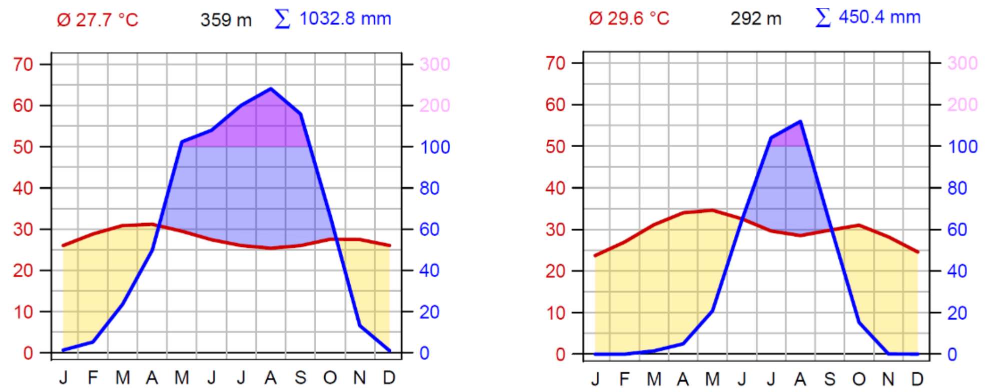


Figure 4: Two climate diagrams displaying the annual distribution of precipitation and temperature in the south [10.75 °N;-3.75 °E] (left) and in the north [14.25 °N;-0.25 °E] (right).

Precipitation amounts in Burkina Faso and the whole Sahel region have shown high variability in recent decades. This includes a severe drying of the extended Sahel in the 1970s and 1980s. Studies have shown that this dry period can indirectly be attributed to the unique combination of aerosols and greenhouse gases that characterised the period after 1950 (Giannini & Kaplan, 2019; Liersch et al., 2020).

At shorter interannual timescales the strength of the WAM has been influenced by the sea surface temperature of the Atlantic Ocean and the Mediterranean as well as temperatures over the Sahara (Chauvin et al., 2010; Schewe & Levermann, 2017), land-use changes (Davin & de Noblet-Ducoudre, 2010; Kothe et al., 2014) and increases in freshwater content due to Greenland ice sheet melting (Defrance et al., 2017). These multifaceted climate interactions lead to uncertainties in the projections of WAM development.

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

Figure 5: The SSPs of the IPCC guided scenario set (O'Neill et al., 2016).

The future emissions scenarios used in this report are based on the standard set of future scenarios used in the IPCC framework. The scenarios are a new set of emissions and land-use scenarios that are used in the 6th report (as compared to the four Representative Concentration Pathways (RCPs) used in the 5th Assessment Report): pathways of societal development, the shared socioeconomic pathways (O'Neill et al., 2017), linked with forcing levels of the representative concentration pathways (Eyring et al., 2016; O'Neill et al., 2016).

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

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

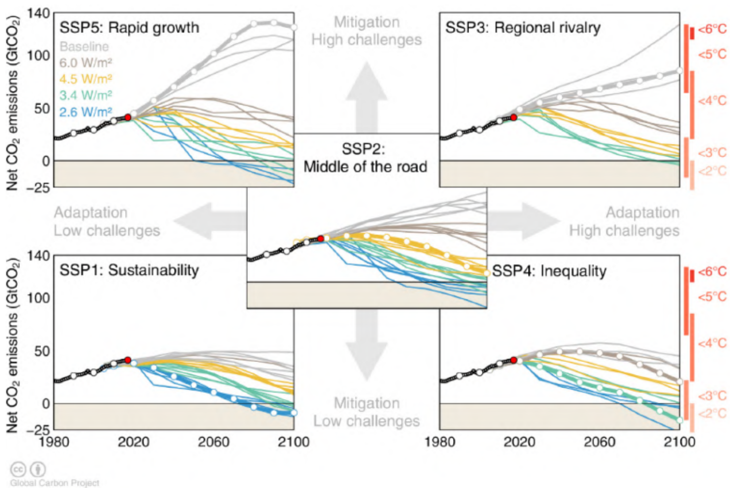


Figure 6: Global CO2 emissions (GrCO2) for all IAM runs in the SSP database. Chart produced by Global Carbon Project.

To show a wide range of possible future socioeconomic and emissions scenarios, this study will concentrate on the scenarios SSP1-RCP2.6 and SSP3-RCP7.0. SSP1-RCP2.6 pictures a sustainable future where global warming is likely to be well below 2°C and is thereby in line with the Paris Agreement. SSP3-RCP7.0 depicts high challenges for mitigation and adaptation in a world with no or little climate policy interventions and temperature increases of up to 5°C until the end of this century (Hausfather, 2018; van Vuuren et al., 2011). These two scenarios give us a range of possible future climates, whereby both framing pathways are still plausible future scenarios.

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

1.2 Data and method

The basis for the evaluation of the current and near-past climate in this study is the climate observational dataset W5E5 (Cucchi et al., 2020; Lange, 2019a), a dataset based on a combination of simulations from global weather models, satellite data and in-situ observations. The dataset covers the time period 1979-2016 at daily temporal resolution and the entire globe at 0.5° x 0.5° grid spacing (corresponding to approximately 55km x 55km in Burkina Faso). W5E5 was compiled to support the bias adjustment of climate data, which drive the impact assessments carried out in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; (Lange, 2019a)), of which this report also makes extensive use.

Future climate projection data simulated by Global Climate Models (GCMs) was obtained from ISIMIP3b. Historical simulations cover the years 1850-2014 and future projections (under both greenhouse gas emissions scenarios) cover the years 2015-2100. W5E5 is the observational reference dataset used for bias adjustment and statistical downscaling of ISIMIP3b. The GCMs[2] included in ISIMIP3b are: CanESM5 (short: Can), CNRM-ESM2-1 (short: CNES), CNRM-CM6-1 (short: CNCM), EC-Earth3 (short: EC), GFDL-ESM4 (short: GFDL), IPSL-CM6A-LR (short: IPSL), MIROC6 (short: MIROC), MPI-ESM1-2-HR (short: MPI), MRI-ESM2-0 (short: MRI) and UKESM1-0-LL (short: UKE) (Lange, 2019a). GCMs have been downscaled in order to have a higher spatial resolution, and were preferred to regional climate models as they could be bias-corrected on observed climate data and were consistent with the models used for the impact assessments.

The indicators analysed in this study are: the annual average mean air temperature, **the number of very hot days** per year (maximum temperature above 35°C), the number of **very hot or tropical nights** per year (minimum temperature above 25°C), the mean annual precipitation sum, the heavy precipitation intensity and frequency, and the rainy season onset. Other parameters such as the length of the rainy season or the distribution of rainy events during the year would have been also relevant for respective climate risk assessment and could be object of future studies.

The indicator for **heavy precipitation intensity** is the maximum daily precipitation amount of a year. The indicator for heavy precipitation frequency is the number of days exceeding a threshold. The threshold is thereby defined as the 95th percentile of days with precipitation (>0.1mm) during the baseline period 1995-2014 for each grid cell. The average 95th percentile for the baseline period for Burkina is 25 mm/day with a range between 20 and 32 mm/day.

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

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

GCMs cannot perfectly represent the current and future climate. They naturally show slightly different projections in modelling the climate, even if they are driven with the same emissions scenario. A detailed validation of all ten GCMs showed that the multi-model ensemble medians (MMEM) is closest to the observations in West Africa. Different projections of all individual models give an indication of the range of uncertainty and the MMEM provides a conservative estimate of possible climatic changes. Thus, the MMEM is shown additionally to the individual model results. Within the report, climate change projections are based on 20-year averages[3], meaning that the mean annual temperature in e.g. 2030 is calculated as an average over the mean temperature between 2021 and 2040. The reference climate, used as the baseline in this study, refers to the climate in 2004 (1995-2014) as the period is included in the historical simulations of ISIMIP3b. The projected climate data is evaluated for the periods 2030 (2021-2040), 2050 (2041-2060) and 2090 (2081-2099). When referring to the changes in

2 An information box on climate models can be found in the supplementary material.

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

the future, the computations have been done for each of these three periods in differentiation to the baseline (2004) for each model and scenario. For the analysis of the observational data sets, the present climate was obtained by averaging over 1997-2016.

1.3 Present climatic conditions

Burkina Faso currently experiences a mean annual temperature between 27-30°C, with higher values in the north of the country. The interseasonal temperature differences are low in the south and increase towards the north, reaching the maximum variance in the upper north with mean monthly temperatures of 35°C in May and 24°C in January (Figure 7). The number of very hot days (tropical nights) per year reaches from 125 days (25 days) in the south to 265 days (150 days) in the north.

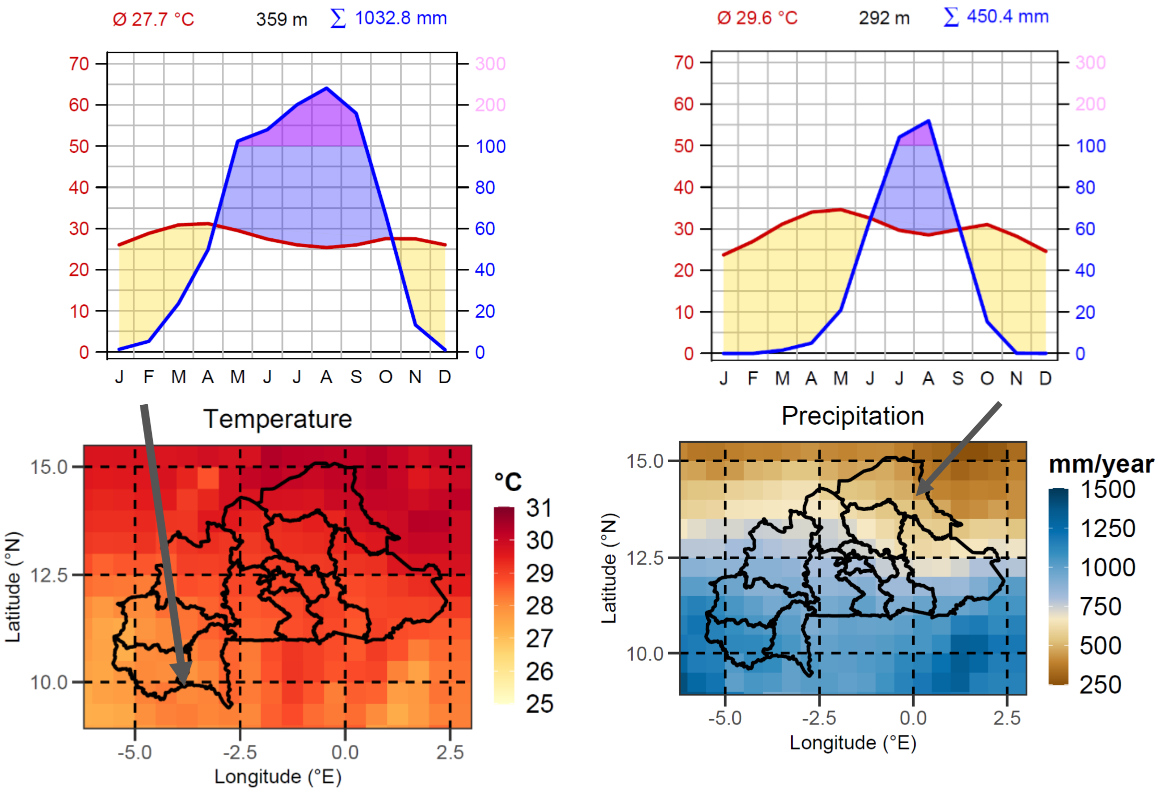


Figure 7: Top: Two climate diagrams displaying the annual distribution of precipitation and temperature in the south [10.75 °N;-3.75 °E] (left) and in the north [14.25 °N;-0.25 °E] (right). Bottom: Mean annual temperature in °C (left) and mean annual precipitation in mm (right) over Burkina Faso 1997-2016.

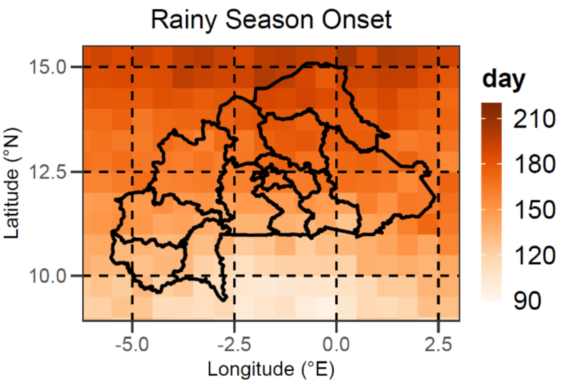


Figure 8: The day of the year marking rainy season onset averaged over the years 1997-2016.

The annual mean precipitation sum is between 300 and 1100mm per year, with decreasing values towards the north (Figure 7; Figure 9). Burkina Faso experiences a pronounced dry and rainy season. The rainy season extends for more than two months in the north and up to six months in the south. In an average year, the rainy season starts between 20th of April (day 110) and 15th of July (day 196), depending on the location (Figure 8). The rainy season onset and length show high year-to-year variability. Year-to-year variability of the annual precipitation sum is also high in the whole country. The northern part of Burkina Faso experiences the highest year-to-year variability. We looked here at interseasonal trends by looking at the start of the rainy season as one of the most important influencing factors for farmers.

While farmers in Burkina Faso express large concerns associated with low precipitation amounts, dry spells or late rainy season onset, farmers are also hit by crop failure due to floods in some years and parts of the country (Sarr et al., 2015), induced by increased heavy precipitation events and enforced by land degradation.

The maximum daily precipitation amount averaged over 1997-2016 is between 30mm and 80mm (Figure 9). Extreme heavy precipitation events can locally reach values of up to 200mm per day.

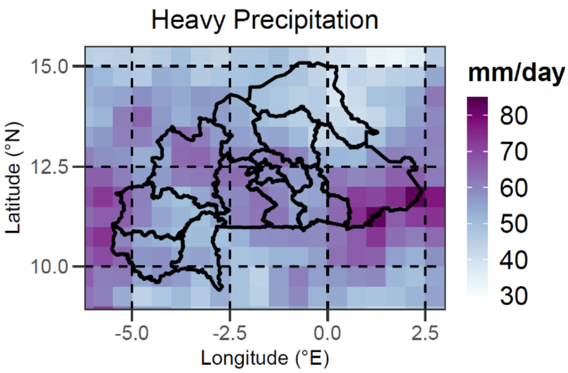


Figure 9: Annual maximum daily precipitation averaged over the years 1997-2016.

1.4 Climate Change and Variability in the Past and Near Future

Temperature

During the recent past, annual mean temperatures showed a rise of 0.27°C between 1988-2006 over Burkina Faso (Figure 10).

Climate models project a robust trend towards increasing temperatures in Burkina Faso over the 21st century. This is evident in both analysed scenarios, albeit to different degrees. The multi-model ensemble median (MMEM) indicates an average increase of the mean daily temperature over Burkina Faso of 0.6°C (2030), 0.9°C (2050) to 1.1°C (2090) under SSP1-RCP2.6 (low emissions scenario) and of 0.5°C (2030), 1.3°C (2050) to 3.6°C (2090) under SSP3-RCP7.0 (high emissions scenario) in reference to 2004

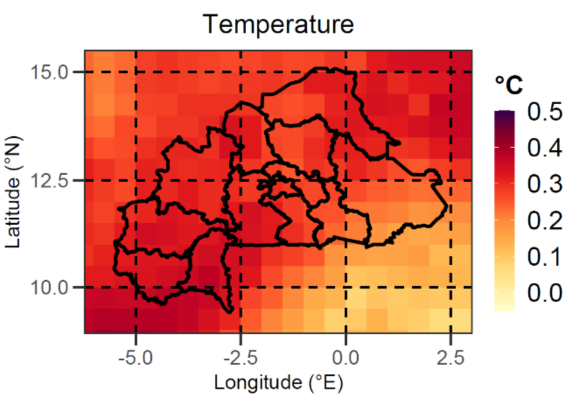


Figure 10: Difference in mean daily temperature in °C over Burkina Faso from 1988 to 2006.

(Figure 12). Under the low emissions scenario, temperatures do not increase strongly after 2050, following the stabilization of GHG emissions before mid-century. Taking the temperature rise before 2004 into account (IPCC, 2014), temperature rise would be well above the 1.5°C target by 2050 for most models, even under the low emissions scenario.

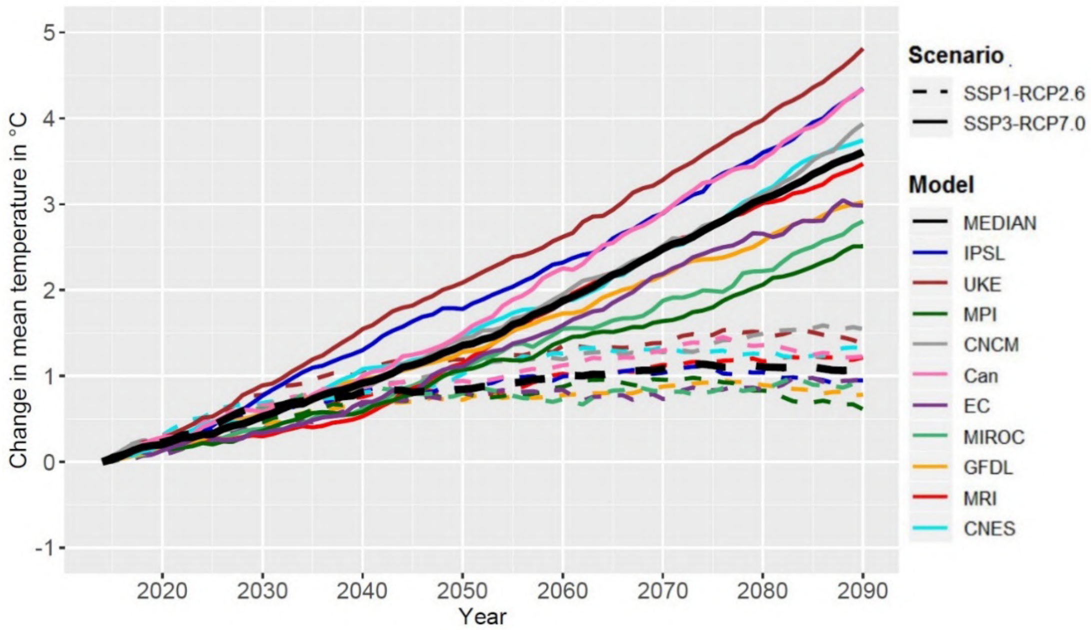


Figure 11: The 21-year moving average of projected change in mean temperature in °C compared to 2014. Values are averages over Burkina Faso. Each variegated line indicates a projection of one of the 10 individual models. The black line displays the MMEM.

Temperature projections show very high confidence, with all models showing the same trend (Figure 11). Even though the models show different ranges of temperature increase, they all show a continuous increase until 2090 under the high emissions scenario. The selection of the ten GCMs has a bias towards models projecting high temperature increases, thus the likely range of future temperature in Burkina Faso might be slightly lower than the indicated values (compare Chapter 10).

Temperature extremes can limit crop growth or even lead to crop failure, depending on the crop type, cultivars and phenological development stage. Consistently with the recent temperature increases, the number of temperature extremes, such as very hot days and tropical nights, increased as well.

In the future, the number of very hot days and tropical nights is projected to increase in all parts of the country and under both emissions scenarios, reaching values of 270 tropical nights per year (Figure 12) and 308 very hot days (Figure 13) on average in Burkina Faso at the end of this century under the high emissions scenario.

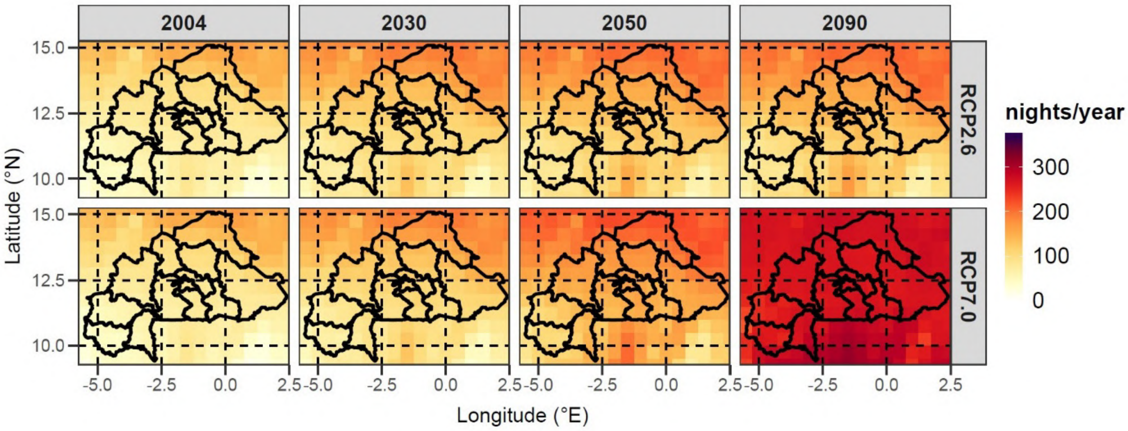


Figure 12: Simulated and projected number of tropical nights per year, for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

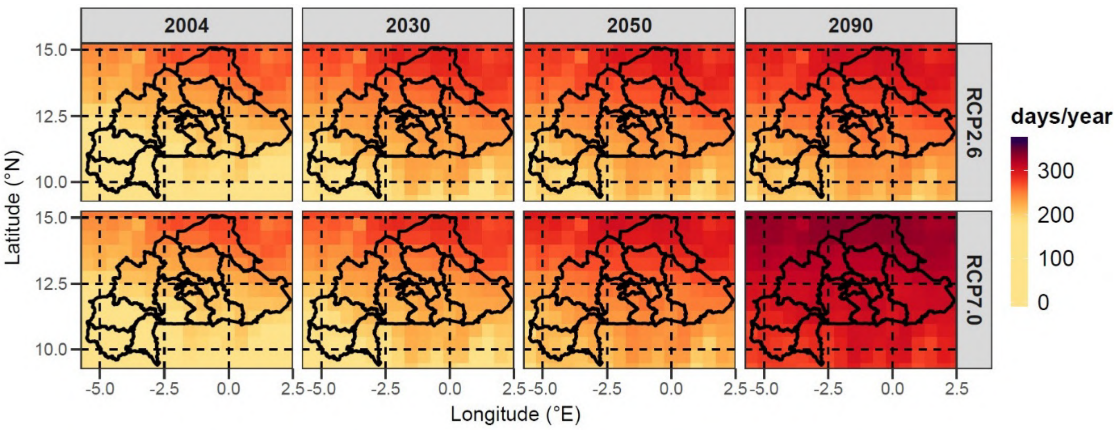


Figure 13: Simulated and projected number of very hot days per year, for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

Precipitation

Burkina Faso experienced decades of drought in the 1970s and 1980s. The mean annual precipitation sum has partially recovered since then but has not yet returned to its pre-1970s values. Annual precipitation values increased in the recent past in almost all parts of Burkina Faso (Figure 14). Additionally, the year-to-year variability of annual precipitation sums have increased in large parts of Burkina Faso.

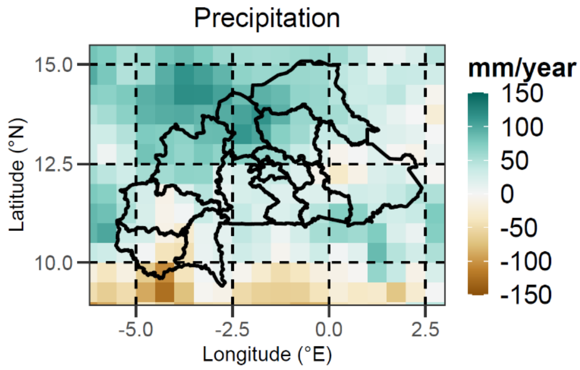


Figure 14: Difference mean annual precipitation in mm (right) over Burkina Faso from 1988 to 2006.

In continuation of this existing trend, the MMEM projects future increases of annual precipitation sums in the whole country under both emissions scenarios until 2050. Under the low emissions scenario, only slight increases are projected for the next decades and after 2050 the mean annual precipitation amount is projected to decrease slightly. Continuous increases of the precipitation amounts are projected under the high emissions scenario (Figure 15). The year-to-year variability of precipitation amounts is projected to remain high.

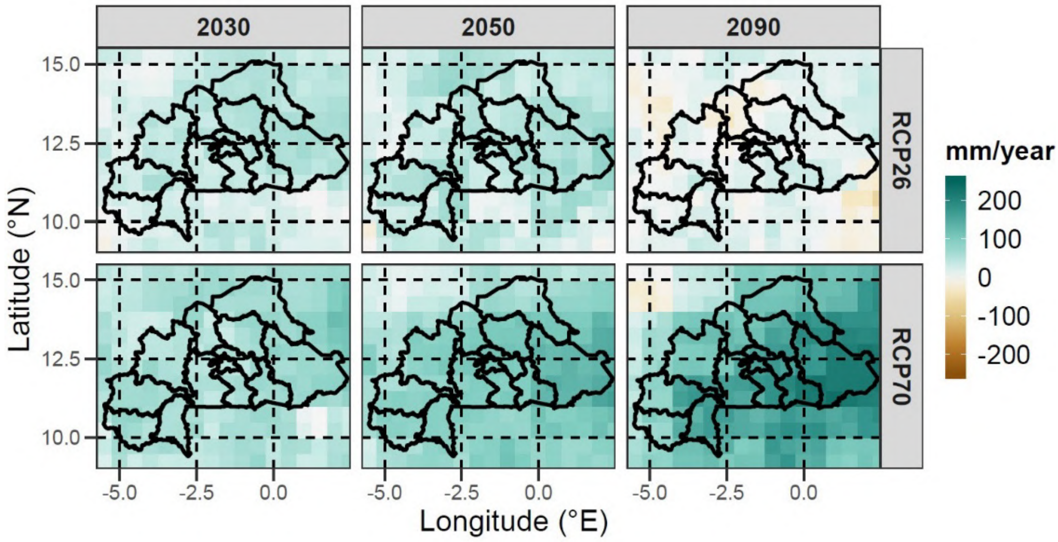


Figure 15: Projected change in mean annual precipitation sum in mm/year in 2030, 2050 and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 and SSP3-RCP7.0.

Generally, there is much less confidence in projected precipitation changes than in temperature changes, as not all models agree on the positive trend in precipitation (Figure 16).

Recent studies have indicated a future strengthening of the WAM and a westwards shift of current precipitation patterns under global warming[4] (Aschenbrenner, 2018; Roehrig et al., 2013; Schewe & Levermann, 2017). This corresponds with a wetter future climate in Burkina Faso that is projected under the high emissions scenario by most models shown here (see Figure 16). However, even though the majority of models and studies point to a wetter climate in Burkina Faso, it cannot be ruled out that the country could experience a drier future climate, for some decades or as a long-term trend, as some models under both scenarios suggest. Defrance et al. (2017) conclude that the continuation of the rapid melting of the Greenland ice sheet could lead to a sudden weakening of the WAM[5] and thus a decrease in annual precipitation amounts in Burkina Faso.

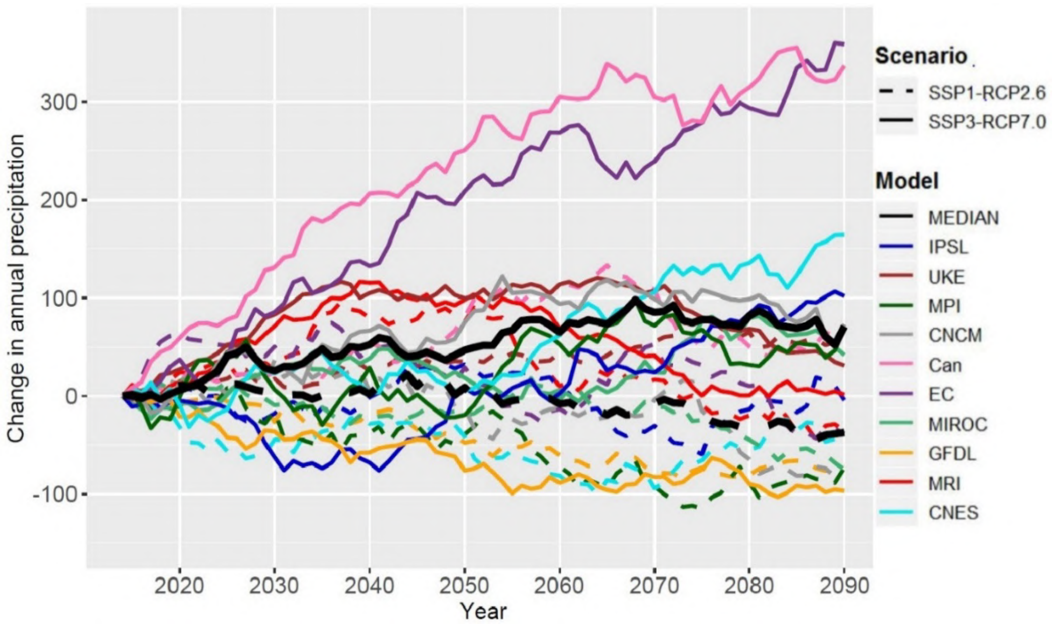


Figure 16: The 21-year moving average of projected change in annual precipitation sums in mm compared to 2014. Values are averages over Burkina Faso. Each variegated line indicates a projection of an individual model. The black line displays the MMEM.

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

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

Heavy precipitation events

Heavy precipitation intensity, as well as frequency, have augmented in the last decades in almost all parts of the country (Heavy precipitation intensity: Figure 17).

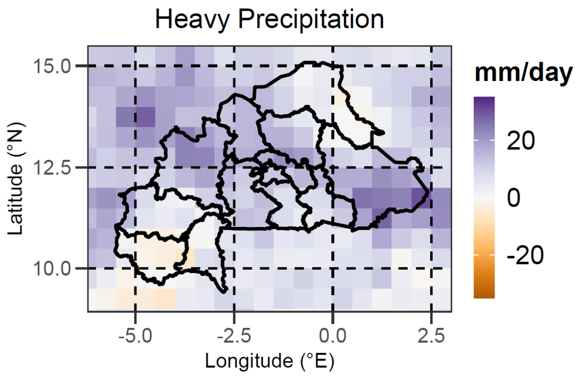


Figure 17: Change in annual maximum daily precipitation from 1988 to 2006

Heavy precipitation intensity, as well as frequency are projected to increase in all parts of the country with similar patterns to the projected increase of the mean annual precipitation amount (Figure 18). Under the high emissions scenario, all models agree on an increasing trend in heavy precipitation intensity until 2050. The models do not agree on an increase under the low emissions scenario.

This also holds for those models that show a decreasing trend in mean annual precipitation sums. Under the low emissions scenario, the models project no or small changes in heavy precipitation intensity until the end of his century.

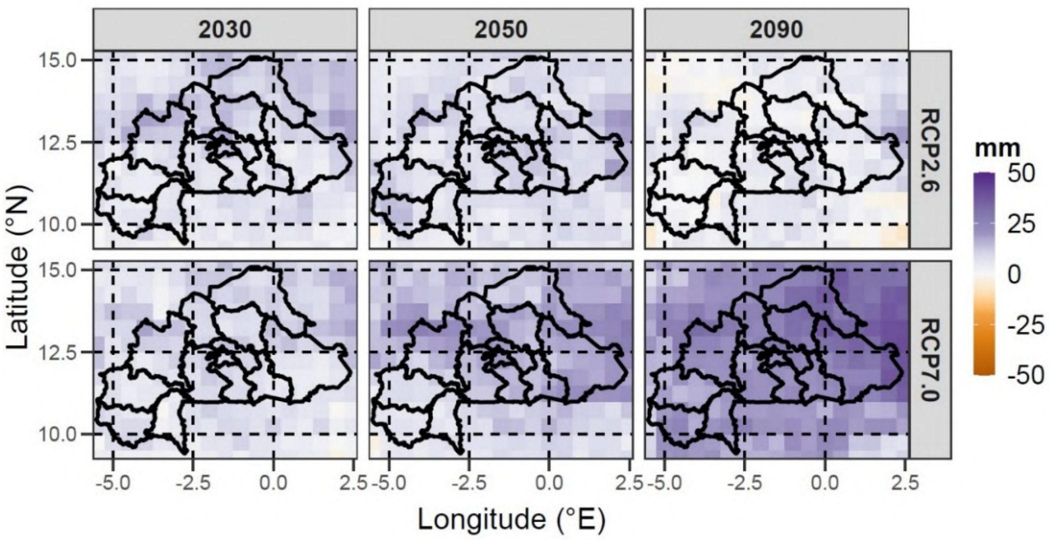


Figure 18: Projected change in annual maximum daily precipitation in 2030, 2050 and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row).

Rainy season onset

Rainy season onset and length showed high variability, but no clear trend in any direction in recent decades. For the future, the climate models tend to project a later start of the rainy season under SSP1-RCP2.6 and no clear trend under SSP3-RCP7.0 with regional differences and changes over time (Figure 19). Yet, the results are characterised by large uncertainties due to the differences between the individual model projections, especially under SSP3-RCP7.0 (Figure 20).

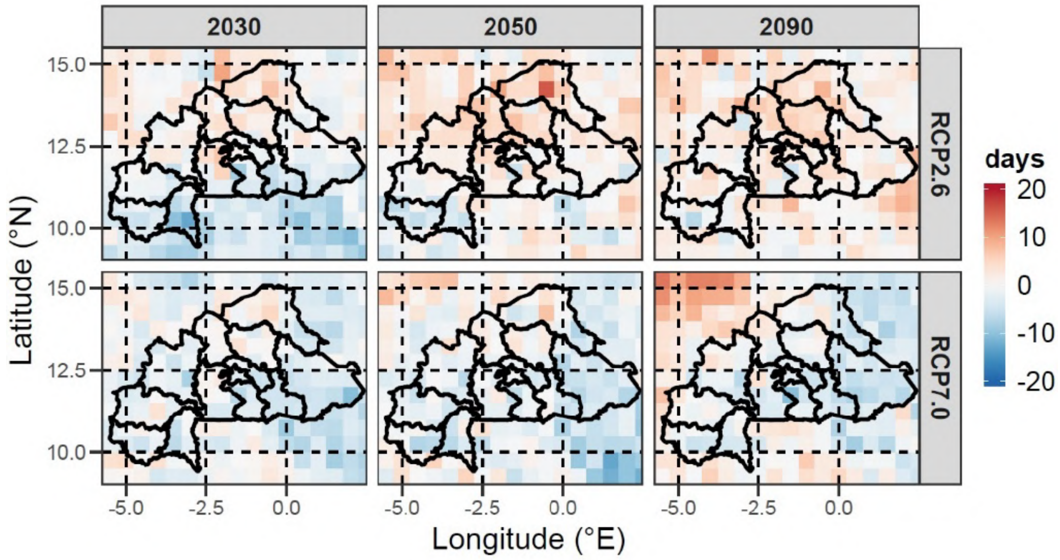


Figure 19: Projected change in rainy season onset in days in 2030, 2050 and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row). Red colour indicates later rain while blue colour indicates earlier rain.

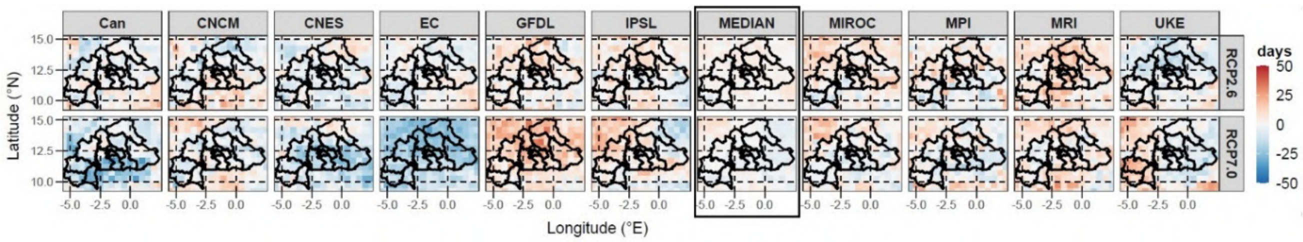


Figure 20: Projected change in rainy season onset in days in 2090 (2081-2100) compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row) for all ten individual models and the MMEM. Red colour indicates later rain while blue colour indicates earlier rain.

Chapter 1 Summary

In addition to natural variability, the climate in Burkina Faso showed a clear changing trend. Future projections mainly show a continuation of the existing trends. For higher future emissions, the projections show stronger climatic changes and higher ranges of possible future climate. Temperature and temperature extremes are clearly projected to rise continuously. Projections related to precipitation are subject to some uncertainties. Nevertheless, annual precipitation sums might increase, and precipitation extremes are likely to rise under the high emissions scenario. The summary table displays the observed past climate trends and projected future trends of different climate variables.

Table 1: Overview of changing climatic conditions for Burkina Faso.

Climate Impact	Trend past	Trend future	Confidence[6]
Mean annual Temperature	Warming ↗	Warming ↗	Very high
Very hot days & tropical nights	Increasing ↗	Increasing ↗	Very high
Heavy precipitation intensity & frequency	No trend	SSP3-RCP7.0: Increasing SSP1-RCP2.6: No trend	High High
Mean annual precipitation	Increasing since the 1980s ↗	Increasing ↗	Medium
Rainy season onset	No trend	SSP3-RCP7.0: No trend SSP1-RCP2.6: Later onset	Low Low
Year to year variability of annual precipitation sums	Increasing ↗	Slightly decreasing ↘	Low

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

Chapter 2 – Hydrological changes

The agricultural sector in Burkina Faso plays a vital role for the country's economy and peoples' livelihoods, yet with its semi-arid to arid climate, water resources are often scarce and present one of the biggest constraints to agricultural production. This chapter therefore evaluates past and future hydrological changes in Burkina Faso using a semi-distributed hydrological model that is driven by the GHG concentration pathway scenarios and GCM outputs presented in Chapter 1. Focusing on the Volta and Niger River basins, which together cover 94% of the country's area, three selected gauges will be assessed to represent and discuss expected changes in vital hydrological parameters relevant to agricultural and communal water supply in Burkina Faso.

2.1 Burkina Faso's hydrology in brief

The distribution of water resources in Burkina Faso follows the increasing north-south precipitation gradient, with an arid desert in the north and a tropical savannah in the south. The rainy season between June and October produces a highly seasonal, intermittent (i.e. drying during the dry season) runoff regime (Mahé, 2006). The main surface water arteries of the country are the rivers White Volta (Nakanbé), Red Volta and Black Volta (Mouhoun) draining south into the Lake Volta (their basins covering approx. 63% of Burkina Faso's territory) and the intermittent Sirba River draining east into the Niger River (its basin covering approx. 31% of Burkina Faso's territory) (Figure 21). Since precipitation typically occurs in the form of heavy and short events and evapotranspiration is equivalent to around 80-95% of annual precipitation, soil crusting is a frequent problem. The soil is sealed and compacted by salt deposits, promoting surface runoff and limiting rates of infiltration (Descroix et al., 2012).

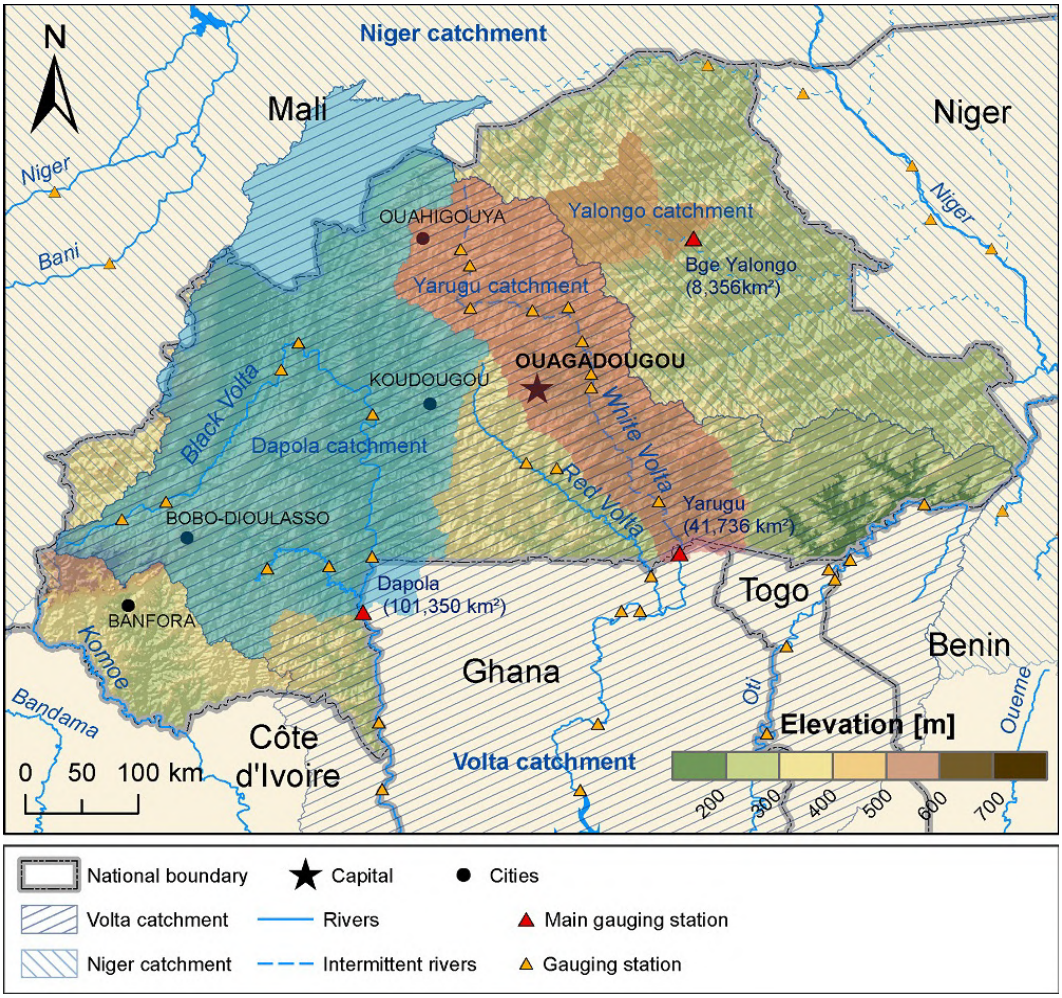


Figure 21: Map of Burkina Faso and the Volta and Niger catchment boundaries.

Due to its primarily rural and on mostly rainfed agriculture depending population and its arid to semi-arid climate, Burkina Faso is considered a water-stressed country. Irrigation potential is low and out of the land with irrigation potential (approx. 233,500 ha), only 27% is actually irrigated. This amounts to a mere 0.5% of the total agricultural area in the country (FAO, 2020). Nevertheless, irrigation accounts for about 64% of the water demand, followed by domestic water use with about 21% and livestock with about 14% (Petit & Baron, 2009).

