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

On behalf of

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Federal Ministry for Economic Cooperation and Development

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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 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 and Rahel Laudien designed the study approach with steering input from stakeholders and coordinated the study. Rahel Laudien edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Abel Chemura analysed climate impacts on sorghum yields and the risk mitigation potential of conservation agriculture using crop models in chapter 3.1 and 4.1; Stephanie Gleixner performed the climate analysis in chapter 2 and the water balance modelling in chapter 3.3. Katarina von Witzke and Lina Staubach conducted the cost-benefit analyses of early warning systems in chapter 4.2. Tim Heckmann analysed crop suitability for sorghum, maize and groundnuts and Benjamin Ruch conducted data preprocessing and provided research support in chapter 3.2 under the supervision of Abel Chemura. Carla Cronauer contributed the sections on Gender in chapters 1 and 4.

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Abstract

KEYWORDS

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climate risk

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biophysical modelling

crop suitability

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gender

Zambia has a high socio-economic dependency on agriculture which is strongly influenced by weather-related factors and highly vulnerable to climate change. To address current and future climate-related risks in the agricultural sector, this study provides a comprehensive climate risk analysis and evaluates suitable adaptation options to promote climate-resilient agricultural intensification in Zambia. Driven by ten global climate models under two climate change scenarios, SSP 1-RCP2.6 and SSP 3-RCP7.0, we used impact models to analyse future trends in climatic conditions and impacts on agriculture. As part of our adaptation analysis, we consider aspects of risk mitigation potential, cost-effectiveness, financing and gender. The results have been complemented and cross-checked by expert and literature-based assessments and two stakeholder workshops.

Climate models project a robust trend towards increasing temperatures all over Zambia ranging between 2 °C and 2.7 °C until mid-century, with the south-western regions showing the strongest increase. Projections of mean precipitation indicate high spatial variations within the country. The drought-prone southern and central parts of the country are projected to experience a decrease in precipitation with ongoing climate change. Overall, there is a shift towards more intense climatic conditions both in terms of dry as well as wet conditions.

Climate change will have various impacts on agriculture, for example, a decrease in sorghum yields. Mean sorghum yields for the whole country are projected to decrease by 5.8 to 12.2 % by mid-century with spatial and temporal disparities. The decreases are, however, only about half of the projected decrease in maize yields. This confirms that sorghum is indeed a more resilient crop compared to other cereals. Climate change also affects the extent and distribution of suitable areas for crop production in Zambia. Areas suitable for maize and sorghum production will decrease between 28 and 37 % by mid-century and move northwards within Zambia. A case study in the Kafue Catchment and parts of the Zambezi Catchment shows an increase in water demand and a decrease in water availability – leading to an overall reduction in the climate-related irrigation potential in future.

The negative climate impacts on agriculture in Zambia underline the need for strong adaptation efforts. The study analyses two adaptation options, which were selected based on stakeholder priorities: Conservation agriculture and early warning systems. Conservation agriculture is a farming system that promotes minimum soil disturbance, maintenance of a permanent soil cover and diversification of plant species. It can buffer climate impacts in the near term and even increase sorghum yields by 25 to 31 % in drought-prone areas in Zambia. It can play a vital role in adapting to increasingly extreme and dry climatic conditions in Zambia in the near future.

Early warning systems have a high potential for anticipating climate risks and thus improving food and nutrition security. In our analysis, we focus on a participatory approach for climate and agricultural extension services that integrates climate information and weather forecasts to inform livelihood decisions of farmers – called PICSA (Participatory Integrated Climate Services for Agriculture). The results show that the initial investment needed to employ PICSA already becomes economically beneficial after one year with returns increasing in the future. Each USD invested in PICSA generates between 3.6 and 3.8 USD in benefits depending upon the climate scenario considered. This suggests that employing PICSA is a highly cost-effective investment that constitutes an important variable in safeguarding farmers' long-term livelihood.

Generally, a combination of different adaptation options entails additional benefits. Active stakeholder engagement as well as participatory, gender-sensitive approaches are needed to ensure the feasibility and long-term sustainability of adaptation options. 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.