Groundwater is an important source of drinking water, covering about 85% of the water demand, and is sourced through either hand-dug wells or mechanized boreholes at depths varying between 10m to more than 40m (Obuobie & Barry, 2012). Although the total nationally abstracted water volume only represents a small fraction of the estimated annual groundwater recharge (approx. 1.5%, (Martin & van de Giesen, 2005)), spatial distribution and depth of the water table vary widely and are influenced by both precipitation patterns and local abstractions.

The country's susceptibility to droughts gave rise to the construction of many small informal reservoirs (approximately 1700) to meet the water demand for irrigation during the dry season (de Fraiture et al., 2014; Fowe et al., 2015). As a consequence, surface runoff as well as groundwater recharge are vital indicators of Burkina Faso's water resources with future climatic changes potentially resulting in far-reaching consequences. Their changes in the past and future will be investigated in the following sections by employing a hydrological model.

2.2 Data and method

Within this study, the hydrological projections under climate change conditions are primarily based on results of the eco-hydrological Soil and Water Integrated Model (SWIM) (Krysanova et al., 2015) driven by the GHG concentration pathway scenarios and GCM results presented in Chapter 1, i.e. an ensemble of 10 GCMs from the ISIMIP3b project. SWIM is used to simulate the hydrological processes in both the Volta and Niger basin. Annual absolute and relative changes in river discharge at various locations are given as well as average monthly changes in the three future periods: 2021-2040 (2030), 2041-2060 (2050) and 2080-2099 (2090). Future changes are differences to the baseline 1995-2014. Different data inputs are used to setup and calibrate the model: The Shuttle Radar Topography Mission (SRTM) 90m digital elevation model is used to delineate sub-basins. Soil parameters are derived from the Harmonised World Soil Database (HWSD v1.0) and data on land use and land cover are derived from the Global Land Cover map (GLC2000). The hydrological model is calibrated and validated using daily discharge data at gauges throughout the basin in the period 1960–2010 depending on each station's data availability. Observations are provided by the Global Runoff Data Centre (GRDC) and a number of time series from hydrological yearbooks (Orstom, 1977; RHV, 1978). Major reservoirs as well as water withdrawals are considered in the simulations, the latter mainly relying on assumptions, as detailed data are unavailable. Land use and land cover are considered to be constant without change in the projected future periods to isolate the climate signal.

2.3 Past changes

Historical hydrological changes in Burkina Faso as well as Western Africa as a whole are dominated by inter-annual and decadal variability. It is generally agreed that the 1950s and 1960s were predominantly wet periods followed by a drying during the 1970s and a pronounced and devastating drought in the 1980s (Conway et al., 2009; Descroix et al., 2012; Mahe et al., 2013). Since then, precipitation amounts and river discharge are recovering with a recently increasing trend. For Burkina Faso, this development is reflected in discharge data and SWIM simulations driven by observation-based data in Figure 21. The arid to semi-arid conditions of the region cause the runoff to be highly sensitive to changes in precipitation. For example, Mahé and Olivry (Mahé & Olivry, 1999) found that a decrease of 15-20% in precipitation values results in disproportionate decreases in discharge of up to 60%.

Apart from the climatic changes that have already been discussed in Chapter 1, changes in surface and groundwater resources are also strongly determined by changes in land use and water management. Both factors have changed drastically in Burkina Faso since the latter half of the 20th century (Mahé et al., 2005). Continuous population growth of over 3% annually has led to extensive conversion of natural vegetation (bush and shrubland) to cultivated land that favour higher rates of overland runoff and lower rates of infiltration to recharge groundwater resources (UN DESA, 2019). Less permanent vegetation and soil compacting lead to a lower infiltration capacity. This has meant that despite the drought conditions of the region, the river discharge has increased nevertheless, a phenomenon termed the 'Sahel paradox' (Mahé et al., 2005). At the same time, water management has increased, seeing the construction of numerous small reservoirs and the construction of an abundance of deep wells (Pavelic et al., 2012). Reservoirs help to store the temporally unequally distributed runoff over the year and are thus important water management infrastructure in the highly seasonal climate.

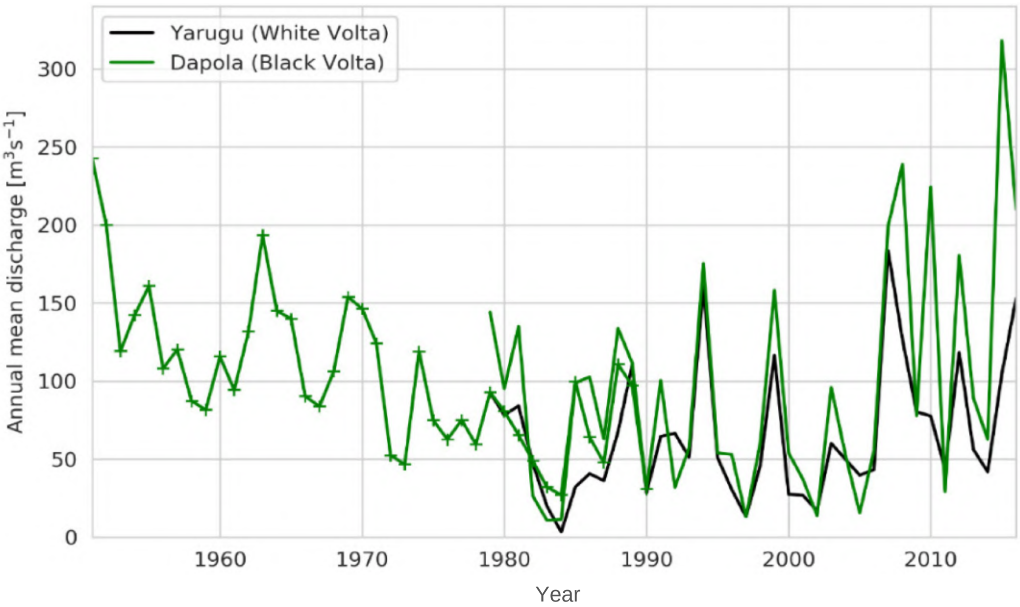


Figure 22: Observed and simulated discharge of Burkina Faso's major rivers. Observations (1951-1990) at Dapola with available long-term records are marked with +. Simulations are driven by the observation-based reanalysis dataset EWEMBI.

2.4 Hydrological changes under 21st century climate change

2.4.1 River discharge

In line with increasing precipitation (Chapter 1, Section 1.4), the annual average of river discharge is also projected to increase generally, although not under all climate scenarios and GCMs (Figure 23). The largest rivers of Burkina Faso, the Black and the White Volta, are projected to carry 18-30% more annual discharge in the near future (2021-2040) in the ensemble median under both emissions scenarios compared to the reference period (1995-2014). Towards the middle of the century (2041-2060), the scenarios diverge.

The discharge is projected to increase by 20-34% under the low GHG concentration pathway and eventually decline to about -10 to -20% in 2080-2099, while under the high- GHG concentration pathway, it is projected to remain 50-60% higher compared to the reference period until the end of the century. This development is also expected for the much smaller and drier catchment of the Sirba River, but with larger increases of up to 80% under the SSP3-RCP7.0 scenario and a decrease of 10% under the SSP1-RCP2.6 scenario towards the end of the century. Ensemble ranges are large, however, hinting at the great variability between the GCMs. Especially under the low GHG concentration path-way, interquartile ranges cover opposite directions of change in the middle and at the end of the century.

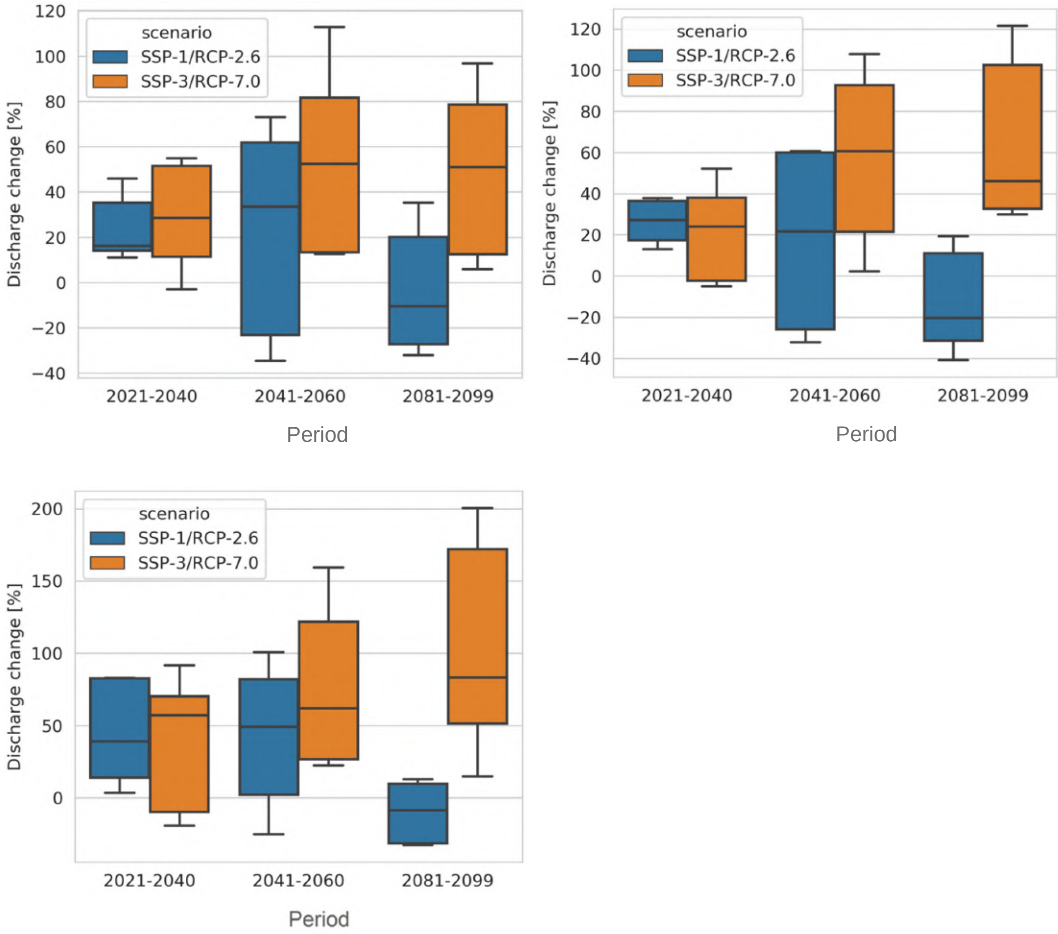


Figure 23: Projected change in annual mean discharge at Dapola, the last gauge in Burkina Faso on the Black Volta (top left), at Yarugu, the first gauge in Ghana on the White Volta (top right) and at Bge Yalogo, the last gauge in Bukina Faso in the headwaters of the ephemeral Sirba River, in the arid northeast (lower left).

In the monthly discharge regime, these annual changes are reflected mainly in the months from August to October during the rainy season for the three rivers (Figure 24). A successive increase in the months of August and September is evident for the 2021-2040 and 2041-2060 periods for nearly all scenarios and stations (except at Bge Yalogo in 2041-2060 under the SSP1-RCP2.6 scenario). At the end of the century (2080-2099), discharge at the three selected stations is projected to decline again under the SSP1-RCP2.6 scenario during the entire rainy season. Under the SSP3-RCP7.0 scenario, a regime shift is projected with a lower median discharge in August, but with higher values from September to December. Where river flows are sustained throughout the year (e.g. the Black Volta), minor changes are projected largely following the annual trend. Ensemble uncertainties (indicated by the interquartile and min.-max. ranges in Figure 23) are particularly large under the high emissions scenario and in the 2080-2099 period. The temporal changes are driven by the strengthening of the West African Monsoon (WAM, cf. Section 1.4) and may well spell more available surface water during the raining season, leading to larger seasonal floods and increased rates of groundwater discharge.

Figure 24: Mean monthly discharge in the reference period (blue) and the three future periods for SSP1-RCP2.6 (left) and SSP3-RCP7.0 (right) at Dapola (Black Volta, top), Yarugu (White Volta, middle) and Bge Yalogo (upper Sirba River, bottom). Error bars refer to the interquartile range (coloured) and the full ensemble range (whiskers).

2.4.2 Groundwater recharge

Apart from the river discharge, changes in groundwater recharge are an important hydrological flow which determines future groundwater resources available for groundwater dependent communities. Groundwater has become an increasingly important source for urban and rural water supply in Burkina Faso. Estimates suggest that over 44% of the population in the Volta River Basin depend on groundwater as their primary source of drinking water (Martin & van de Giesen, 2005). Changing precipitation regimes and the continuous development of boreholes across the country are likely going to increase the groundwater dependency in the future.

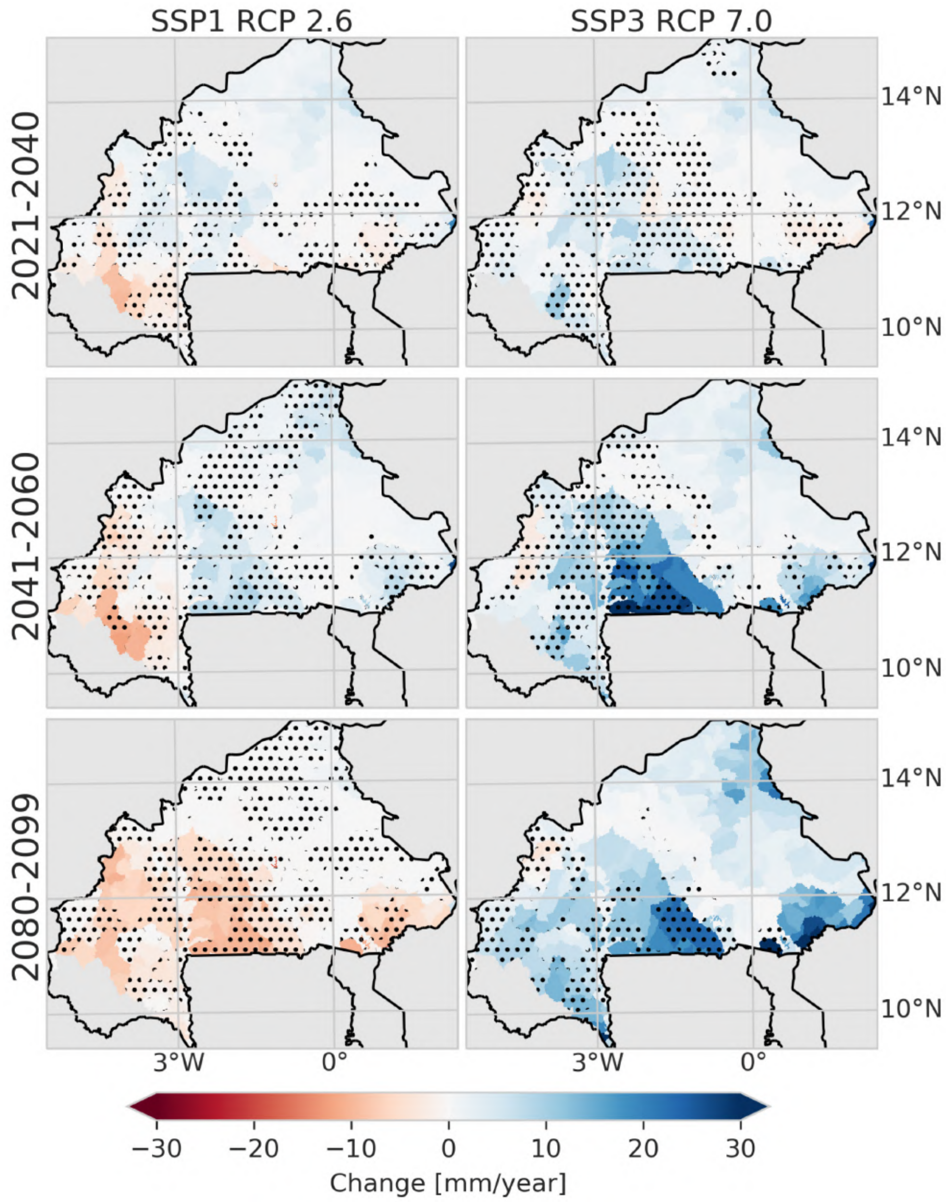


Figure 25: Median change in groundwater recharge (at sub-basin level) compared to the reference period (1995-2014) for both scenarios (left/right) and the three future periods (top to bottom rows). Dotted areas indicate statistically insignificant changes (5% significance level) considering the period means of the ensemble. Areas in grey are either outside of Burkina Faso or outside of the model domain.

The increases in precipitation amounts partially also translate to greater annual rates of groundwater recharge mainly under the SSP3-RCP7.0 scenario in large parts of the country, especially in the agriculturally important south (Figure 25). Under the low GHG concentration pathway, decreases are more likely towards the end of the century, especially in the south-west of the country.

Given the large ensemble range, much of the change is statistically not significant (comparing the period means of the baseline and the future periods). Especially the decrease in the ensemble median under the low GHG concentration pathway as well as the south-west of the country show no significant changes as a result. This is largely in line with the climatic variability of the region that is reflected in the disagreement of the climate models. However, the results still give important indications of general trends and clearly show the differences between the GHG concentration pathways.

With the projected rise in temperature (Chapter 1) and the associated intensification of the hydrological cycle, other hydrological indicators are also projected to increase in Burkina Faso. Actual evapotranspiration is projected to increase moderately by 2-6% assuming equal vegetation cover than in the reference period, i.e. lower than runoff. Annual peak discharge, an indicator for the seasonal flood, is projected to increase in line with seasonal increases in discharge (Figure 24), making dangerous flooding more likely.

It is important to note that the climate of Burkina Faso is dominated by strong inter-annual and multi-year fluctuations, exemplified by the historical observations of the very wet 1960s and the very dry 1970s and particularly the 1980s. This quasi-oscillation pattern is also reflected in the hydrological indicators and in many cases the amplitude is larger than the projected changes presented here. The choice of the baseline and future periods can thus have a significant influence on the projected changes, as discussed by (Liersch et al., 2020) with an example of the Volta River. GCM results are a synthetic realisation of the weather in the baseline and future periods. Although these quasi-oscillation patterns are reflected in the models, they are not synchronised between them (Figure 26). That is, one model might project a wet period for the 2050s and several others very dry ones. This partly explains the large range of uncertainties and opposing signals of change.

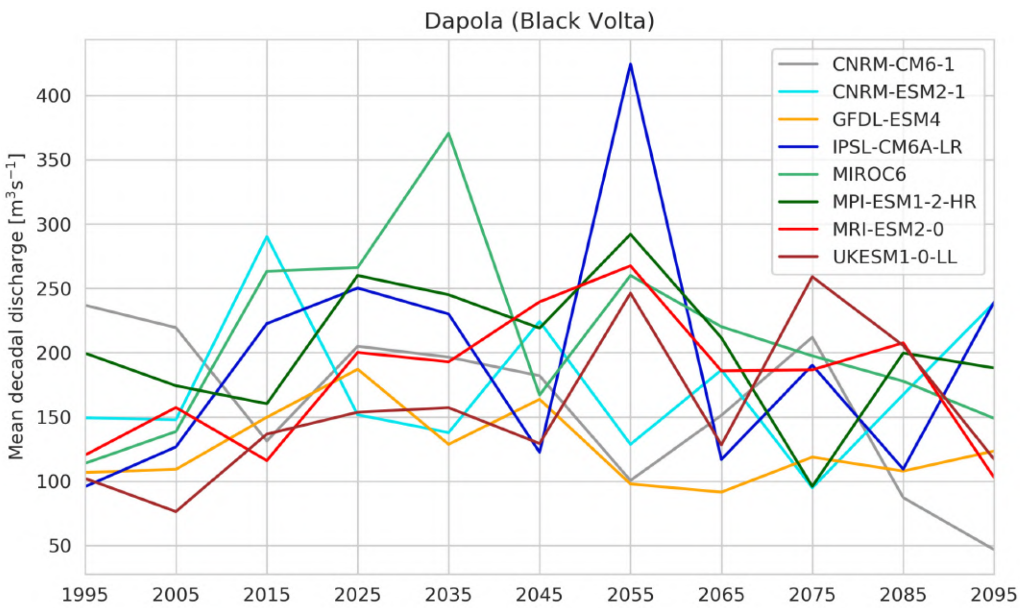
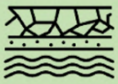
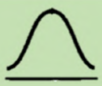


Figure 26: Decadal mean discharge at Dapola station (Black Volta) simulated by SWIM under SSP1-RCP2.6 scenario driven by the GCM ensemble given in the legend.

Chapter 2 Summary

Future projections mainly show a continuation of the past trends but slight variations, e.g. shifts in regime of flood peak discharge, are possible. For higher future GHG concentrations, the projections show an increase of river discharge whereas under the SSP1-RCP2.6 scenario river discharges tend to decrease. Groundwater recharge is projected to rise, but stronger under higher future emissions. Evapotranspiration is clearly projected to increase moderately. Key impacts and trends are summarized again in the table below. Trends refer to long-term annual averages and ensemble medians.

Table 2: Summary hydrological changes.

Impact		Trend past	Trend future	Confidence[7]
	**River discharge**	Increasing ↗	Increasing, decreases possible under SSP1-RCP2.6 ↗	Medium
	**Groundwater recharge**	Increasing ↗	Increasing ↗	Medium
	**Evapotranspiration**	No major change	Increasing ↗	High
	**Flood peak discharge**	Increasing since the 1990s ↗	Increasing, but shifts in regime possible ↗	Medium

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

Chapter 3 – Climate impacts on agricultural production

Sorghum, millet[8], maize, cowpeas, cotton and groundnuts are the most important crops in Burkina Faso by planted area, volume of production and demand. The ability to produce these crops is largely dependent on the ability of the weather variables to sustain the crop cycle as the majority of the crops are produced on rain-fed land. Weather, soil fertility and agricultural management are the main drivers of agricultural crop yield variations. Climate change therefore threatens both livelihoods and the economy of Burkina Faso as it is dependent on agriculture and agricultural value chains. The extent to which these factors determine crop yield levels varies over time and space. In this chapter, we therefore take a closer look at climate impacts on crop production, drawing on the insights we gained from the previous chapters in terms of climatic changes and water availability under the two future emissions scenarios of SSP1-RCP2.6 and SSP3-RCP7.0.

We provide the crop model assessment from three perspectives. In the first part, we use the semi-statistical crop model AMPLIFY (Agricultural Model for Production Loss Identification to Insure Failures of Yields) to assess the role that current day-to-day weather variability plays in determining crop yields for sorghum, millet and maize in Burkina Faso, at both national and sub-national level. We focus on cereals as main staple crops in the statistical analysis for which AMPLIFY has also been sufficiently scientifically validated. AMPLIFY indicates the share of historical yield variability explainable by weather and therefore show the importance of weather in agricultural production in the country.

In the second part, we assess the biophysical suitability for selected crops to be grown in specific areas of Burkina Faso and how that suitability might change under changing climatic conditions towards the end of the century. Crop suitability determines if an area has the season-long climatic conditions able to sustain a crop production cycle under current and future climatic conditions. We focus again on the main cereals sorghum, millet and maize, further adding cowpeas for a broader picture of the analysis. Finally, in the third part we use the process-based crop model DSSAT for a deep-dive analysis of the medium and long-term projected impacts of climate change on agricultural yields by 2030, 2050 and 2090, using a case study of sorghum. DSSAT is a process-based model that simulates the day-to-day physiological response of a crop to weather variables and is able simulate the current and projected crop yields.

3.1 Historical weather influence on crop production

3.1.1 Data and method

In order to elicit the share of weather in crop yield variation in Burkina Faso, we use the semi-statistical crop modelling approach of the AMPLIFY model (Gornott & Wechsung, 2016). For each of the 45 provinces in Burkina Faso, we set up a separate multiple linear regression model comprising of province-specific variables and parameters to account for the diverse climatic conditions within the country. As weather input data, we used CHIRPS (Funk et al., 2015) (resolution 0.25°, or approx. 27 km in Burkina Faso) for precipitation and ERA5 (Copernicus Climate Change Service (C3S), 2017) (also at a resolution of 0.25°) for temperature. Vapour pressure deficit was calculated based on temperature data. To represent the weather conditions that influence crop development, we only considered weather data of the growing season using the FAO crop calendar (FAO, 2010). All input variables were standardised to allow for a better comparability of

[8] There are 9 different types of crop millets. In Burkina Faso two of them are mainly produced: pearl and finger millet. The analysis focuses on pearl millet.

the beta coefficients. For crop yields, we used reported yields for all three crops on province level between 1984 and 2018, provided by WASCAL. Yields (kg/ha) were calculated as total production over total area per province.

We removed the trend in yield observations – stemming from e.g. technological progress in crop management, by first testing different de-trending methods (mean, linear, quadratic) and then applying the one that resulted in the highest fit, measured by the Akaike Information Criterion (AIC) (Bozdogan, 1987). The variables were selected based on the LASSO algorithm, which performs a co-variate selection through regularize-tion (Tibshirani, 1996). The "full model" results show the explained yield variability when all available yield observations are used to train the model. The more robust out-of-sample validation (coined OOS) results show the performance of the model for independent yield observations that have not been used to train the model, achieved by omitting each year in turn from model training and then predicting yield variation for this 'new' year which was unknown to the model. This limits overfitting, which is otherwise common for statistical models, and thus provides more conclusive evidence for the influence of weather on yields. The goodness of fit between the observed data and the modelled data is evaluated based on R^2, which represents the share of the yield variability that can be explained by the model. If forecast weather data is available, this tool can be used to make crop yield forecasts, which can provide information on yields and food availability before the harvest.

3.1.2 Results

Figure 27 shows the weather-related influences on crop yields in Burkina Faso for maize, sorghum and millet. The results show that on national average, about 70% of maize and millet yield variability can be explained by weather influences; for sorghum this share is about 50%. These high percentages indicate that a majority of the observed variation in crop yields is owed to variation in climate, and thus will change with climate change. The weather-attributable influence is comparable with the results found in (Belesova et al., 2019) for the Kossi province in Burkina Faso. As shown by Belesova et al. (2019), negative yield anomalies can have a strong influence on food availability and cascading effects on the health situation in rural areas. Thus the large share of weather-related yield variation indicates that climate vagaries may have a direct effect on human nutrition and health.

By breaking model results down to individual assessments at province level, a more nuanced picture can be given (Figure 28). The share of weather-related yield losses for maize is highest in northern Burkina Faso, evidenced by the higher R^2 values there (dark blue shades), although maize yields show substantial dependence on weather in almost all provinces. For sorghum and millet, a clear spatial pattern does not emerge – the influence of weather is evident in most provinces, but slightly lower than for maize.

Model results on province level are usually lower compared to the national level, but still show a robust influence of weather variation on crop yield variation (Figure 27: full $R^2 > 0.5$ [left column] and out-of-sample $R^2 > 0.3$ [right column]). Weather influences on national level are higher since province-specific uncertainties or data inaccuracies usually balance out.

These estimated shares of weather-related yield variation relate to the past (1984-2018), under-lining the critical importance of climatic factors for growing cereals. This allows to base future projections of crop yields based on weather factors, which will be performed in the next sections.

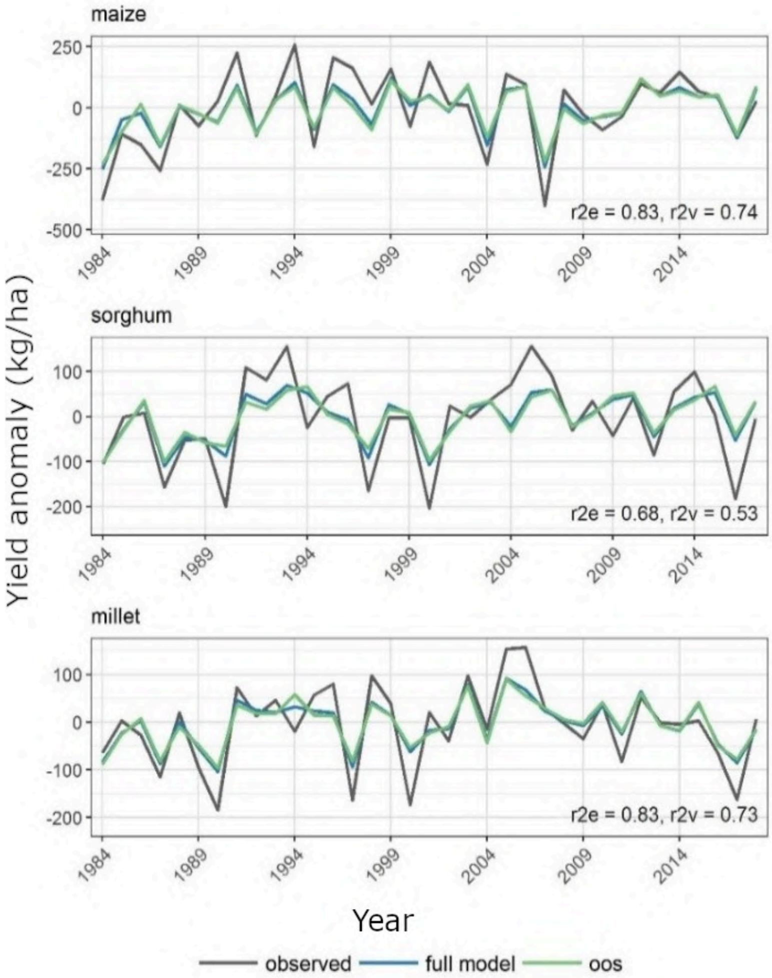


Figure 27: Explained yield variability by weather influences for maize, sorghum and millet on national level; on the y-axis, yield is shown as de-trended yield anomalies in kg/ha, whereas the "full model"-results are prone to overfitting, the out-of-sample validation results represent a more realistic result of the weather-related influences on yields. The r2 values in the lower right corner show the explained yield variability for the full model (r2e) and the out-of-sample validation (r2v).

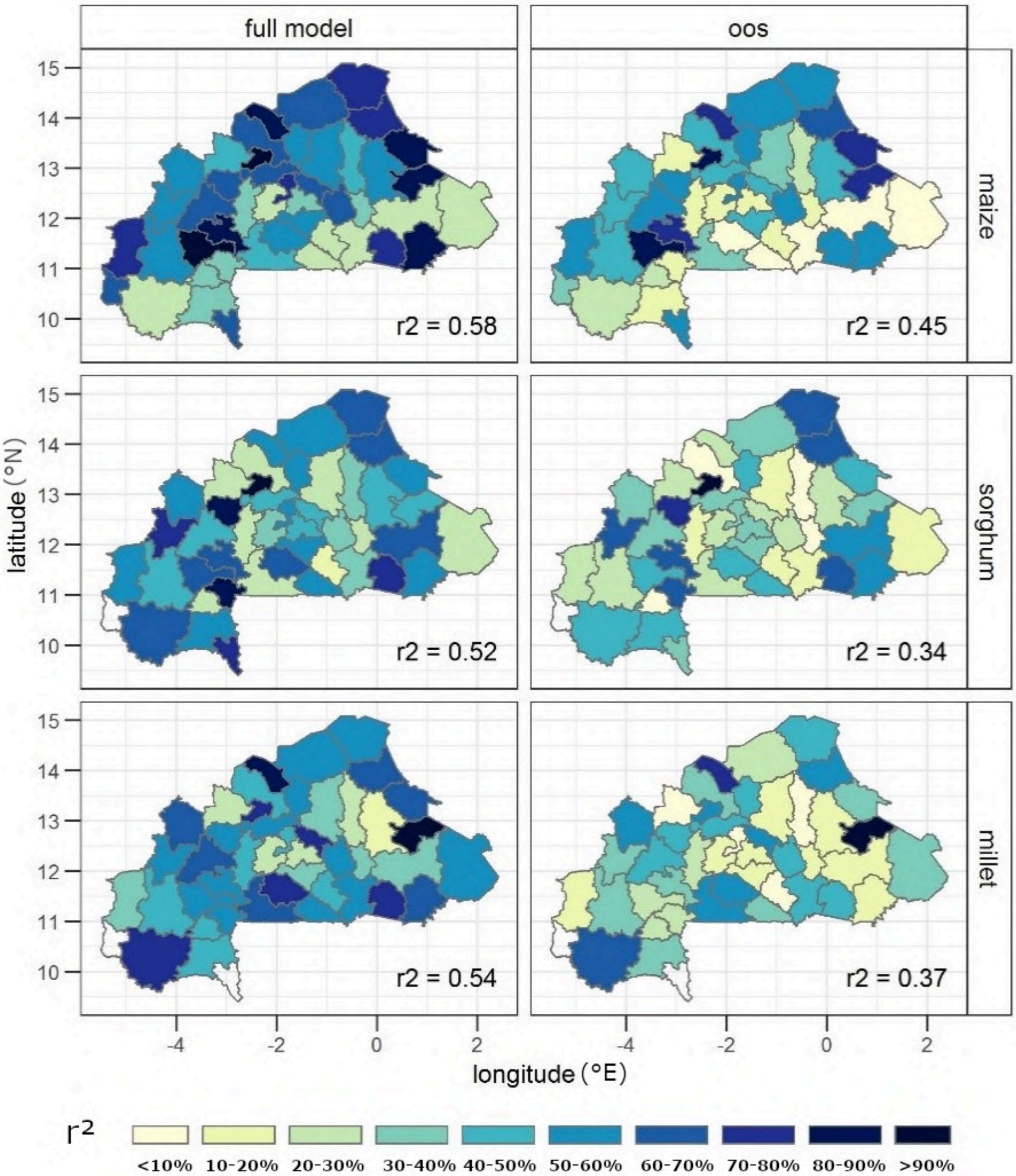


Figure 28: The share of yield variability owed to weather influences for maize, sorghum and millet on province level. Full model results are shown on the left and out-of-sample (OOS) results on the right. The r2 values represent the share of weather in crop yield variation, i.e. the higher, the more yield formation depends on weather. Provinces shown in white (for sorghum and millet) have not provided crop data.

3.2 Crop suitability assessment and changing climatic conditions

3.2.1 Data and method

Climatic crop suitability models have been applied to assess the impact of climate change on the potential for sorghum, millet, maize and cowpeas as individual crops in Burkina Faso. Crop suitability models are a class of crop models that are used in climate change risk assessments. Crop suitability assessments are based on the understanding that the biophysical parameters (e.g. soil organic carbon) and climatic variables (e.g. total amount of precipitation received in the growing season) play an important role in determining crop production rates, which is true in many tropical areas where agriculture is influenced by weather. A suitability model therefore uses these variables to create a score for each crop, each period and each location depending on how the variables meet the crop requirements or conditions in known current production areas (Evangelista et al., 2013). Replacing the climatic variables with those projected under climate change shows the change in the potentially cultivatable arable land of an area for a specific crop. Thus, crop suitability models are used in assessing the impact of climate change on season-long crop production potential for national and local level adaptation planning.

Nine agronomically important biophysical parameters (such as temperature or precipitation amount during different plant production stages) are used in modelling the climatic suitability of the four crops under current and future climatic conditions. The eXtreme Gradient Boosting (XGBoost) machine learning approach (Chen & Guestrin, 2016) is used to model suitability. The crop production data for each of the four crops is split into four groups (optimal, moderate, marginal and limited) using percentiles of the average yield. For example, areas with optimal suitability are defined as areas that are above the 75th percentile of the long-term average crop yield, representing areas with no significant limitations to sustained production and stability over time. Moderate suitability corresponds to areas allowing for crop production within the 50th to 75th yield percentile, marginal suitability to the 25th to 50th yield percentile, and limited suitability to areas with less than the 25th percentile of long-term average yield, thus indicating that the biophysical conditions in these areas are not apt for the crop under analysis.

The models were evaluated before application using leave-one-out cross validation. In addition to the class based performance indicators for each crop such as specificity, sensitivity and balanced accuracy, we calculated the multi-class area under the receiver operating curve (AUC) for assessing the overall model performance as defined by (Hand & Till, 2001). We also combined the results of the four crops to identify how the potential for multiple cropping will change under climate change, as an indicator of diversification or crop switching potential.

After assessing the individual crop suitability for the four crops in Burkina Faso, we combined the suitability of the crops to understand which areas are suitable for which multiple crops using the method by Chemura et al. (2020). In this approach, the individual suitability maps are stacked to determine the number of crops that were suitable for each cell and then the cells with the levels of suitability for each crop are counted. Changes in suitability proportion and distribution between the current and the projected climatic conditions were assessed by comparing areas between time periods and climatic scenarios.

3.2.2 Determinants of crop suitability in Burkina Faso

The factors that determine the suitability of crops in Burkina Faso are different depending on the type of crop. The temperature influence on crop suitability is most important for all crops in the country with temperature-based factors explaining 43% for sorghum, 38% for millet, 44% for maize and 45% of the suitability for cowpeas. Precipitation based factors are also important explaining 34% of sorghum, 33% of millet, 20% of maize and 27% of cowpea suitability (Figure 29). However, when individual factors are considered, the amount of rainfall in the growing season is the most significant determinant of crop suitability for sorghum and cowpea while the annual range is important for millet and growing season temperature is the most important for maize suitability. Soils, particularly soil organic carbon, are also important for maize suitability (37%), indicating that this crop requires areas with good soils, compared to the other crops. For sorghum (2%), millet (1%) and maize (6%), the least important are temperatures in the sowing months while for cowpeas, the most limiting factors include the growing season, temperature (8%) and annual temperature range (9%).

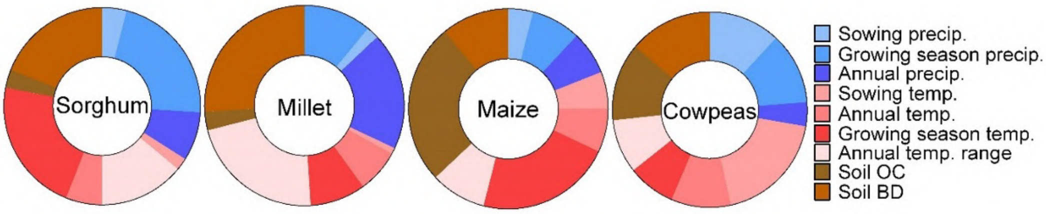


Figure 29: Importance of variables in modelling the suitability of sorghum, millet, maize and cowpeas in Burkina Faso. Soil OC stands for soil organic carbon, and Soil BD for soil biodiversity.

3.2.3 Results

A good model fit for sorghum, millet, maize and cowpeas (AUC>0.82) was achieved compared to reported crop yields, giving confidence in the application of the models in the climate change impact assessments in Burkina Faso.

Suitability for sorghum, millet, maize and cowpea are shown in Figure 30. More than half of the country's territory is considered either optimally or moderately suitable for sorghum production under current climatic conditions. These areas are located in the Sudanian and Sudano-Sahelian regions in the south-west and stretching around 13°N latitude to the east (Figure 31). A third of Burkina Faso (33.3%) is optimally suitable for millet production with current climatic conditions mainly in the south of the country. The optimal and moderately suitable areas are 60.9% of the country, which are all agricultural areas that can successfully produce millet (Figure 32). Only a fifth of Burkina Faso is optimally suitable for maize production under current climatic conditions, and these areas are mainly located in the south-western and the central-southern parts of the country (Figure 33). The distribution for suitability for cowpea under current climatic conditions are shown in Figure 34. Current suitable areas for cowpeas are in the southern parts of the country extending to the western areas.

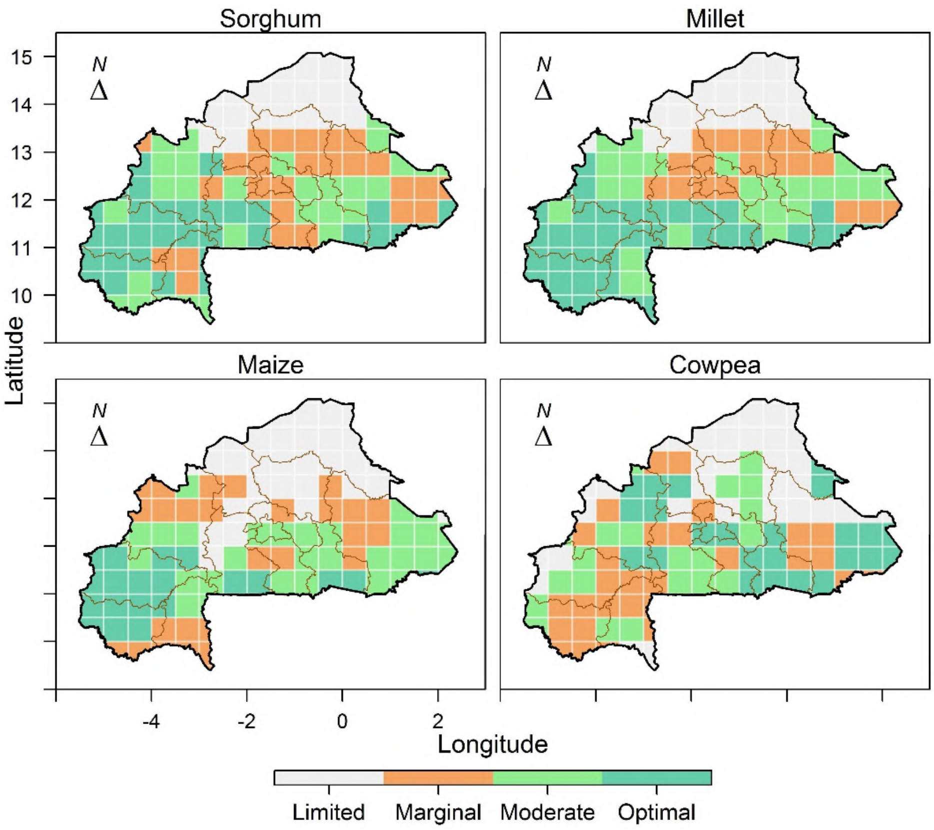


Figure 30: Maps showing the current climatic suitability for sorghum, millet, maize and cowpea in Burkina Faso as modelled from observed yields.

a) Sorghum

Climate change will result in some areas having increases in suitability of sorghum while some will have decreases in 2030, 2050 and 2090 (Figure 31). The areas that will have decreased suitability will be more than those that will have increased suitability for sorghum except for decreased suitability for SSP3-RCP7.0 in 2090 where a slight net increase is projected. At worst, 10.3% of the areas that are currently suitable for sorghum will lose their suitability under SSP1-RCP2.6 by 2090 (Table 3). The results that sorghum suitability will remain stable in Burkina Faso under climate change correspond to projections that show no change and increases in precipitation in most parts of the country (See Chapter 1, Figure 15). Therefore, with precipitation-based factors driving over a third of the suitability for sorghum and specifically precipitation in the growing season being the most important variable for the model, the results are not unexpected. These results also concur with findings by Ramirez (2013) that sorghum suitability in the semi-arid regions of southern Burkina Faso, Mali and Niger will increase under climate change. These results underscore the fact that the effects of climate change on sorghum suitability are spatially variable and adaptation planning should be targeted to the loss areas while intensification can be targeted for the areas where suitability will remain stable or increase. While we project stability or increases in areas whose climatic conditions meet the requirements of sorghum in Burkina Faso, these do not directly translate to yield gains. Expanding production areas as more areas become suitable can compensate for projected yield losses (Adam et al., 2020; Sultan et al., 2013) to meet production and demand requirements for sorghum.