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List of abbreviations

ARC	Africa Risk Capacity
BCR	Benefit-Cost Ratio
BIP	Basin Irrigation Potential
CA	Conservation Agriculture
CASTP	Comprehensive Agricultural Transformational Support Programme
CBA	Cost-Benefit Analysis
CDRF	Climate and Disaster Risk Finance
COMACO	Community Markets for Conservation
CMIP	Coupled Model Intercomparison Project
CREWS	Climate Risk and Early Warning Systems Initiative
CWD	Crop Water Demand
DMMU	Disaster Management and Mitigation Unit
DSSAT	Decision Support System for Agrotechnology Transfer
ETS	Emissions Trading System
EWS	Early warning systems
FISP	Farmer Input Support Program
GCM	Global Climate Model
GHG	Greenhouse Gas Emissions
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GRMA	Global Risk Modelling Alliance
GWL	Global Warming Level
IRR	Internal Rate of Return
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
IPCC	Intergovernmental Panel on Climate Change
IWN	Irrigation Water Need
LDC	Least Developed Countries
MFIs	Micro Finance Institutions
MHEWS	Multi-Hazard Early Warning Systems
MMEM	Multi-Model Ensemble Median
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NDRT Fund	National Disaster Relief Trust Fund
NFV	National Financing Vehicles
NPV	Net Present Value
PICSA	Participatory Integrated Climate Services for Agriculture
SADC	Southern African Development Community
SI	Supplementary Information
SIDS	Small Island Developing States
SME	Small and Medium-sized Enterprises
SPI	Standardized Precipitation Index
WA	Water Availability

AGRICA

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1. Introduction

Zambia has a high socio-economic dependency on agriculture which is strongly influenced by weather-related factors and highly 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.

> The study provides a comprehensive analysis of current and future climate-related risks in the agricultural sector and evaluates suitable adaptation options to promote climate-resilient agricultural intensification.

Several policies and plans are in place and are currently developed in Zambia to counteract these increasing risks and mainstream climate change into sectoral policies, including the Comprehensive Agricultural Transformational Support Programme (CASTP), the 8th National Development Plan, the Water Resources Management Act, the Irrigation Master Plan, the National Adaption Plan Water, the Climate Change Gender Action Plan, the Climate-smart Agriculture Investment Plan, the National Agricultural Policy, the National Water Resources Management Strategy and the National Adaptation Plan (NAP). As part of Zambia's commitments to the Paris Agreement, it has adopted various national policies, including the Nationally Determined Contribution (NDC).

In support of science-based and forward-looking planning, a better understanding of projected climate impacts, together with sound information on the suitability of adaptation options is important. To guide, incentivise and accelerate public and private sector investments for climate-resilient agricultural development, this study provides a comprehensive climate risk analysis.

Driven by ten Global Climate Models (GCMs) under two climate change scenarios, SSP1-RCP2.6 and SSP3-RCP7.0, we used impact models to analyse future trends in climatic conditions. Based on stakeholder priorities, we further analysed climate impacts on sorghum yields, crop suitability for sorghum, maize and groundnuts; and water availability in the Zambian Kafue Catchment and parts of the Zambezi Catchment. Together with stakeholders, we selected two adaptation options to assess the overall suitability to reduce climate impacts in the agricultural sector in Zambia: conservation agriculture and early warning systems. Using climate change impact and economic models, we analysed the potential of the selected options to cost-effectively mitigate climate risks, which was complemented by expert- and literature-based assessments, informed by two stakeholder workshops. Moreover, the study presents suitable financing options for the adaptation options and proposes a roadmap for managing residual risk through a climate and disaster risk financing strategy.