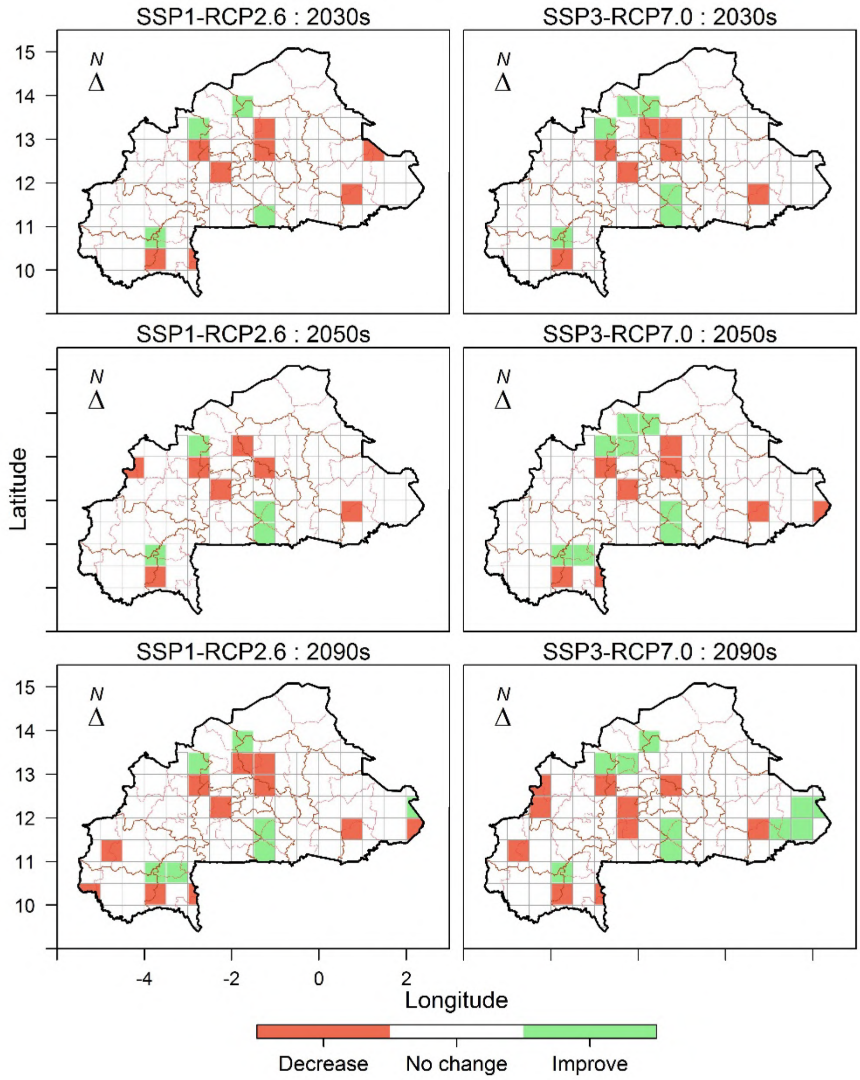


Figure 31: Maps showing the modelled changes in climatic suitability for sorghum in Burkina Faso for the 2030s (upper), 2050s (middle) and 2090s (lower) under the SSP1-RCP2.6 (left column) and SSP3-RCP7.0 scenarios.

b) Millet

We project marginal decreases in suitability of millet under climate change in Burkina Faso, as areas remain largely suitable for the crop (Table 3). In all years and scenarios, net changes in suitability remain positive especially for 2090 where a net gain in suitable areas for millet will be 6.9% (SSP1-RCP2.6) and 3.5% (SSP3-RCP7.0) (Figure 32). This means that the general climatic conditions will meet the production requirements for millet under climate change except for a few areas where loss in suitability is projected. As a warm season crop, millet is resilient as it has originated and adapted to the drylands of Africa where soil quality is poor, rainfall is limited, air temperatures are high and the growing season lengths are short and variable (Mason et al., 2015). With projected changes in climatic conditions, particularly in rainfall over Burkina Faso, the conditions for millet production may improve, as modelled. Similar positive climate change impacts on millet suitability have been reported (Egbebiyi et al., 2020) and explained by the physiological resilience of the crop. Given that about 19.5% of the food consumed and 17.5% of the area planted in Burkina Faso is of millet (Jalloh et al., 2013), these results indicate low to marginal risk of the crop's suitability to climate change. As such, it can be intensified and expanded, even to areas where other crops are projected to have reduced suitability under climate change.

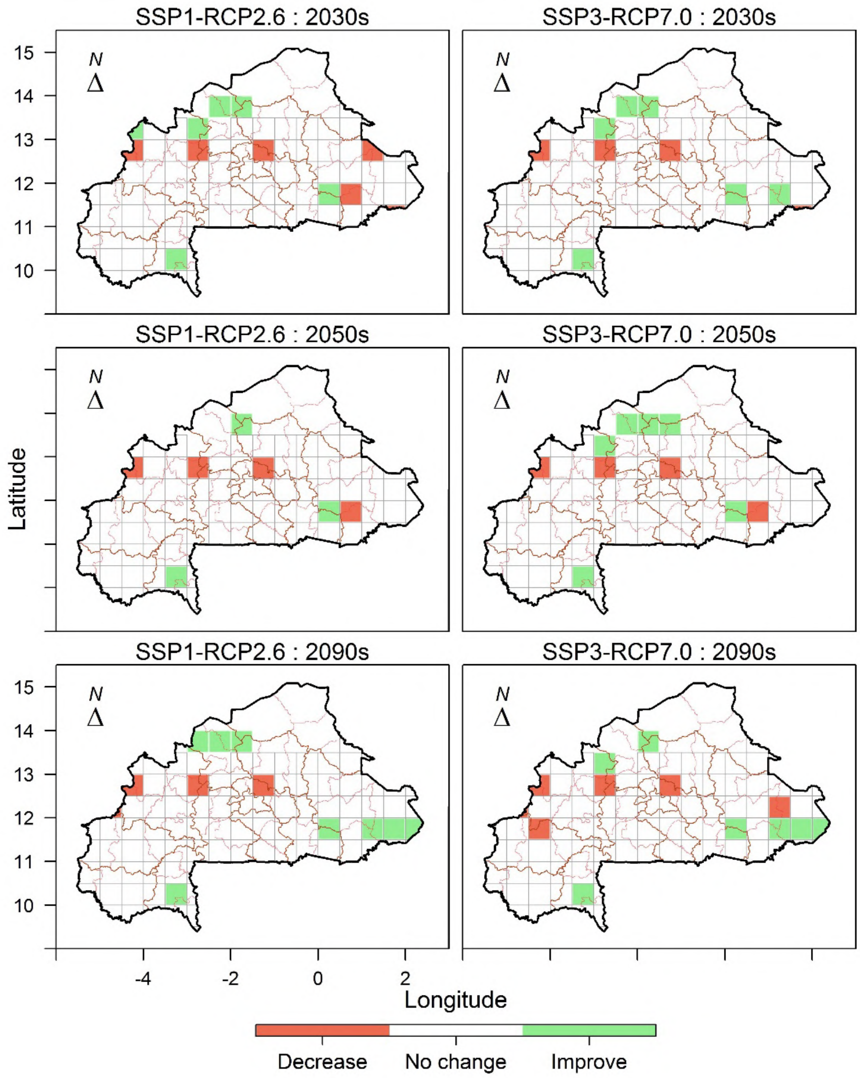


Figure 32: Maps showing the modelled changes in climatic suitability for pearl millet in Burkina Faso for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios.

c) Maize

The impacts of climate change on suitability of maize are shown in Figure 33. The majority of the country is projected to maintain their suitability levels for maize production, with even slightly more areas that will become more suitable for maize production than those that will become less suitable. Net changes in maize suitability at national level are always less than 4% indicating that the suitability of maize will largely remain unchanged in Burkina Faso with no changes in overall area suitable projected for 2090 under both scenarios (Table 3). Maize is a weather-sensitive crop as shown by the large significance of growing season temperature in modelling its suitability and as such it was expected to respond more to climate change than other crops. However, the projections (See Chapter 1) indicate increases in temperature and also increases in precipitation in Burkina Faso and the interaction of the two determine the modelled climate change impacts. It is interesting that positive suitability changes are projected in the Boucle du Mouhoun in the near and mid future with less change in the far future (Figure 33). These findings concur with projections by Jalloh et al. (2013) that maize will be positively influenced by climate change in this region and as such there could be potential to increase the area density of the crop outside the traditional maize producing regions. With no change in the majority of the areas, crop intensification measures to close the yield gap are suggested to increase national maize production.

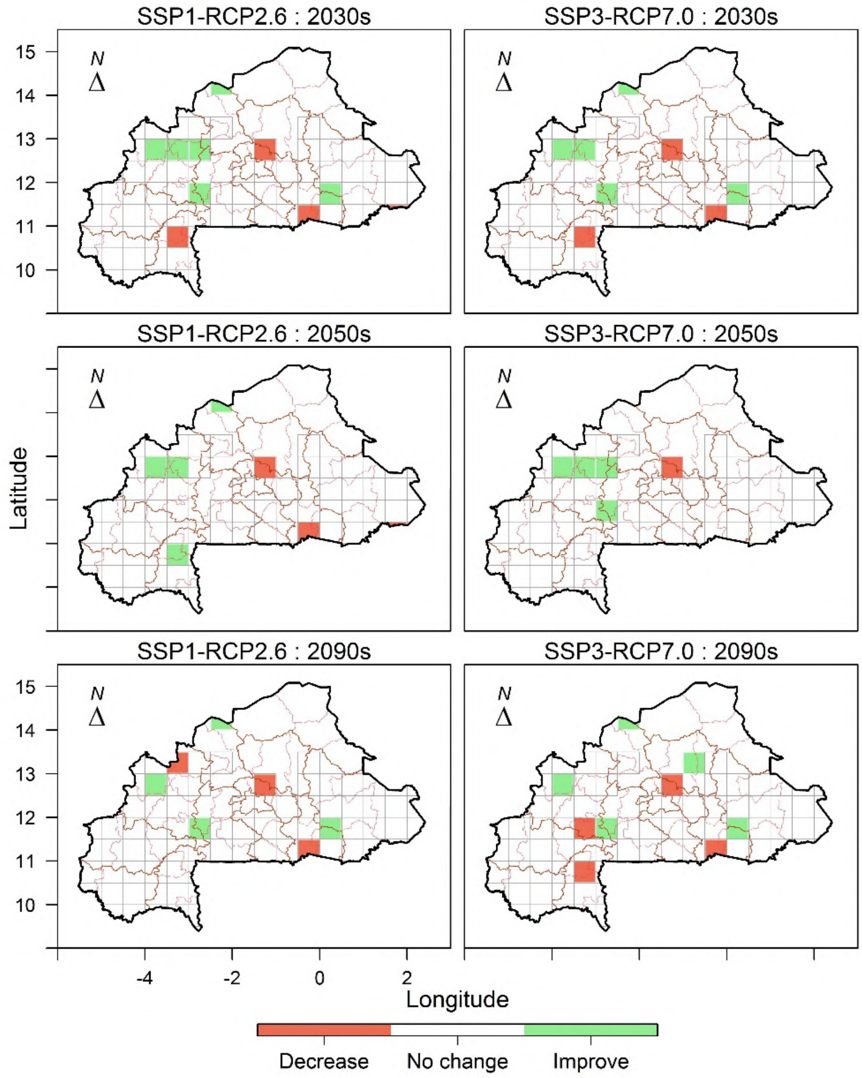


Figure 33: Maps showing the modelled changes in climatic suitability for maize in Burkina Faso for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios.

d) Cowpeas

The distribution of the changes in suitability for cowpea under future climatic conditions are shown in Figure 34. The results show that by 2050, 10.3% and 12.6% of the areas that are currently suitable for cowpea will have reduced suitability while 6.9% and 8% will have increased suitability, resulting in net losses in suitability for cowpea (Table 3). These losses in suitability are projected to increase by 2050 and 2090. However, the results also show that more areas will have reduced suitability for cowpea compared to current and this means that cowpea will be affected by climate change in Burkina Faso in some areas with adaptation measures required. The southwestern parts of the country will however retain conditions that are able to sustain cowpea production (Figure 34). We therefore conclude that climate change will limit cowpea production in Burkina Faso as limited and marginal areas extend southwards. Cowpeas is a grain legume and therefore different to maize, sorghum and millet that are in the grass family in terms of its requirements and response. The modelling results showed that 45% of the suitability of cowpea, the highest of all the crops modelled, is from temperature-based variables with the majority of varieties being planted in the region being photoperiod-sensitive and therefore sensitive to planting dates.

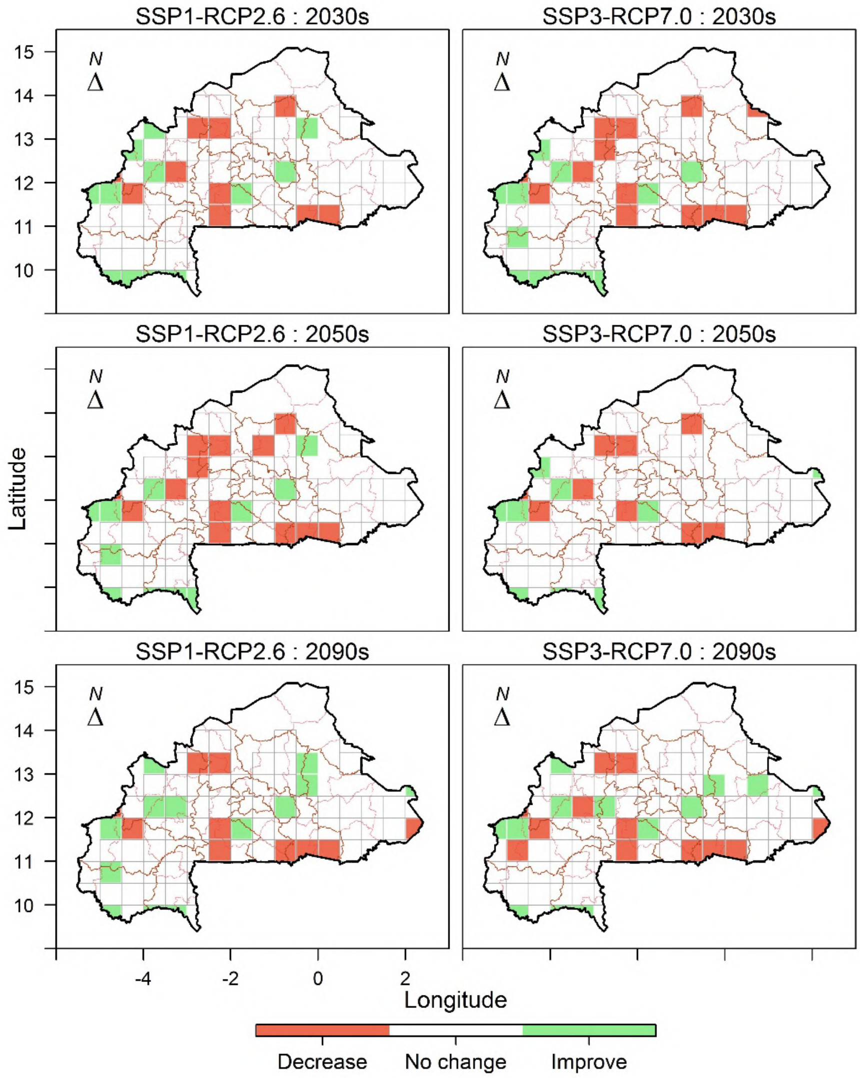


Figure 34: Maps showing the modelled changes in climatic suitability for cowpeas in Burkina Faso for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios.

In addition, the relatively higher losses in suitability for cowpea under climate change are also related to the fact that the crop is mainly intercropped with maize, sorghum or other crops and therefore modelling it as an open crop exposes it to higher temperatures that limit its suitability. The projected losses in suitability of cowpeas is concerning given that the cowpeas enables households to harvest cowpea leaves and grains for consumption or sale during the lean season when grain reserves from other cereal harvests have been depleted and current crops are not ready for harvest. As such, adaptation measures are required to sustain cowpea production under climate change, especially as Burkina Faso is among the top three cowpeas producing countries in the world.

Table 3: Percentage area changes for suitability for sorghum, millet, maize and cowpea by 2030, 2050 and 2090 under SSP1-RCP2.6 and SSP3-RCP7.0 scenarios in Burkina Faso.

Crop		2030		2050		2090	
		SSP1-RCP2.6	SSP3-RCP7.0	SSP1-RCP2.6	SSP3-RCP7.0	SSP1-RCP2.6	SSP3-RCP7.0
Sorghum	Decrease	8.0	8.0	6.9	8.0	10.3	9.2
	No Change	87.4	85.1	88.5	82.8	82.8	80.5
	Increase	4.6	6.9	4.6	9.2	6.9	10.3
Millet	Decrease	4.6	2.3	3.4	3.4	2.3	4.6
	No Change	89.7	90.8	93.1	89.7	88.5	87.4
	Increase	5.7	6.9	3.4	6.9	9.2	8.0
Maize	Decrease	3.4	3.4	2.3	1.1	3.4	4.6
	No Change	90.8	92.0	94.3	94.3	93.1	90.8
	Increase	5.7	4.6	3.4	4.6	3.4	4.6
Cowpea	Decrease	10.3	12.6	13.8	9.2	10.3	12.6
	No Change	81.6	80.5	78.2	86.2	79.3	77.0
	Increase	8.0	6.9	8.0	4.6	10.3	10.3

Multiple crop suitability

Figure 35 shows the potential for multiple crop suitability based on the combined suitability of the four selected crop types. As expected, the areas with higher multiple crop suitability are in the southern and western parts in Cascades, Haut-Bassins, Centre-Ouest, Centre-Sud and Centre-Est. Our model shows that by 2050 the potential for multiple crop suitability will decrease especially in the Boucle du Mouhoun, Nord and Centre-Ouest regions as few crops will become suitable but increase in Haut-Bassins (south-west) under SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. Overall, crop suitability will shift southwards under climate change conditions with more severe shifts under SSP3-RCP7.0.

Very few areas are suitable for producing all four crops (sorghum, millet maize, and cowpeas). Notable decreases are projected in the areas that are optimally suitable for at least three crops, as more areas become optimally suitable for only two or one crop. Under current conditions, 11.5% of the country is suitable for producing at least 3 of the 4 crops but this will decrease to only 9.2% (SSP1-RCP2.6) and 8% (SSP3-RCP7.0) by 2090.

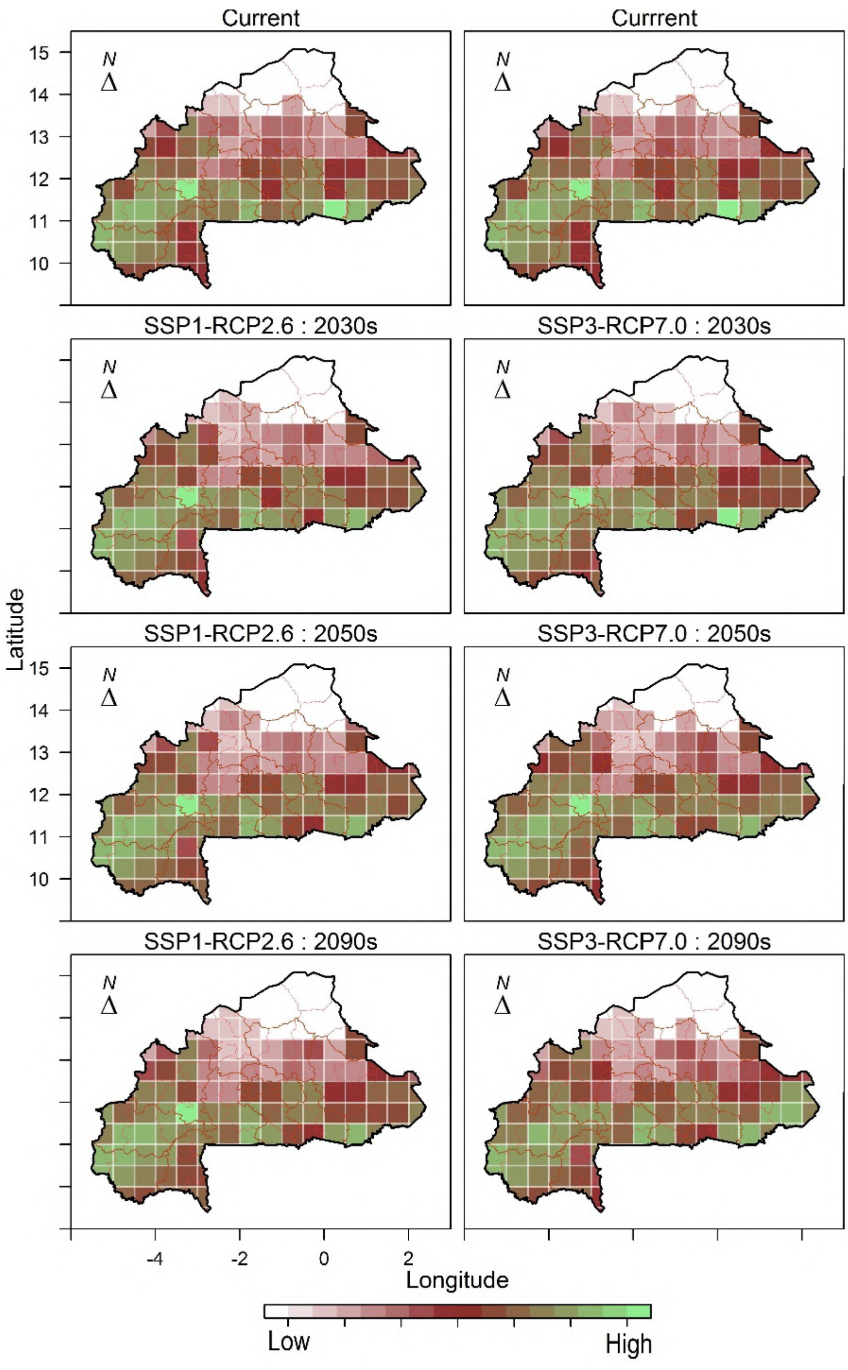


Figure 35: Potential for multiple crop suitability under current, SSP1-RCP2.6, and SSP3-RCP7.0 scenarios in Burkina Faso in 2030, 2050 and 2090.

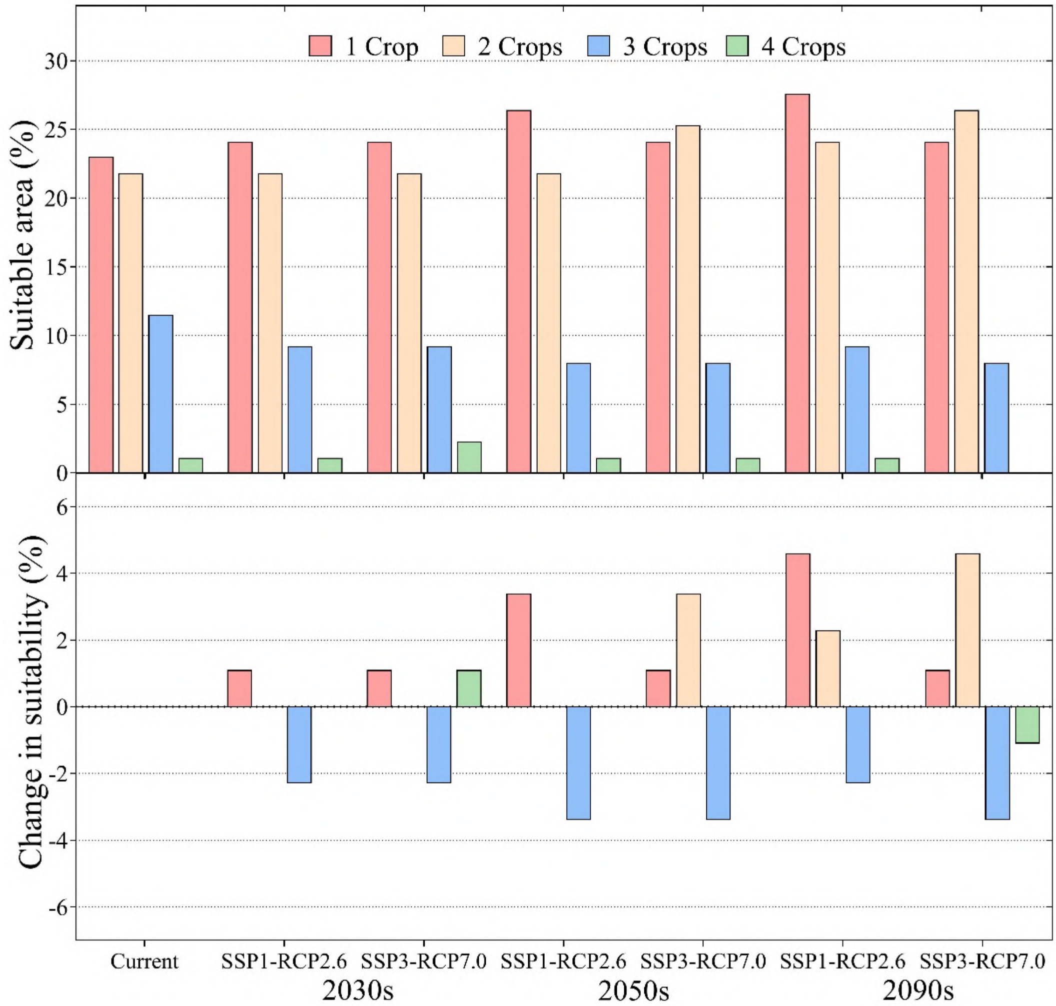


Figure 36: Impact of climate change on area that is optimally suitable for producing multiple crops in Burkina Faso in absolute area per crop combination (upper graphic) and change of suitability per crop combination (lower graphic).

In conclusion, crop suitability models show that the areas that are suitable for cowpea will decrease in Burkina under climate change while that for millet, sorghum and maize will remain stable. We project a southward extension of the limited suitability areas especially for all crops. What this indicates is that under climate change these crops will increasingly become difficult to produce in Burkina Faso. Therefore, technical and policy adaptation plans are required to maintain agricultural production at current levels. We also show that the potential for farmers to produce more crops will increasingly become difficult in Burkina Faso, which limits farmers' diversification potential and associated food security and economic hedging benefits of producing multiple crops.

3.3 Yield loss assessment under future climatic conditions

3.3.1 Data and method

Crop yield is a specific plant response to weather variables and other field inputs such as soil and farmer's practices. These interactions can be formed as equations representing a crop's physiological response to environmental variables (Jones et al., 2003). Biophysical crop simulation models simultaneously incorporate interacting soil, plant and field inputs, as well as weather information. In this study, we used DSSAT (Hoogenboom et al., 2017, 2019; Jones et al., 2003), a widely used process-based crop simulation model that simulates crop growth as a function of the soil-plant-atmosphere dynamics. The model requires daily weather data, soil surface and profile information, detailed crop management information, and genetic coefficients of the chosen crop variety as inputs to simulate crop growth. DSSAT calculates plant and soil water, nitrogen, phosphorus, and carbon balances, as well as the vegetative and reproductive development of crops at the daily temporal interval.

We simulate sorghum production at grid level with 0.5° spacing (approx. 55km x 55km) over Burkina Faso, under current and future climate projections. In line with Chapters 1 and 2, we use the emissions scenarios SSP1-RCP2.6 and SSP3-RCP7.0 for yield projections in the years 2030 (2021-2040), 2050 (2041-2060), and 2090 (2081-2100). Future climate projection data simulated by GCMs were obtained from ISIMIP3b (Lange, 2019a, 2019b).

For the assessment, we assume rain-fed conditions and no fertiliser application as a default management strategy in sorghum and use the DSSAT model's default West African sorghum variety for model calibration. The sowing date is automatically calculated by the model when the field meets at least 10% of soil moisture, and the temperature is between 10 and 40°C. Simultaneously, harvest dates are also automatically calculated by DSSAT, indicating when the crop has reached maturity. Planting depth was set to 3cm, row spacing to 45cm, and plant density to 13 plants/m², according to common practice in Burkina Faso (White et al., 2015). We rely on yield statistics provided on province level by the Ministry of Agriculture in Burkina Faso for model calibration (MAAH/DGESS, 2020).

The model has produced a good agreement at the province level between long-term (2001-2016) average observed and simulated yields (a correlation of Pearson's r=0.63 & Willmott's index of agreement d=0.78). Regarding the inter-annual variability from 2001-2016, the model has produced a correlation of r=0.75 and an index agreement of d=0.83 between observed and simulated yields at a national scale, indicating a sufficient model fit for analysing future scenarios.

In contrast to suitability models that typically use an empirical model to measure the general seasonal, long-term climate conditions (employed in the previous section), this section uses biophysical mechanistic modelling of climate change impacts on agricultural yield. Yield is thereby calculated from the daily, possibly non-linear response to weather variables and other field inputs such as soil and farmer's practices.

3.3.2 Results

Current sorghum yields in Burkina Faso reach on average 990 kg/ha in observed data (MAAH/DGESS, 2020) and 890 kg/ha in simulated data. The range of yields within the country lies mostly within 800 – 1200 kg/ha, with the most productive areas in the west and southwest of the country. Exceptions to this range are found in the north and northeast, where yields are generally lower.

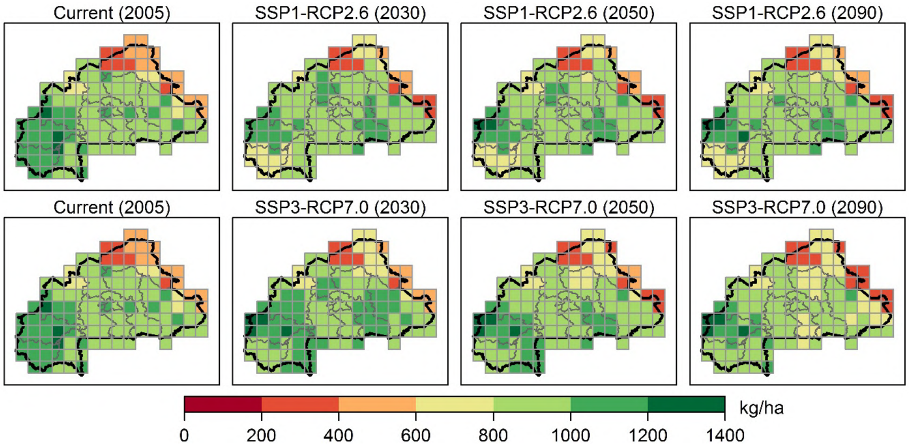


Figure 37: Current and projected future sorghum yield levels (kg/ha) in Burkina Faso at 0.5° grid spacing under SSP1-RCP2.6 (top row) and SSP3-RCP7.0 (bottom row) for the years 2005 ("current"), 2030, 2050, and 2090.

Figure 37 shows the current distribution of absolute yield levels in Burkina Faso (left column) together with projected future changes for 2030, 2050, and 2090 under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row). Yield projections until 2090 show regionally distinct trends due to the regional disparities of climate in the future. At the national level, future yields are projected to stay similar to current (simulated) yields under SSP1-RCP2.6 with 891 kg/ha. Under SSP3-RCP7.0, nationally averaged yields decrease to 856 kg/ha (-3.8%) compared to current average simulated yields.

The regional distribution of yield anomalies becomes especially evident in Figure 38. Until the end of the century, the yields are projected to remain nearly unchanged on the national scale. However, at the regional level, yields are projected with partly opposing trends down to -30% in SSP1-RCP2.6 and up to +20% in SSP3-RCP7.0. Few regions in the north (Sahel, Nord, and Centre_Nord) show increased yields (up to +30% in SSP1-RCP2.6 and up to +20% in SSP3-RCP7.0), while few regions in the south (Cascades, Haut-Bassins, and Sud-Ouest) present decreased yields (down to -30% in SSP1-RCP2.6 and down to -20% in SSP3-RCP7.0). A possible explanation is a combination of higher CO_2 fertilisation and a projected increase in precipitation events towards the north as well as a decrease in the south. An increased yield projection in the north (Sahel and Nord) could be due to the improved crop water availability for these dry regions, especially in higher emissions scenarios.

Comparing both scenarios, crop yield trends in some regions are more pronounced under SSP1-RCP2.6 than under SSP3-RCP7.0 due to regional disparities of precipitation events such as heavy precipitation intensity or frequency and monsoon onset change. The low emissions scenario SSP1-RCP2.6 results in similar yield impacts in most regions over time due to lacking trends in heavy precipitation intensity or frequency (Chapter 1); there is no significant trend in rainfall changes over time (Figure 15). At the same time, for some regions, SSP1-RCP2.6 may lead to stronger yield losses than SSP3-RCP7.0 due to late monsoon onset, where SSP3-RCP7.0 remains nearly the same compared with the current monsoon onset scenario (Chapter 1). Specifically, the regions from the south, such as Cascades, Haut Bassins, and Sud-Ouest are projected to receive less intense or frequent heavy precipitation events compared with the other regions (Figure 16), which could be the reason for higher yield losses than in other regions.

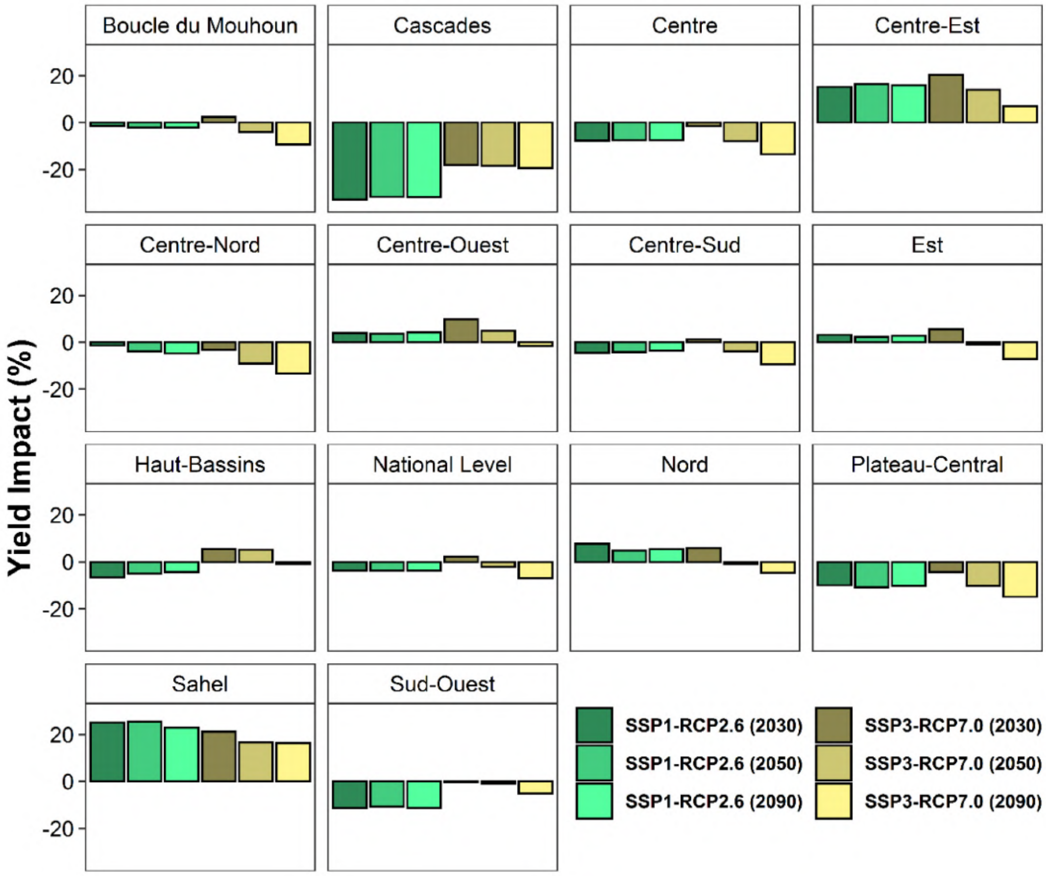


Figure 38: Simulated yield loss by region in Burkina Faso for 2030s, 2050s and 2090s under SSP1-RCP2.6 and SSP3-RCP7.0.

An analysis of climate indicators suggests that most of the projected yield loss can be explained by increases in maximum and minimum temperatures of between 1 to 4°C during the sowing and germination stage (May and June), whereas precipitation amounts and distribution throughout the season is projected to remain relatively unchanged with a slightly increasing trend (see also Chapter 1). Overall, our results are in line with other studies indicating that sorghum yields are projected to decrease in Burkina Faso in the future because of the expected warming, irrespective of whether precipitation sums increase or decrease (Sultan et al., 2013).

AMPLIFY showed that only about 50% of the variability on sorghum yield in Burkina Faso is explainable by weather variables, indicating that other factors such as soil and management could explain the other half. The results from the suitability modelling shows that the season-long conditions for sorghum will remain stable in Burkina Faso (previous section), albeit at a reduced yield levels as shown from this process-based modelling. This is because the suitability considers the season long conditions while the process-based modelling is based on daily conditions. For example, total precipitation in a season may be sufficient to indicate general suitability, while few dry days in that season can significantly reduce the yield. The same may hold for temperature – even in optimal "average" year, a series of hot days can substantially diminish harvests. Overall, the areas shown to be highly suitable for sorghum production (Figure 30) correspond to the simulated high yield areas (Figure 35). In addition, our findings show that the yield changes are more dramatic than the suitability changes, which is expected as yield is more sensitive to climate change than crop suitability.

Chapter 3 Summary

This chapter assessed climate impacts on crop production from three perspectives: the first part showed that weather influence plays a key part in determining crop yields, with 70% of maize and millet yield variability and 20% of sorghum yield variability being attributable to weather influences.

Crop suitability models have shown that the areas that are suitable for sorghum, millet and maize will remain mostly stable under climate change by 2050, while suitability cowpeas will decrease in the same period. We project a southward extension of the limited suitability areas, especially for maize and cowpeas. This indicates that under climate change conditions, these crops will become increasingly difficult to grow in Burkina Faso. Therefore, technical and policy adaptation plans are required to maintain agricultural production at current levels. We also show that the potential for farmers to produce multiple crops will become more and more difficult in Burkina Faso, which limits farmers' diversification potential, associated food security, and economic benefits through the production of multiple crops. Moreover, the specific scientific question should be kept in mind, justifying the parallel use of empirical models for suitability and mechanistic models for scrutinizing sub-seasonal weather effects.

An in-depth analysis of sorghum yield projections under two emissions-scenarios (SSP1-RCP2.6 and SSP3-RCP7.0) by 2030, 2050, and 2090 indicated reduced yields (down to -20%) in both scenarios. However, the high emission scenario projected higher yields (or attenuated losses) than a lower emission scenario due to the higher CO_2 concentration and comparatively more beneficial precipitation patterns in the future (Figure 15).

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

Impact		Current	Trend future	Confidence
	Weather influence in sorghum yields	50%	-	Medium
	Sorghum suitability	Medium	SSP1-RCP2.6 Relatively stable SSP3-RCP7.0 Relatively stable	High
	Sorghum yields	Medium	SSP1-RCP2.6 Decreasing ↘ SSP3-RCP7.0 Decreasing ↘	Medium
	Weather influence in millet yields	70%	-	Medium
	Millet suitability	Medium	SSP1-RCP2.6 Relatively stable SSP3-RCP7.0 Relatively stable	High
	Weather influence in maize yields	70%		Medium
	Maize suitability	Low to medium	SSP1-RCP2.6 Relatively stable SSP3-RCP7.0 Relatively stable	High
	Cowpea suitability	Medium	SSP1-RCP2.6 Decreasing ↘ SSP3-RCP7.0 Decreasing ↘	High

Chapter 4 – Climate impacts on livestock production

The livestock sector plays a critical role in Burkina Faso's economy and contributes substantially to food and nutritional security (Tiemtoré, 2004). As highlighted in its National Climate Change Adaptation Plan (NAP), the livestock sector is expected to experience high to moderate risks due to climate change. Climate change induced impacts, such as drought causing shortage of grazing and reduced agricultural production cycles, will result in loss of livestock production in multiple ways. Climate change is already today affecting livestock numbers, forage quality and pasture composition in the region (Pfeifer et al., 2020). Given that grassland systems are highly vulnerable to climate fluctuations (Knauer et al., 2017), it is important to understand how grassland productivity has changed in the past and how it is expected to change under future emissions scenarios. Moreover, it is critical to understand the implications of future fodder availability for livestock production in Burkina Faso.

In the first part of the chapter, we provide an excursion on how climate change can have an impact on the security situation in Burkina Faso by looking at the different ethnic groups in Burkina Faso: The Fulani who typically engage in nomadic/semi-nomadic pastoralism for their livelihood and Mossi who commonly practice sedentary farming. A literature synthesis shows the interactions and conflicts that their coexistence may entail under the growing challenges of climate change.

In the second part, the impacts of climate change on grassland productivity and grazing-based livestock production in Burkina Faso are assessed by using the dynamic global vegetation model LPJmL.

In the last part, the adaptation option mowing for livestock systems is presented. This is an additional strategy which is not considered in the multi-criteria assessment.

4.1 The livestock sector in Burkina Faso

Livestock production in Burkina Faso accounts for approx. 13% of GDP, and represents 36-40% of agricultural value added (FAO, 2018a). Many rural households in Burkina Faso are heavily dependent on livestock, as they live below the poverty line and face major constraints in producing or buying food to meet a satisfactory intake of calories and proteins (Sanfo & Gérard, 2012). Like in other sub-Saharan countries, livestock in Burkina Faso is equal to wealth for the rural population and, since historical times, holds great cultural value. Its multiple benefits especially to the rural poor include the provision of high-quality food, services (transport and traction), an additional source of income, savings and climate risk insurance, as well as their production of manure as valuable fertiliser for crop production (Keil et al., 2020). Small ruminants are usually carried by poorer households and typically managed by women, while larger ruminants are mostly held by wealthier households and are managed by men (Morgan, Pica-Ciamarra, 2011).