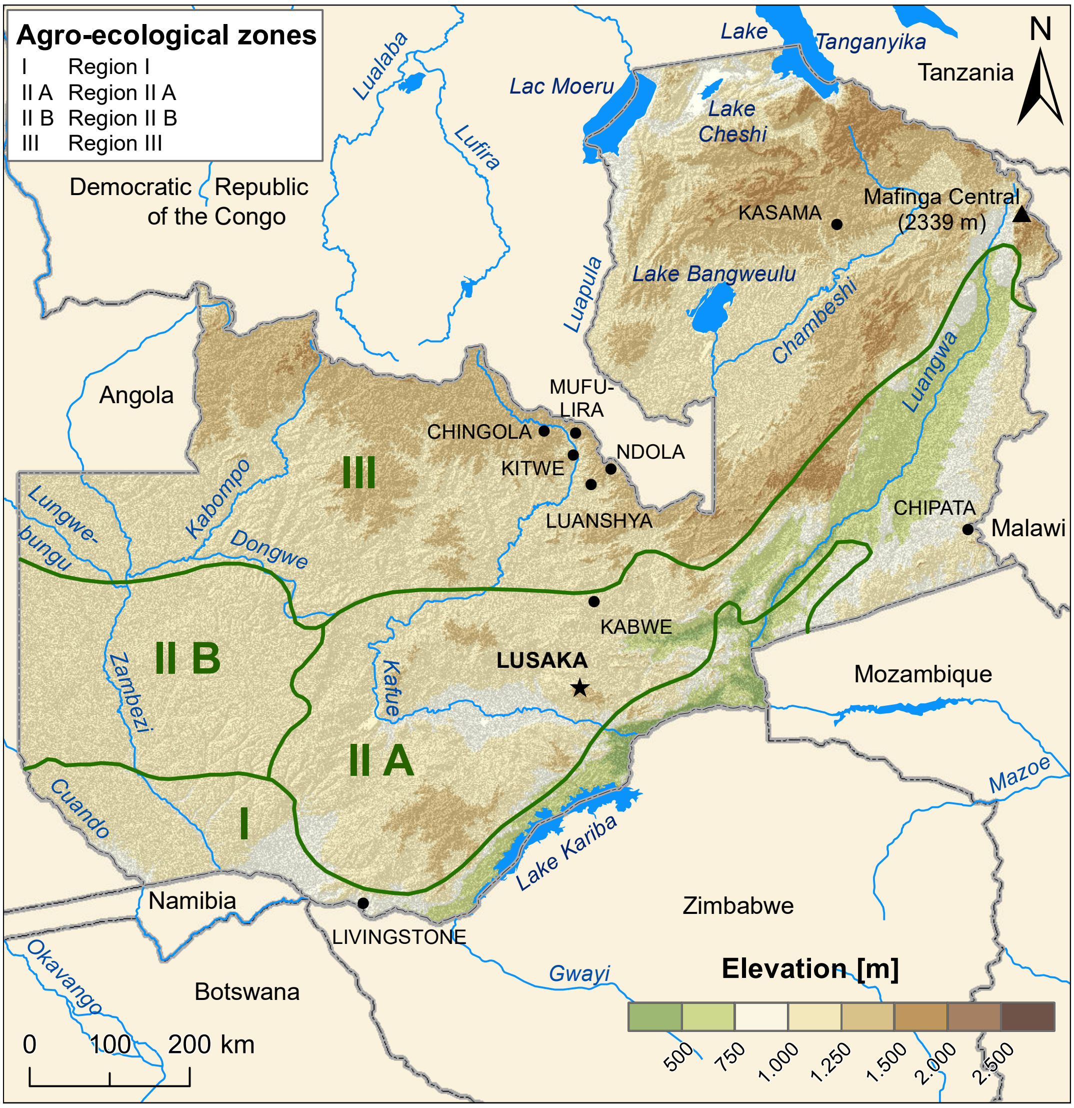

Figure 1: Map of Zambia

1.1 The study area

Zambia is a landlocked country in Southern Africa. The country has a mostly tropical climate with a unimodal rainy season which is influenced by the Inner-Tropical Convergence Zone. The rainy season spans from November to April with higher amounts of precipitation in the north-west and lower amounts in the south-east. Accordingly, Zambia is commonly divided into four agro-ecological zones (Figure 1: Map of Zambia Figure 1), based on precipitation levels as a key marker of climatic differences: The southern river valley (I), the central and eastern plateaus (II A), the western plains (II B) and the northern part (III) (Agboola et al., 2019). Each of these zones is characterised by specific temperature and moisture regimes, and consequently specific patterns of crop production and pastoral activities.

Zambia is highly vulnerable to climate change. Out of 181 countries, Zambia ranks 139 on the ND-GAIN Vulnerability Index (ND-Gain, 2022). As in other countries in sub-Saharan Africa, the vulnerability is mainly driven by a combination of naturally high levels of climate variability, high reliance on rainfed agriculture, and limited economic and institutional capacity to cope with and adapt to climate variability and change (Challinor et al., 2007; Müller et al., 2010). Despite increases in per-capita economic growth, poverty and inequalities remain high in Zambia, particularly for the rural population (The World Bank, 2019). Moreover, 69.5 % of the total population suffers from either moderate or severe food insecurity (FAO, 2020; statistics from 2018–2020).

Although Zambia's economy has clearly shifted towards services and industry in past years, the agricultural sector continues to be the primary means of livelihood for the country's population, especially in rural areas. Even though agriculture only accounts for 5.8 % of the Gross Domestic Product, it provides livelihoods to more than 70 % of the population (MoFNP, 2022). Moreover, agriculture directly impacts the food and nutrition security of the rural population as there is a high degree of subsistence farming in Zambia. The majority of smallholder farmers practice rainfed agriculture (Ngoma et al., 2021), leaving them particularly vulnerable to climate extremes and climate change (MoA & MFL, 2016).

Sufficient and timely water availability is therefore key for agricultural production, but also for the energy security of the country, which draws 85 % of its electricity production from hydropower. In some parts of the country, water resources are already under severe stress. Moreover, Zambia's vegetation, especially forests have been affected by degradation from human activities mainly through smallholder farming and charcoal production (WWF, 2021), putting the country's water resources and biodiversity at risk. This underlines the need for sustainable water and landscape management practices. As Zambia is estimated to hold about half of the surface and underground water resources of Southern Africa (Hamududu & Ngoma, 2019), integrated water resource management also plays an important role from a regional perspective.

1.2 The study approach

The study presents a comprehensive climate risk analysis to deepen the understanding of current and projected climate risks and their impacts on agriculture as well as possible adaptation benefits at both national and sub-national level. The study models the whole chain from the impact dimension of climate change to an action dimension which is assessing specific adaptation options and policy recommendations, as well as a discussion on the uncertainty of results (Figure 2). This study thereby combines a model-based climate impact assessment driven by ten global climate models with an economic analysis to evaluate adaptation options under two greenhouse gas emissions scenarios, SSP1-RCP2.6 and SSP3-RCP7.0. Moreover, the study includes gender aspects and assesses possible financing options of adaptation and climate and disaster risk financing.

The study design was co-developed together with stakeholders from Zambian national and local governmental institutions, civil society, academia, the private sector, practitioners and development partners. Together with them, a selection of specific crops and adaptation options was made to narrow down the study focus and provide concrete results to inform long-term climate adaptation planning and investment decisions in Zambia. The selection process of specific crops and adaptation options considered national priorities, stakeholder priorities identified during the kick-off workshop and feasibility criteria (i.e. compatibility with model analyses and data availability). Chapter 1 in the supplementary information (SI) provides a detailed description of the selection process. The process led to the selection of sorghum, maize and groundnuts for the analysis of climate impacts on agriculture. Moreover, the following two adaptation options were selected that are going to be evaluated in this study:

- Conservation agriculture
- Early warning systems

The selected crops and adaptation options represent stakeholder priorities. They are not meant to provide silver-bullet solutions but should be interpreted as two possible adaptation options within the wider context of building climate-resilient agri-food systems.

Given the importance of sufficient water resources for agricultural production, energy supply and biodiversity, we additionally provide a case study on water availability under climate change and its implications for the irrigation potential. For this analysis, we focus on the Kafue Catchment and parts of the Zambezi Catchment, which was the case study area that was prioritized by stakeholders.