A substantial diversity of ruminant and non-ruminant animals occurs with its major constituents being cattle, sheep, goat, pigs and poultry (chicken and guinea fowl). As the demand for livestock production is increasing, a simultaneous growth can be noticed in livestock numbers since the 1990s. For sheep and poultry, the numbers have increased by 3%, and for cattle, pig and goat, the numbers have increased by 2%. In 2019, there were an estimated 10 million cattle, 10.7 million sheep, 16.1 million goats, 2.5 million pigs and 49 million poultry in the country (MRAH/DGSS, 2020). However, the national-averaged livestock numbers are unevenly spread across regions and provinces in Burkina Faso as can be seen in Figure 39, which depicts the distribution of the main ruminant animals (cattle, sheep and goat) at province level.

Similar to most Sub-Sahara countries, rural areas with better soils and sufficient precipitation generally see livestock as part of an integrated mixed crop-livestock production system. In contrast, areas with low crop production potential often see livestock at the core of agro-pastoral and pastoral systems. In Burkina Faso, sedentary agro-pastoral farming is the most common system of livestock keeping. It is especially practiced in the southern and central parts of the country, whereas in the semiarid north (Sahel), the east and the cotton basin in the west of the country, transhumant pastoral systems are predominant (FAO, 2018a; Zoma-Traoré et al., 2020). In sedentary mixed crop-livestock systems, farmers usually have a herd size of 5-100 heads (both cattle and small ruminants), which are housed in fixed cow sheds around the farm.

In contrast, transhumant pastoralists can have herd sizes varying between one hundred to several thousand animals (FAO, 2018a). In these systems, pastoralists constantly move their herds across the country in search of feed and water (Zoma-Traoré et al., 2020). Pastures are the most important feed source for transhumant livestock, together with occasional crop by-products, whereas water is sourced from rivers and streams. Herd movement is facilitated through established and marked transhumance corridors, and herds are usually trekked hundreds of kilometres across the country or even across national borders (FAO, 2018a).

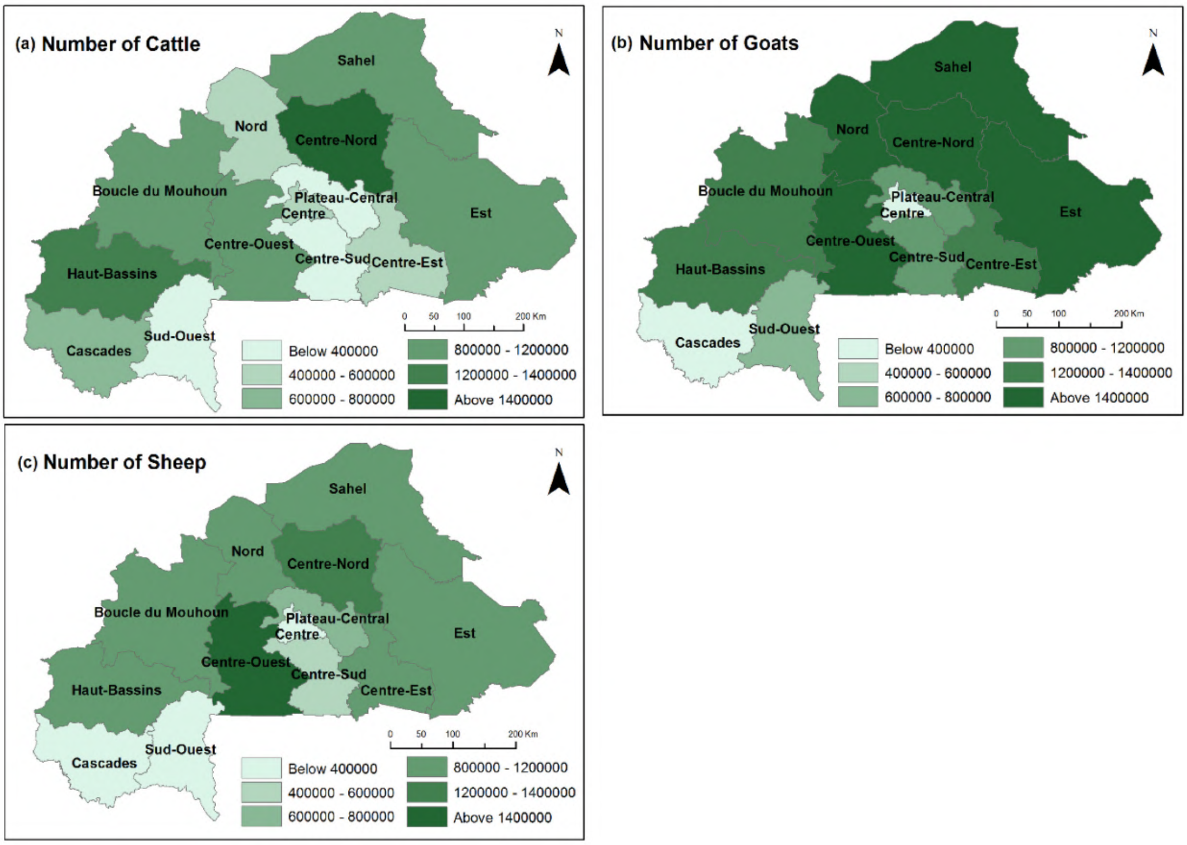


Figure 39: Distribution of cattle, sheep and goat for provinces in Burkina Faso for the year of 2019.

The Climate Change and Security Nexus in Burkina Faso

State of the Art of the Scientific Literature on the Climate Change-Conflict Nexus

There is an increasing consensus within the scientific literature that climate change can indeed have a significant impact on armed conflict outbreak and prolongation (Brzoska and Scheffran 2020; Kelley et al., 2015; Mach et al., 2019; Schilling, Scheffran, and Link 2010; Schleussner et al., 2016; Von Uexkull et al., 2016). However, the underlying mechanisms by which increasing climate extremes affect conflict situations are unclear. Some studies show a reciprocal relationship between environmental disasters and armed conflict, with both factors increasing the damage caused by the other (Von Uexkull et al., 2016). Overall, climate impacts meet vastly varying socio-economic circumstances around the world and hence, play out differently depending on the local context and history of conflict. Particularly in already fragile and politically and ethnically fragmented regions, climate change poses a significant risk for the emergence and exacerbation of conflict constellations (Schleussner et al., 2016). Other, more established drivers of conflict such as socio-economic inequalities, ethnic fragmentation, and a lack of government resources and capacities, are still considered to be more influential in the development of conflicts than climate change itself (Mach et al., 2019). Meanwhile, these conflict drivers add to the vulnerabilities of already marginalized communities towards climatic extreme events. Furthermore, climate change can further marginalize socio-economically disenfranchised communities, increase competition for resources among different user groups, and exacerbate weak governance. A high level of dependence of a large part of the population on agriculture harbors an additional risk since the consequences of climate change in agriculture directly threaten the existence of large populations and can also lead to widespread displacement (Kelley et al., 2015). Due to the adverse impact of climate change on all of these other potential conflict drivers, it is recognized as a threat multiplier throughout scientific literature.

Impacts of Climate Change on Subsistence Farmers and Herders and the Armed Conflict Pathway

Threat multiplier dynamics, such as the ones caused by climate change, play out most severely in societies that are particularly dependant on subsistence farming and pastoralism and rely on rain-fed agriculture (Von Uexkull et al., 2016). Despite their comparatively small carbon footprint, Sahelian farmers and pastoralists are particularly vulnerable to the impacts of climate change as they are greatly exposed to extreme weather events while their states lack the capacity to adapt adequately. Besides the great droughts of the 70s and 80s, Northern Burkina Faso experienceed droughts more recently in 2004, 2010 and 2012 (Lodoun et al., 2013; Snorek et al., 2014). This has had great impacts on forage availability and thus has negatively affected pastoralists´ ability to practice their annual transhumance (Traore and Owiyo, 2013). Such natural disaster as droughts are projected to increase in frequency and intensity. As suitable common land resources tend to diminish due to these climatic changes, existing underlying conflict cleavages can serve as a catalyst for violence, even between communities whose relationships were previously marked by cooperation (Schilling et al., 2010). The Fulani, an ethnic group of roughly 40 million scattered across West-Africa, typically engage in nomadic/ semi-nomadic pastoralism to cover their livelihood needs. Within the context of Burkina Faso, they make up the largest minority. The Mossi ethnic group represent the majority in the country and commonly practice sedentary farming. They engage in traditional worship, while the Fulani adhere to the Islamic faith. Considering their nomadic/semi-nomadic lifestyle, pastoralists are particularly vulnerable to climate impacts as they not only depend on precipitation but indeed follow the rain on their transhumance (Traore and Owiyo, 2013). This brings them in contact with local farmers as well as other pastoralists along the way. While these relationships can be cooperative, changing patterns of precipitation also means changing routes on the quest to follow the rain and find pasture (Schilling et al., 2010). Relations with farmers of potentially different ethnic groups therefore have to be established, which bears conflict potential, particularly during the growing season (Von Uexkull et al., 2016). Issues with respect to land tenure and land use between pastoralists and outside groups are common (Traore and Owiyo, 2013).

A Crowded Field of Conflict Actors in Burkina Faso

Until recently, Burkina Faso was heralded as one of the role models of stability in an otherwise volatile region. Moreover, it was seen as an example of peaceful coexistence of different ethnic and religious groups (Aboagye et al., 2008). However, regional instability ensued in the Sahel region in the aftermath of the Tuareg Rebellion and consequent Coup d´Etat in neighboring Mali in 2012. The resulting power vacuum gave room for several extremist groups to take root (People´s Coalition for the Sahel, 2021). Within the last five years, these groups have intensified their campaigns in Niger, Chad and Burkina Faso, with deadly attacks on state institutions, security forces and civilians (Human Rights Watch, 2018; International Crisis Group, 2020b, 2020a). Counter-insurgency operations on behalf of national security forces have been heavy-handed (Amnesty International, 2020). Fulani pastoralists, the largest minority group in Burkina Faso, have been caught between the two belligerent parties. The home-grown extremist group Ansarul, founded by Fulani Mallam Dicko, was particularly supportive of pastoral grievances, and was able to attract support from pastoralists throughout the initial stage of group formation (International Crisis Group, 2020a). Thereafter, Ansarul´s tactics became increasingly less about providing a platform for grievances with respect to challenges of traditional herding and corruption from state and religious clergy. Instead, gaining territory and forcing societal changes, supposedly in line with religious doctrine, in those affected communities became a focal point for the group. Additionally, the Koglweogo, also referred to as "self-defense" groups, started to add to an already chaotic scene of armed conflict actors in the region. Despite originally setting out to protect Burkina´s Sahelian villages from extremist and bandit groups, massacres of entire Fulani villages ensued to avenge supposed Fulani support for extremist activities (Human Rights Watch, 2018). All of this has added to an atmosphere of distrust between communities, in particular between the socio-economically marginalized minority of the Fulani and the majority Mossi.

NGO reports have shown that in Burkina Faso, Fulani are inextricably linked to recent instability in several ways. There have been many reports on extrajudicial killings, abuse of suspects, as well as capricious arrests, all of which intimidate particularly marginalized groups, chief among them the Fulani (Human Rights Watch, 2018). This, along with the presence of extremist groups, has led to widespread internal displacement, which has recently surpassed 2 million displaced persons within the region, 1 million for the case of Burkina Faso alone (World Food Programme, 2020). Locally grown extremists' groups such as Ansarul Islam were not only initiated by members of the Fulani ethnic group but also focused their recruitment on young Fulani men in Northern Burkina Faso (International Crisis Group, 2020). This dynamic of fear and distrust has contributed to ethnic tensions. Violence on behalf of security forces, armed extremist groups and communities has become prevalent in recent years in the region bordering Mali and Niger, namely the provinces of Seno, Ouadalan, Yagha and Soum.

With all of the aforementioned conflict drivers at work, a changing climate is adding to existing pressures. Changing weather patterns greatly exacerbate existing tensions as it perpetuated cycles of socio-economic disenfranchisement and marginalization. Policy makers should pay special attention to the needs of marginalized communities in agriculture. Transhumance infrastructure is key to elevating much of the underlying inter-communal tensions. Specifically, this means that pastoralist corridors need to be clearly identified and enforced. When farmland is extended onto transhumance routes, social conflict over trampled produce is a likely result. Efforts should be made to reform insecure land tenure systems. Furthermore, in light of increasingly unpredictable patterns of precipitation, water and forage service along the routes could be a strategy to mitigate the impacts. Considering the current state of security in the country as well as the greater region, along with its low adaptive capacity to the effects of climate change, climate change impacts on the development of violent conflict requires further analysis. Implementing agencies need to consider conflict dynamics when undertaking adaptation projects, as adaptation measures could exacerbate existing violent conflict or even facilitate conflict outbreak in the context of underlying inter-communal tensions. The do-no-harm principle needs to be front and center from the outset of the planning stage.

4.2 Data and method

The analysis in this chapter focuses on the impacts of climate change on grassland productivity and therefore grazing-based livestock production in Burkina Faso. Hence, the analysis is relevant for the main grazing animals including cattle, sheep and goat. For this, the dynamic global vegetation model LPJmL (Lund-Potsdam-Jena with managed land) has been used, which is mainly developed at PIK (Schaphoff et al., 2018; Von Bloh et al., 2018).

As a process-based dynamic global vegetation model LPJmL simulates key ecosystem processes such as photosynthesis, plant and soil respiration, carbon allocation, evapotranspiration and phenology of natural as well as managed vegetation, as coherently linked through their carbon, water and nitrogen fluxes (Schaphoff et al., 2018; Von Bloh et al., 2018). Dynamic global vegetation models are often used to study the impact of climate change on vegetation cover. In addition, LPJmL features a representation of different grassland management schemes, enabling it to simulate the impacts of grazing, grazing intensities and mowing systems in managed grasslands (Rolinski et al., 2018). Following the spatial resolution of the climate data, LPJmL simulates the land surface as discrete grid cells with a grid size of 0.5° x 0.5°, roughly 55 x 55 km.

Daily forage requirements vary by animal type. To make them comparable, animal types can be converted to a generic Tropical Livestock Unit (TLU) using the conversion factors in Table 5. A daily forage requirement of 6.25 kg dry matter per TLU is assumed (MRAH, 2020), and no distinction between specific animal types is made in the following analysis.

Table 5: Conversion factors for different types of animals to Tropical Livestock Units (TLUs)

Livestock species	Number of TLUs
Cattle	0.8
Sheep	0.1
Goat	0.1

In the model simulations, the effect of grazing by livestock is represented as a daily partial removal of the leaf biomass of grasses. Grazing is assumed to always leave a minimum stubble height of about 1 cm. On the demand side, the amount of removed biomass depends on the density of grazing animals (number of TLUs per hectare). On the supply side, available biomass changes between seasons and between years in response to weather, but also in response to previous grazing. There are no spatially and temporally explicit data available for the actual livestock grazing density in Burkina Faso for the historical period. Estimating grazing demand at sub annual scale is complicated by the practice of transhumance, which involves seasonal movement of herds over often large distances. Furthermore, forage statistics from Burkina Faso indicate a substantial use of agricultural wastes to supplement fodder from grazing (MRAH, 2020).

Given these data limitations, we do not attempt to reproduce the actual grazing regimes found in Burkina Faso. Instead, we systematically test a range of biomass removal rates (corresponding to livestock densities between 0 and 5 TLU/ha) and select in each grid cell and year the removal rate that produces the highest total annual grass yield. Figure 40 illustrates the procedure for one example cell and year. We consider this grass yield a grazing potential but caution that it is not equivalent to a carrying capacity. As shown in Figure 40, grass yield varies seasonally so in order to utilize the full grazing potential would either require a seasonal adjustment of the livestock density or supplemental fodder from other sources. The grazing potential we calculate acknowledges that both of these management techniques are currently practiced in Burkina Faso while not explicitly accounting for them quantitatively, as would be required in order to estimate the carrying capacity.

When aggregating grid-cell yield levels to regions or to the country scale, any land that is not cropland in a cell is considered to be potentially available as grazing land. As such, cells with high cropland shares contribute less to the regional or country average than cells without cropland. Cropland maps are taken from the LUH2 dataset, which provides a time series of annual gridded maps of land use that are consistent with country-level land use areas reported in the FAOSTAT database (Hurtt et al., 2020). Simulations of historical and future grassland production under different management regimes are driven by the 10 Global Climate Models (GCMs) and two emissions scenarios as presented in Chapter 1. Future changes in annual grazing potential are presented for three time periods: ~2030 (2021–2040), ~2050 (2041–2060), and ~2090 (2081–2100). All changes are in comparison to the historical period 1995–2014.

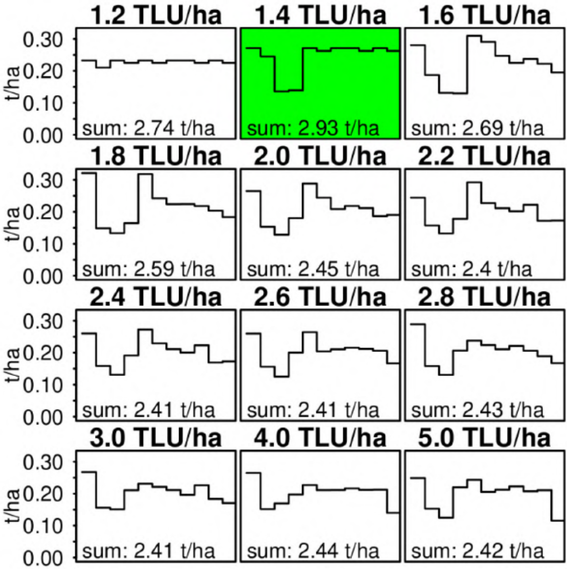


Figure 40: Monthly grass yields under different livestock densities in one cell and year; livestock density with highest annual yield is considered as grazing potential (marked in green in plot).

4.3 Results

Figure 41 shows the multi-model ensemble median of annual grazing potential for the historical period 1995–2014. Grazing potentials are highest in the Cascades Region, exceeding 3.5 tonnes dry matter per hectare per year along the border with Côte d'Ivoire. Grazing potentials decrease towards the north-east following the decreasing precipitation gradient across Burkina Faso. The lowest grazing potentials are found in the Sahel region, going down to less than 1.5 t/ha/yr along the border with Niger and Mali.

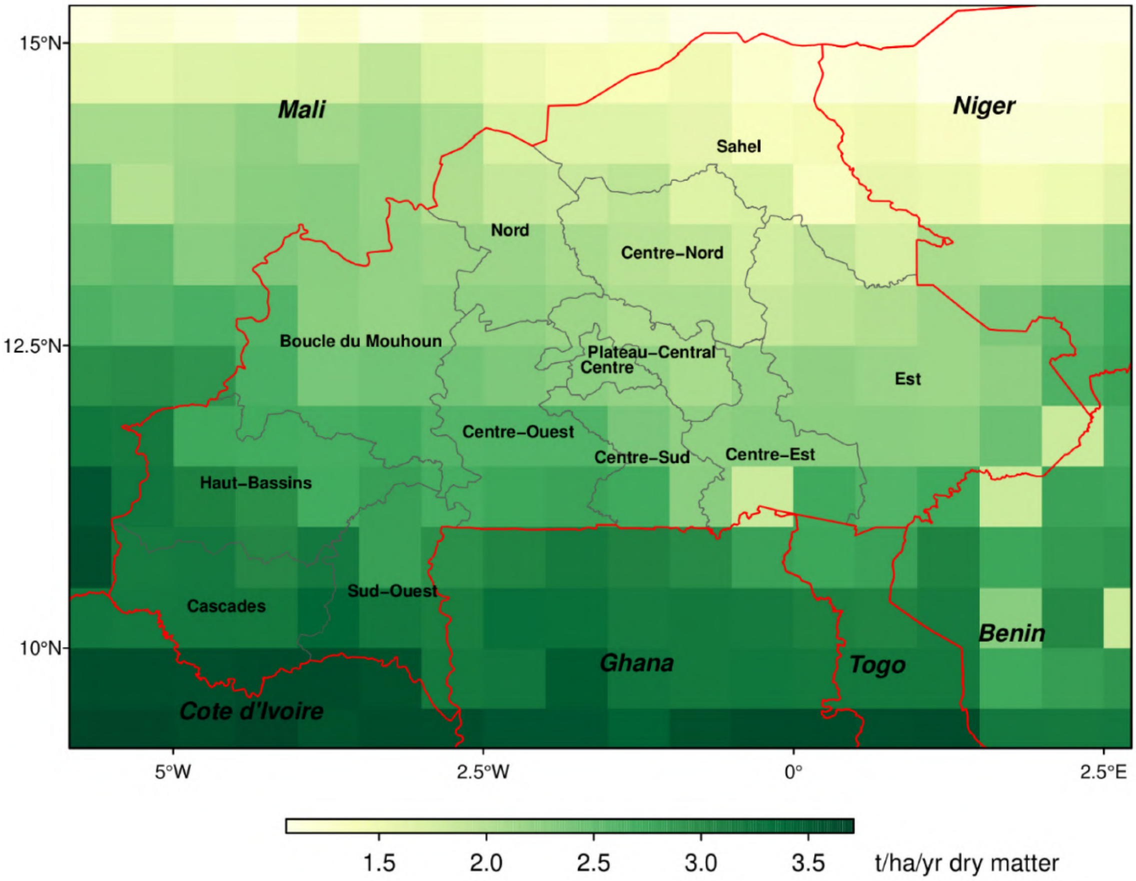


Figure 41: Multi-model ensemble median of simulated annual grazing potential for the historical period 1995-2014 in Burkina Faso.

It is important to note that grazing potential varies substantially between seasons and between years, as illustrated in Figure 42 for the monthly grazing potential in the 13 regions of Burkina Faso. In this figure, the colour gradient from light green to dark green denotes the variability across the 10 GCMs and 20 years making up the multi-model ensemble median. Inverse to the annual grazing potential, seasonal and multi-annual variability of grazing potentials is smallest in the south-west (Cascades, Sud-Ouest, Haut-Bassins) and increases towards the north-east, with the highest variability in the regions of Centre-Nord, Nord, and Sahel.

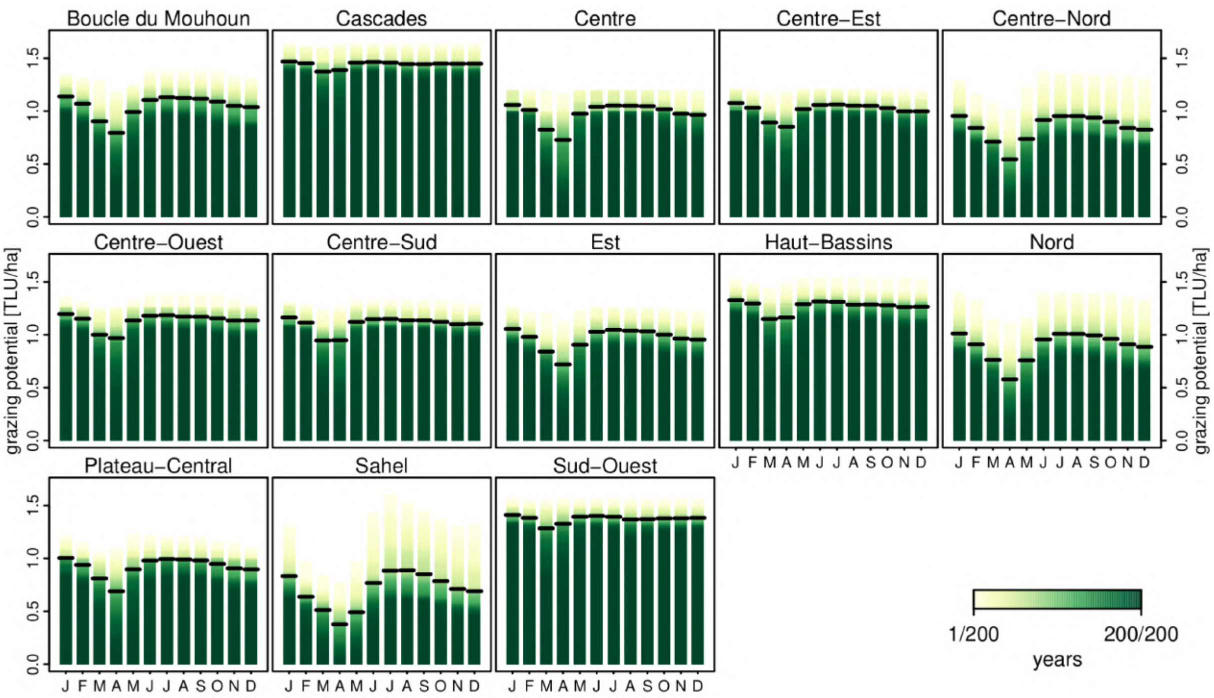


Figure 42: Variability of historical grazing potential within and across years in the multi-model historical ensemble. Each bar represents the range of monthly grazing potential across 20 years' time 10 GCMs. Lighter colours denote high values reached only in a few years. The black horizontal line in each bar marks the mean across all years and GCMs.

At country scale, grazing potentials are projected to decrease in Burkina Faso over the course of the 21st century (Figure 43). These changes are the smallest in the 2030 period and intensify towards the end of the century. Losses in grazing potentials are more pronounced under the low emissions scenario SSP1-RCP2.6 where they increase from a multi-model median of 3% in 2030 to 5% in 2050 and 10% in 2090. In contrast, losses in grazing potential under SSP3-RCP7.0 increase from about 2% in 2030 to 3% in 2050 and 4% in 2090. While there is some climate model spread regarding the magnitude of losses in grazing potential, all 10 GCMs agree on the direction of change and the general trend of larger losses under the low emissions scenario SSP1-RCP2.6. The effect of higher warming under SSP3-RCP7.0 may be partially offset by an increase in precipitation, combined with a better water-use efficiency of plants due to the higher atmospheric CO_2 concentration, whereas lower warming is projected to coincide with a decrease in precipitation during the second half of the 21st century in SSP1-RCP2.6.

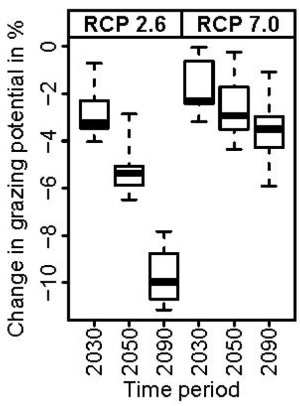


Figure 43: Change in country-scale annual grazing potential for the two emissions scenarios and three time periods. Boxplots show range over 10 GCMs.

The picture becomes more varied when going from the national to the regional scale (Figure 44). While the overall trend for Burkina Faso is negative, parts of the Sahel region are projected to experience a slight increase in grazing potential in 2030 under SSP1-RCP2.6. This positive trend reverses later in the century with grazing potential in the Sahel region falling by 1% below historical levels around 2050 and by 4% below historical levels by 2090. However, there is substantial uncertainty among the GCMs: Only 4 of the 10 GCMs show a positive change in grazing potential in 2030. This goes down to 3 GCMs in 2090. So, while the multi-model mean shows a decrease in grazing potential, the model range still includes the possibility of a positive trend in the Sahel region.

The Sahel region is projected to experience a more pronounced increase in grazing potential under SSP3-RCP7.0, going from 1.5% in 2030 to 4% in 2050 and 10% in 2090. There is also better confidence, with 8-10 of the 10 GCMs agreeing on the direction of change. Positive trends in grazing potential also extend into parts of the Centre-Nord and Est regions. However, the majority of GCMs show an overall decrease of grazing potential for both regions.

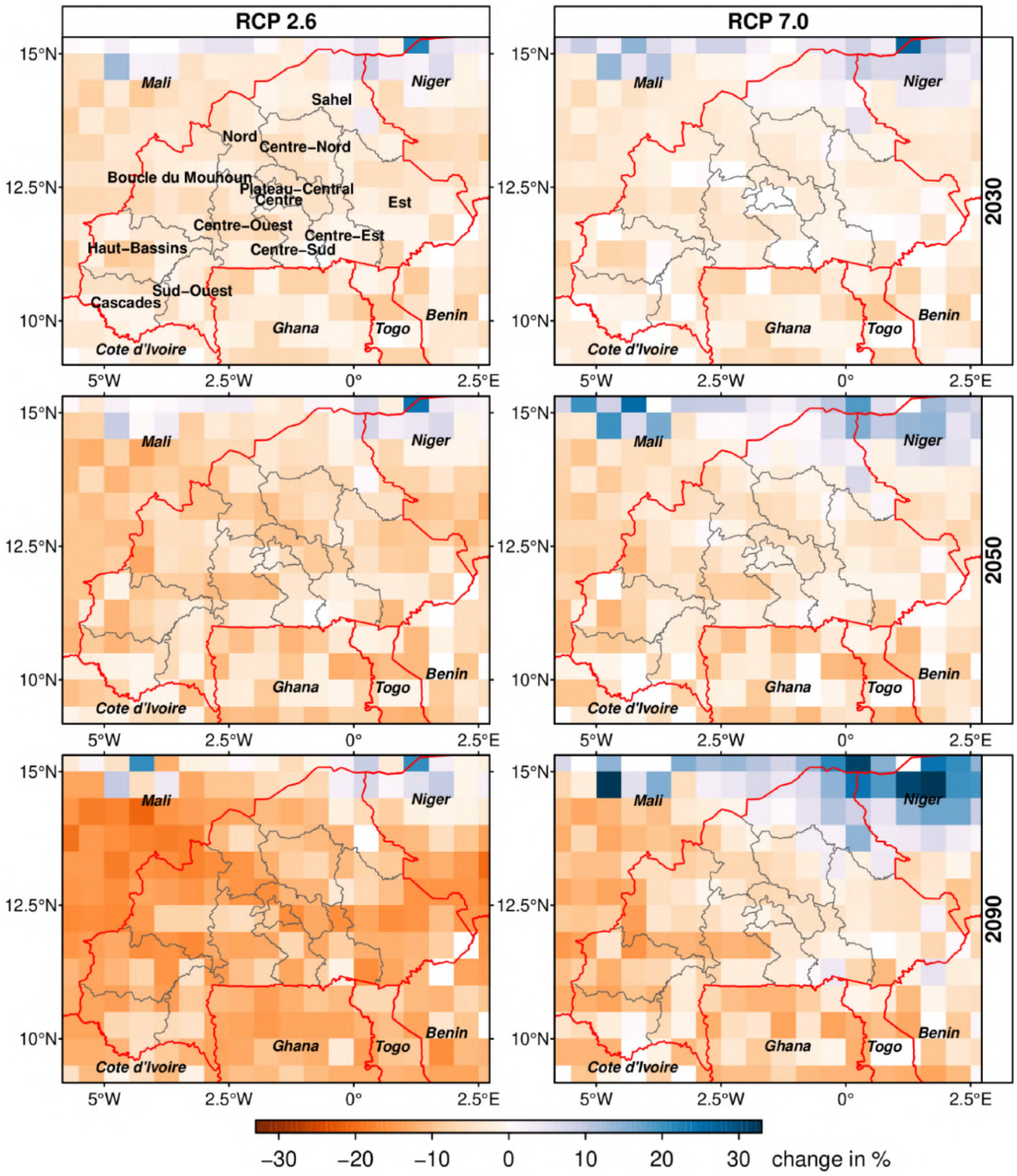


Figure 44: Multi-model ensemble median of change in annual grazing potential for three time periods (2030 top, 2050 middle, 2090 bottom) and two emissions scenarios (SSP1-RCP2.6 left, SSP3-RCP7.0 right). Changes are relative to the historical period shown in Figure 36.

Box: Mowing as an adaptation option

One adaptation option for the livestock sector is mowing.[9] Mowing and storage of fodder have been proposed by the Burkinabe government as a good pastoral practice for sustainable land management (Government of Burkina Faso, 2015a), as this practice is expected to:

- improve the availability of fodder in terms of quantity and quality during the dry season,
- lead to better pasture management and better use of fodder,
- allow for intensification of animal production and
- reduce the risk of bush fires.

To analyse the potential of mowing as an adaptation option, four different mowing regimes have been tested: one single mowing event per year on October 1st (M1), two mowing events per year on August 1st and October 1st (M2), three mowing events per year on May 1st, August 1st and October 1st (M3), and one single late mowing event on November 1st (M4). The potential effects of mowing are represented in the model as the complete removal of the leaf biomass of grasses down to a stubble height of roughly 5 cm on predetermined mowing days.

Figure 45 compares annual yields in the different regions of Burkina Faso under grazing management (marked "G" in the Figure) and four different mowing management regimes (marked "M1" to "M4" in the Figure). The first column presents results for the historical period (1995–2014). Averaged across all years and GCMs making up the historical ensemble, mowing leads to higher grassland yields than grazing in all regions except Centre-Nord, Nord and Sahel. Mowing is shown to improve yields by up to 60% compared to grazing in the Cascades region and by up to 56% in the Sud-Ouest region. The positive effect lessens towards the north. The regime with two annual mowing events on August 1st and October 1st (M2) is shown to be the most productive of the four tested options. The regime with one late mowing event on November 1st(M4) is not beneficial as it leads to lower yields than grazing in most regions.

The beneficial effect of mowing on grassland yields continues under climate change. There is a slight increase over the three future periods under both emissions scenarios. Mowing is projected to increase yields by up to 89% over grazing yields in the 2090 period (multi-model ensemble mean, SSP1-RCP2.6, Sud-Ouest region). More importantly, whereas grazing yields are projected to decrease under future climate change in all regions except the Sahel, mowing yields are not only higher than grazing yields, they also increase compared to the historical period. These results provide a strong argument in favour of expanding mowing as a grassland management regime in order to adapt to climate change. There are some caveats though:

- Mowing yields appear to have a larger uncertainty than grazing yields, as evidenced by the larger length of the boxplots in Figure 45. These show the spread of annual mowing yields over the 20 years and 10 GCMs that fall into the period mean and suggest a higher inter-annual variability of mowing yields compared to grazing.
- Mowing only one or two times a year implies the need for storage facilities to safely conserve fodder for the rest of the year. Losses during storage may partially offset the benefits of higher mowing yields.
- Mowing requires more manual labour and equipment than grazing.

Mowing could be used to replace grazing completely. This would take full advantage of the higher yield potentials of mowing compared to grazing. Even if grazing remains the dominant form of livestock rearing, dedicating part of the grazing land to mowing could provide fodder reserves to bridge lower grazing potentials during the dry season on the rest of grazing land.

9 While mowing was one of the pre-selected adaptation strategies, it was not chosen as a priority adaptation strategy during the stakeholder workshops for a detailed three-step adaptation analysis conducted in the second part of the study. Therefore, it is discussed as a short discursion as part of the climate impacts on livestock chapter.

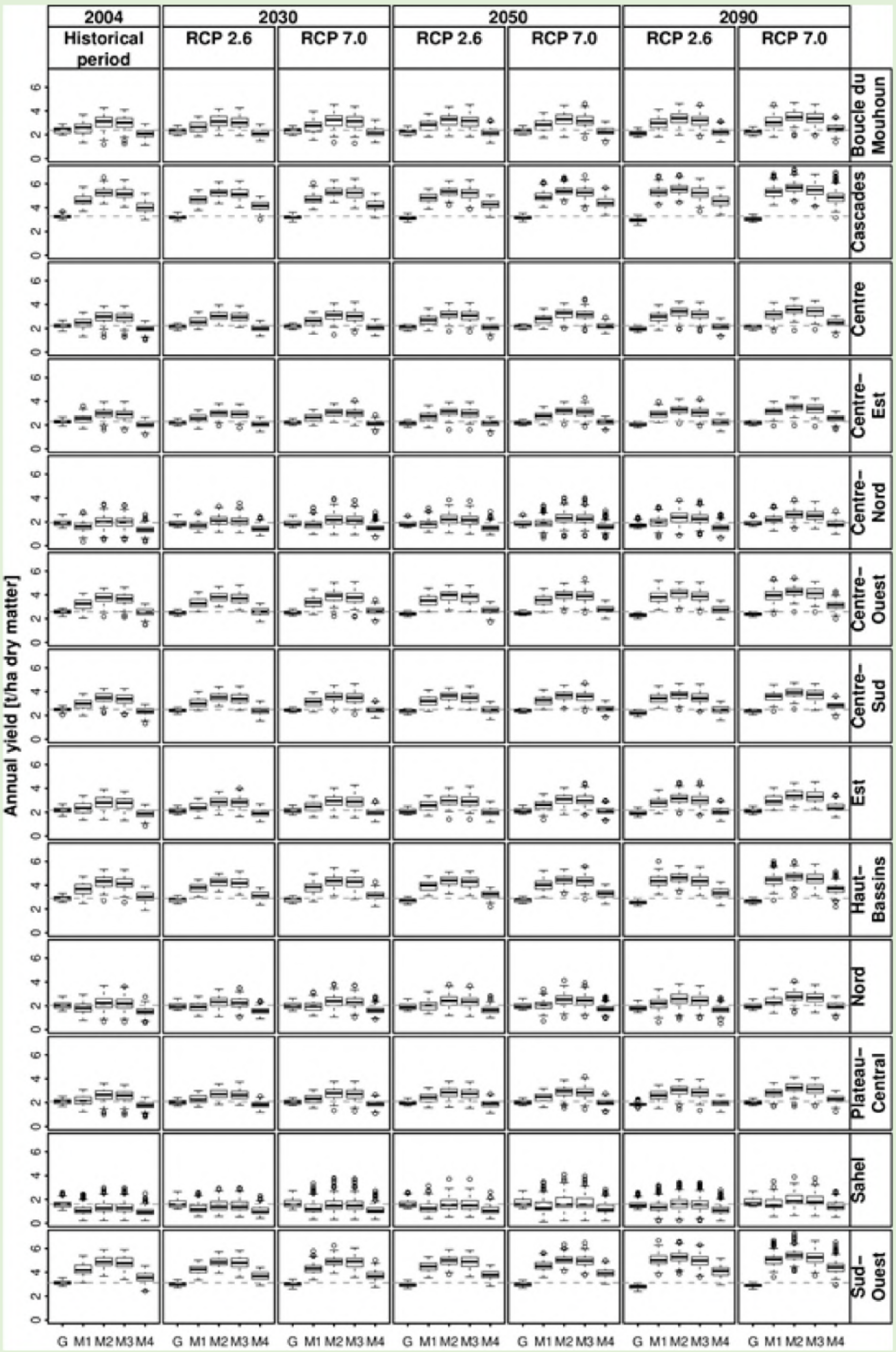


Figure 45: Grassland yields under grazing and mowing management. Each row shows results for one region. Each panel in a row is for one time period and emissions scenario. Within each panel, the first boxplot shows annual yield under grazing, the other four boxplots show yields for four different mowing regimes (see text for details). The length of each boxplot illustrates the spread across 10 GCMs and 20 years and can be considered a measure of uncertainty. The horizontal dashed line in each row denotes the grazing yield during the historical period and provides a visual guide to quickly assess whether yields increase or decrease under the mowing regimes or under climate change.

Chapter 4 Summary

This chapter analysed the consequences of climate change on the livestock sector. The analysis focused on climate-driven changes in grazing potential under two future climate change scenarios (SSP1-RCP2.6 and SSP3-RCP7.0). Historical grazing potentials show a substantial spatial gradient across Burkina Faso, with grazing potentials in the south more than twice as high as those in the north. There is high agreement among climate models that grazing potentials will decrease under both future climate change scenarios.

Projected losses in grazing potential are higher under the low emissions scenario SSP1-RCP2.6 than the high emissions scenario SSP3-RCP7.0. Grazing potentials in the Sahel region show a slight increasing trend in some climate model simulations that is contrary to the trend for the rest of the country. While there is high model agreement on this positive trend under the SSP3-RCP7.0 scenario, only a small minority of models project an increasing trend in the Sahel region under the SSP1-RCP2.6 scenario.

Table 6: Climate impacts on livestock production.

Impact		Trend past	Trend future	Confidence
	Livestock number	Increasing	- no data -	-
	Fodder availability, grazing potential	Decreasing	SSP1-RCP2.6 Decreasing SSP3-RCP7.0 Decreasing slightly	High

PART II – ADAPTATION

The first part of the climate risk analysis focused on the impact dimension, starting with climate impacts on temperature and precipitation, moving on to impacts on water availability and, finally, looking at impacts on crop and livestock production. In the second part of the climate risk analysis, these findings will support the assessment of four selected adaptation strategies in the context of Burkina Faso's agricultural sector.

As part I shows, Burkina Faso's agricultural sector will be significantly impacted by projected climatic changes. Adaptation will be necessary to safeguard livelihoods and ensure food and nutrition security. From a wide variety of possible adaptation strategies, four adaptation strategies – namely provision of climate information, integrated soil fertility management, irrigation and use of improved crop varieties – were carefully selected for analysis based on the interest of a wide range of local stakeholders and experts as well as on priorities outlined in Burkina Faso's National Adaptation Plan (NAP). The NAP emphasises the exposure of the agricultural sector to the effects of climate variability and climate change (Government of Burkina Faso, 2015a). It rates the agricultural sector as one of the four most vulnerable sectors in the country, next to water resources, livestock and forestry, all of which are interconnected and depend on each other. Hence, Burkina Faso's NAP recognises the importance of adaptation to climate change, putting forward long-term adaptation objectives to ensure sustainable food and nutrition security (Government of Burkina Faso, 2015a). The country's Accelerated Growth and Sustainable Development Strategy (AGSDS), on the other hand, identifies the agricultural sector as a priority area, with efforts focusing on developing cereal, oilseed, vegetable, fruit and cotton production (Ministry of Economy and Finance, 2012). However, the NAP rightly states that the objectives of the AGSDS will be difficult to achieve unless adaptation to climate change is addressed (Government of Burkina Faso, 2015a).

Chapter 5 – Methods and data for adaptation assessment

Having established the impacts of climate change on agriculture, the four selected adaptation strategies are now assessed within a multi-criteria framework to facilitate policy design and derive recommendations for adaptation investments on the ground. The discussed adaptation strategies were selected based on national policy priorities, stakeholder interest and in consideration of the results of the climate impact analysis described in Part I of this study. Then, a multi-criteria analysis has been applied with the help of eight assessment indicators. The overall assessment is based on three pillars: a modelling approach, literature review, and local knowledge gathered during stakeholder workshops, expert interviews and household-level data collection.

To ensure the suitability of our study results for decision-makers and to achieve a continuous engagement of local experts and stakeholders we closely collaborated with a regional partner organization throughout the entire study process: the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

In the following, the methods applied for the selection and assessment of adaptation strategies will be described in more detail.

5.1 Selection of adaptation strategies

The selection of adaptation strategies represented the first step of the analysis. To enhance the policy relevance of this study, the selection process was carefully designed to best align with local priorities and interests of different stakeholders from across government, academia, private sector and civil society. As the results of this study are meant to inform adaptation policy, to incentivise adaptation action and to be useful also for the implementation of adaptation strategies on the ground, special emphasis was placed on engaging relevant stakeholders in a process of continuous learning and collaborative adjustment. This was achieved through several engagement steps, namely stakeholder workshops, expert consultations, validation of decisions and feedback rounds with stakeholders, expert surveys, farmer interviews as well as a final presentation and validation of results.

In the first phase of the process, a stakeholder workshop was held in Ouagadougou in May 2020. Participants from government, academia, civil society and development organisations with backgrounds in climate change, agriculture, livestock, forestry, water management and development came together. Due to prevailing health and safety as well as international travel restrictions during the Covid-19 pandemic, the workshop was organized by WASCAL repeatedly over several days with a limited number of participants attending each day and abiding to strict social distancing and hygiene rules. PIK scientists joined virtually from Germany for a 2-hour discussion at each workshop day. Despite challenging circumstances, a total of 46 stakeholders were able to join the workshop. The main objectives were to introduce the study approach, to jointly discuss crucial design elements of the study and to foster a common understanding of the relevance of the study. In addition, the workshop served to discuss and prioritize four adaptation strategies to be included in the study.

Burkina Faso's NAP and NDC served as a starting point for creating a long list of adaptation strategies, complemented by additional strategies collected from the National Climate Change Learning Strategy (SNACC 2016-2025) and from an overview document on "Good Practices of Sustainable Land Management in Burkina Faso" from the Ministry of Environment (Government of Burkina Faso, 2011, 2015a, 2015b, 2016). The authors of this study then made a pre-selection of adaptation strategies that aligned with the identified climate risks, matched the purpose of this analysis (crop and livestock related) and were suitable for the analysis with our crop and economic models. This generated a list of eight potential adaptation strategies, out of which stakeholders then prioritised four strategies to be included in the analysis (Figure 46).

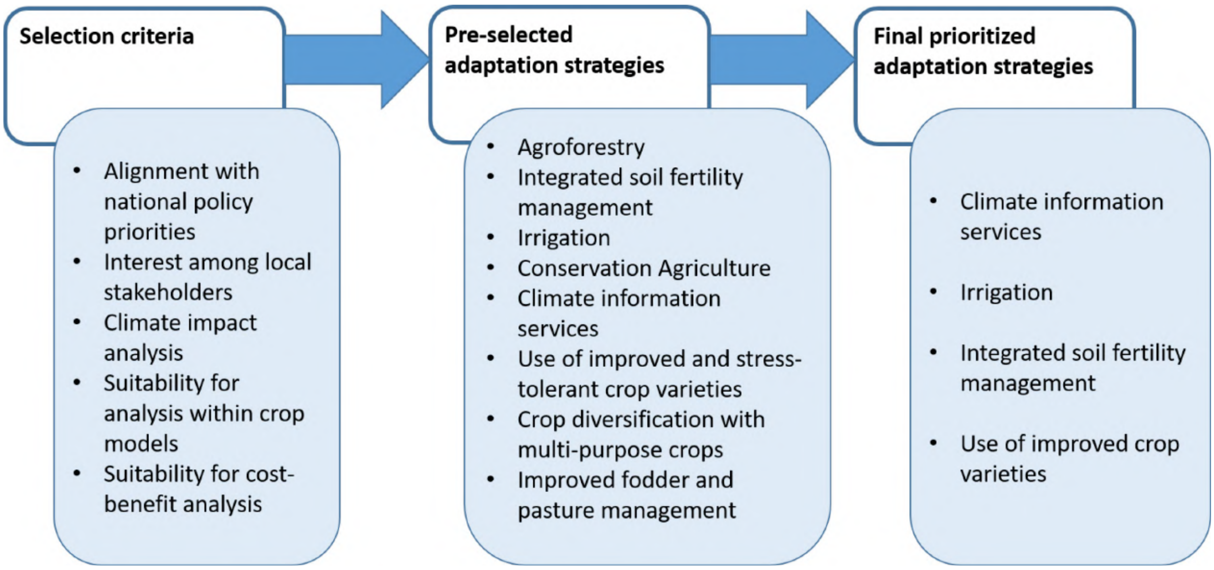


Figure 46: Overview of the selection process of adaptation strategies assessed in the study.

Across all documents, the term "adaptation strategy" was used in different degrees of specification. For the long list of adaptation strategies and the prioritization process with stakeholders, we subsumed several specific technologies under umbrella terms. For example, the term "Integrated soil fertility management" was defined to encompass different specific single or combination of technologies with the purpose of soil conservation such as use of compost, creation of zai pits, half-moons, contour stone walls or infiltration basins (for detailed descriptions see Chapter 9). This served to ensure that priorities of stakeholders were first of all captured regarding overall problem areas and not with regard to preferences of specific technologies within these areas. Stakeholders were invited to discuss the current use in small groups, as well as the state of knowledge and potential of each adaptation strategy in the context of Burkina Faso, before voting individually for the four strategies they deemed most relevant for the analysis. After the selection process, the four adaptation strategies were further specified together with WASCAL, using concrete interventions subsumed under the general adaptation strategies to enable model-based analysis.

The four final adaptation strategies are:

- climate information services
- irrigation
- integrated soil fertility management
- use of improved crop varieties.

They will be assessed in individual chapters (Chapters 7-10 of this report), following eight assessment criteria that will be further presented in the next section.

5.2 Multi-criteria assessment of adaptation strategies

The selected adaptation strategies were subjected to an in-depth assessment based on a mixed-method approach based on the following eight criteria:

1. **Risk mitigation potential:** A key assessment criterion for adaptation strategies is their potential to mitigate climate risks, i.e. to reduce yield losses due to climate change. This is assessed based on the crop model results.
2. **Risk gradient (risk-independent vs. risk-specific):** Adaptation strategies can be useful even in the absence of climate change. Such risk-independence is relevant especially in case of uncertainty regarding future climate change impacts. Risk specific strategies are only beneficial if the projected climate impacts actually occur. The risk gradient is assessed based on the crop model results.
3. **Cost-effectiveness:** A cost-benefit analysis on farm level provides information on the costs and cost-effectiveness of the different adaptation strategies depending on the emissions scenario.
4. **Upscaling potential:** In this category, we explore how much further potential there is to apply different adaptation strategies in Burkina Faso, based on current adoption and expert opinion.
5. **Potential co-benefits:** Many adaptation strategies do not only adjust systems to cope with climate risks but have other potential benefits, such as reducing socio-economic or gender inequalities, environmental benefits or creating new market opportunities.
6. **Potential maladaptive outcomes:** Some adaptation strategies may also produce undesired effects for society, climate and environment, which need to be considered for a comprehensive assessment and which are discussed within the scope of this indicator.
7. **Barriers for implementation:** Potential barriers to adopting an adaptation strategy and possible solutions are discussed.
8. **Institutional support requirements:** While all adaptation strategies benefit from an enabling environment that can be created through institutional support, the amount of support needed differs. A distinction can be made between strategies which generally require high institutional support and those that can be initiated by farmers themselves (institution-led vs. autonomous).

Criteria 1-3 are evaluated based on our crop and economic models, while criteria 4-8 are evaluated based on literature review, expert consultations and farmer interviews. In the following sub-chapters, we will describe the method applied for criteria 1 and 2 using crop models, followed by a description of the method for criteria 3 using a cost-benefit analysis.

5.3 Biophysical assessment of risk mitigation potential

We used the process-based crop model DSSAT as employed in chapter 3 to quantify the risk mitigation potential of adaptation strategies using sorghum as a case study. Within the crop model, it is possible to perform simulated experiments to predict and understand the effects of different agricultural practices, with enough certainty to guide the development of agricultural policies. We changed key parameters in the model as compared to the baseline settings to simulate the yield effect of the applied adaptation strategy under current as well as future climate. To assess the risk mitigation potential of the adaptation strategy, we assess the yield impact of the adaptation strategy under current and projected future climate conditions. For a positive risk mitigation potential, the adaptation strategy needs to create a net positive yield impact under future climate conditions compared to current climate conditions.

As a crop model-based assessment is not possible for all adaptation strategies and crops, we complemented the analysis with findings from literature.

5.4 Cost-benefit analysis

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

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

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

The CBA for each adaptation strategy is based on selected case studies from different villages in Burkina Faso. For each strategy, we collected detailed cost and production data from 10 farmers who were implementing the technology as well as from 10 control farmers who did not. Local yield levels were used as baseline values for the no-adaptation scenario. Future yield changes resulting from climate impacts under different emissions scenarios are calculated from our crop model outputs in the case of sorghum. For maize projections, due to a lack of data for Burkina Faso, we rely on crop model results from selected districts in North-West Ghana, where production and climate conditions are largely comparable to case study districts of Burkina Faso. We have conducted the following CBA case studies:

1. Complementary irrigation in rain-fed maize cultivation
2. Implementation of soil and water management technologies in rain-fed sorghum cultivation
3. Use of improved varieties in rain-fed sorghum cultivation
4. Use of climate information services in rain-fed maize cultivation

Chapter 6 – Adaptive capacity and relevant factors in adaptation planning

Before analysing the potential of the four identified adaptation strategies in detail, this chapter presents various aspects of the concept of adaptive capacities, as well as factors that need to be taken into consideration when planning for adaptation, including access to resources, the local context and diversity, knowledge and information, as well as governance, institutions and networks. In addition, the aspect of gender and its constituting differential vulnerabilities and implications on adaptation capacity will be discussed.

6.1 Adaptation and adaptive capacity

Moser and Ekstrom define adaptation as follow: “Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting non-climatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities” (Moser & Ekstrom, 2010). In a similar way, Adger et al. (2005) state that adaptation to climate change can be motivated by many factors, including economic well-being and safety.

Successful adaptation requires not only the selection of suitable adaptation strategies but also increasing the adaptive capacity of human and natural systems since this will determine the potential for sustainably implementing adaptation strategies. The IPCC defines adaptive capacity as “the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences” (IPCC, 2014). While the historical underpinnings of adaptive capacity lie in sociology and in organisational and business management, the term has become integral in addressing climate change. As the above definition already shows, there are different types of adaptive capacity. Adaptation can be implemented in preparation for or in response to impacts generated by a changing climate (Adger et al., 2005; Engle, 2011). Reactive adaptation refers to the ability to adapt to a changing environment, i.e. responding to a stress that has occurred in the past, anticipatory adaptation means the ability to anticipate future stresses, based upon “one’s ability to understand what the future might resemble [and] influenced by one’s ability to have learned from past experiences” (Engle, 2011). This climate risk analysis is based on the principle of anticipatory adaptation, i.e. to model the future climate based on historical data and in this way select suitable adaptation strategies for anticipatory planning.

6.2 Factors in adaptation planning

There are a variety of factors which need to be considered when planning suitable climate change adaptation. Adaptation should be considered as a dynamic social process. According to Basson et al., leadership, organisational structure, collaboration, networking, stakeholder engagement and access to information are factors which allow for a successful adaptation process (Basson et al., 2020). In a similar way, Tompkins lists support networks, strong governance and willingness to learn as enablers of successful adaptation to climate change (Tompkins, 2005). Adaptation processes are dependent on each actor’s capability of power to exercise choices and more broadly on social capital, meaning the interdependence of the various actors through their relationships with each other, with the institutions in which they reside, and with the resource base on which they depend (Adger, 2003, Ribot and Peluso, 2003). In a climate risk study carried out for Ethiopia, (Murken et al., 2020) four factors have been identified: access to assets, diversity and flexibility, learning and knowledge, and governance and institutions. In the following, these four factors will be further adapted and discussed in the context of climate change adaptation in Burkina Faso.

6.2.1 Access to resources

Several studies mention the lack of access to resources as the main barrier to climate change adaptation (Acquah, 2011; Moser & Ekstrom, 2010; Shackleton et al., 2015; Sorgho et al., 2020). Resources are important at every stage of the adaptation process and include natural, financial and technical resources, information and expertise regarding climate change and adaptation options, labour, transportation and time. In a study conducted in two farming communities in northern and southern Burkina Faso, 78% of farmers responded that the high cost of inputs (e.g. improved seeds, fertilisers or pesticides) has been the main barrier to adopting climate-smart agricultural practices. 55% of farmers reported the lack of financial resources, including lack of capital and lack of access to credit, as another barrier (Yaméogo et al., 2017). According to Moser and Ekstrom (2010), inadequate resources are often the first response to the question why practitioners have not yet begun to plan for climate change adaptation. Furthermore, both Murken et al. (2020) and Shackleton et al. (2015) mention shortages in water availability as a frequent challenge to adopting adaptation strategies in agriculture, such as irrigation. It is important to notice that the ability to benefit from the various resources needed is mediated by constraints established by the specific political-economic and cultural frames within which farmers seek to access those resources. Constituting factors include a number of "structural and relational access mechanisms", including access to education and knowledge, access to technologies, access to markets, access to labour and labour opportunities, access to authority and access via the negotiation of other social relations (Ribot and Peluso, 2003).

6.2.2 Local context and diversity

The design and implementation of adaptation strategies frequently fails to adequately recognise local contexts and the heterogeneity inherent to them. Local contexts are shaped by culture (e.g. values, norms and beliefs), different levels of governance and political systems, ecosystems and social networks. These interacting factors are crucial in planning for climate adaptation (Shackleton et al., 2015). They can either serve as enablers or as barriers to successful adaptation strategies. In northern Burkina Faso, different ethnic groups and, accordingly, different cultural values allowed one group while preventing another from diversifying their livelihood strategies, for example by taking advantage of development projects, gardening and engaging women in economic activities (Nielsen & Reenberg, 2010). Different factors, including gender, age, class, religion and ethnicity, influence people's adaptive capacities (Biesbroek et al., 2013; Shackleton et al., 2015). Nielsen and Reenberg (2010) refer to these factors as "varied sensitivities": Different groups experience climate risks, impacts and opportunities for adaptation differently. Poor and marginalised people in low-income countries are likely to face barriers to adaptation, such as lack of access to credit, decision-making power, information and natural resources, like land or forests (Engle, 2011; Shackleton et al., 2015). Also, some groups, in particular women, will find it more difficult to migrate (Shackleton et al., 2015). "An explicit focus on intersecting dimensions of inequalities would help identify the complex drivers that prevent certain groups of disadvantaged people from successfully adapting to climatic change, while others may be more fortunate or even benefit" (Shackleton et al., 2015). Furthermore, even if adaptation strategies are in place, their mere existence does not guarantee equal access: According to Ludi et al. (2012), the establishment of irrigation infrastructure can serve to maintain social exclusion, in particular that of women, who may lack the money to pay for bribes or the social status necessary to make claims to it.

While from an external perspective, climate change may seem a pressing issue in countries around the world, including those of the Sahel region, several scholars argue that there may be other, possibly even more immediate problems (Brockhaus et al., 2012; Shackleton et al., 2015). According to Brockhaus et al. (2012), this is also the situation in Burkina Faso, where various stakeholders at the community and subnational level named climate change as only one of many stressors. Other issues are related to, for example, population growth, ethnic conflicts or health risks (e.g. HIV/AIDS) (Shackleton et al., 2015). Indeed, in the climate risk analysis conducted in Ethiopia, informants identified population growth as a major pressure, increasingly reducing farmland size and leading to farmland fragmentation (Murken et al., 2020). These are often more immediate and more short-term stressors and are, therefore, given priority.

6.2.3 Knowledge and information

According to Shackleton et al. (2015), climate uncertainty and variability, a lack of information regarding extreme weather events and poor predictive capacity at a local scale present frequent barriers to climate adaptation. Hence, knowledge and information on climate risks are key in designing and implementing suitable adaptation strategies. Local value and belief systems determine the ways in which people understand and interpret climate risks (Moser & Ekstrom, 2010). Concrete experiences with climatic stressors and responses to these stressors also play an important role: On the one hand, experience with climatic stressors, such as droughts, can serve as a critical trigger and motivate people to invest in adaptation strategies (Shackleton et al., 2015). This is particularly true when yields are negatively affected, since, according to Akponikpè et al. (2010), farmers do not perceive climate in meteorological terms but in terms of agricultural activities. On the other hand, phenomena like climate variability have been an integral part of many people's lives across the Sahel. This is why they may view it as a natural phenomenon and beyond human control, and as a result under-estimate the severity of a changing climate (Shackleton et al., 2015). Therefore, effective communication about climate risks is important to increase awareness and understanding. According to a study conducted in two villages in northern and southern Burkina Faso, limited access to knowledge and lack of access to information acted as major obstacles to adopting climate-smart agricultural practices (Yaméogo et al., 2017). Conversely, Mubaya et al. (2012) found that farmers with access to weather information were more likely to be aware of changes and to adjust accordingly.

One of the major problems underlying climate information is that it relies on knowledge about long-term impacts, and "this knowledge is riddled with uncertainties" (Vink et al., 2013). Also, the long-term character of adaptation to climate change requires several policy cycles before the effects of adaptation strategies can be evaluated. This temporal dimension and the (perceived) uncertainty attached to it complicate prioritisation and decision making in adaptation planning (Hovi et al., 2009; Lazarus, 2009).

6.2.4 Governance, institutions and networks

Governance, institutions and networks are key elements to create an enabling environment for climate change adaptation (Adger et al., 2005; Biermann et al., 2010; Brockhaus et al., 2012; Moser & Ekstrom, 2010). Those elements involve different actors, levels, scales and sectors, all of which interact with each other.

The design and implementation of adaptation strategies is conditioned by existing policies, laws, rules, regulations, programs and mandates (Moser & Ekstrom, 2010). These institutional frameworks, Brockhaus et al. (2012) argue, are necessary for a shift from a reactive response to climate impacts, often happening on the local level, to sustainable and systematic climate action. Macro-level adaptation planning, such as at the national or international level, must also take location-specific adaptation needs, capacities, and capabilities of local communities into consideration: "While the institutions operating at the macro level may be able to create an enabling environment for adaptation at the national level, their levels of engagement tend to leave large gaps in adaptive responses at the local level, ignoring important actors in understanding the relationship between climate trends and adaptation outcomes at the local level" (Amaru & Chhetri, 2013).

Therefore, Amaru and Chhetri (2013), argue that adaptation to climate change should draw attention to and actively engage a broad set of stakeholders, including farmers, their supporting organisations, communities, public institutions, civil society (e.g. NGOs), international agencies and the private sector. These interdependent stakeholders bring different interests, responsibilities and problem framings to the table, some of which may conflict with each other (Rodima-Taylor, 2012; Vink et al., 2013). At the same time, they contribute with their insights, knowledge and resources which can greatly facilitate successful adaptation planning. Adger et al. (2005) say that adaptation to climate change involves "cascading decisions" across this stakeholder landscape. While it is important to bring different stakeholders together, it is also important to mainstream climate change adaptation across various sectors. Brockhaus et al. (2012) conducted several studies at different levels in Burkina Faso and Mali and observed a strong sectoral thinking among government actors who did not see climate change adaptation as a cross-sectoral activity but looked at sectors like water and forests independently.

Finally, in addition to governance and institutional frameworks, it is important to include local communities in adaptation planning to create ownership, taking into account informal networks which are organised around kinship and friendship, and customary institutions such as locally accepted resource management practices, norms and taboos (Amaru & Chhetri, 2013; Yaméogo et al., 2018). Informal networks can provide quick and more easily accessible help in climate adaptation, for example, through shared information and knowledge. These networks can also serve as financial resources for credit, either informally from relatives or friends or more formally through farmers' associations (Yaméogo et al., 2018). Social connectivity can have also negative effects: If exclusive and rigid, social networks can serve to reinforce existing power structures and further marginalise already disadvantaged groups. They can also serve as a barrier to learning, if conventional wisdom is left unchallenged (Newman & Dale, 2005; Wolf et al., 2010).

6.3 Gender, vulnerability and climate adaptation in Burkina Faso

A growing body of literature recognises the fact that different social groups experience different levels of vulnerability to climate change as well as different levels of adaptive capacity (Alston, 2013; Arora-Jonsson, 2011; Perez et al., 2015; Rao et al., 2019). Different social groups have different assets and skills available to them as well as different responsibilities and roles within their families and communities (Carr & Thompson, 2014). At the same time, these diverse roles and specific knowledge e.g. with regard to agricultural practices make them powerful agents of change while facing the challenges of climate change, highlighting thus the importance of acknowledging gender differences and marginalized groups in decision making. Although gender is not the only factor, it is regarded as critical in determining vulnerability to climate change and adaptive capacity (Ahmed et al., 2016). "In the vulnerable space following disasters, it appears that gender inequalities are being consolidated and legitimated in ways that reduce women's adaptive capacity," says Alston (2013).

6.3.1 Gender in national plans and policies

In its NDC, Burkina Faso barely touches upon gender and women's situation in the face of climate change (Government of Burkina Faso, 2015b). The NAP, on the other hand, addresses gender more systematically, as it recognises a male bias in adaptation planning and emphasises the need for gender mainstreaming in adaptation planning (Government of Burkina Faso, 2015a). It also highlights gender as one of six guiding principles, among participation, coherent intervention, stakeholder empowerment, equitable implementation and principle of partnership (Government of Burkina Faso, 2015a). More specifically, the NAP identifies education and training about climate risks, access to technical equipment and access to decision-making processes as priority areas for women (Government of Burkina Faso, 2015a). Further commitments to gender are reflected in the Strategy for Accelerated Growth and Sustainable Development (AGSDS), which addresses gender inequalities, particularly in rural areas, and the need for improved access to resources, basic social services and decision-making spheres for women (Ministry of Economy and Finance, 2012). Like the NAP, it calls to the National Gender Policy, which was adopted in 2009 and which is meant to promote the equitable development of men and women and ensures equal access to and control of resources, decision-making processes and basic rights (Ministere de la Promotion de la Femme, 2009).

6.3.2 Determining factors of gender-specific vulnerability to climate change

Assets and resources

Women tend to have poorer access to and control over income and production factors, such as seeds, fertilisers or ploughs (Ahmed et al., 2016; Alston, 2013; Kakota et al., 2011; Tall et al., 2014). Kieran et al. (2012) conducted interviews in Didyr and Doudoulcy, two rural communities in central Burkina Faso, and the majority of women reported that joint decision-making among couples was rare, with men making the majority of decisions. Dickin et al. (2020) confirm this inequality in their study of household water security in the Centre-East region of Burkina Faso: Women had limited control over income and assets such as cash to pay for water fees or bicycles/motorbikes for transportation of water. A FAO report estimates that if women had the same access to resources as their male counterparts, they could increase crop yields on their farms by 20–30% (FAO, 2011).

Land and tenure insecurity

Tenure insecurity and social customs result in few women owning land (Kieran et al., 2012). Participants in a multi-national study, including Burkina Faso, report that in reality only men own and inherit land, while women cultivate land that is given to them by their husbands or which they rent from their community (Perez et al., 2015; Rigg et al., 2016). Even Muslim women who have normally the right to inherit a half of their husbands' land assign most of the time their bequest to their brothers (FAO, 2007). This goes along with the overall trends identified for Sub-Saharan Africa, showing that around 61% of those working in agricultural and related activities are women, whereas women make up only 14% of landholders (UN Women, 2019). Hence, restricted access to and control of land keep women from making longer-term investments, such as implementing adaptation strategies (Bryan et al., 2018; Jost et al., 2016).

Climate change knowledge

There are enduring differences of climate change knowledge. Women also face barriers when accessing climate information, e.g. due to insufficient literacy or lack of a radio or mobile phone, which translates into gendered perceptions of climate risks and corresponding adaptation decisions (Bryan et al., 2018; Rigg et al., 2016; Tall et al., 2014). Needs with respect to climate information can also be gendered: In a rural community in Senegal, women farmers specifically required information on precipitation because men were planting their plots first, only later assisting the women. Hence, it was particularly important for women to know about potential dry spells and the end of the rainy season (Tall et al., 2014).

Social customs and household responsibilities

Due to social customs, patterns of household responsibility and labour are also highly gendered, with women often taking on a triple role in productive, reproductive and community-managing activeties (Moser, 1993; Rigg et al., 2016). In the study by Kieran et al. (2012), women reported that men worked 14 hours and women 11 hours a day, however, they did not include the time for household chores, collecting wood or water. These are almost exclusively women's responsibilities (Dickin et al., 2020; Rigg et al., 2016). A study by Dickin et al. (2020) showed that water collection was carried out largely by adult women (92%). Adding this chore to other household responsibilities and work on the fields, including travel time to water wells, women are presented with multiple burdens (Dickin et al., 2020). This is particularly true for the dry season, when travel time to water wells increases and when many men migrate for work, either to larger cities, gold mining areas or neighbouring countries, such as Côte d'Ivoire (Dabiré et al., 2018; Kieran et al., 2012). These are all factors limiting women's mobility and income sources. Hence, women's livelihoods heavily depend on farming and livestock, which are increasingly sensitive to climate impacts (Alston, 2013; Belcore et al., 2020).

6.3.3 An intersectional perspective

It is not only gender, which determines vulnerability to climate change. Instead of focusing exclusively on gender, Ahmed et al. (2016) adopt a broader lens, speaking of "a landscape of vulnerability where diverse social descriptors including disability, social class, ethnicity and value systems create heterogeneous conditions" for climate adaptation. Factors, such as marital status (e.g. married, divorced, widowed), a growing family or poor health can all increase women's vulnerability (Nyantakyi-Frimpong, 2019; Van Aelst & Holvoet, 2016). Nyantakyi-Frimpong (2019) carried out research on smallholder farmers' vulnerability to climate extremes in northern Ghana. The study was highlighting the importance of an intersectional perspective. i.e. taking into account different social factors, with the example of a woman farmer, who was "not just a woman, but also a woman, who is HIV-positive, poor and widowed, with no spouse to handle the everyday village politics of securing a plough" (Nyantakyi-Frimpong, 2019).

While much has been written about gender and vulnerability, there is a growing body of literature emphasising women's agency in climate adaptation (Aguilar, 2013; Alston, 2013; Bee et al., 2013; Rao et al., 2019). While it is true that women have limited access to finance, land or information, they also hold critical local knowledge related to agriculture, fisheries, water and energy which can help to address the design of effective climate adaptation policies and the implementation of adaptation strategies (Alston, 2013). Often being the principal managers of natural resources, women tend to be closer to nature, partly due to their stronger reliance on natural resources, and therefore more environmentally conscious (Arora-Jonsson, 2011; Figueiredo & Perkins, 2013). Therefore, equal participation and influence by women and men in adaptation-related decision making, including representatives of marginalized groups, enables capacity building and creates the conditions for inclusive implementation.


SAMSUNG

Chapter 7 – Climate information services

7.1 Context and description of the adaptation strategy

Information and knowledge exchange are key to managing climate risks and mitigating climate-related impacts on agricultural crops, water resources and food security. Climate information services (CIS) can help to bridge existing information and knowledge gaps. Tall (2013) defines CIS as a timely decision aide based on climate information that assists individuals and organisations to improve ex-ante planning, policy and practical decision-making. CIS thus include the production, translation, dissemination and use of climate information for different target audiences, usually in climate-sensitive sectors, such as agriculture, water, health or disaster risk reduction (Carr et al., 2020; Tall, 2013). According to Zongo et al. (2015a), CIS usually provide seasonal estimates of the starting and ending dates of the rainy season, the length of the rainy season, the number of days with precipitation, the annual cumulative precipitation, and the average and maximum duration of dry spells during the rainy season. Hence, CIS can facilitate the choice of planting dates, crop varieties, fertiliser application and other production factors (Klopper et al., 2006). CIS are typically produced by national meteorological agencies, research institutes and other intermediary organisations, such as environmental consultancies, but also increasingly by the private sector (Singh et al., 2018). According to a study by Zongo et al. (2015a), 93% of farmers who were interviewed for the study expressed an interest in climate information, in particular regarding the start of the rainy season.

The majority of weather and climate information for Africa is derived from global datasets, such as the Coupled Model Intercomparison Project (CMIP) Phase 5, and other projects with a broad geographical coverage (Singh et al., 2018). In addition to this global data, national meteorological agencies are mandated with the collection of observational data and the dissemination of weather and climate forecasts to different actors, including to communities, governments and the private sector (ibid). In West Africa, the AGRHYMET Regional Center, which is an institution of the Permanent Interstates Committee for Drought Control in the Sahel (CILSS), monitors and makes forecasts regarding meteorological, hydrological, crops and pastures conditions (Traore et al., 2014).

In Burkina Faso, a number of institutions provide weather and CIS. The National Meteorological Agency (ANAM), under the Ministry of Transportation, Urban Mobility and Road Safety, is responsible for the provision of weather and climate information to public and private users from different sectors (World Bank, 2017). However, according to a World Bank report (2017), ANAM's main observation infrastructure is considered fragile, with needs to strengthen technical, human and financial capacity. Furthermore, the range of services and levels of accuracy and reliability were considered limited. Finally, because of poor territorial coverage by observation equipment, data scale does not allow the provision of enough detailed information.

The Directorate General of Water Resources (DGRE), which is part of the Ministry of Water and Sanitation, is responsible for the monitoring of surface and groundwater resources and its different uses as well as the establishment of a relevant information system (WMO, 2006). The World Bank report (2017) cited earlier attests a poor network with few stations in Burkina Faso which are functioning properly or operating at all. Data collection and transmission are deemed equally poor as well as the state of technical equipment for discharge measurements.

With regard to monitoring food security and nutrition, the Early Warning System (Système d'Alerte Précoce, SAP) of the Ministry of Agriculture is a key institution. The SAP is responsible for monitoring the agricultural season, including through field missions, use of information transmitted by the ministries and analysis of satellite imagery. This monitoring helps to determine the start and end of the agricultural season, which is key for smallholder farmers, as well as food availability and the general food situation, including, for example, nutritional diversity. It is also used to monitor regional risks and to identify vulnerable populations based on both socio-economic data and level of exposure.

CIS development and policy

The development of CIS presents a priority area in agricultural development as well as in climate adaptation in Burkina Faso, which is reflected in several national policies and initiatives taken by the government improvement. For instance, the country's NAP is based on five strategic axes, one of which is the use of information systems (Government of Burkina Faso, 2015a). The NAP highlights the need for data, ranging from biophysical data, such as climate impact models, to socio-economic data, such as at the household and community level. The National Water Policy also emphasises the need for (1) a functioning water information system, including instruments for acquiring, processing and disseminating information on water needs, uses, impacts of uses and potential risks; and (2) for conducting relevant research at the intersection of water and climate change (Ministry of Agriculture and Irrigation Development of Burkina Faso, 2015b). In a similar way, the Rural Sector Programme stresses poor knowledge and information regarding water resources as major constraints to agricultural production (Government of Burkina Faso, 2012). It also mentions the need for the collection and dissemination of food and nutritional information in order to strengthen the SAP. The Rural Development Strategy 2016-2025 specifically stresses the weak state of water information systems in the country as well as the poor quality of meteorological information (Government of Burkina Faso, 2015b).

7.2 Biophysical assessment of risk mitigation potential

CIS are a promising adaptation strategy to address climate variability and change in Burkina Faso. As illustrated in Chapter 1, climate change leads to increasingly uncertain precipitation amounts. In addition, the number of dry spells, even during the rainy season, and the onset and length of the latter are becoming more and more uncertain. These climatic changes and uncertainties translate into uncertainties regarding water availability and agricultural production. CIS can help to compensate for these uncertainties by providing accessible, reliable and relevant weather and climate information data, e.g. by predicting amounts and seasonal distributions of precipitation (Carr et al., 2020) or by providing farmers with advice on the date for land preparation to reduce weeding or the choice of a particular crop variety (Alvar-Beltrán et al., 2020). In this way, CIS can help to mitigate the impacts of climate risks, enhance water resources and improve food security (Tall, 2013). Different studies have been conducted to assess both the impact and the potential impact of CIS on agricultural yields and farmer incomes. Evidence is generally positive, although it should be noted that results depend on the local context, the climate, the type of crops as well as the type and accuracy of CIS, which was investigated. For example, Ouédraogo et al. (2015) conducted a study among cowpea farmers in different villages across Burkina Faso and found that farmers with access to seasonal and daily weather forecasting had greater yields (847 kg/ha for climate-informed farmers versus 685 kg/ha for the control group) and greater gross margins. Similarly, Roudier et al. (2016) assessed the impacts of 10-days and seasonal forecasts on Nigerien millet growers' cropping practices and their income. Their results show that 10-days forecasts alone or a combination of 10-days and seasonal forecasts could be beneficial for all types of farmers and those farmers with access to fertilisers and larger arable land benefited more from forecasts. Study results from Senegal also suggest a positive impact of CIS on crop yields: Groundnut yields were 15% higher for farmers with access to climate information compared to those without access (Lo & Dieng, 2015).

7.3 Cost-benefit analysis for rainfed maize cultivation using climate information

The following CBA is intended to analyse whether switching from a rainfed maize production system following the traditional calendar to a production guided by weather and climate data via mobile phone is economically feasible. Therefore, we compare costs and benefits of adaptation vs. non-adaptation scenarios for two climate scenarios each projected until 2050 with reference to a baseline (scenario) describing the status quo as of today.

7.3.1 Baseline and scenarios

The baseline and scenarios are defined as follows:

Baseline (no action, no climate impacts): Rainfed maize production under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under SSP1-RCP2.6 and SSP5-RCP8.5[10]: Rainfed maize production which is following the traditional calendar. The revenues and costs of the production system are extrapolated until 2050 assuming a climate change yield impact under SSP1-RCP2.6 and SSP5-RCP8.5.

Adaptation (action, climate change impacts under SSP1-RCP2.6 and SSP5-RCP8.5): Rainfed maize production with the use of climate information. The revenues and costs of the production system are extrapolated until 2050 assuming a climate change yield impact under SSP1-RCP2.6 and SSP5-RCP8.5.

7.3.2 Survey data

The underlying economic calculations are mainly based on household data collected in September 2020 by WASCAL and retrieved by HFFA from ten farming families in the southwest of Burkina Faso (in the Dano commune, Ioba province) cultivating an average farming area of 1.6 hectare with maize. However, following the standard level of consideration in farm economics, we analyse the subsequent revenues and costs of production associated to one hectare.

In comparison with the non-adoption scenario, the surveyed farmers obtained specific information on weather and climate data via mobile phone in the adoption scenario. The specific information concerned the start and end dates of the rainy season, as well as the distribution of rainfall over season. This data and information determine the best time for individual production steps and farmers can align their farming and management practices accordingly.

To meaningfully determine the subsequent changes of revenues and production costs, the following aspects must be considered:

- As the use of climate information requires only a mobile phone, no other additional equipment (investment) costs for switching to that adaptation strategy occur. From the survey, it was retrieved that the farmers must newly acquire the phone in the year prior to adaptation and renew it every three years. However, we assume that the phone is used for other purposes, too. Hence, the costs are distributed to the total farm size and not only the farm area where the here analyzed maize production is pursued.
- In addition to acquisition costs, the farmers' workload dedicated to the phone for information gathering is assumed to take five minutes per day. Using the average daily labour rate for farm work of 2,188 CFA (~ 4 USD[11]), the total labour cost dedicated to the phone accounts to 8,317 CFA (~ 15 USD) per year and hectare. In addition, the famers spend two days for

[10] Different to the rest of the climate risk analysis, which is based on climate projections in line with the 6th Assessment Report of the IPCC to be released in 2021, the cost benefit analyses conducted in Chapter 7 and Chapter 8 are based on PIK projections for northern Ghana (which has similar agroecological conditions as the southwest of Burkina Faso) and still use the scenarios of the 5th Assessment Report of the IPCC (2014a), i.e. SSP1-RCP2.6 and SSP5-RCP8.5 instead of SSP1-RCP2.6 and SSP3-RCP7.0. The reason why data from northern Ghana was used, is because the yield projections for Burkina Faso were conducted for Sorghum (see Chapter 3), but the cost benefit analysis assesses Maize production.

[11] All exchange rates were retrieved on 04.3.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en.

training, planning and processing of the retrieved information accumulating to 1,838 CFA (~ 3,3 USD) in the first year and half of it in the second and each following year.
- With respect to the workload, another aspect must be kept in mind. The higher yield induced by the adapted growing strategy also leads to an increased workload for harvesting, drying and threshing. The respective labour costs for these three activities are annually adjusted using the ratio of the expected yield in a particular year vs. the yield for which the original labour costs for harvesting, drying and threshing were allocated, i.e. taking into consideration the yield in the baseline scenario (WASCAL, 2021).
- In order to calculate the revenues, the market price of 123 CFA (~ 0.20 USD) for one kg maize has been set, which was indicated in the household survey. According to the interviewed farmers, the maize yield increased by 84 kg per hectare in the first year of adaptation and again by 87 kg in the second year. Based on the revenues calculated in this way, the revenues and costs have been extrapolated until 2050.

7.3.3 Assumptions

While doing so, a few additional qualified assumptions had to be made due to some missing information. The following shall be highlighted in this respect:
- Climate change induced yield developments are derived from PIK projections for northern Ghana (which has similar agroecological conditions as the southwest of Burkina Faso) under SSP1-RCP2.6 and SSP5-RCP8.5, including a positive effect on yield developments with adaptation (Aschenbrenner et al., forthcoming).
- In terms of technological change, we assume that the farmers' area productivity increases due to autonomous technological change by 0.6% per annum. This is an extrapolation of previous yield increases over the last 30 years in Burkina Faso (FAOSTAT, 2021).
- To depict the inflation rate, we calculated the growth rate of the Gross Domestic Product per capita of Burkina Faso from the last 30 years, its value is 3.88% (FAOSTAT, 2021).

7.3.4 Results

The CBA results show that in 2050, the adaptation strategy of switching from a traditional growing calendar to the use of scientific climate information for rainfed maize production would be highly beneficial, as it has a positive return on a rather small-scale investment. This applies to both climate change scenarios, whereby the scenario under SSP5-RCP8.5 performs slightly better, possibly caused by an increased CO_2 fertilisation effect. In particular, the following is noteworthy:
- The net cash flow for the farmers is already positive from the third year on leading to an increasing net present value (NPV) from the same year on (see Figure 47). The NPV is negative in the first two years, starting with -2,091 CFA (~ -3.8 USD) in year 2020 for both scenarios, becoming positive in year 2022.
- The reinvestment costs for the mobile phone every three years cause a nonlinear development of the NPV, but together with the training, as well as harvesting, drying and threshing costs never lead to a negative net cash flow in the following years. By further increase, in 2050, the NPV thus becomes 243,880 CFA ~ 455 USD) under the SSP1-RCP2.6 scenario and 258,656 CFA (~ 482 USD) under the SSP5-RCP8.5 scenario.

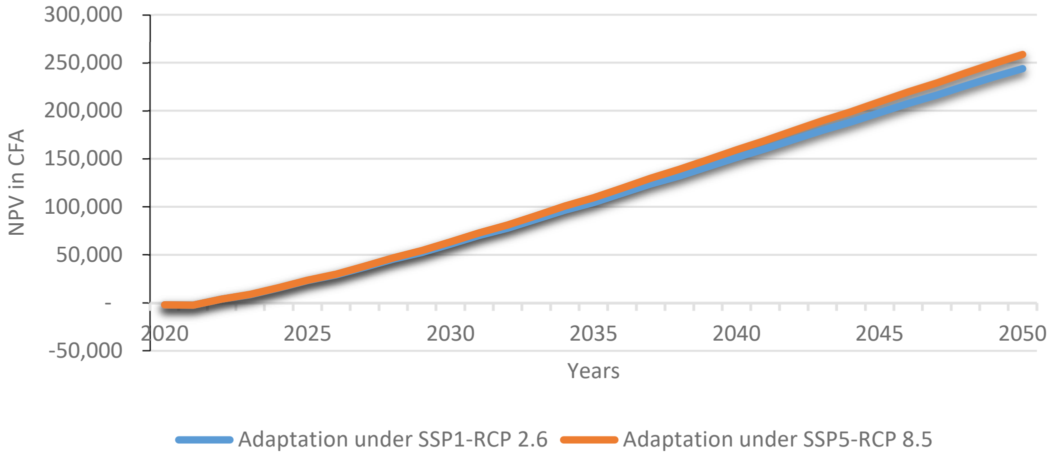


Figure 47: Development of the net present value of switching to rainfed maize cultivation using climate information, Source: Own figure based on own calculations.

The results show that the farmer's investment in the access to weather forecast and climate information pays off after two years under both climate change scenarios. The break-even point between accumulated net costs and net benefits is in 2022. Consequently, the internal rate of return (IRR) is very positive and yields 130% for an adaptation under the SSP1-RCP2.6 scenario and 132% for an adaptation under the SSP5-RCP8.5 scenario. In order to indicate a profitable investment, the IRR must be higher than the local interest rate. According to the survey, this is at 15% for our case study site.[12] As the IRRs for both, the SSP1-RCP2.6 and the SSP5-RCP8.5 scenario, are much higher, the switch from using a traditional calendar to the use of precise climate information via mobile phones is highly profitable for the farmers.

This is also directly reflected in the cost benefit ratio (BCR), which is 1.95 in 2050 for a climate change under the SSP1-RCP2.6 scenario and 2.00 under the SSP5-RCP8.5 scenario (see Table 7).

Table 7: Summary on major CBA indicators for of switching to rainfed maize cultivation using climate information.

	Adaptation under SSP1-RCP2.6	Adaptation under SSP5-RCP8.5
IRR	130.39%	132.22%
NPV	243,880 CFA (= 455 USD)	258,656 CFA (= 482 USD)
BCR	1.95	2.00

We therefore conclude, that switching to a cropping calendar guided by precise climate information is much more feasible in economic terms than adhering to a traditional cropping calendar. With very low investment costs and little additional working effort remarkable yield increases and, thus, revenues (or – valued at opportunity costs – food supply to be directly consumed on-farm) can be achieved, which gives the strategy a great potential for upscaling. The main reasons for not using climate information, as revealed from the survey, are less of financial nature, but rather related to the lack of information and knowledge.

12 More generally speaking, any IRR higher than 6%, the "global" average interest achievable at stock market level, shall be considered a profitable investment.

7.4 Qualitative assessment of climate information services

7.4.1 Upscaling potential

The number of available climate services in Burkina Faso is low, which is likely due to a lack of production and provision of climate information from databases and research (Alvar-Beltrán et al., 2020). Study results by Zongo et al. (2015a) reveal that in four different study sites in the Sahelian and Sudano-sahelian zones in Burkina Faso, only 22% of farmers had access to official seasonal forecasts prior to the agricultural season.

Currently, the main communication channels for delivering climate and weather information to Burkinabe farmers are the radio (39%), followed by television (27%), word of mouth (26%), and mobile phones (SMS) (3%) (Alvar-Beltrán et al., 2020). However, there are regional differences: In the Sahel, the radio and word of mouth are the main channels, while further south, the majority of farmers receive information through radio and TV (ibid). In some regions, word of mouth is still widespread due to infrastructure constraints, such as access to energy, which is needed to charge mobile phones, and due to illiteracy and innumeracy (Lo & Dieng, 2015). Hence, weekly markets or the Friday prayers present important opportunities for disseminating CIS.