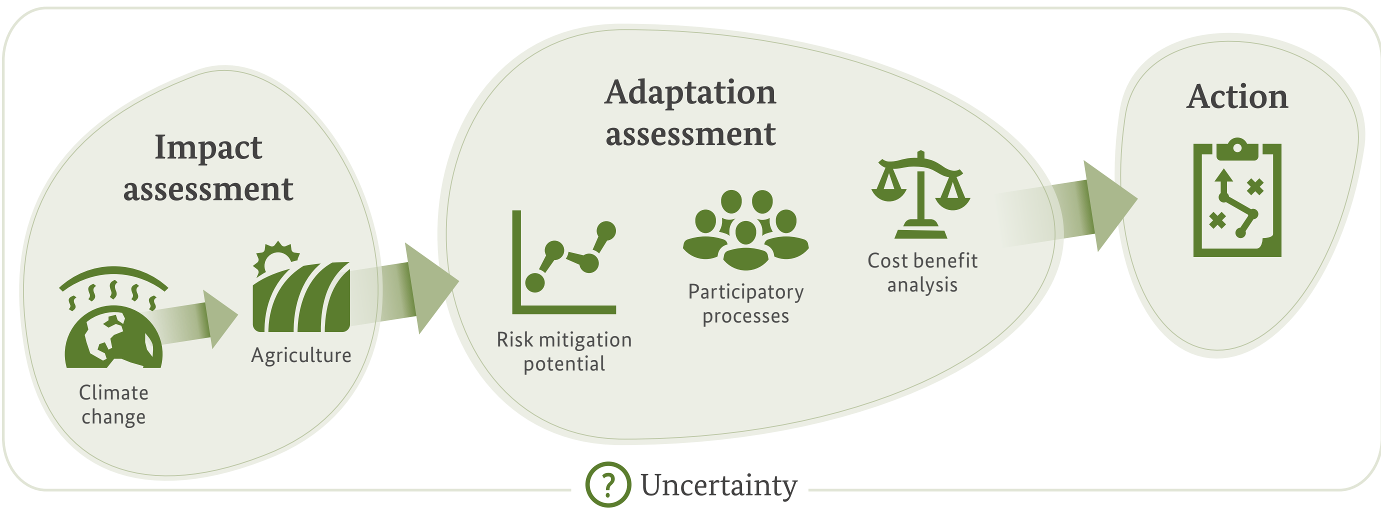

Figure 2: The impact-action chain of the climate risk analysis

Box 1: Gender-specific vulnerability to climate change in Zambia

Climate impacts and adaptation processes are intrinsically linked with gender and other social factors, such as age, ethnicity, marital status or disability (Ahmed et al., 2016). Different social groups experience climate impacts differently and have varying opportunities to respond. This is particularly true for women. 78 % of Zambian women are engaged in agriculture (Sitko et al., 2011), making them the main contributors in this sector, but only 12 % of the female workforce in agriculture is covered by social security (Government of Zambia, 2021b), resulting in a higher vulnerability to the impacts of climate change. Furthermore, women's and men's access, ownership and control over resources differ strongly due to social norms. An important element which is shaping farmers' adaptation decisions and their vulnerability is their respective land tenure system (Murken and Gornott, 2022). About 65 % to 95 % of land in Zambia is customary land, which means that it is not protected under the jurisdiction of the government. Instead, it is administered by regional chiefs (Kalinda et al., 2022), who divide the land among village headmen and – less often – headwomen (Burke et al., 2018). Married woman in rural areas commonly have access to farmland through their husbands. They are prone to tenure insecurity in case of divorce or widowhood as they are dependent on the decision of the deceased's relatives as to whether they may continue to use the land (Kapihya, 2017).

Differences in the traditional division of labour also lead to gendered vulnerability to climate impacts (Mphande et al., 2022). Mulenga et al. (2017) found that female farmers in Southern, Eastern and Northern Province of Zambia were more vulnerable to certain climate impacts than male farmers. Women were considered responsible to fetch water and had to travel longer distances in case of declining water levels in streams and wells. Moreover, they were considered being responsible for feeding their families – so that climate-related yield shortages had a stronger impact on them. In addition, women were less mobile and accordingly had fewer opportunities to reach markets where they could sell their products at higher prices or diversify their income. While men could look for alternative work opportunities in mining or fishing, these opportunities were not available to women.

Adaptation behaviour is also influenced by knowledge and perception of climate change, which can differ based on gender. Studies from Ghana (Owusu et al., 2019) and Uganda (Kisauzi et al., 2012) demonstrate a lower level of awareness about climate change among women related to lower levels of education and access to information sources (Kisauzi et al., 2012). This shows that the combination of various social factors can increase the burden on women and other social groups in a process of "cumulative disadvantage" (de la Rocha, 2007), and serve to reinforce existing inequalities.

Provided that women and other social groups are moved to the center of relevant policies – both as a target group and leaders of action – agricultural systems can be transformed towards greater gender equity, inclusion and climate resilience. In recent Zambian policy development and formulation, gender mainstreaming has become increasingly important (Samboko and Dlamini, 2016; SADC, 2022). The Zambian Constitution was amended in 2016 to include articles on gender equality, for example, providing that nominations to public office must ensure a 50 % representation of men and women (Government of Zambia, 2016). Furthermore, there are many policies, like the National Policy on Climate Change (Government of Zambia, 2016b), the National Agriculture Policy 2012–2030 (Government of Zambia, 2012) or Zambia's NDC (Government of Zambia, 2021) that advocate for gender mainstreaming in the respective sectoral fields. In 2018, the Climate Change Gender Action Plan was launched with the intention to reduce the existing implementation gap (Samboko and Dlamini, 2016; SADC, 2022) and enforce gender considerations in concrete programs and projects related to agriculture, natural resource management, and climate change (Government of Zambia, 2018).