Given the limited access to CIS and the poor exploitation of various communication channels, CIS have a great upscaling potential. Alvar-Beltrán et al. (2020) recommend to scale up CIS through the main communication channels, which are radio and television. According to Lo and Dieng (2015), who conducted a study among farmers in Senegal, the evening news on the radio were particularly crucial since this time coincided with farmers coming home from farms. However, there are also new channels, such as mobile phones, smart-phones and other internet-based devices, which are increasingly emerging throughout Burkina Faso. In particular SMS present a means for diversifying dissemination channels, since more and more farmers own a mobile phone (Lo & Dieng, 2015). For example, in Senegal, the SMS is widely used for CIS dissemination, e.g. in case of storms, strong winds or early/late rains (ibid).

7.4.2 Potential co-benefits

If produced and disseminated in an equitable manner, CIS bear several development co-benefits. The use of CIS allows for a more targeted agricultural production: Current climate and weather data can help farmers to make timely adaptation decisions, e.g. through change of sowing dates, choice of crop varieties or use of fertilisers. While CIS are usually consulted for short-term planning, regular CIS use can also change agricultural practices in the long term and result in streamlining labour and farm spending, e.g. due to energy and water savings (USAID, 2013). CIS can thus help farmers to increase agricultural yields, ensuring food security, also for the dry season, and contributing to good health. The increase in agricultural yields can generate surplus, which can be sold at the market. This additional income can be either reinvested in better agricultural equipment and further agricultural activities, e.g. related to livestock, or used to improve family welfare, e.g. through investing in health insurance or children's education (Lo & Dieng, 2015). CIS can also be used to ensure the safety of human lives and livestock and to protect property: For example, when a thunderstorm is announced, Lo and Dieng (2015) report in their study of Senegalese farmers, children and livestock are kept at home. CIS can also create a more general awareness of climate change and variability and increase the willingness to pay for forecasts and thus improve the quality of forecasts in the long term (USAID, 2013). Ouédraogo et al. (2018) conducted a study among Burkinabe farmers and found that 63% were willing to pay for CIS. Greater awareness can also serve as an enabler for the implementation of other adaptation strategies mentioned in this report.

7.4.3 Potential maladaptive outcomes

Compared to other adaptation strategies, little attention has been given thus far to potential maladaptive outcomes and ethical considerations of CIS (Lugen, 2020). However, two aspects should be mentioned. The first is equity and the question of access to and use of CIS. Equitable access to and use of CIS depend on different social factors, including gender, age, marital status, migration status, or health (Lo & Dieng, 2015; Lugen, 2020; McOmber et al., 2013). According to McOmber et al. (2013), especially age in combination with gender can illuminate social inequities in the access and use of CIS. A study conducted among Kenyan farmers confirms this picture: Age of the household head reduced access to CIS and age and sex reduced the likelihood of using CIS (Muema et al., 2018). Factors like income, farm size or television ownership had the opposite effect. Hence, while CIS can be an effective adaptation strategy, CIS can also serve to reinforce existing inequalities. The second aspect relates to the politics of CIS and the ways in which governance and power are impacted (Lugen, 2020). Webber (2017) criticises the commercialisation of CIS and the competition around CIS development, which happens at the expense of building collaborative relationships, widening the gap between science and policy instead of closing it.

7.4.4 Barriers for implementation

The development of CIS faces several barriers and constraints. Different from other adaptation strategies, CIS usually require high institutional, technical and financial support. This is partly why CIS production and dissemination remain poor in Burkina Faso (World Bank, 2017). The number of field observers is limited, and their payment is too low to ensure reliable data collection, says the World Bank. Necessary instruments and equipment are scarce.

Another challenge relates to the identification of end users. CIS needs are highly context-specific and can vary between one village and the next (Guido et al., 2020; Tall, 2013). Hence, it is important to identify the end users and their needs and ensure that these aspects are taken into account all along the CIS value chain (Carr et al., 2020). According to Tall (2013), the perspective of end users is often overlooked, particularly in the design phase of CIS, however, it is crucial in determining the success of CIS. Information on end users should also be considered in the management and implementation phase of CIS. Carr et al. (2020) note that it is important to make sure that end users receive the information and that they can make use of it in their decision-making processes. All too often, CIS are developed without effective communication. Tall (2013) emphasises the role of different delivery channels to ensure that vulnerable communities and planners at different levels receive the right CIS. Potential channels include the radio, SMS, voice messages or bulletin boards posted in strategic locations (Tall, 2013). Here, it is crucial to ensure timely communication in the local language(s).

Finally, Carr et al. (2020) point to the cross-cutting challenge of dealing with changing conditions. This challenge relates to different actors and levels, including changing user needs and knowledge but also dynamics in communities and among funders and providers. Given the fact that CIS function over many years, the aspect of uncertainty needs to be taken into account and CIS need to be produced as part of an iterative process (Tall, 2013).

Gender still largely influences farmers' access to assets and resources (Alston, 2013; Backiny-Yetna & McGee, 2015). Men are usually the primary income providers and, therefore, in control of expenses. This gendered control over financial means makes it difficult for women to access information and communication technologies (ICTs) and CIS. Hence, they depend on their male counterparts in purchasing equipment, such as radios or mobile phones, as well as in using them (McOmber et al., 2013). McOmber et al. (2013) note, "While climate information may be entering the household, it does not always mean that women are included in the sharing of this information." Another barrier relates to the usage of CIS: Women tend to be more inexperienced in using ICTs, less likely to speak national languages and more likely to be illiterate and innumerate, all of which limits their abilities to use CIS, even when available (McOmber et al., 2013). This is particularly true for older women, but also for older men (ibid). Another important aspect are the different needs of men and women with respect to CIS (Tall et al., 2014). In a study conducted by Tall et al. (2014), Senegalese women farmers planted their plots after the men were done planting theirs. Hence, they specifically required information on potential dry spells and the end of the rainy season (ibid). Despite numerous barriers, however, CIS can help to improve the lives of different social groups, especially those of women, who traditionally rely on men for their information. Hence, provided that women are given equal access and the opportunity to use CIS as well as the training needed to use ICTs, to understand CIS and the ways of implementing this information, CIS can help promote gender equality.

7.4.5 Institutional support requirements

Especially the development and provision of CIS require high institutional support. CIS are usually developed by national meteorological agencies and research institutes specialised in climate and weather forecasting (Singh et al., 2018). The post-processing of raw climate and weather data, including the interpretation and translation of complex climate and weather data into sector-tailored, localised, easy-to-understand and usable CIS, also requires institutional support, e.g. from ministries and extension services (Tall, 2013). Hence, CIS present an effective adaptation strategy. However, their uptake cannot be done by individual farmers or small groups of farmers, even though they play an important role as the end users of CIS. Instead, CIS have to be provided to end users through different communication channels and with the help of various actors, including meteorological agencies, research institutes, ministries and agricultural extension services. Linking these actors in the CIS value chain presents one of the challenges in providing CIS. Here, other intermediary organisations, such as the media, NGOs, community and women's organisations, can facilitate the provision of CIS, especially when it comes to co-producing and disseminating CIS (Tall, 2013; WMO, 2019). Table 8 summarizes the multi criteria assessment.

7.5 Conclusion

Considering all mentioned aspects, CIS presents through its various formats a high-risk mitigation potential with a high cost-effectiveness as shown in the CBA analysis. With very little investment costs and additional working efforts, remarkable yield increases can be achieved. However, the access to CIS requires high institutional support for efficient collection, analysis and timely and actionable dissemination to ensure proper and effective use by the farmers.

Table 8: Summary of multi-criteria assessment of CIS as adaptation strategy.

Risk mitigation	Risk-gradient	Cost-Effective-ness	Upscaling	Potential Co-benefits	Potential maladaptive outcomes	Barriers to implemen-tation	Institutional support requirements
High	Risk-independent	High	High	High	Low	Medium	High

Chapter 8 – Irrigation

8.1 Context and description of the adaptation strategy

The agricultural sector in Burkina Faso is heavily dependent on water from precipitation. Since precipitation is increasingly erratic, irrigation can help farmers to adapt to these changing conditions. Irrigation can be defined as the artificial process of applying water to crops or land in order to support plant growth. The FAO distinguishes between three types of irrigation: (1) surface irrigation, where water flows over the land; (2) sprinkler irrigation, where water is sprayed under pressure over the land; and (3) drip irrigation, where water is directly brought to the plant (FAO, 2001).

The majority of irrigation systems in Burkina Faso is initiated and managed by farmers themselves – either individually or in small groups – and referred to as small private irrigation (De Fraiture & Giordano, 2014). Irrigated areas are small, typically less than 2 ha, and technologies are low-cost: In most cases, a treadle pump is used to transport water to the crop, in some cases also motor pumps, hand pumps or simple watering cans (De Fraiture & Giordano, 2014; Zongo et al., 2015b). Water typically comes from small reservoirs, which collect surface runoff during the wet season (De Fraiture & Giordano, 2014). In Burkina Faso, a small reservoir is defined by the height of the surrounding dam, which should be below 10 m (Boelee et al., 2009). Water retention is subject to seasonal variation and depends on the location in Burkina Faso: While in the south-western part of the country, more than half of the reservoirs retain water year-round, in the north, the share is less than one third (Boelee et al., 2009). According to different estimates, there are currently between 1450 and 1650 such reservoirs in Burkina Faso (Boelee et al., 2009; Cecchi et al., 2009).

In addition to traditional water management techniques, such as Zaï and half-moon (see Chapter 9), the Burkinabe government as well as international donors have developed large and smaller-scale dams and irrigation systems (Fossi Tuekam et al., 2012). The two largest dams include the Kompienga Dam (total capacity: 2 Bm^3) on the Koulpeleogo River, located in south-eastern Burkina Faso, and the Bagré Dam (total capacity: 1.7 Bm^3) on the White Volta, located in the southern part of the country (Boelee et al., 2009). While the Kompienga Dam is used for hydropower and fishing, the Bagré Dam feeds a downstream irrigation system, which covers an area of 37.28 km^2 (2014), being one of the biggest irrigation systems in Burkina Faso (Boelee et al., 2009; Knauer et al., 2017). Other irrigated areas include the Kou Valley in western Burkina Faso, the Sourou Plain in the north-west and another area in the Comoé Province in the south-east (Boelee et al., 2009). Irrigated crops include (i) cereals, mainly rice and maize; and (ii) vegetable crops dominated by onion and tomato, followed by small-scale traditional market gardening (cabbage, eggplant) and green beans for export (MAAHA, 2019). Depending on the type of crop, irrigation is practiced in the dry season between December and April, as is the case for vegetable crops (Gross & Jaubert, 2019), or as supplemental irrigation in case of dry spells during the rainy season (Zongo et al., 2015b).

8.2 Biophysical assessment of risk mitigation potential

To analyse the risk mitigation potential of irrigation as an adaptation strategy in Burkina Faso, we used sorghum as a case study as it is an important staple crop in Burkina Faso. Traditionally a rainfed crop, this case study explores the harboured potential of risk mitigation by switching to irrigation. However, farmers traditional knowledge and management practises should be taken into account for a holistic evaluation. The option "automatic irrigation when it required" was chosen in DSSAT with a set irrigation flood depth of 5cm. This option enables the model to provide 5cm of flood depth irrigation in the field when the crop requires water. Due to transpiration and evaporation processes, the crop requires water. The major climatic factors that influence the crop water requirement are sunshine hours, temperature, humidity, and wind speed. In our case, we had given 5cm of water flood when the crop needed water, considering the limitation of irrigation facilities. However, accounting average seasonal water requirements of sorghum (450-650mm), increasing temperature, changes in rainfall, and crop growth period, our model setup of 5cm flood irrigation might not be sufficient to attain potential outcomes in few grids.

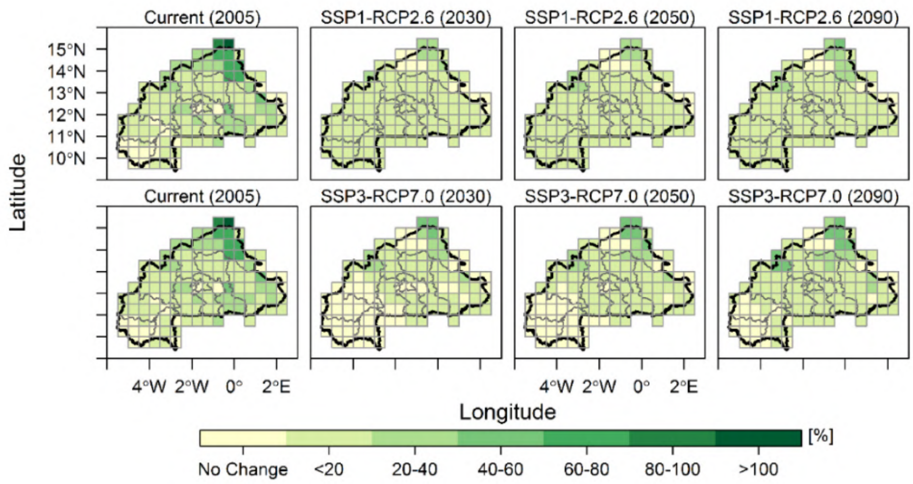


Figure 48: Spatial distribution of projected impact of irrigation application on Sorghum yield under various emissions scenarios and over different time steps.

The outcomes of the modelling show that irrigation increases yield over most of the grids significantly (Figure 48), especially over northern Burkina Faso under both emissions scenarios. Overall, at the national scale, irrigation is projected to lead to higher yields under both scenarios and at all-time steps. In Burkina Faso's southern part (Cascades, Haut-Bassins, and Sud-Ouest), irrigation is projected to increase yields under SSP1-RCP2.6 more than under SSP3-RCP7.0. Overall, in the low emissions scenario (SSP1-RCP2.6), the yield impacts remained unchanged over time (2030s, 2050s and 2090s), which might be due to the unchanged climatic patterns. In the south-western part of Burkina Faso (Centre-Ouest, Centre-Sud, Centre-Est, and the lower Est) yields are projected to remain relatively unchanged under SSP3-RCP7.0. In the northern regions (Boucle du Mouhoun, Nord, Centre Nord, Centre, and Plateau Central) irrigation is projected to positively impact yields under both of the scenarios with a higher positive impact under SSP3-RCP7.0, than under the low emissions scenario (SSP1-RCP2.6).

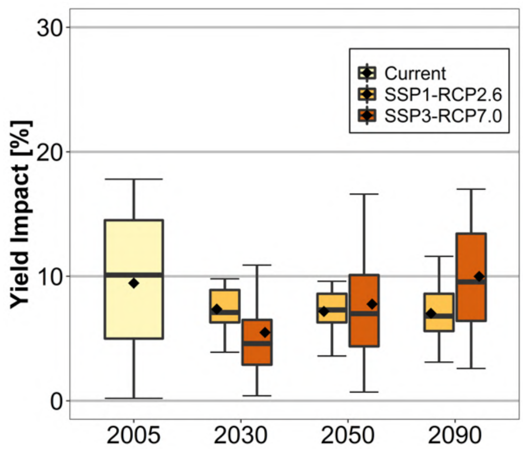


Figure 49: The intercomparison of the yield impacts between different time steps with automatic irrigation.

Figure 49 shows the variability of irrigation application on yield impacts over different time steps. Comparing both scenarios, there are only minor yield changes over time under SSP1-RCP2.6 but an increasing trend over time under SSP3-RCP7.0.

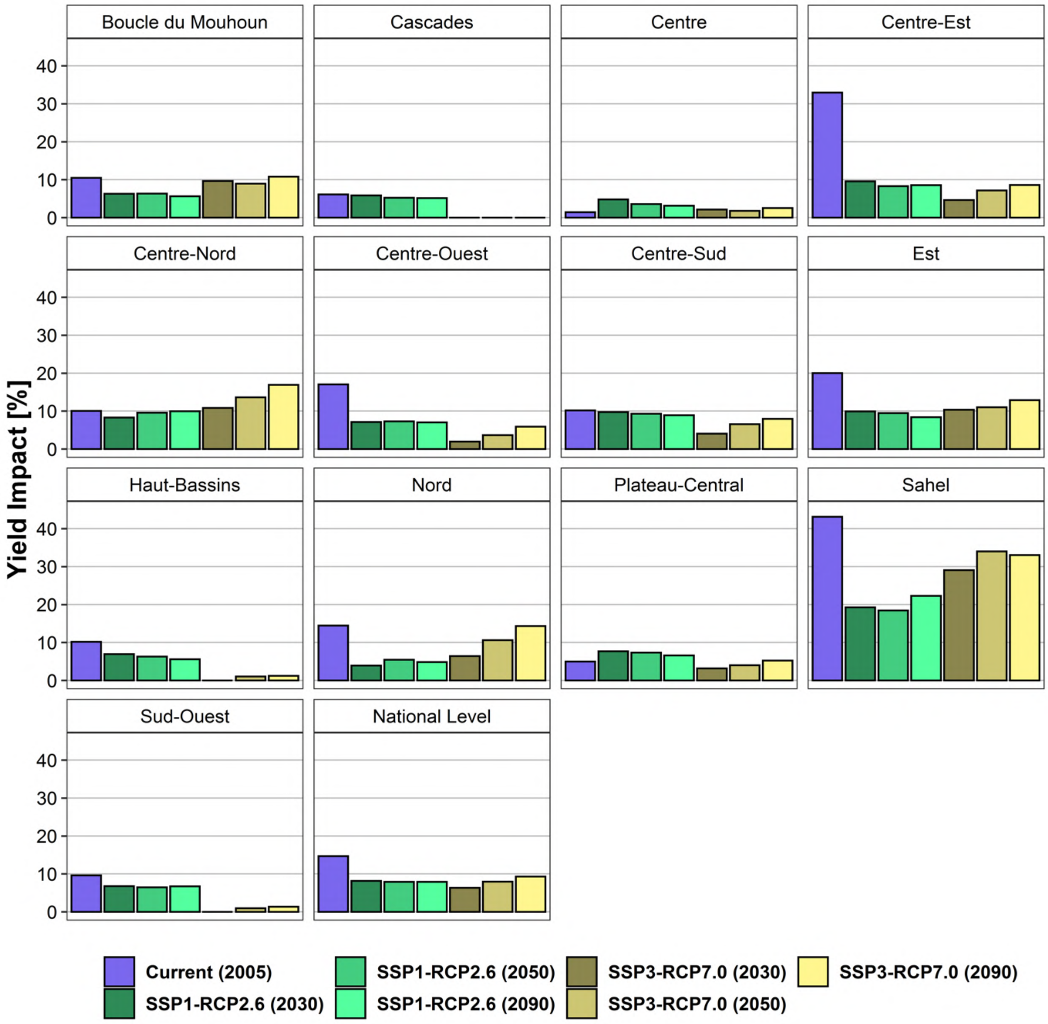


Figure 50: Regional-wise yield impacts with irrigation over different scenarios and time-steps.

Furthermore, Figure 50 shows how irrigation impacts yields under the two emissions scenarios and over different time steps, as compared by administrative regions. The impact of irrigation on yields varies across regions and time steps. As can be seen, irrigation does not lead to significant positive changes in yield under emissions scenario SSP3-RCP7.0 in some parts of the country including Cascadas, Centre, Haut-Bassins and Sud-Ouest. This can be explained by the processes of unproductive soil evaporation, interception losses, deep percolation, and surface runoff, which are the result of a combination of higher rainfalls than projected under SSP1-RCP2.6 and irrigation in southern Burkina Faso (Rockstrom, 2000). In the northern part of the country, the Crop Water Requirement (CWR) is optimal, respective to rainfall and irrigation, which is why higher yields are projected as a result of irrigation application.

This chapter focused on Sorghum as it is an important crop in the semi-arid and arid regions of Africa and in terms of yield, and regarding climate impacts it is more resilient than maize and millets (Orr et al., 2020). It is specifically more drought tolerant, most suitable where and when long dry periods are experienced or expected in the growing season or in naturally dry environments (Muitire et al., 2021). Sorghum's heterotic mechanisms allow for greater biomass and yield components production at a shorter period, an efficient rooting system, dehydration avoidance and escape mechanisms, 'stay green' and lodging tolerance and desiccation tolerance compared to other cereal crops (Blum, 2004; Choudhary, 2021). Considering these points, the risk mitigation effect of irrigation could be even greater for other cereals, such as maize or millet, which are more susceptible to climatic changes.

8.3 Cost-benefit analysis for rainfed maize production with supplementary irrigation

To assess the economic feasibility of supplementary irrigation for rainfed maize, costs and benefits of an adaptation scenario vs. a non-adaptation scenario have been compared. The adaptation scenario describes farmers who built ponds and basins to collect runoff water and store it to irrigate their maize fields in dry periods during rainy season (no dry season production). In the non-adaptation scenario farmers produce maize without any supplementary irrigation. The costs and benefits are projected until 2050 with reference to a baseline (scenario) describing the status quo as of today.

8.3.1 Baseline and scenarios

The baseline and scenarios are defined as follows:

Baseline (no action, no climate impacts): Rainfed maize production under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under SSP1-RCP2.6 and SSP5-RCP8.5)[13]**:** Rainfed maize production without supplementary irrigation techniques. The market revenues and costs of the production system are extrapolated until 2050 assuming a climate change yield impact under SSP1-RCP2.6 and SSP5-RCP8.5.

Adaptation (action, climate change impacts under SSP1-RCP2.6 and SSP5-RCP8.5): Maize production during rainy season with the support of supplementary irrigation in dry spells (all other things being equal). The market revenues and production costs are extrapolated until 2050 assuming a climate change yield impact under SSP1-RCP2.6 and the SSP5-RCP8.5.

8.3.2 Survey data

The following calculations are based on cost and revenue data from five farms in Yatenga province in the Northern region of Burkina Faso. The average size of each farm is four hectares, including 0.25 hectares for irrigated maize. To assure for comparability between adaptation scenarios, all analysed market revenues and costs of production are associated to one hectare.

The irrigation infrastructure consists of water ponds made of cement, stone and sand with an average volume of 250 m^3, except one pond, which has a volume of 2000 m^3. The water is pumped with either a generator or a foot pump and then transported with buckets to the field.

To determine the subsequent changes of market revenues and production costs, the following aspects are considered for an average farmer who adopts the new technology.

- The major cost driver of supplementary irrigation are the costs for equipment and material necessary for the installation of the ponds. The surveyed farmers expect the ponds to have a lifespan of 36 years, there-fore renewal costs are not considered in the period under review for this CBA. Costs for construction material such as sand, cement and stones accumulate to 122,400 CFA (~ 222 USD[14]) only in the year of construction. The same applies for digger and cart, which are purchased for installation in

[13] Different to the rest of the climate risk analysis, which is based on climate projections in line with the 6th Assessment Report of the IPCC to be released in 2021, the cost benefit analyses conducted in Chapter 7 and Chapter 8 are based on PIK projections for northern Ghana (which has similar agroecological conditions as the southwest of Burkina Faso) and still use the scenarios of the 5th Assessment Report of the IPCC (2014a), i.e. SSP1-RCP2.6 and SSP5-RCP8.5 instead of SSP1-RCP2.6 and SSP3-RCP7.0. The reason why data from northern Ghana was used, is because the yield projections for Burkina Faso were conducted for Sorghum (see Chapter 3), but the cost benefit analysis specifically assesses Maize production.

[14] All exchange rates were retrieved on 09.04.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en.

the first year for 150,117 CFA (~ 272 USD), but do not cause any renewal costs (WASCAL, 2020).

- Even if the whole pond infrastructure does not have to be renewed before 36 years, some of the material such as tarpaulin, wooden poles and meshwire need to be replaced at certain intervals (information retrieved from the survey) causing varying costs in each year.
- In addition to the acquisition costs for material and equipment, the farmers' labour costs for the installation of the pond is calculated using the average daily labour rate for farm work of 1,900 CFA (~ 3.4 USD) and the average working days of 319 days per hectare from the survey. The total labour cost dedicated to installation, including training and digging, is therefore 606,311 CFA (~ 1,099 USD). The labour input for irrigation is 60 days accumulating to 114,000 CFA (~ 207 USD) (ibid.).
- Opportunity costs arise from off-farm activities, in which farmers would engage, if they would not irrigate their fields. The interviewed farmers reported that without supplementary irrigation they would usually spend 84 days per year with off-farm activities. Using the average daily rate for each activity, opportunity costs add up to 64,737 CFA (~ 117 USD) per year and hectare (ibid.).
- The higher yield induced by irrigation also leads to an increased workload for harvesting, drying, and conservation. Hence, the labour costs for these three activities are annually adjusted using the ratio between the expected yield with adaptation and the reference yield prior to adaptation (WASCAL, 2020).
- To calculate the revenues, we use a market price of 176 CFA (~ 0.32 USD) for one kg of maize, which was indicated in the household survey. According to the interviewed farmers, the maize yield increased by 1,489 kg per hectare due to irrigation. Based on the market revenues gained from the yield surplus, we extrapolated the revenues and costs until 2050 (WASCAL, 2020).

8.3.3 Assumptions

To conduct the CBA, the survey data had to be complemented with the following assumptions:

- The climate change effects on yields under SSP1-RCP2.6 and SSP5-RCP8.5 are derived from PIK projections for northern Ghana (which has similar agroecological conditions as the southwest of Burkina Faso) showing a positive development with adaptation (Aschenbrenner et al., forthcoming).
- We assume that the farmers' area productivity increases due to autonomous technological change by 0.6% per annum. This is an extrapolation of previous maize yield increases over the last 30 years in Burkina Faso (FAOSTAT, 2021).
- To depict the inflation rate, we calculated the exponential growth rate of the Gross Domestic Product per capita of Burkina Faso from the last 30 years, its value is 3.88% (FAOSTAT, 2021).

8.3.4 Results

The CBA results show that under both emissions scenarios the adaptation strategy of switching from rainfed to irrigated production of maize has a positive return on investment (Figure 51):

- After the high initial investment costs of 1,484,226 CFA (~ 2,691 USD), the net cash flow becomes positive already in the second year of adaptation. The NPV thus increases from the same year on and also becomes positive with 27,102 CFA (~ 49 USD) in year 2041 under SSP1-RCP2.6, indicating the break-even point for the investment. Under SSP5-RCP8.5, the break-even point is even one year earlier, in 2040, showing a NPV of 762 CFA (~ 1.4 USD).
- Caused by the re-investment costs for some of the material and equipment, the NPV develops non-linear. In year 2035 and in year 2050, the renewal costs of pumps and tarpaulin lead to a negative cash flow for the farmers and a decreasing NPV.
- But again, from the subsequent year on the NPV increases and in 2050 amounts to 804,369 CFA (~ 1,458 USD) under the SSP1-RCP2.6 scenario and 959,230 (~ 1,739 USD) under the SSP5-RCP8.5 scenario.

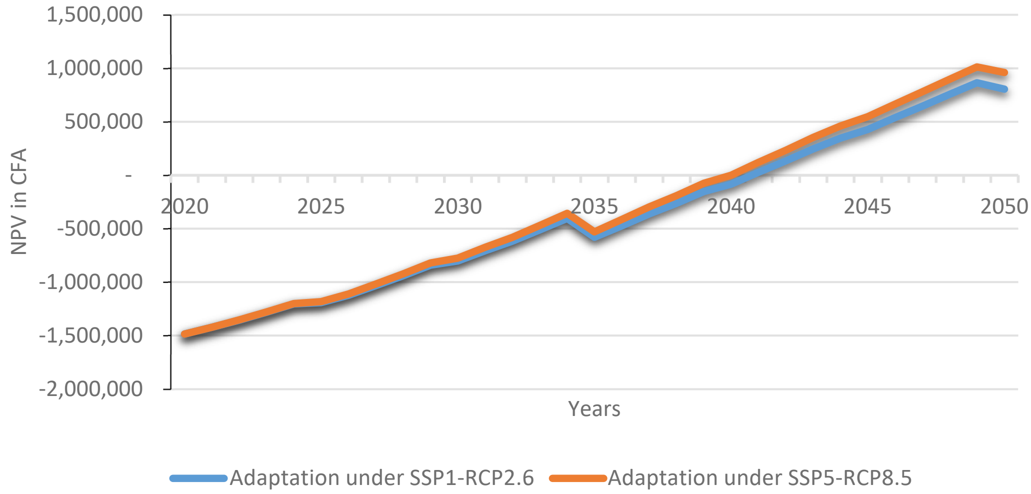


Figure 51: Development of the net present value of switching to rainfed maize cultivation under supplementary irrigation.

In other words, the farmers' investment into supplementary irrigation pays off after ten years under SSP1-RCP2.6. and after eleven years under SSP5-RCP8.5. In consequence, the IRR is positive and yields 6.89% for an adaption under the SSP1-RCP2.6 scenario and 7.35% for an adaptation under the SSP5-RCP8.5 scenario, both for the year 2050. Considering a global rentability perspective, which is often taken for local CBAs, any IRR higher than 6%, is considered as a profitable investment. As the IRRs for both scenarios are greater than that, the switch from rainfed to irrigated maize production is profitable for the farmers. This is also reflected in the cost benefit ratio (BCR) of the adaptation investment, which is 1.14 in 2050 under SSP1-RCP2.6 scenario and 1.17 under SSP5-RCP8.5 scenario (see also Table 9).

Table 9: Summary of major CBA indicators for switching to rainfed maize cultivation under supplementary irrigation.

	Adaptation under SSP1-RCP2.6	Adaptation under SSP5-RCP8.5
IRR	6.89%	7.35%
NPV	804,369 CFA (= 1,458 USD)	959,230 (= 1,739 USD)
BCR	1.14	1.17

As explained above, switching from a rainfed maize production system to a production with supplementary irrigation is economically feasible since the partial change of the production system leads to a high IRR and a BCR above 1.0. That means that attributable additional revenues to the change are higher than the associable additional costs. However, the particular outcome does not mean that the entire production system is feasible in terms of internationally standardized calculation of economic margins. In fact, given the household survey data it must be determined that the production of maize in the baseline (no action, no climate impacts) scenario, i.e., rainfed maize production under current climatic and technological conditions in the region is characterized by a negative gross and net margin. In other words: variable and fixed costs are higher than market revenues.

From a pure economic perspective that would mean to not produce maize under current circumstances. However, the positive IRR suggests that the production system becomes more profitable in the future due to significantly higher yields achieved. The decision making of maize farmers in the region may also be guided by other than pure rational behaviour. Most small-scale farmers and even more so subsistence farmers tend to exploit themselves by allocating a lower and in many cases even no price to own and family labour. In addition, other criteria such as food security and the lack of job alternatives may apply. This does not contradict the results of the CBA, as the CBA is only a partial cost accounting and does not include all production factors as considered in a full cost analysis.

8.4 Qualitative assessment

8.4.1 Upscaling potential

Irrigation development in Burkina Faso dates back to the colonial period, when French missionaries introduced this technology to teach horticultural production to the local population (Gross & Jaubert, 2019). However, with only around 100 reservoirs built at the time, irrigation remained a marginal activity until after its Independence in 1960. In the 1970s and 1980s, Burkina Faso, along with other Sahelian countries, faced severe droughts, which is when the Burkinabe government recognised the need to improve water availability for agricultural production and food security (Gross & Jaubert, 2019). As a result, at least 500 reservoirs were built between 1974 and 1987 (Cecchi et al., 2009). While these reservoirs were mainly targeted towards smallholder farmers, in the 1990s and 2000s, irrigation policy moved away from this group to focus on private-sector development, targeting more commercial farmers (Gross & Jaubert, 2019). Since the late 2000s, irrigation development has focused primarily on the promotion of low-cost drip irrigation (Gross & Jaubert, 2019). A prominent example of this trend is the African Market Garden Project (AMGP) initiated by ICRISAT in 2004 (Gross & Jaubert, 2019). As part of this project, pre-packaged drip irrigation kits were distributed to smallholder farmers across Burkina Faso (Wanvoeke, 2015). While the AMGP started out as a promising model for improving agricultural production, food security and nutrition, after its official termination, very few farmers continued to use the kits, among other things due to a lack of support services and their inability to further operate the technology (Wanvoeke et al., 2015).

Today, irrigation presents a priority area in agricultural development in Burkina Faso. It particularly regained centre stage with the Dakar Declaration on Irrigation made in 2013, where government representatives from six Sahelian countries (Burkina Faso, Chad, Mali, Mauritania, Niger and Senegal) called for strengthening the role of irrigated agriculture in economic growth, rural poverty reduction, food and nutritional security, and balanced land use (International Commission on Irrigation and Drainage, 2013). This commitment is reflected in several national policies and initiatives taken by the Burkinabe government. The National Strategy for the Sustainable Development of Irrigated Agriculture aims at boosting the irrigation sector as a means of tackling poverty and food insecurity, and creating employment opportunities (Ministry of Agriculture and Irrigation Development of Burkina Faso, 2015a). In a similar way, the National Water Policy emphasises the potential of irrigated agriculture, noting, however, that this sector is currently being unexploited (Ministry of Agriculture and Irrigation Development of Burkina Faso, 2015b). Other documents highlighting irrigation include the Rural Development Strategy for Burkina Faso and the National Food Security and Nutrition Policy, which aims at increasing the share of irrigated agriculture and at improving access so more farmers get the chance to participate in this adaptation strategy (Government of Burkina Faso, 2013, 2015c).

According to the FAO, Burkina Faso had an estimated irrigation potential of 165 000 ha of irrigable land in 2017 (FAO, n.d.). As of the same year, only 28% of this potential was used, which corresponded to only 8% of the total national cropland in 2017 (FAO, n.d.; FAOSTAT, 2017). Besides groundwater resources, there are various types of surface water resources through which the full irrigation potential could be exploited: Burkina Faso can be divided into three large basins and a smaller fourth basin. These include the Mouhoun Basin, which is the largest in the country, covering 33% of the land area, in addition to the Comoé Basin, the Nakambé Basin and the Niger Basin (Boelee et al., 2009). Nevertheless, Burkina Faso's climate presents a limiting factor for irrigation, which is characterised by hot temperatures, limited amounts of precipitation and high rates of evapotranspiration (Lange, 2016). Burkina Faso has a single rainy season (unimodal precipitation regime), receiving 80–90% of its annual precipitation between June and September. The length of the rainy season is decreasing towards the north, reaching 500 mm in the north, where people turn to pastoralism instead of farming. According to (Boelee et al., 2009), soil quality is another limiting factor: Soils in many regions of Burkina Faso, especially in the northern part of the country, are poor in nutrients, sandy and shallow, which makes them vulnerable to drying, erosion and flooding, due to the weak water-holding capacity (Boelee et al., 2009; USAID, 2017).

8.4.2 Potential co-benefits

If developed in a planned and equitable manner, irrigation bears several development co-benefits. Irrigation allows for the production of non-traditional, high-value crops, such as vegetables which can be sold at the market. Market-oriented production can help to increase farmers' household incomes, thereby reduce poverty and enable farmers to pay for education and health-related expenses (Boelee et al., 2009). Access to irrigation in Burkina Faso can help farmers to grow vegetables and fruits for household consumption and for sale at the market during the dry season. Hence, irrigation can help to diversify diets and ensure food security at times when famine is most common, thereby contributing to good health (Boelee et al., 2009; Gross & Jaubert, 2019; Wanvoeke, Venot, Zwarteveen, et al., 2016). In terms of employment, irrigation can create new jobs, especially for farmers in the dry season. Depending on the size and the degree of mechanisation of an irrigation facility, labour is required for the construction, operation and maintenance of facilities. Hence, irrigation facilities can create employment opportunities for non-farming households as well as for farming households during the dry season. Larger commercial irrigation facilities, such as those irrigating tomatoes for export, can contribute to overall economic growth and stability. For example, the irrigation facility in Mogtedo in central Burkina Faso has turned this region into an important trading centre supplied by producers, cooperatives and traders (Traore et al., 2019). In this way, irrigation can also help to prevent rural exodus, which is common in Burkina Faso, where especially younger people migrate to cities or neighbouring countries, such as Côte d'Ivoire. This is particularly true for the dry season, when food stocks run low. However, irrigation not only has socioeconomic benefits. Irrigation facilities, including small dams and reservoirs, can also act as protective infrastructures to control seasonal floods: To the north of the town of Kaya in the central part of the country, the presence of a dozen reservoirs in a small catchment area reduced the flood flow from 38 m^3/s to 23 m^3/s, while the time of flow was prolonged from one and a half to 4 days (Boelee et al., 2009).

8.4.3 Potential maladaptive outcomes

The adoption of irrigation can also produce negative effects and maladaptive outcomes that need to be carefully considered when thinking about upscaling efforts. Especially larger irrigation systems come with high operation and maintenance costs (De Fraiture et al., 2014). These are frequently covered by water fees or contribution of labour to operation and maintenance activities, however, not all farmers are able or willing to pay fees or contribute otherwise to the functioning of irrigation systems. Hence, conflicts can develop between those paying for water abstractions and those not paying for it (De Fraiture et al., 2014; Evans et al., 2012). As it was the case in a study conducted by De Fraiture et al. (2014), where vegetable farmers were abstracting water further upstream and doing so without paying water fees, contributing to maintenance or seeking permission from rice farmers, who felt that they had priority rights. Furthermore, uncontrolled water abstractions can also affect livelihoods such as fishery or pastoralism. For example, for fishermen, the use of fertilisers and agrichemicals and their accumulation in reservoirs may be a serious issue, while for pastoralists, irrigation infrastructures, such as pipes or canals, may keep livestock from accessing water holes (De Fraiture et al., 2014; Evans et al., 2012; Korbéogo, 2020). And conversely, irrigation farmers may be concerned about straying livestock, which can cause damage to irrigation infrastructures and crops (Evans et al., 2012). Compared to farmers, fishermen and pastoralists lack formal organisation and, hence, the power to address these problems (De Fraiture et al., 2014). Irrigation can also have negative impacts on the environment, for example, petrol can leak from motor pumps and increase the pollution load (Evans et al., 2012). The expansion of irrigation can also increase energy needs and lead to higher GHG emissions from agriculture (Zou et al., 2013), conflicting with efforts for climate change mitigation. Finally, irrigation can have a negative impact on human health: The construction of water reservoirs can create new aquatic ecosystems in previously semi-arid or arid areas and foster the development of water-related diseases, such as cholera, diarrhoea or schistosomiasis (Boelee et al., 2009).

8.4.4 Barriers for implementation

The development and implementation of irrigation faces several barriers and constraints. Depending on the type of irrigation and the size of the irrigation system, high institutional, technical and financial support may be required. While small-scale irrigation on only a few hectares of land may be more easily initiated and operated by farmers themselves, larger areas require, among other factors, machinery, technical expertise and labour, some of which may be not available or too expensive (Fossi Tuekam et al., 2012). The cost of developing irrigated land, including the construction of canals and dams, is estimated between 10 000 USD and 20 000 USD (De Fraiture et al., 2014). A simple motor pump that can irrigate 2 to 3 ha costs between 500 USD and 750 USD, with additional operation costs, mainly for fuel, between 250 USD and 350 USD per ha per crop cycle (De Fraiture et al., 2014). For smallholder subsistence farmers, it is usually hard to access the credit required to cover these initial investment costs (Evans et al., 2012). Many larger irrigation facilities come with user fees, however, not all farmers are willing or able to pay this fee. For example, the irrigation facility at Bagré charges a biannual user fee of around 23 USD for one hectare, which may put a strain on farmers' financial resources (Korbéogo, 2020).

Furthermore, there are biophysical constraints to setting up irrigation facilities, such as water availability. Oftentimes, rivers and reservoirs dry out for several months in a row, limiting the potential for irrigation. Even larger dams experience large evaporation losses. For example, the Bagré Dam has a relatively high water level of 600 million m^3, however, this accounts for less than 30% of the dam's potential capacity of 2 billion m^3 (Kambou, 2019). The pressure is not only high on water resources but also on available land, which is becoming increasingly scarce due to population growth, unsustainable agricultural practices and soil erosion (Nyamekye et al., 2018).

Another important issue relating to land is tenure insecurity, which is persistent in Burkina Faso and which makes it difficult to access both land and water resources (Evans et al., 2012). Since irrigated farming is not common in all parts of Burkina Faso, there are farmers who have too little information on the correct use of irrigation facilities (Evans et al., 2012). This can lead to loss of water, pest infestations, leaching of fertiliser and high maintenance costs of the irrigation facilities. Also, the low level of education of smallholder farmers, many of whom are illiterate, presents a constraint in carrying out capacity building programs.

Since the development, operation and maintenance of irrigation systems comes with high financial costs, it may prevent certain social groups of farmers to participate in and benefit from this adaptation strategy. Social factors, such as gender, marital status, migration status, age or health, still largely influence farmers' access to assets and resources (Aguilar, 2013; De Fraiture & Giordano, 2014; Kakota et al., 2011). This differential access also translates into access to irrigation systems. This is particularly true for women, who are overrepresented in using watering buckets, cans or hoses, compared to their male counterparts, who are more likely to be better off and, therefore, own motorised pumps (De Fraiture & Giordano, 2014; Wanvoeke, 2015). Nevertheless, irrigation can help to improve the lives of different social groups, especially those of women, who are traditionally engaged in small-scale vegetable gardening to enhance food security, household health and incomes (Wanvoeke, 2015). Hence, provided that women are given equal access to irrigation facilities, respective training, financing tools and technological equipment, irrigation can help promote gender equality.

8.4.5 Institutional support requirements

Depending on the type of irrigation, institutional support is required in different domains. For example, small-scale private irrigation is usually initiated and managed by farmers themselves, requiring as little as watering can or low-cost technologies, such as hand pumps or treadle pumps. However, these technologies are very labour-intensive. Therefore, farmers are increasingly using motor pumps, especially diesel and kerosene pumps from China (De Fraiture & Giordano, 2014). According to De Fraiture & Giordano (2014), these pumps are popular among smallholder farmers due to the lower purchasing price and operating costs, as compared to Japanese or European pumps. Hence, the initial investment costs may be low for small-scale private irrigation. The picture is different for larger, more mechanised irrigation systems. According to Wanvoeke et al. (2016), there are irrigation systems, which are rarely developed outside of the sphere of development cooperation, due to the dependency on external financing through international donors. This is, for example, the case for drip irrigation, special kits which were provided to smallholder farmers in the past, however, usually via intermediaries, such as donors or NGOs, instead through direct sales. Hence, many smallholder farmers stopped using these applications, once the official project support ended (Wanvoeke et al., 2016).

8.5 Conclusion

Considering all mentioned criteria, the adaptation strategy irrigation shows risk mitigation potential with medium cost-effectiveness and has several positive co-benefits, for instance applying irrigation can help to diversify diets and ensure food security (Table 10). However, there are numerous barriers for a sustainable implementation and also institutional support would be needed where appropriate to support the access and maintenance of equipment to increase the adoption by smallholder farmers. All in all, the potential negative implications of irrigation on groundwater levels and associated environmental and social discrepancies need to be carefully considered and addressed when promoting and upscaling irrigation.

Table 10: Summary of multi-criteria assessment of irrigation as adaptation strategy.

Risk mitigation	Risk-gradient	Cost-Effectiveness	Upscaling	Potential Co-benefits	Potential maladaptive outcomes	Barriers to implementation	Institutional support requirements
Medium-high	Risk-independent	Medium	High	High	High	Medium to high	High

Chapter 9 – Integrated soil fertility management

9.1 Context and description of the technology

Burkina Faso faces natural soil poverty as well as a continuous decline in soil fertility due the overexploitation of land and soil water resources caused by population growth and the resulting increased demand for food. Poor management practices (e.g. bush burning) often result in soil erosion and the subsequent loss of topsoil, thereby further limiting land suitable for crop production (Nyamekye et al., 2018). The increasing occurrence of droughts puts added stress on soils, contributing to land degradation and reduced soil fertility.

Integrated Soil Fertility Management, commonly referred to as ISFM, can help to secure agricultural outputs under those conditions and has been promoted in Burkina Faso for several decades (Zougmoré et al., 2004). Considered a key factor in improving low soil and crop productivity in Africa, ISFM is defined as "a set of soil fertility management practices that necessarily include the use of fertiliser, organic inputs and improved germplasm, combined with the knowledge on how to adapt these practices to local conditions in aim of maximizing the agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles." (Vanlauwe et al., 2010). ISFM is not characterised by specific field practices, but is "a fresh approach to combining available technologies in a manner that preserves soil quality while promoting its productivity" (Sanginga & Woomer, 2009). ISFM requires interventions to be aligned with prevalent biophysical and socio-economic conditions at farm and plot level (Vanlauwe et al., 2015). Typical for drylands, ISFM in Burkina Faso is based on the following objectives: 1) maximising water capture and decreasing runoff, 2) reducing water and wind erosion, 3) managing limited available organic resources and 4) strategically applying mineral fertilisers (Sanginga & Woomer, 2009). Suitable interventions include, for example, Zaï, half-moons, stone bunds, filter bunds, grass strips and mulching. In the following, we describe some of those interventions in more detail.

In Burkina Faso, the **Zaï** farming practice and **half-moon planting** structures are widely used as water harvesting techniques to retain water for sorghum and millet production (Sawadogo, 2011). Translating into "to prepare in advance" from the national Mooré language, Zaï is a local adaptation of conservation agriculture that is used to rehabilitate strongly degraded land. At the beginning of the dry season, farmers dig small planting pits (20-40 cm in diameter, 10-30 cm deep and 40-150 cm apart), which help to capture rainfall and thereby improve soil moisture (Abdoussalam et al., 2017; Savadogo et al., 2011; Schuler et al., 2016; Techniques et al., n.d.). Half-moons work similarly, but involve digging pits of about 2 m in diameter and 15-20 cm in depth in a crescent shape with a distance of around 8 m (Savadogo et al., 2011). Both good practices have the goal to accumulate water before subsequent planting to improve soil moisture. Adding compost, plant residues and manure further improves the performance of the good practices (Sawadogo, 2011). Furthermore, a method called micro-dosing, which involves adding small amounts of mineral fertilisers to planting points within fields where water conservation is practiced, is often used in the Sahel (Sanginga & Woomer, 2009).

In many cases, half-moons are constructed in combination with **trenches**, which also aim to rehabilitate soils. Dug just behind half-moons, trenches are usually 5 m long and around 30 cm wide and 30 cm deep (Abdoussalam et al., 2017). Sometimes organic matter is added to the trenches. Trenches are designed to reduce the run-off water and to facilitate the recharge of water into the ground. Having a similar effect, **stone bunds**, also called contour bunds ("cordon de pierres" or "cordon pierreux") are an anti-erosion measure that involves piling stones at close spacing along the natural contours of the land to decrease the flow of runoff water, improve water infiltration and reduce the removal of topsoil by wind and water. A stone bund is typically 25 cm high and has a base width of 35-40 cm. Many farmers in north-western

Burkina Faso use a combination of Zaï and stone bunds, compost and manure on their farms to help vegetation regenerate more rapidly (Sawadogo, 2011).

Due to its ability to improve water use efficiency, prevent erosion and restore degraded lands, ISFM holds great potential for climate change adaptation. In Burkina Faso, such measures have proven successful in ameliorating soil structure, crop yield, ground water recharge, rainfall infiltration and tree density (Sawadogo, 2011; Zougmore et al., 2003). Combining organic inputs and fertiliser can help to reduce the sensitivity of crop production to climate impacts. A study in semi-arid Burkina Faso showed that in an erratic rainy season led to frequent periods of water stress, stone bunds or grass strips combined with compost reduced runoff, increased soil water storage and sorghum biomass production (Zougmore et al., 2003). The promotion of intercropping and rotation promoted by ISFM helps to further reduce the risk of crop failure. Lastly, the increases in crop productivity achieved by ISFM contribute to food security, thereby generally increasing the resilience of livelihoods of rural communities (Roobroeck et al., 2015). Lamachere and Sewantie (1990) for example, found that stone bunds can increase crop production by 30 to 80% in years with well distributed rains.

9.2 Biophysical assessment of risk mitigation potential

The yield impact of implementing ISFM for sorghum production in Burkina Faso is simulated using the DSSAT crop model approach introduced in chapter 3.3. We use the Zaï technology as a case study to showcase the risk mitigation potential for ISFM. Since this adaptation strategy is not directly available as an option in DSSAT, it is simulated using proxy values. Based on field experimental data from the region, we set initial soil conditions with Zaï equivalent to a water availability of 60% due to limited water sources (out of 100% of water availability needed to reach potential yields) and nitrogen content of 62 kg/ha. The latter results from the assumption of approximately 2-3 tons/ha compost and manure application within the Zaï pits (Fatondji et al., 2012; Faye et al., 2018).

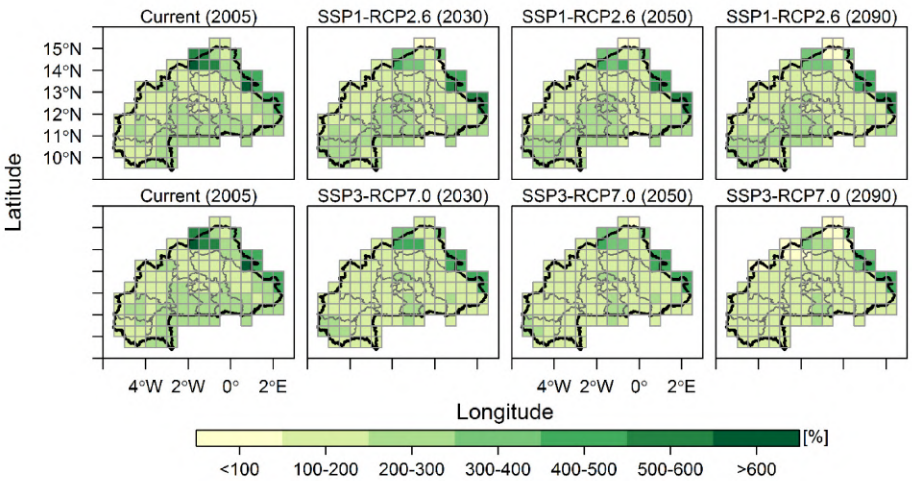


Figure 52: The spatial distribution maps for yield impacts (%) in sorghum using integrated soil fertility management in Burkina Faso.

As visualised in Figure 52, applying Zaï as an ISFM strategy is projected to increase sorghum yields over all regions of Burkina Faso significantly, by up to 600%. The highest impact is achieved over northern Burkina Faso in both emissions scenarios. Comparing both emissions scenarios, the strategy is likely to achieve the best results under the low emissions scenario SSP1-RCP2.6 throughout the next century, especially in Burkina Faso's southern part. However, Zaï technology is expected to produce highly positive impacts on Sorghum yield under both scenarios, suggesting that this technology is a very promising adaptation strategy under all future climate change scenarios.

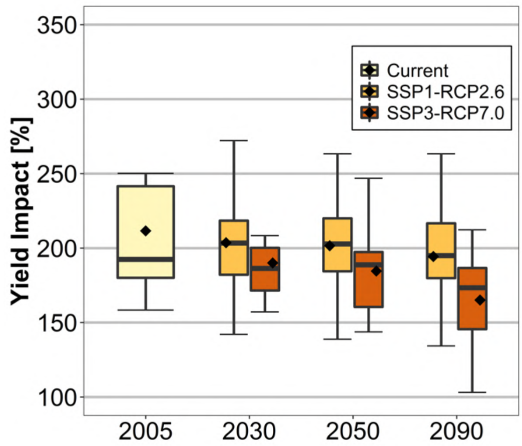


Figure 53: The inter-comparison of the impacts on Sorghum yield between different time steps at national level.

Figure 53 shows the variability of yield impacts over different time steps at national level. Comparing both scenarios, SSP1-RCP2.6 suggests that standard yield impacts are maintained over time, while SSP3-RCP7.0 displays a decreasing trend over time. Nevertheless, at the regional level both future scenarios suggest an improvement of at least twice (100%) the current yield in a scenario *with* the application of the Zaï technology compared to a non-adoption scenario.

The overall positive trend is maintained also when disaggregating results at the regional level (Figure 54). Results indicate that the Zaï technology for both scenarios and for all future time-steps will have positive sorghum yield impacts of between 100% to 300%. In most of the regions, the Zaï technology performs better under SSP1-RCP2.6 than under SSP3-RCP7.0. The 2090s results under SSP3-RCP7.0 suggest the lowest yield gains in most regions.

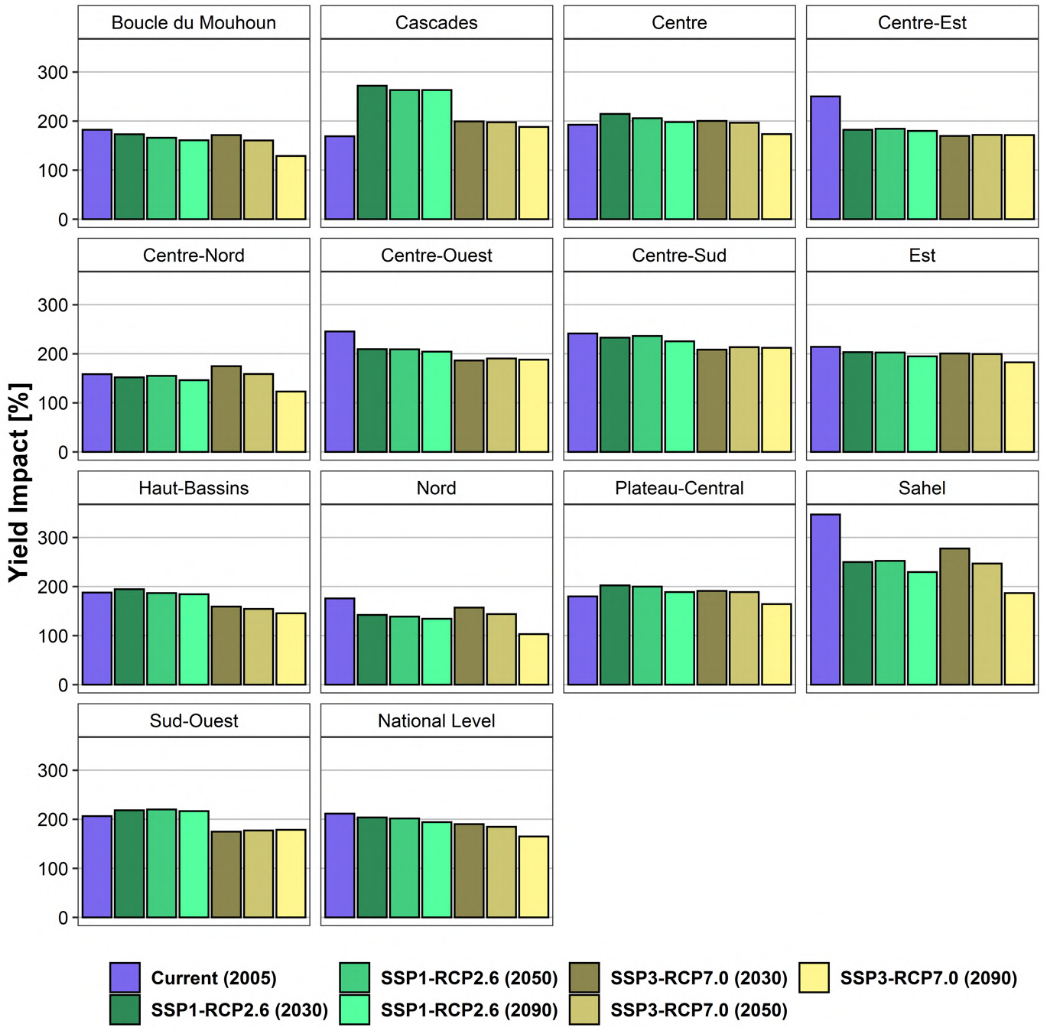


Figure 54: Regional disaggregation of yield impacts using integrated soil fertility management over different scenarios and time-steps.

9.3 Cost-benefit analysis of integrated soil fertility management for sorghum production

To analyse the economic feasibility of ISFM technology as an adaptation strategy, we compare costs and benefits of a sorghum production system in the Plateau Central region that adopted the use of ISFM technology with a conventional farming system that did not adopt the ISFM technology. We use a case of ISFM that is based on a combination of Zaï pits, embankments, dams, infiltration basins and trenches around the fields used as soil and water conservation techniques. We compare the results under the two climate change scenarios of SSP1-RCP2.6 and SSP3-RCP7.0 projected until 2050 with reference to a baseline scenario describing the status quo as of today.

9.3.1 Baseline and scenarios

The baseline and scenarios are defined as follows:

Baseline (no action, no climate impacts): Rain-fed sorghum production under current climatic and technological conditions in the Plateau Central region.

Non-adaptation (no action, climate change impacts under SSP1-RCP2.6 and SSP3-RCP7.0): Rain-fed sorghum production without the use of ISFM. The market revenues and production costs of the system are extrapolated until 2050 assuming a climate change yield impact as simulated with the DSSAT model (see chapter 3.3) under the SSP1-RCP2.6 scenario and the SSP3-RCP7.0 scenario.

Adaptation (action, climate change impacts under SSP1-RCP2.6 and SSP3-RCP7.0): Rain-fed sorghum production with the use of ISFM technology. The market revenues and production costs of the system are extrapolated until 2050 assuming a similar climate change yield impact as under "non-adaptation" under the SSP1-RCP2.6 scenario and the SSP3-RCP7.0 scenario.

9.3.2 Survey data

The CBA of the ISFM technology is calculated using detailed farm-level production and economic data collected from ten farms in the Plateau Central region in the centre of Burkina Faso. The surveyed farmers installed embankments, dams, infiltration basins and trenches around their fields, which they currently use to conserve soil and water. In addition, every year, the farmers dig Zaï pits in their fields, to collect water and nutrients from compost or manure (see 9.1 for further definition). Each surveyed farmer cultivates an area of about two hectares with sorghum using ISFM. However, following the standard level in farm economics and for better comparison across scenarios, we analyse the subsequent average market revenues and production costs associated to one hectare.

Farmers from the survey were asked to provide detailed information on the costs of installation of the technique, yields before and after adaptation and market prices. To determine the subsequent changes of market revenues and production costs, the following aspects are considered for an average farmer who adopts.

- The main cost drivers of the CBA are the labour costs for the installation of the ISFM technology (embankments, basins and trenches) and the costs for Zaï pits preparation. According to the surveyed farmers, embankments, dams, basins, and trenches have to be renewed every 15 years, while Zaï pits must be dug every year. To calculate the associated additional costs for labour, we used the mean value of the average daily labour rate for off-farm activities retrieved from the survey, which is 929 CFA (~ 1.65 USD), and the daily rate of 2000 CFA (~ 3.5 USD), which is commonly paid for comparable work in the region and thus arrive at a rate of 1.464 CFA (~ 2.6 USD) per day (WASCAL, 2020a).
- Another substantial production cost factor are opportunity costs, i.e. the income that farmers would have generated with other activities during the time used for the installation of the ISFM technology. Most of such activities are conducted off-farm, for example brick making or trading, but can also be performed on other farms. As indicated from the survey, we used the average daily labour rate for off-farm activities of 929 CFA (~ 1.65 USD[15]) to calculate the opportunity costs derived from the income losses endured while installing ISFM.
- As embankments, dams, basins and trenches are constructed from naturally occurring materials such as sand and stones collected from the fields, no additional costs occur in this regard. The same accounts for the equipment used for construction. Most tools are needed for other farm activities, too, and, hence, do not produce additional costs for adaptation, especially as they are only needed every 15 years (with the exception of tools used for digging Zaï pits).
- The higher yields induced by improved soil fertility and water management, however, lead to an increased workload for harvesting and seed conservation. The labour costs for these activities are therefore adjusted annually using the ratio between the yield with adaptation and the reference yield prior to adaptation (WASCAL, 2020a).
- To calculate the revenues, we use a market price of 165 CFA (~ 0.30 USD) for one kg of

[15] All exchange rates were retrieved on 18.3.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en.

sorghum. The price is an average value of the sorghum market price indicated in the household survey adjusted for the mean common market price level of past five years in the region (FEWS NET, 2020). According to the interviewed farmers, the sorghum yield increased by 97 kg per hectare in the first year of adaptation and again by additional 20 kg in the second year. Based on the revenues gained from the yield surplus, we extrapolated the additional market revenues and extra labour costs until 2050 (WASCAL, 2020a).

9.3.3 Assumptions

To complete the information from the survey data, additional assumptions on the effects of technological progress, inflation and climate change had to be made:

- Climate change induced yield developments in the Plateau Central region are derived from PIK projections under the SSP1-RCP2.6 and SSP3-RCP7.0 scenario including a positive effect on yield developments with adaptation (see also chapter 7.2).
- We assume that the farmers' area productivity increases due to autonomous technological change by 2.4% per annum. This is an extrapolation of sorghum yield increases between 1984 and 2010 in the target region (WASCAL, 2020b).
- To depict the inflation rate, we calculated the exponential growth rate of the GDP per capita of Burkina Faso from the last 30 years, its value is 3.88% (FAOSTAT, 2021).

9.3.4 Results

The CBA results show that implementing the ISFM techniques would be beneficial for the farmers, as it has a positive return on a rather small-scale investment (Figure 55). This applies to both climate change scenarios, whereby the scenario under SSP3-RCP7.0 performs considerably better, due to the embedded additional climate change related yield effects. In particular, the following results should be highlighted:

- Starting with a net present value (NPV) of -35,830 CFA (~ -63 USD), the net cash flow for the farmers is already positive from the second year on. The comparably low initial investment costs lead to an increasing NPV right from the beginning, resulting in a positive NPV under the SSP1-RCP2.6 scenario from year 2030 on. For the SSP3-RCP7.0 scenario, the NPV becomes already positive in year 2026.
- The NPV further increases. Only in year 2035 and again in 2050, the reinstallation of the ISFM technologies leads to negative cash flows under both climate change scenarios, thus temporarily lowering the NPV. However, from the subsequent year on the NPV increases again.
- In year 2050, the NPV accumulates to 77,142 CFA (~ 136 USD) under SSP1-RCP2.6 and to 175,604 CFA (~ 310 USD) under SSP3-RCP7.0.

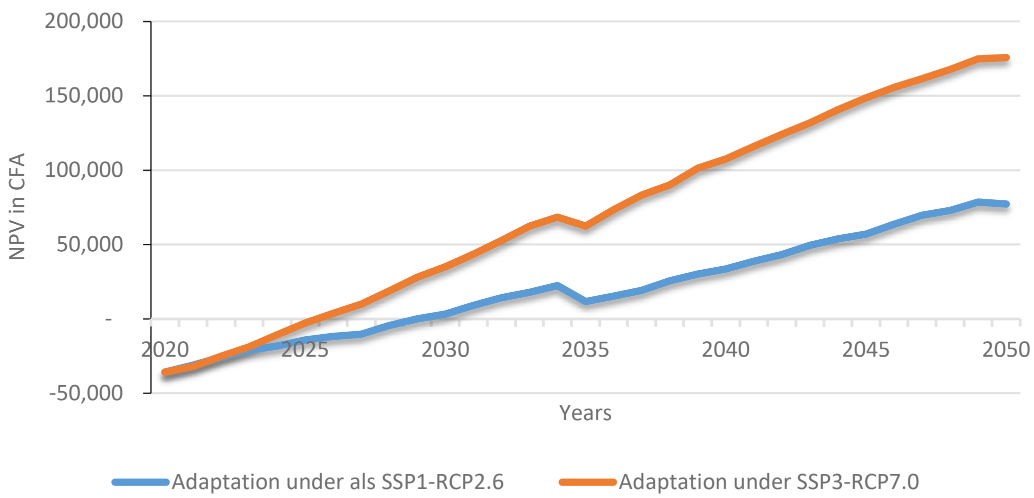


Figure 55: Development of the net present value of switching to sorghum cultivation using ISFM.

The results of the calculations suggest that the farmers' investment into ISFM technologies pays off after ten years under the SSP1-RCP2.6 scenario and already after six years under the SSP3-RCP7.0 scenario. The break-even points between accumulated net costs and net benefits are therefore in 2030 and in 2026, respectively. As a consequence, the internal rate of return (IRR) is positive and yields 14% for an adaptation effort under the SSP1-RCP2.6 scenario and 23% for an adaptation effort under the SSP3-RCP7.0 scenario. Assuming a global rentability perspective, which is often taken for a local CBA, any IRR higher than 6.0% is considered a profitable investment. As this is the case for both future scenarios (SSP1-RCP2.6 and SSP3-RCP7.0), the investment into techniques to enhance soil fertility for sorghum production can be regarded as profitable for the farmers. This is also evident from the cost benefit ratio (BCR) of the adaptation investment, which is 1.29 in 2050 under the SSP1-RCP2.6 scenario and 1.65 under the SSP3-RCP7.0 scenario (Table 11).

Table 11: Summary of major CBA indicators for switching to sorghum cultivation with ISFM.

	Adaptation SSP1-RCP2.6	Adaptation SSP3-RCP7.0
IRR	14.38%	23.28%
NPV	77,142 CFA (= 136 USD)	175,604 CFA (= 310 USD)
BCR	1.29	1.65

9.4 Qualitative assessment of integrated soil fertility management

9.4.1 Upscaling potential

To reduce the risk of land degradation, farmers in Burkina Faso have been practicing ISFM for decades, particularly in central and northern areas of the country (Zougmoré et al., 2004). Zaï and half-moons are mostly practiced on degraded, crusted soils in Sahelian, southern Sahelian and northern Sudanese climates with precipitation ranging from 400 to 600 mm annually. It is common in the Sahel, northern, central northern and central plateau regions and on land intended for rain-fed crops. Stone-cord bunds and filter bunds are being adopted throughout the country to solve land gullying problems, but more so in the Sahel, North, North Central, Central and Central Plateau regions, on rain-fed land and on cultivated lowland land (CILSS, 2012). Grass strips and mulching are practiced in all climatic zones of Burkina Faso, and on all types of soils for land regeneration (Government of Burkina Faso, 2011).

The substantial promotion of ISFM through donors and NGOs, as well as favouring national policies, led to a wide dissemination of ISFM (Kabore-Sawadogo et al., 2013). Alongside this external support, farmers continued to improve existing water harvesting technologies and began spreading the good practices among themselves. Particularly worth mentioning is Yacouba Swadogo, a farmer from Gourcy, who enhanced the traditional use of Zaï in the 1980s and successfully stopped desertification in his village. Since then, farmers in Burkina Faso have managed to transform large swaths of the arid landscape into productive agricultural land using ISFM. In some villages, up to 90% of cultivated land has been treated with water harvesting techniques (Kabore-Sawadogo et al., 2013). Sawadogo (2011) highlights that in the provinces of of Yatenga, Zondoma, Lorum and Passore in Northern Burkina Faso every household uses Zaï on at least one farm. In the Central Plateau Region, it is estimated that ISFM has helped to rehabilitate 200,000 to 300,000 ha of land and to produce an additional 80,000 to 120,000 tons of cereal per year over the last three decades (Reij et al., 2009).

Considering the rather limited extent of irrigation coverage, rain-fed agriculture still plays a significant role in Burkina Faso. According to the FAO, only 28% of the irrigable land in Burkina Faso was irrigated in 2017, corresponding to 8% of the total national cropland (FAO, n.d.; FAOSTAT, 2017). Therefore, the water harvesting aspects of ISFM continue to hold great potential offering farmers a cheaper method to more efficiently use rainfall water and thereby limiting the impacts of recurring droughts. While already widely used in central and northern areas of Burkina Faso, all regions in the country would benefit from area-specific technologies to manage soil moisture and fertility to be able to cope with climate stress (Kabore-Sawadogo et al., 2013).

9.4.2 Potential co-benefits

The effects of ISFM on soil structure, crop yield, and ground water recharge leads to substantial co-benefits in regard to land restoration, food security and poverty reduction. As mentioned earlier, ISFM has helped to rehabilitate considerable areas of degraded land in Burkina Faso. Other environmental co-benefits include increased plant diversity and rising groundwater levels (Reij et al., 2005; Roose et al., 1999). The implementation of ISFM also holds great potential for climate change mitigation, as greenhouse gas (GHG) emissions are reduced due to the created uptake of N fertilisers by crops and soil C sequestration (Roobroeck et al., 2015).

The increased crop production caused by the implementation of ISFM contributes to food security in the country. A study in north-western Burkina Faso by (Sawadogo, 2011) found that in the years of average rainfall, crop yields increased by 63 to 74% on farms in the study villages using rock bunds, and by over 100% on farms using Zaï. Furthermore, ISFM can have a positive impact on the availability of forage for livestock due to the regeneration of vegetation and increased crop residues. (Reij et al., 2005) refer to one village in the Bam region, in which herds no longer need to be moved, because of the abundance of crop residues and perennial grasses.

Overall, those factors can lead to a significant reduction in rural poverty, often resulting in decreased out-migration. (Reij et al., 2005) reported poverty decreases of up to 50% in villages in the Central Plateau that started implementing ISFM since the 1980s, as well as a 25% population increase between 1985 and 1996 due to the implementation of ISFM.

9.4.3 Potential negative outcomes

The literature cites very few maladaptive outcomes. Roose et al. (1999) point to potential pit clogging and nutrient leaching in Zaï holes due to excessive rains, as observed in the case of cereal production in Cameroon.

The high labour requirements of implementing ISFM may have some negative side-effects. A study in Tigray, Ethiopia found that ISFM did not lead to household incomes because the intense labour needed for the application of ISFM absorbed labour resources that could otherwise be used productively elsewhere (Hörner & Wollni, 2021).

Overall, the few references made to potential maladaptive outcomes suggest that there is high potential for the upscaling of ISFM as an adaptation strategy in Burkina Faso.

9.4.4 Barriers for implementation

Researchers have widely pointed to the high potential of ISFM as a way to improve soil fertility and thereby increase food productivity (Kabore-Sawadogo et al., 2013; Mugwe et al., 2019; Sanginga & Woomer, 2009). However, there are various barriers to the adoption of ISFM, that need to be taken into consideration when promoting the adaptation strategy.

One of the major constraints of implementing ISFM are its strenuous manual labour requirements. Estimated labour requirements for Zaï, for example, vary between about 300 hours (Roose et al., 1999) to 600 hours per hectare of hard work digging holes and an additional estimated 300 hours for the production of manure and its transport and spreading into pits (Kabore-Sawadogo et al., 2013). This may have implications on farmers' income.

Furthermore, ISFM is knowledge-intensive and many smallholder farmers still lack adequate information on the implementation of ISFM and also on the benefits of this adaptation strategy (Mugwe et al. 2019). Furthermore, access to equipment for extraction and transport (carts, pickaxes, wheelbarrows) and to the required input (mineral fertilisers, compost, manure, rubble, straw), as well as access to markets and financial resources can also hinder the uptake of ISFM in Burkina Faso (Roobroeck et al., 2015; Sanginga & Woomer, 2009; Savadogo et al., 2011; Vanlauwe et al., 2010).

Other barriers include poor research-extension-farmer linkages, insecure land tenure, gender consideration and insufficient adaptation of technologies to farmer condition (Sanginga and Woomer, 2009; Vanlauwe et al., 2010).

9.4.5 Institutional support requirements

ISFM is knowledge-driven and requires access not only to input and labour but also enough information that allows farmers to make better decisions concerning soil management, based on a set of flexible principles that constitute ISFM. Recognition of land degradation as a risk for agricultural production is an important first step. In Burkina Faso, for example, (Sidibé, 2005) found that education and the perception of soil degradation are important factors for the adoption of Zaï and stone bunds. Knowledge of the correct implementation of ISFM is also a prerequisite (Savadogo et al., 2011). The government should therefore put emphasis on the promotion of farmer education and extension on the causes and effects of land degradation and improve awareness and training on ISFM (Partey et al., 2018). Existing extension services and farmers associations are useful structures to support farmers with the adoption of ISFM techniques. In addition, agro-dealers and out-grower agencies are well placed to lead market-led dissemination and extension (Sanginga & Woomer, 2009). To ensure the effective promotion of ISFM, recommendations should be well-targeted to the local context taking site-specific bio-physical and socio-economic conditions into consideration that determine technological performance and feasibility of ISFM (Vanlauwe et al., 2015).

Furthermore, strategic policies are needed that stimulate institutional and market response toward ISFM and resulting crop surpluses (Sanginga & Woomer, 2009). Policies towards sustainable land use intensification, as well as the rehabilitation of degraded soils and the necessary mechanisms to implement and evaluate these can help to promote the uptake of ISFM (Vanlauwe et al., 2010). In Burkina Faso, there are already several initiatives that promote the adoption of ISFM, including the Action Plan for the Integrated Management of Water Resources (PAGIRE) (MEA, 2016), and several projects implemented by the National Federation of Groupements Naam created in 1967 and which promotes the adoption and upscaling of Zaï, filtering bunds, stone barriers and half-moons. The Association Zoramb Naagtaaba (AZN) through the green land farms has been working for the extension of the bocage system since 1988. By granting villagers land tenure security, the Agrarian Land Re-organization (ALR), which was introduced in 1984, was an important step in incentivising farmers to invest in their land and implement ISFM. During the same time, various projects and programmes were initiated with the aim to rehabilitate the productive capacity of the land through better control of rainfall and runoff, as well as through improved soil fertility management and reforestation. This includes, for example, the National Program for Combating Desertification, the Programme Sahel Burkina (PSDB9), the Combating Desertification in Burkina (LUCODEB), and the National Programme for the Management of Rural Areas (Nyamekye et al., 2018; Reij et al., 2005).

Policies that incentivise credit and loan schemes and subsidy programmes for the production of organic inputs could address the issue of lack of access to equipment and input (Roobroeck et al., 2015). In Burkina Faso, making use of the *Warrantage* systems, well established farmers' marketing systems, could be an option to provide farmers with access to credit for the implementation of ISFM. Better linkages to credit and fair commodity markets increase productivity and returns on investment, as farmers profit from crop surpluses (Sanginga & Woomer, 2009).

For the widespread upscaling of ISFM, there is a need to invest in broad partnerships. Research on and dissemination of practices needs to be strengthened. The public sector can play an important role in creating a platform for bringing together and linking key partners in research, education, extension, service providers, input providers, and farmers to facilitate farmer mobilisation, capacity building and linking farmers to credit and markets (Stewart et al., 2020).

The added value of institutional support for the upscaling of the good practice was documented by Reij and Thiombiano (2003). They showed how investments in soil and water conservation combined with other components of ISFM led to a drastic increase in millet and sorghum yield between 1996 and 2000 after decades of land degradation and out-migration in the Central Plateau of Burkina Faso. This included an increased investment in livestock, which, in combination with improved management, led to increased availability of manure. Table 12 summarizes the different indicators.

9.5 Conclusion

In a context like Burkina Faso, where there is significant population pressure on land resources and little irrigation infrastructure available, the upscaling of ISFM holds great potential offering farmers a cheaper method to more efficiently use rainfall water and thereby limiting the impacts of negative climate impacts. In addition, the strategy holds various socio-economic co-benefits include-ing increased agricultural-production, food security and restoration of degraded land and biodiversity.

Table 12: Summary of multi-criteria assessment of ISFM as adaptation strategy.

Risk mitigation	Risk-gradient	Cost-Effective-ness	Upscaling	Potential Co-benefits	Potential maladaptive outcomes	Barriers to implemen-tation	Institutional support requirements
High	Risk-independent	High	High	High	Low	Medium	Medium to low

Chapter 10 – Improved crop varieties

10.1 Context and description of the technology

One option to help farmers to make more productive use of land, water, nutrients and other resources to improve food security is the genetic improvement of crops under stress and optimal growing conditions (IPCC, 2019; Searchinger et al., 2014; Voss-Fels et al., 2019). Hence, this represents a very promising strategy for adaptation to climate change (Sanou et al., 2016). An improved or modern variety is a new variety of a plant species which produces higher yields, higher quality or provides better resistance to plant pests and diseases while minimizing the pressure on the natural environment (Access to Seeds Index, 2020). Such modern varieties are genetically uniform, which means that their characteristics are constant within all individuals of that specific variety. The exact definition and requirements of improved varieties depend on a country's legislation and international treaties (e.g., harmonized Seed Regulation adopted by ECOWAS). Improved varieties have e.g. higher tolerances to abiotic stressors such as drought (Fisher et al., 2015), resistances to biotic stressors (diseases and pests), improved resource use, or other changes that permit altering the agronomic management by e.g. needing shorter growing cycles. Along with labour saving technologies, flexible credits, locally adapted seed varieties are among the most needed inputs for farmers in Burkina Faso (Roncoli et al., 2001). Along with sufficiently high yields, important seed characteristics for farmers are early maturity, drought resistance, seed color and seed size (Ishikawa et al., 2020). It is important to note that there are large differences between seeds no matter if they are considered landraces or improved varieties. Formal plant breeding for improved plant varieties is an ancient activity tightly connected to agricultural systems. And already in the mid-1800's Gregor Mendel found the principles for scientific breeding. To achieve the optimal adaptation effect of improved varieties, a variety must fulfill several conditions, such as farmer's preference (including traditional and culinary aspects), local suitability, agronomic management and many more. Therefore, it is necessary to ensure that new locally adapted good quality seeds are available and accessible. Older improved varieties might have become susceptible to certain pathogens and do not represent the latest state of breeding efforts.

In Burkina Faso, improved varieties exist mainly for the staple crops maize, millet, sorghum, cowpea, rice, cassava, sesame and also vegetables and the cash crop cotton. Nevertheless, the adoption rate of improved varieties remains very low and is estimated at around 10% (Access to Seeds, 2018; Compaoré et al., 2020). The total area sown with improved seeds in 2008 was estimated at 587,882 ha, or 11% of the country's total cultivated area (RGA, 2008). Most of the area sown with improved seeds is cotton (82% of the overall cotton production), maize follows with 12%, while sorghum and millet have an improved seed coverage rate of below 2% even though they cover most of Burkina Faso's cultivated area (Compaoré et al., 2008). Also improved rice, sesame and cowpea varieties cover only a marginal share of that area (Compaoré et al., 2008). In terms of the proportion of area under improved varieties compared to the total cultivated area, the Haut-Bassins region ranks first with 32.93% of area under improved seed. It is followed by the Cascades (24.44%), the Boucle du Mouhoun (16.67%) and the Southwest (15.52%). The central-western, northern and central plateau regions account for less than 2% of the area under improved seeds.

As the adoption rate of improved seeds is low, most seeds planted by smallholder farmers are landraces. Such landraces evolve in agricultural systems maintained by smallholder farmers. Farmers' seed selection and environmental processes (including genetic interactions with wild relatives) shaped today's landraces over generations of cultivation. In Burkina Faso these landraces come from family inheritance or exchange between producers. Usually landraces do not constitute a variety according to professional plant breeders' or legal definitions as their characteristics can be heterogenous when segregate genetically (Harlan, 1992; Smale & Jamora, 2020). Also, their seed quality standards are not proofed. Thus, their characteristics such as appearance or yield must not be constant over time and within all individuals.

The availability of good quality and local adapted improved seeds is a precondition to implement the adoption strategy. The modes of production and availability of improved seeds for food crops have changed significantly in sub-Saharan African countries over the last 50 years (Kaboré et al., 2010), moving from a state-managed sector where varieties were mainly developed by national research institutes and CGIAR centers to today's sector with an increasing private sector constituted by mainly regional companies (Access to Seeds, 2018). Nevertheless, national or international institutions are still dominant for Burkina Faso's seed sector (Access to Seeds, 2019).

Burkina Faso implemented a seed policy and regulations for the seed sector, which include the variety release and registration and also enable active actors within its seed sectors (Access to Seeds, 2019). Therefore, its seed sector is leading in West Africa (Access to Seeds, 2019). The main actors involved in the production chain of improved seeds are the scientists and technicians from the public institute for agricultural research (Institut de l'Environnement et de Recherches Agricoles (INERA)), the seeds inspectors for the ministry of agriculture, seed producing agricultural cooperatives and also private actors organized in associations. Further development agencies and international institutes pursuing agricultural research for development (e.g., the CGIAR centers) play a role in technology transfer. For example, the International Institute of Tropical Agriculture (IITA) collaborated with the Burkinabe government to create improved cowpea varieties with participatory varietal selection by farmers. There is also a collaboration of national agricultural research institutes with the West and Central African Millet Research Network on the one hand and ICRISAT on the other hand has made it possible to give farmers in Sahelian countries access to an increasing number of millet varieties (Compaore et al., 2020).

Access to seeds (2019) analyses country-specific information for 17 (mostly regional) private companies which operate in the country, of which most pursue the activity of selling seeds (n = 16), a minority has breeding locations in the country (2), testing locations (3) seed production (5) or extension services (2) and involve smallholder farmers in seed production activities.

One of INERA's tasks is to promote the adoption of improved varieties and it has therefore established an agreement for future public-private partnerships for seed production (Access to Seeds, 2019). Also, research institutes such as INERA and the National Union of Seed Producers of Burkina Faso (UNPS-BF) regularly organize improved variety seed fairs with a view to popularizing new varieties among producers. In this perspective, several projects and programs have been created on national level to support seed production and extension of improved varieties. Several seed enterprises have benefited from financial support from projects and NGOs including the Alliance for the Green Revolution in Africa (AGRA).

10.2 Biophysical risk mitigation potential

Improved sorghum variety was chosen based on its selection history, phenology (maturity and photoperiod sensitivity), and grain yield productivity to represent contrasting sorghum types cultivated in West Africa (Adam et al., 2018). In this study, we used Fadda, a single-cross hybrid with Guinea-race-derived parents, and grain yield productivity exceeding that of farmers' local varieties (Rattunde et al., 2016).

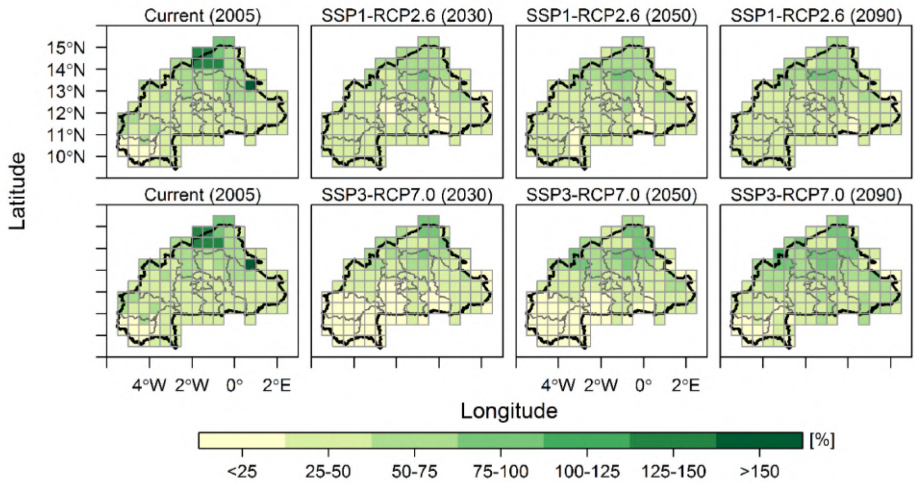


Figure 56: The grid-level spatial distribution map for projected yield impacts of improved variety (Fadda) in Burkina Faso for various scenarios and time-steps.

Overall, improved variety had increased the yield over all of the grids significantly up to 150% (Figure 56), especially over northern Burkina Faso (Boucle du Mouhoun, Nord, Centre-Nord, Centre, and Plateau Central) in both the emissions scenarios. Comparing both scenarios, the south-western of the Burkina Faso (Centre-Ouest, Centre-Sud, Centre-Est, and the lower Est) region remains nearly unchanged in the low emissions scenario (SSP1-RCP2.6), but the high emissions scenario (SSP3-RCP7.0) had projected an increasing trend over time. The higher yield impacts in the northern region (Boucle du Mouhoun, Nord, Centre-Nord, Centre, and Plateau Central) can be explained by the higher rainfall as compared to the southern region (Cascades, Haut-Bassins, and Sud-Ouest) leading to an optimal condition for the respective Crop Water Requirement (CWR) of the crops. However, under the low emissions scenario (SSP1-RCP2.6) the southern regions (Cascades, Haut-Bassins, and Sud-Ouest) of Burkina Faso have higher yield impacts than under the SSP3-RCP7.0 scenario. Nevertheless, both the scenarios have produced significantly positive yield impacts with improved variety (Fadda).

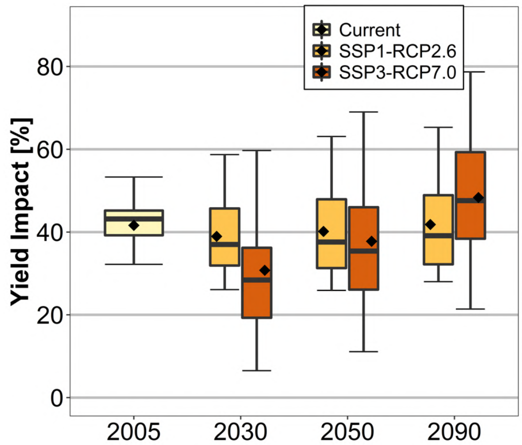


Figure 57: The regional-level intercomparison of the yield impacts between different time steps with improved variety.

Figure 57 shows the yield impact variability with improved varieties for both the scenarios and different time-steps. Comparing both the scenarios SSP1-RCP2.6, the low emissions scenario had maintained standard yield impacts over time (2030s, 2050s, and 2090s), but SSP3-RCP7.0 had an increasing trend over time. In the current (if improved variety would have used), improved variety had projected to increase yields up to 60%. From the current, yields are projected to increase over time in the SSP3-RCP7.0 and to remain unchanged in SSP1-RCP2.6.