This study is organized as follows: After this introduction (chapter 1), chapter 2 provides an overview of past and projected future climatic changes in Zambia focusing on changing temperature and precipitation regimes in the country. In chapter 3, we analyse how climate change impacts agriculture both in terms of changes in crop yields (chapter 3.1) and changes in the area that is suitable for crop production (chapter 3.2). Moreover, we analyse how climate change impacts the water availability in the case study area, i.e. the Kafue Catchment and parts of the Zambezi Catchment (chapter 3.3). Chapter 4 evaluates two adaptation options. Whereas chapter 4.1. focuses on conservation agriculture and assesses the risk-mitigation potential of conservation agriculture based on process-based crop model results, chapter 4.2. provides an economic assessment of costs and benefits of early warning systems, focusing on the Participatory Integrated Climate Services for Agriculture (PICSA) approach. Additionally, both adaptation options are evaluated in terms of gender aspects and possible financing options. Acknowledging that adaptation will not be sufficient to mitigate climate impacts completely with increasing climate change, we discuss possible financing options to deal with residual risks based on climate and disaster risk financing in chapter 5. Chapter 6 presents a conclusion and policy recommendation, which were informed by stakeholders.

2. Changing climatic conditions

To identify changes in future climatic conditions in Zambia, this chapter analyses several indicators concerning temperature and precipitation under two global greenhouse gas (GHG) emissions scenarios, scenario SSP1-RCP2.6 and scenario SSP3-RCP7.0, which constitute a low and high GHG concentration pathway, as used in the reports of the Intergovernmental Panel on Climate Change (IPCC). SSP1-RCP2.6 represents a scenario with global temperature increases of 2 °C compared to pre-industrial times (van Vuuren et al., 2011). SSP3-RCP7.0 refers to the "without climate policy" scenario and is therefore a high emissions scenario. Projected climate data were analysed to show the full range of possible future climatic conditions by 2030, 2050 and 2090 and thus inform political decision makers and implementers in the medium and long term.

First, the drivers of the current climate in Zambia are presented in the subsequent section (chapter 2.1). This is followed by an outline of future climate trends of mean annual climate variables and extreme climate events (chapter 2.2).

2.1 What drives Zambia's climate?

Zambia's climate is largely influenced by latitude and elevation. The country has a mostly tropical climate with higher amounts of precipitation in the north-west and lower amounts in the south-east. Mean annual temperatures range from 19 °C to 25 °C (Figure 3, left) with lower values in the mountainous regions in the north and north-east and higher values in the rest of the country, in particular along the Luangwa and Zambezi Rivers. Annual precipitation sums range from 620 mm in south-western Zambia, which has a drier mountain climate, to 1 480 mm in the north-east (Figure 3, right), which is also characterized by higher altitudes, but in addition shows some savannah features. Zambia has a single rainy season (unimodal precipitation regime), which lasts from November to April in most parts of Zambia.