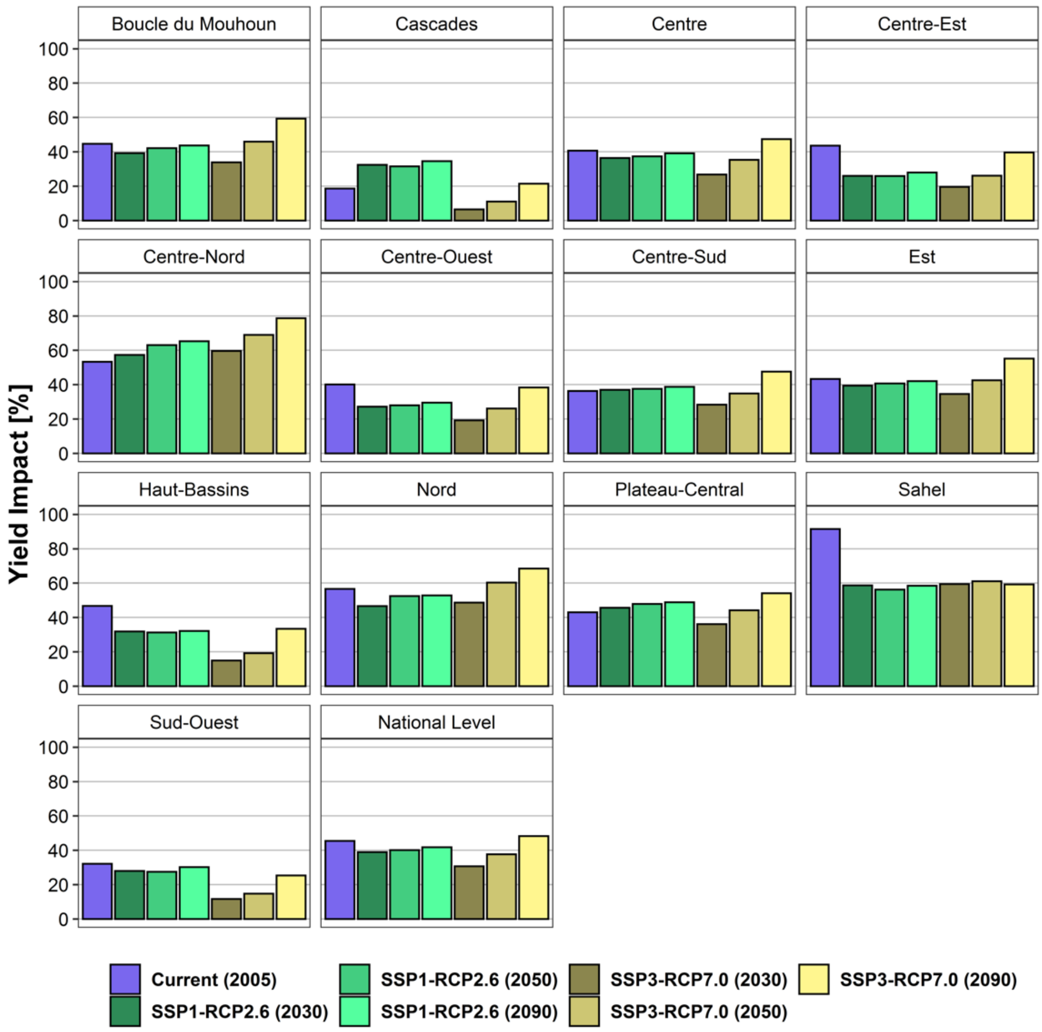


Figure 58: Regional-wise yield impacts with improved variety over different scenarios and time-steps.

Figure 58 shows the regional-wise yield impacts of improved variety for both the scenarios and different time-steps. All regions have yield impacts of at least 10-80%. Comparing all the time-steps, the southern regions of Burkina Faso (Cascades, Haut-Bassins, and Sud-Ouest) have higher yields in SSP1-RCP2.6 than SSP3-RCP7.0, and northern yields Faso (Boucle du Mouhoun, Nord, Centre Nord, Centre, and Plateau Central) are higher in SSP3-RCP7.0 than SSP1-RCP2.6. However, the region, Sahel is projected nearly the same impacts in both scenarios.

Improved varieties can help farmers to produce higher production quantities and qualities under stress and optimal growing conditions (Voss-Fels et al., 2019), hence they are also an important strategy to adapt to climate change (Sanou et al., 2016). This is achieved through higher tolerances to abiotic stressors such as drought (Fisher et al., 2015), resistances to biotic stressors (diseases and pests), improved resource use, or other changes that permit altering the agronomic management by e.g. needing shorter growing cycles. Along with labour saving technologies, flexible credits, locally adapted seed varieties are among the most needed inputs for farmers in Burkina Faso (Roncoli et al., 2001). Along with sufficiently high yields, important seed characteristics for farmers are early maturity, drought resistance, seed color, seed size (Ishikawa et al., 2020).

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10.3 Cost-benefit analysis for rainfed sorghum cultivation using improved crop varieties

The following CBA intends to evaluate whether switching from traditional sorghum varieties, so called landraces, to improved crop varieties (ICV) is an economic feasible adaptation strategy. Costs and benefits of using improved seeds are compared to a non-adaptation scenario and projected until 2050, considering two different climate change scenarios. As reference we use a baseline (scenario) describing the status quo as of today.

10.3.1 Baseline and scenarios

Baseline (no action, no climate impacts): Rainfed sorghum production under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under SSP1-RCP2.6 and SSP3-RCP7.0): Rainfed sorghum production growing traditional sorghum varieties. The market revenues and costs of the production system are extrapolated until 2050 assuming a climate change yield impact under a SSP1-RCP2.6 scenario and SSP3-RCP7.0 scenario.

Adaptation (action, climate change impacts under SSP1-RCP2.6 and SSP3-RCP7.0): Rainfed sorghum production with improved varieties. The market revenues and production costs are extrapolated until 2050 assuming a climate change yield impact under a SSP1-RCP2.6 scenario and SSP3-RCP7.0 scenario.

10.3.2 Survey data

The CBA of improved sorghum varieties was conducted using detailed production and economic data collected from Sanmatenga in the North Centre of Burkina Faso. The data was assembled from ten farms that are using ICV since more than 12 years. The average total farm size of each farm is about 7 hectares, with an area of 2 hectares cultivated with sorghum. However, following the standards in farm economics and for better comparison across scenarios, we analyse the subsequent market revenues and costs of production associated to one hectare.

In comparison with the non-adaptation scenario, that uses a local sorghum race called Roco, in the adaptation scenario, improved varieties, namely ICSV 10.49 and CSM63E, are grown. Other than traditional races, which are inherited from generation to generation or obtained from neighbours, ICV must be purchased on the local markets.

To identify the associated changes in market revenues and production costs, the following aspects are considered:

- Unlike for the other adaptation strategies, the use of ICV does neither require any equipment or material nor substantial additional labour input. Hence, the main cost factor are the costs for ICV seeds. From the surveyed farms we retrieved average costs of 1,932 CFA (~ 3.5 USD[16])

[16] All exchange rates were retrieved on 04.3.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en.

per hectare and year (WASCAL, 2020a). The costs are considered as additional costs for the farmers to adopt, since the seeds of traditional sorghum races are usually passed on between generations and hence have no official price.

- In addition to acquisition costs for seeds, the farmers spend half of a day for training and planning with the new varieties accumulating to 744 CFA (~ 1.3 USD) per hectare in the first year of using ICV and then every five years again. Assuming that changes to the seeds are made every five years, farmers must again receive training on the modified seeds in the same year. However, in expecting that farmers need to spend some time on planning of their cultivation period regardless the fact, whether varieties have changed or not, we also assume costs of 372 CFA (~ 0.70 USD) in each year (ibid.).
- As for the other adaptation strategies, the higher yields of ICV increase the workload for harvesting, seed conservation, and drying. Therefore, the labour costs for these activities are annually adjusted using the ratio between the yields with improved sorghum seeds and the reference yield with landraces (ibid.).
- To calculate the market revenues, we use a market price of 189 CFA (~ 0.34 USD) for one kg improved sorghum and 147 CFA (~ 0.27 USD) for one kg of the conventional variety, which was indicated in the household survey. The higher price can be explained by the better characteristics of the variety regarding taste and protein content (WASCAL, 2020a). According to the interviewed farmers, the sorghum yield increased by 380 kg per hectare with ICV compared to the traditional race. Based on the market revenues gained from the yield surplus, we extrapolated the revenues and costs until 2050 (ibid.).

10.3.3 Assumptions

In addition to the information retrieved from the survey, some assumptions on climate change and technological impacts as well as on inflation rates had to be made:

- Climate change induced yield developments in the Plateau Central region are derived from PIK projections under the SSP1-RCP2.6 and SSP3-RCP7.0 scenario including a positive effect on yield developments with adaptation (see chapter 3).
- We assume that the farmers' area productivity increases due to autonomous technological change by 2.4% per annum. This is an extrapolation of sorghum yield increases between 1984 and 2010 in the target region (WASCAL, 2020b).
- To depict the inflation rate, we calculated the exponential growth rate of the GDP per capita of Burkina Faso from the last 30 years, its value is 3.88% (FAOSTAT, 2021).

10.3.4 Results

The CBA results, as depicted in Figure 58, show, that in 2050, the adaptation strategy of switching from traditional sorghum varieties to improved breeds is highly beneficial, as it has a very positive return on a rather small-scale investment. This applies to both climate change scenarios, whereby the scenario under SSP1-RCP2.6 performs slightly better than the SSP3-RCP7.0 scenario. In particular, the following key figures are worth mentioning:

Due to the very low investment costs, the net cash flow for the farmers is already positive from the second year on and the higher costs for seeds are covered with immediate effect. Accordingly, the net present value (NPV) increases and becomes positive right from the beginning (see Figure 59). It further develops rapidly in a positive direction. Since the costs for the farmers are the same every year and only increase slightly every five years due to training costs, the NPV develops almost linearly until the year 2050. It reaches a value of 1,991,184 CFA (= 3,592 USD) in 2050 under the 2.6 climate scenario and a value of 1,686,852 CFA (= 3,043 USD) under a 7.0 climate change scenario.

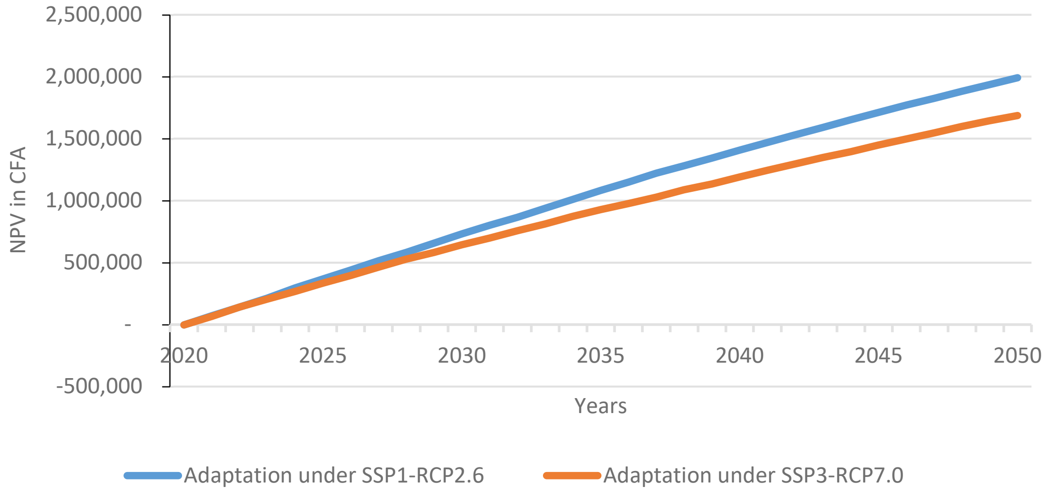

Figure 59: Development of the net present value of switching to sorghum cultivation using ICV.

The results show that the farmers' investment into improved sorghum varieties pays off in the first year of usage. The year 2021 marks the break-even point between accumulated net production costs and net market revenues. Consequently, the internal rate of return (IRR) is very positive and yields 2,829% for an adaption under the SSP1-RCP2.6 scenario and 2,709% t for an adaptation under the SSP3-RCP7.0 scenario, both for the year 2050. Considering a global rentability perspective, which is often taken for local CBAs, any IRR higher than 6%, is considered as a profitable investment. The excessively high values are not unusual for investments in improved varieties. With only a marginal change in expenditure, the profit nevertheless increases due to the enormous increase in yields accordingly (Lotze-Campen et al., 2015).

This is also directly reflected in the cost benefit ratio (BCR) of the adaptation investment, which is 7.87 in 2050 under SSP1-RCP2.6 scenario and 6.82 under SSP3-RCP7.0 scenario (see also Table 13). Switching to improved high yielding sorghum varieties is therefore much more profitable in economic terms than growing traditional sorghum breeds and thus a highly recommendable adaptation strategy.

Table 13: Summary of major CBA indicators for switching to sorghum cultivation with ICV.

	Adaptation under SSP1-RCP2.6	Adaptation under SSP3-RCP7.0
IRR	2,829%	2,709%
NPV	1,991,184 CFA (= 3,592 USD)	1,686,852 CFA (= 3,043 USD)
BCR	7.87	6.82

Switching from traditional sorghum varieties to improved crop varieties is economically meaningful, because the partial change of the production system leads to a high IRR and a BCR above 1.0. That means that attributable additional revenues to the change are higher than the associable additional costs. However, the particular outcome does not mean that the entire production system is profitable in terms of internationally standardized calculation of economic margins. From the household survey data it becomes clear that the production of sorghum in the baseline (no action, no climate impacts) scenario, i.e., sorghum production with traditional varieties under current climatic and technological conditions in the region is characterized by a negative gross and net margin. In other words: variable and fixed costs are higher than market revenues with labour being the major cost factor.

From a pure economic perspective sorghum production is therefore not recommendable, even though the positive IRR leads one to expect a more profitable production system in the future. But the decision making of maize farmers in the region may also be guided by other than only rational behaviour. Food security and the lack of other employment opportunities are few. What also needs to be considered is that monetizing farm work (which is mostly done by family members) does not reflect the reality of small-scale and subsistence farmers who usually do not pay themselves a salary.

Therefore, the results of the CBA do not contradict the results from the analysis of whole production system, since the CBA is only a partial cost accounting and does not include all production factors as considered in a full cost analysis.

10.4 Multi-criteria assessment

10.4.1 Upscaling potential

Most seeds in Burkina Faso are farmer-saved landraces, so there is huge potential for upscaling the adaptation measure improved varieties. Agriculture is a crucial pillar of the country's economy, so it can have tremendous multiplier effects on the macroeconomic level when agricultural production is improved, even under adverse climate change conditions.

10.4.2 Potential co-benefits

Improved varieties can help to fight undernutrition, because they achieve higher and more stable yields under current and climate change conditions. Through improved levels of nutrients, they can also help to decrease malnutrition. Higher harvest qualities also enable farmers to sell their produce for higher prices and hence increase a household's income. Improved varieties have also ameliorated the agronomic management through e.g., short straw varieties which are more stable. Great co-benefits could be also generated if the adoption of improved varieties goes hand in hand with new knowledge on how to improve agricultural production. Seemingly small changes in seed availability may make farmers adopt radically new strategies (Mertz et al., 2009).

Beyond co-benefits in the agricultural and food sector, the use of improved crop varieties has led to increased financial independence, hence farmers are able to enroll their children in school or use health services. According to a study, the adoption of at least one improved variety creates higher household incomes and consequently reduces poverty (CORAF, 2018). During the surveys farmers also mentioned co-benefits such as increased respect by peers, comfort, fulfillment, resources to construct housing. The ability to improve other life areas through their savings instead of investing them in food is important.

The adoption of new varieties can also entail climatic-environmental co-benefits. The high productivity potential of the improved crop varieties can lead to a reduction in the area under sowing and plays a significant role in reducing land conversion through e.g., slash and burn agriculture. Therefore, improved seeds can also reduce biodiversity loss.

10.4.3 Potential maladaptive outcomes

With insufficiently regulated seed markets and import of varieties that are not optimal for the local conditions, paired with insufficient agronomic knowledge, farmers could plant unsuitable varieties that have not the expected outcomes.

The gradual introduction and adoption of improveed varieties has led researchers to formulate and debate the replacement hypothesis with a focus on traditional Andean smallholder agriculture where improved varieties were introduced in the 1950's. It states that improved varieties will replace landraces (Brush, 2004; Harlan, 1976; Popenoe et al., 1989). Other studies (Brush et al., 1992; Ortega, 1997) conclude that no one-on-one replacement occurs, as there is a certain saturation point at which farmers stop adopting new varieties. Landraces and improved varieties fulfill a set of traits that include agronomic, food security-related and also traditional and culinary preferences. Therefore there exist smallholder farmer managed agricultural systems where both, landraces and improved varieties, coexist and complement each other (Brush, 1991; Haan, 2009).

10.4.4 Barriers for implementation

In Burkina Faso, the agricultural sector employs 86% of the population, but agriculture still faces many challenges, including the low adoption of improved seeds. The formal and informal seed sector is not supplying farmers sufficiently with improved seeds. Often, they are unavailable, poor-quality or do not match farmers' preferences. Also a lack of knowledge regarding the varieties' potential and the best way to cultivate them hinders higher adoption rates (Juana et al., 2013). The inadequacy between the price of agricultural inputs and the price for agricultural products, insufficiency of logistical and financial support (e.g., lack of an appropriate credit system), poor organization of the sector, the resulting lack of motivation by seed producers to enter the market, climatic risks associated with agricultural production and a decline in soil fertility hinders the use of technical innovations, such as improved seeds, by farmers in Burkina Faso.

A binary gender analysis of rice production reveals a yield gap between plots operated by men and those operated by women (Yameogo et al., 2019). The average rice yield in male-farmed plots is significantly higher than that in female-farmed plots in West Africa, suggesting the existence of a gender effect. In the opinion of the extension agents, this is probably due to a lack of maintenance caused by insufficient (household) labour force and time. In general, women are required to look after their husbands' plots first before their own. In addition, women's plots are less supplied with fertilisers and plant protection, since husbands' plots are given priority for fertiliser application (Yameogo et al., 2019). Together with a lack of training and access to extension services for women, these factors could explain the unequal yields. With respect to variety selection, only a small difference between women's and men's variety selection criteria exists (Ishikawa et al., 2020).

10.4.5 Institutional support requirements

To foster the adoption of improved varieties and also agricultural development in general, it is necessary to ameliorate the functioning of the agricultural value chain so that an adoption becomes possible and profitable. This includes functioning infrastructure and agriculture markets to make agricultural inputs available and accessible (e.g., ensuring affordable prices for improved seeds) and also provide opportunities to sell goods for prices that cover production costs (Barbier et al., 2009).

Regulations to foster the seed sector should target both, the formal and informal sector as both are important to proliferate seeds to farmers (Smale & King, 2005). Since centuries, the informal sector, has created a flow of seeds even to the remotest areas whilst creating a high diversity of seeds with accompanied knowledge, addressing farmers' needs (Access to Seeds, 2018). The seed sector must ensure the availability and accessibility of high-quality seeds. Therefore, efforts should be directed to creating a seed sector that covers the overall process for improved seeds from plant breeding and pre-breeding to seed propagation, marketing and advisory whilst focusing on farmers' needs. Such a comprehensive system can also ensure an ongoing process of innovation adoption. Researchers and the government have highlighted room for improvement in terms of coordination for greater efficiency of the seed system and discuss the substitution of indirect state support to a direct form of market intervention for sustainable use of improved seeds (Kaboré et al., 2010). Also a better communication and interaction of seed sector stakeholders is necessary to improve seed dissemination (Ishikawa et al., 2013) and overcome technical challenges. To optimally reap the benefits of variety improvement, farmers regularly need new improved varieties. A certain speed of adoption is desirable For example, in our CBA case study the improved varieties were on average released eleven years ago. This means that newer varieties with improved traits could be already available. Research to better understand local growing conditions Your text here (Worou et al., 2019) and seed selection criteria (Ishikawa et al., 2020)must be fostered to improve the seed sector. Innovation-centered breeding systems that enable stakeholders to share knowledge and breeding material have generated large economic surpluses for farmers and the overall society (Lüttringhaus et al., 2020). General agronomic knowledge and particular knowledge on the potential of improved seeds and how to select, access and cultivate them must be made available. Here digital tools that can be consulted e.g., via smart phones can complement extension services.

Along with a promotion of improved seeds, policies and implementation activities should also highlight the value of local landraces. This is also an important pillar for safeguarding local traditions, agronomic practices, and accompanying knowledge. Such a safeguarding of seeds and practices could be institutionalized by in-situ conservation projects, local seed banks, corporations with national or international gene banks and diversity fairs.

10.5 Conclusion

Considering all mentioned criteria, the adaptation strategy improved varieties presents a high-risk mitigation potential and high cost-effectiveness (see Table 14). However, the strategy should be implemented carefully addressing potential negative outcomes due to a lack of seeds suitable for the local context, in addition to limited knowledge on the use of the available improved varieties. Institutional support would be needed to support the availability and access to quality seeds suitable for the local context to increase the adoption by smallholder farmers.

Table 14: Summary assessment of improved crop varieties as adaptation strategy in Burkina Faso.

Risk mitigation	Risk-gradient	Cost-Effectiveness	Upscaling	Potential Co-benefits	Potential maladaptive outcomes	Barriers to implementation	Institutional support requirements
High	Risk-Independent	High	High	High	Medium	Medium to high	Medium to high

Chapter 11 – 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 presents and discusses the uncertainties attached to the different types of analysis in this study and highlights their relevance in the context of Burkina Faso.

11.1 Climate model data

The development of climate models has made vast improvements in recent decades, but climate models still display substantial uncertainties in simulating the current climate (Tebaldi and Knutti, 2007). To remove the biases in the climate simulations thereby making the models suitable for our crop model analysis, climate data is statistically processed (bias-adjustment) with the help of observational climate data sets (in our case W5E5). This approach has critical limitations (Ehret et al., 2012; Maraun, 2016) as it adjusts the simulated data to fit to the observations without fixing the inability of the models to represent some physical processes of the earth's system. Nevertheless, the step is necessary and suitable to obtain realistic simulations of climate impacts (Chen et al., 2013; Teutschbein & Seibert, 2012). We analysed the performance of each individual climate model to represent the current climate to ensure that none of the models shows extraordinary strong biases. Working with a climate model ensemble can additionally support reducing the biases that individual models show. In addition, the observational climate data sets themselves are imperfect, especially in areas with few weather stations. The used data sets are based on re-analysis models, satellite observations and stationary data. Due to the low density of long-term, reliable stationary data in West Africa, the data sets have strong biases, especially on a fine-gridded scale.

The analysis of future climate in this report is based on ten bias-adjusted GCMs produced within the ISIMIP3b project (www.isimip.org/protocol/3) and is a sub-ensemble of the Coupled Model Intercomparison Project Phase 6 (CMIP6) used for the next IPCC report AR6.

Furthermore, future climate projections come with uncertainties, which can be seen in the diverging temperature and precipitation projections of different climate models. The GCMs project the same temperature trend over Africa, whereas precipitation projections show agreeing trends only in some regions (Niang et al., 2014). For general conclusions on future climate impacts, it is important to select models that cover the whole range of climate model outputs, namely applying models with wet and dry trends in precipitation projections (if applicable) as well as different magnitudes of projected temperature changes in the target region. The diverging trends related to precipitation projections of the ten chosen models show similar patterns as the earlier used complete CMIP5 model ensemble (Niang et al., 2014) and thus we can assume that the models are suitable to cover the range of possible future precipitation in Burkina Faso.

The ten models cover a wide range of climate sensitivity with equilibrium climate sensitivity[17] (ECS)[18] values of 1.53-5.41°C (Nijsse et al., 2020). Nevertheless, the selection of models shows a bias towards higher ECS, with five out of ten models having an ECS higher than 4.5°C, which is, according to various studies, very unlikely (Nijsse et al., 2020). This means that the displayed temperature increases from five models show unlikely high future temperatures under increasing greenhouse gas concentrations and also the multi model median will shows a bias towards warm future projections.

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

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

11.2 Hydrological modelling

The largest source of uncertainty in hydrological modelling and impact assessment comes from climate model outputs (see e.g. Vetter et al., 2015; Vetter et al., 2017). As explained in section 11.1, we observed a high deviation of some climate models, which lead to extreme changes in the river discharge and water balance towards the end of the century. Two examples are the CanESM5 and EC-Earth3 models where annual precipitation increases much stronger compared to other models and can almost double in comparison to the historical period.

However, a number of data related issues add to the impact of uncertainty:

- Data availability of observed river 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 Volta and Niger basins are needed for the parametrisation of SWIM. Therefore, (gridded) global climate data sets (WFD-ERA40 and W5E5, depending on the availability of observed discharge data) 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). Especially the impact of the numerous small or micro dams used for irrigation is difficult to assess, because data are lacking. There is much higher confidence in the parameterisation of larger dams, such as Bagré, Kompienga, Loumbila, Ziga, where more data are available and were provided by different institutions, e.g., WASCAL and water resources organisations.
- Furthermore, it would be good to employ more advanced quality checks for the input data (soil parameterisation including, for instance, an adaptation of soil depth, land use/cover parameterisation combined with a validation on vegetation cycles etc.).

All these factors increase the uncertainty of the hydrological modelling and climate impact assessment in general. At the same time, we are confident in analysed trends of changes for the regions and the direction of key messages obtained during the research would not change with more precise data and models.

11.3 Crop models

Crop models are used to determine the share of weather-related variation in yields and to project impacts of changing climatic conditions on crop yields. Such analyses can support farmers in taking decisions related to yield stabilisation and crop yield improvement to cope with uncertain climatic conditions in the future. Crop models are widely used to project these impacts – beyond the observed range of yield and weather variability – of climate change on future yields (Ewert et al., 2015; Folberth et al., 2012; Rosenzweig et al., 2014). However, when employing crop models some limitations need to be considered. For instance, limited data availability may restrict model fitting, such as a lack of information on growing season dates, yields, land use allocation, intercropping or information on fertiliser application (Müller et al., 2016). Also, the quality of soil data contributes to uncertain yield assessments (Folberth et al., 2016). Fragmented and imprecise weather data from regions with few weather stations further increase uncertainty (Van Wart et al., 2013), especially if highly localised weather data is needed as it is for this district study. Moreover, the selection of climate scenario data adds another layer of uncertainty (Müller et al., 2021). Specific to our analysis, three main challenges occurred: First, the model input data may contain errors. This holds true for weather, soil and yield data. On the weather side, all past climate data sets carry uncertainties. Regarding the yield database, we applied pre-processing filters. Yet, this cannot exclude biases, which eventually result in unstable models. Second, short time series of crop yield and management data can make it difficult to estimate climatic impacts on crop yields. However, the available data set in Burkina Faso is very complete and long (1984-2018) compared to other countries which strengthens the significance of the results. Third, the model design could be flawed, and a more apt formulation could better capture observed yield variation, in particular extreme losses. There are certain disagreements between the different model types – statistical, machine learning and process based – (Schauberger et al., 2017), but however, these three model types in this case study have been used in past studies and are unlikely to be inapt in general.

11.4 Cost-benefit analysis

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

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

Uncertainty on assumptions with regard to future changes in prices and costs and the choice of the discount rate are further increasing the uncertainty of the CBA results. However, the assumptions made in our study are based on studies conducted in comparable socio-economic conditions of Burkina Faso, different data sources were triangulated, and expert opinion sought. The results of the CBA should not be taken as definite outcomes to expect when implementing the adaptation strategies, but they can guide decision-making and provide case studies for adaptation scenarios.
Assumptions regarding yields under climate change with and without adaptation were made based on crop yield simulations, which in turn were based on climate data predicted by climate models. Therefore, any uncertainty in climate models and crop models also translated into the analysis.

Chapter 12 – Conclusion and policy recommendations

12.1 Conclusion

This study provides a comprehensive climate risk analysis for Burkina Faso with the aim to offer an in-depth decision-basis for national and local decision-makers on current and future climate risks for the agricultural sector to guide suitable adaptation planning and implementation in the country. The whole impact chain was modelled from a changing climate and hydrological changes to resulting impacts on agricultural and livestock production.

Climate change reinforces the challenging conditions that smallholder farmers are facing in Burkina Faso. Already today, variable climatic conditions are influencing the agricultural sector and climate risks are projected to become even higher in the future. In addition to natural variability, the climate in Burkina Faso is showing a clear changing trend. In particular temperature projections show very high confidence with all models projecting a continuous increase of temperature until 2090 under the high emissions scenario. Under the low emissions scenario, temperatures do not increase strongly after 2050. Taking the temperature rise before 2004 into account (IPCC, 2014), temperature rise would be well above the 1.5°C target by 2050 for most models, even under the low emissions scenario. The number of very hot days and tropical nights is projected to increase in all parts of the country under both emissions scenarios. Annual precipitation sums are projected to increase in the whole country under both emissions scenarios until 2050. After 2050, annual precipitation sums are projected to continuously increase under the high emissions scenario and to decrease slightly under the low emissions scenario. The year-to-year variability of precipitation amounts is projected to remain high. However, there is much less confidence in the projected precipitation changes than in temperature changes.

We also analysed future water availability under climate change in the Volta and Niger River basins that together cover 94% of Burkina Faso. The projections show an increase of river discharge under the high emissions scenario, whereas under the SSP1-RCP2.6 scenario river discharges tend to decrease. Groundwater recharge is projected to rise, but stronger under higher future emissions. Evapotranspiration is projected to increase moderately.

Yield variability of major crops in Burkina Faso is mainly attributable to weather influences, making their production particularly exposed to climate change. Although our crop model analysis carries some uncertainties, the projections show that under climate change, the analysed crops will become increasingly difficult to produce in Burkina Faso. Crop suitability models show that in some areas of the country crop suitability for sorghum, millet and maize will increase and in others it will decrease, so it can be concluded that overall the areas suitable for sorghum, millet and maize will remain relatively stable in Burkina under climate change. The suitability for cowpea is projected to decrease. We also show that the potential for farmers to produce multiple crops will become more and more difficult in Burkina Faso, which limits farmers' diversification potential, associated food security, and economic benefits through the production of multiple crops. Projected impacts of climate change on yields vary between regions and show partly opposing trends. Few regions in the north (Sahel, Nord, and Centre_Nord) show increased yields (up to +30% in SSP1-RCP2.6 and up to +20% in SSP3-RCP7.0), while few regions in the south (Cascades, Haut-Bassins, and Sud-Ouest) present decreased yields (down to -30% in SSP1-RCP2.6 and down to -20% in SSP3-RCP7.0). This may be due to a combination of higher CO_2 fertilisation and a projected increase in precipitation events towards the north as well as a decrease in the south. An increased yield projection in the north (Sahel and Nord) could be due to the projected improved crop water availability for these dry regions, especially under higher emissions scenarios.

Due to the importance of livestock for Burkina Faso's economy and food and nutrition security, we also analysed climate impacts on livestock production, more specifically on grassland productivity for grazing-based livestock. There is high agreement among climate models that grazing potentials will decrease under both future climate change scenarios with higher decreases under the low emissions scenario than under the high emissions scenario. The effect of higher warming under SSP3-RCP7.0 may be partially offset by an increase in precipitation, combined with a better water-use efficiency of plants due to the higher atmospheric CO_2 concentration. Some climate model simulations even show increases of up to 10% in 2090 in grazing potentials in the Sahel region under the high emissions scenario.

Based on these projected climate change impacts and expressed stakeholder interests, we assessed four crop-related adaptation strategies: climate services, irrigation, integrated soil fertility management and improved seeds with regard to their risk reduction potential, their cost-effectiveness, and other socio-economic evaluation criteria, such as upscaling potential and potential co-benefits. The assessment was conducted within a multi-criteria framework, combining assessment indicators from a biophysical mode, economic analysis and soft assessment indicators based on a literature analysis. The table below shows the results.

Table 15: Summary of multi-criteria assessment for all adaptation strategies.

Adaptation strategy	Climate Services	Irrigation	ISFM	Improved varieties
Risk mitigation potential	High	Medium to high	High	High
Risk-gradient	Risk-Independent	Risk-Independent	Risk-Independent	Risk-Independent
Cost effectiveness	High	Medium	High	High
Upscaling potential	High	High	High	High
Potential co-benefits	High	High	High	High
Potential maladaptive outcomes	Low	High	Low	Medium
Barriers to implementation	Medium	Medium to high	Medium	Medium to high
Institutional support requirements	High	High	Medium to low	Medium to high

Colour legend: red = negative; yellow = medium; green = positive

While all four adaptation strategies were found to have high potential for risk mitigation, they all bring different co-benefits, and some may also have potential negative outcomes that need to carefully be considered when promoting their implementation. Institutional support requirements slightly vary, but all adaptation strategies need at least accompanying knowledge transfer and access to information. Carefully assessed combinations of multiple adaptation strategies can often be an option to tap into the merits of more than one strategy.

Generally, there is no single adaptation strategy that is suitable for the whole country, since their effectiveness and co-benefits ultimately depend on the projected climate impacts, as well as on the concrete design tailored to the local context and farmers' needs. The actual impact of the projected climatic changes is not only shaped by the actual hazard, but also by the vulnerability and exposure of the affected farming communities. Differing social characteristics like gender, age, education and health can substantially shape farmers' vulnerability and therefore their exposure to climate change. Taking these characteristics into consideration is an important prerequisite to build resilience across farming communities.

Adaptation strategies that are well-designed and correctly implemented offer an important mechanism to curtail projected yield losses and have various social and environmental co-benefits. National adaptation planning needs to build on existing knowledge end take into consideration the differing realities on the ground. Giving farmers access to tailored information, tools and incentives will help to scale up adaptation action across the country.

12.2 Policy recommendations

Based on the analyses conducted within this climate risk study and in close consultation with various stakeholders and experts, various concrete policy recommendations on adaptation in Burkina's agricultural sector have been identified.

12.2.1 Climate information services

Several studies have shown the positive impact of CIS on crop yields which underlines its great potential as an adaptation strategy. Having access to actionable climate information can help farmers to make informed decisions and thereby reduce the impact of climate risk. With a rather small-scale investment and its positive return, CIS represents a highly beneficial strategy. However, setting up well-functioning CIS requires high institutional and technical support. Based on the literature review, multi-criteria assessment and CBA, specific recommendations can be given to support the implementation of CIS:

- Awareness raising campaigns can help to inform farmers and rural communities about the great advantage of CIS and gain trust in the information received. Trainings on CIS can help farmers and especially rural women to fully understand the communicated information and to be able to act on it. Ensuring that women and other minority groups have equal access to CIS can help to promote gender equality in agricultural production.
- For now, existing communication channels (radio, television, word of mouth) represent the most effective way for CIS upscaling but new information channels (mobile phones, smartphones, internet-based devices) and sources are being developed and sources are developing throughout Burkina Faso and should be considered as well to reach optimal coverage.
- Access to more modern information and communication technology (e.g. smartphone, internet) should be supported.
- CIS should be targeted to the various end-users needs. An analysis along the whole value chain and gender-disaggregated data can help to identify those needs and develop target-oriented formats and makes communication more effective.
- When disseminating information through CIS it is crucial to ensure timely and actionable communication in the local language(s) and effective use of e.g. visualisation and audio formats to overcome the access barrier for poor educated or illiterate people.

12.2.2 Irrigation

Irrigation is a promising adaptation strategy in Burkina Faso. Irrigation can help smallholder farmers to compensate for the negative impacts of erratic and insufficient precipitation and signify-cantly stabilise agricultural production. Water retention, which is essential for the used irrigation systems in Burkina Faso is dependent on seasonal variation and specific location which influence the accessibility and effect of irrigation. Besides, irrigation requires a significant investment and only becomes profitable after some years, depending on the type of irrigation system and the farm location. Continuous institutional support is usually require-ed and care has to be taken to avoid potential maladaptive outcomes from irrigation. Water use for irrigation has to be carefully managed to prevent groundwater table decrease and associated consequences.

Specific recommendations regarding irrigation in Burkina Faso are:

- Low-cost irrigation options with low maintenance requirements can be promoted across Burkina Faso, where water resources are available.
- Awareness raising about water-saving irrigation management is crucial to ensure a long-term responsible use of natural resources.
- Ideally, water saving equipment such as drip irrigation and smart irrigation systems are

promoted and supported by extension services to encourage farmers to use sustainable and environment responsible techniques.
- Provision of support services is needed to ensure the ability of farmers to further operate the technology and take care of their maintenance.
- For upscaling irrigation, all user interests in water and energy should be carefully considered. Dispute settlement mechanisms can be implemented to address potential conflicts between upstream and downstream users.
- Developing financing mechanism, such as access to loans or credits, can support the accessibility for irrigation equipment.

12.2.3 Integrated soil fertility management

ISFM is a promising adaptation strategy under all future climate change scenarios supporting additionally the rehabilitation of considerable areas of already degraded land and increasing the plant diversity in Burkina Faso. Currently especially used in central and northern areas of Burkina Faso, the technology could be beneficial for all regions in the country to manage soil moisture and fertility to be able to cope with climate stress. There are specific recommendations that can be given for Burkina Faso:

- Awareness raising and training on the advantages and implementation of ISFM support the effectiveness of this strategy which is relatively time consuming for farmers. The consideration of the technology in education and extension programs can also help to support the effective dissemination.
- Policies towards sustainable land use intensification, as well as the rehabilitation of degraded soils and the necessary mechanisms to implement and evaluate these can help to promote the uptake of ISFM.
- Research on innovative ISFM practices as well as the dissemination of the results can improve the effectiveness of the technology and further strengthen the adoption rate.
- The public sector can play an important role in creating a platform for bringing together and linking key partners in research, education, extension, service providers, input providers, and farmers to facilitate farmer mobilisation and capacity development.
- Policies that incentivise credit and loan schemes and subsidy programmes for the production of organic inputs could address the issue of lack of access to equipment and input.

12.2.4 Improved crop varieties

Improved crop varieties are a highly beneficial adaptation strategy in Burkina Faso. Furthermore, the cost-benefit analysis shows a very positive return on a rather small-scale investment. Due to its positive impact on yield increase and stability as well as increased levels of nutrients, improved varieties can also help to decrease malnutrition and undernutrition. However, there are several factors such as high prices of agricultural inputs, the insufficiency of logistical and financial support, the poor organization of the sector, the lack of motivation by seed producers to enter the market, the climatic risks associated with agricultural production and a decline in soil fertility which impede the use of improved seeds by farmers. Besides that, insufficient agronomic knowledge or non-locally adapted varieties can lead to controversial effects and negative outcomes of this strategy.

To achieve the optimal adaptation effect of improved varieties, specific recommendations should be considered:

- Ideally, improved varieties are promoted that fulfil several conditions, such as farmer's preference, local suitability, agronomic management and that are available and accessible for smallholder farmers. The sufficient supply of locally adapted good quality seeds on local level should be therefore supported.
- To promote a continuing process of innovation adoption, efforts should be directed to creating a seed sector that covers the overall process for improved seeds from plant breeding and prebreeding to seed propagation, marketing and advisory whilst focusing on farmers' needs.
- Knowledge transfer regarding the varieties' potential and the best way to cultivate them can help farmers to use improved varieties.

- For a profitable adoption it is necessary to ameliorate the functioning of the agricultural value chain including functioning infrastructure and agriculture markets to make agricultural inputs available and accessible.
- It is also important to highlight the value of local landraces as they are a pillar for safeguarding local traditions, agronomic practices, and accompanying knowledge. Such a safeguarding of seeds and practices could be institutionalized by in-situ conservation projects, local seed banks, corporations with national or international gene banks and diversity fairs.
- A better communication and interaction of seed sector stakeholders can help to improve seed and knowledge dissemination on a local, regional and national level.

12.2.5 General recommendations

In addition to recommendations for the specific four adaptation strategies, some general recommendations regarding adaptation in Burkina Faso can be given:

- Planning for adaptation should be regionally specific, as different areas in Burkina Faso will be impacted by climate change differently.
- The response of crops to adaptation strategies also differs according to crop and region, which requires crop-specific adaptation response.
- Improved soil and water management should be mainstreamed in all adaptation activities and be considered wherever possible.
- Grazing potentials for livestock will decrease under both future climate change scenarios. Mowing is a promising adaptation strategy to provide fodder reserves.
- Considering the current state of security in the country as well as the greater region, along with its low adaptive capacity to the effects of climate change, adaptation projects need to consider conflict dynamics. Policy makers should pay special attention to the needs of marginalized communities in agriculture. Transhumance infrastructure is key to elevating much of the underlying intercommunal tensions.
- Regardless of the specific climate risk addressed, combinations of adaptation strategies are often more effective than single approaches. To avoid negative side effects, each combination should be carefully assessed.
- Rich and diverse indigenous and traditional knowledge exists on adaptation in Burkina Faso's regions, which should be seized for successful adaptation. However, more research into this is needed as well as reactivation of formerly practiced indigenous adaptation strategies, which have partly lost traction in the past decades.
- Smart adaptation incentives are key to induce uptake of suitable adaptation strategies. Such incentive structures are for instance built around land tenure systems, credit accessibility and market access.
- Farmers need support in bridging the financing gap between investment and the break-even point, where the adaptation strategy becomes profitable. This is usually only after a couple of years, transitional financial support is thus needed.
- Trainings and extension services should be provided to farmers to support them in setting up and maintaining the adaptation strategies.
- The right timing of input provision and capacity building is key, as otherwise, farmers may be unable to store the inputs adequately or to retain knowledge and use it when needed. Late training provision can also negatively affect adaptation strategies, where farmers may not be able to fully implement what they have learned. Oftentimes, repeated trainings may be needed to ensure that information provided turns into long-term knowledge.
- Marketability of adaptation technologies and products is important. Value chains and access to markets should be considered in adaptation strategies for smallholder farmers to enable them to commercialise their agricultural activities.
- Adaptation strategies bring a variety of co-benefits. Leveraging those co-benefits, adaptation strategies should especially be designed to ensure gender equality, climate change mitigation and to protect soils.
- Adaptation design should be inclusive. Communities should be engaged at all planning stages, for instance through community conversation sessions. Collecting gender-disaggregated data is key to design gender-responsive adaptation strategies.
- Financial support should be by for instance the Global Environment Facility, the Green Climate Fund, NGOs, technical and financial partners can help to efficiently implement and upscale the adaptation strategies. The results of this

report build the evidence based background information to support an application to the e.g. GCF.

- The adaptation strategies ought to be integrated or further underlined in the existing national programmes such as the NAP, the Plan National de Développement Economique et Social (PNDES), the Programme National du Secteur Rural (PNSR), the Programme National pour la Gestion Intégrée des Ressources en Eau (PN-GIRE) among others.

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