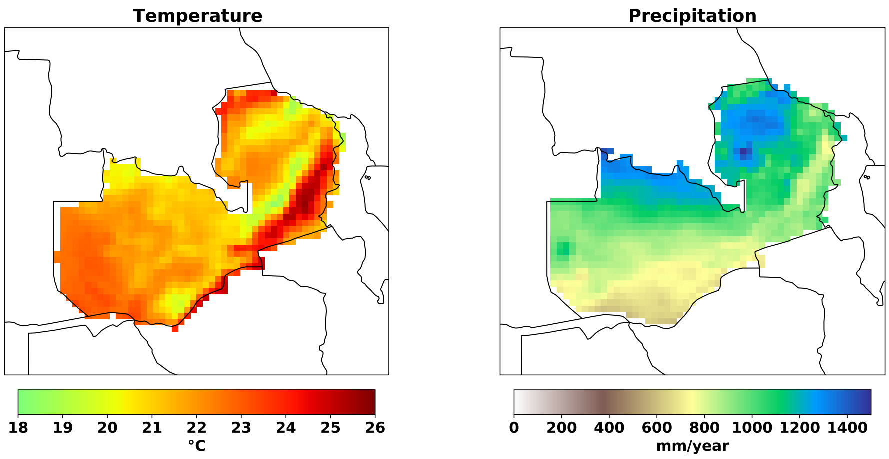

Figure 3: Mean temperature and precipitation sum in Zambia from 1981 to 2021

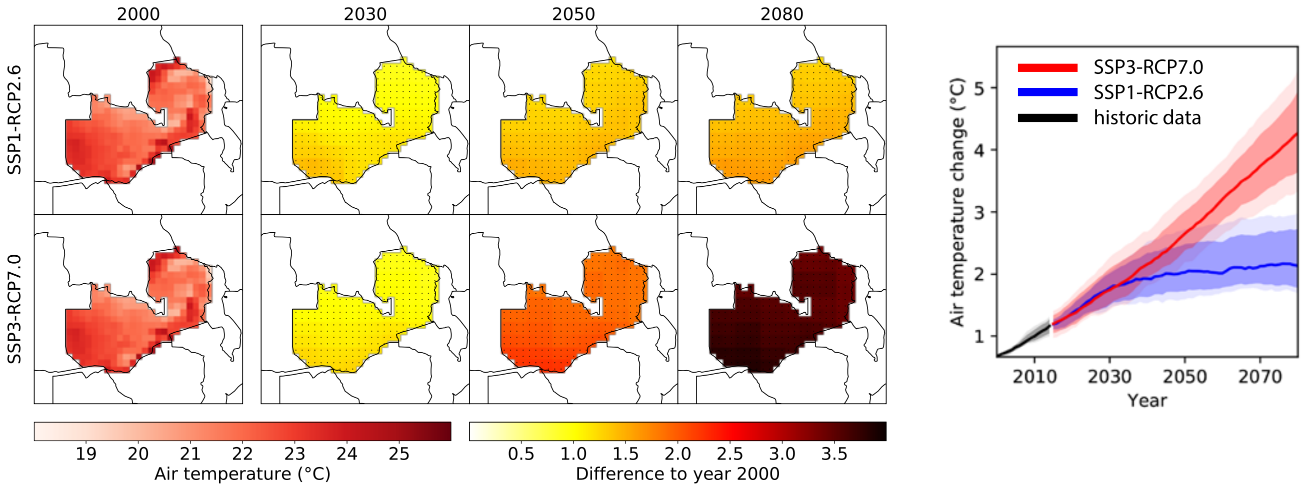

Figure 4: Projected temperature change in Zambia for SSP1-RCP2.6 and SSP3-RCP7.0

2.2 Climate change and variability in the future

Future temperature changes – mean and extremes

Climate models project a robust trend towards increasing temperatures all over Zambia during the 21st century. This is evident in both analysed scenarios, albeit to different degrees. Under the low emissions scenario SSP1-RCP2.6, the multi-model ensemble median (MMEM) indicates a stabilization of **mean annual temperatures** over Zambia at around 2 °C increase in the late 21st century compared to pre-industrial levels. Under the high emission scenario SSP3-RCP7.0, temperatures continually increase throughout the 21st century. The 2 °C threshold is already well passed by the middle of the century and by 2080 the MMEM projects an increase of over 4 °C (Figure 4).

Consistently with the projected temperature increases, the number of temperature extremes increases as well. The **number of very hot days** is projected to increase in all parts of the country with the south-western part showing the strongest increase under the high emissions scenario SSP3-RCP7.0. Whereas for the country average, models project around 88 very hot days more per year by 2080, the southern parts reach up to 140 more hot days (Figure 5) under the high emissions scenario in the MMEM. Some of these regions already experience up to 70 hot days per year under the current climate, so the projected changes indicate that most of the year will be very hot.

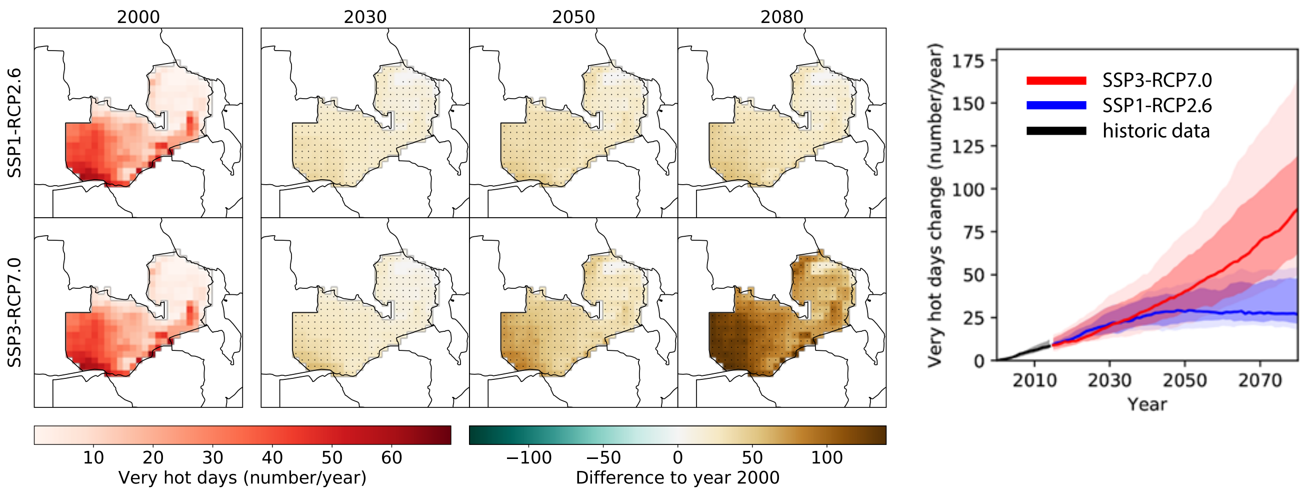

Figure 5: Projected change in the number of very hot days per year under SSP1-RCP2.6 and SSP3-RCP7.0; very hot days refer to days with a maximum near-surface air temperature above 35 °C

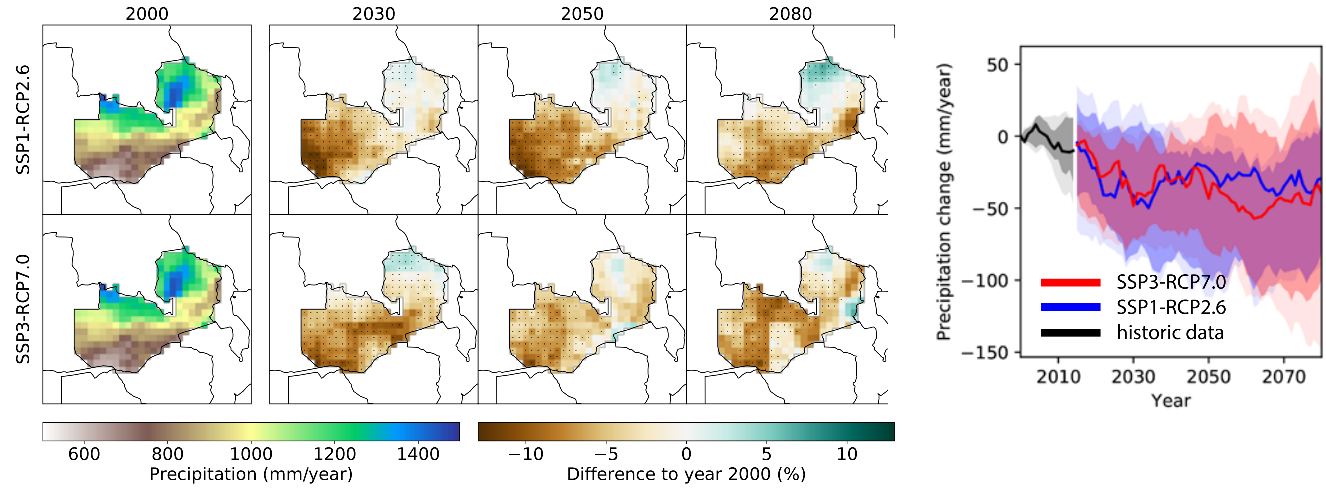

Figure 6: Projected change in annual precipitation in Zambia for SSP1-RCP2.6 and SSP3-RCP7.0

Future precipitation changes – mean and extremes

Projections of **mean precipitation** indicate high spatial variations within the country. The most northern parts are projected to experience a slight increase in annual precipitation of up to ca. 6 % locally under the low emissions scenario SSP1-RCP2.6 by 2080. The southern and central parts of the country, which are already today drought prone, show a decrease in precipitation of around 12 % (10 %) by 2050 (2080). Under the high emission scenario SSP3-RCP7.0, most of the country shows a drying trend throughout the 21st century. In addition, both emissions scenarios predict a drier future climate, most pronounced in the southern part of the country, and the models largely agree on these results (Figure 6).

Heavy precipitation intensity is projected to increase in the north and decrease in the western and southern parts of the country with similar patterns to the projected changes in the mean annual precipitation amount under SSP1-RCP2.6 (Figure 7). Under SSP3-RCP7.0, the MMEM projects an intensification of rainfall for the eastern half of Zambia of up to 9 %, even though these regions will overall become drier.

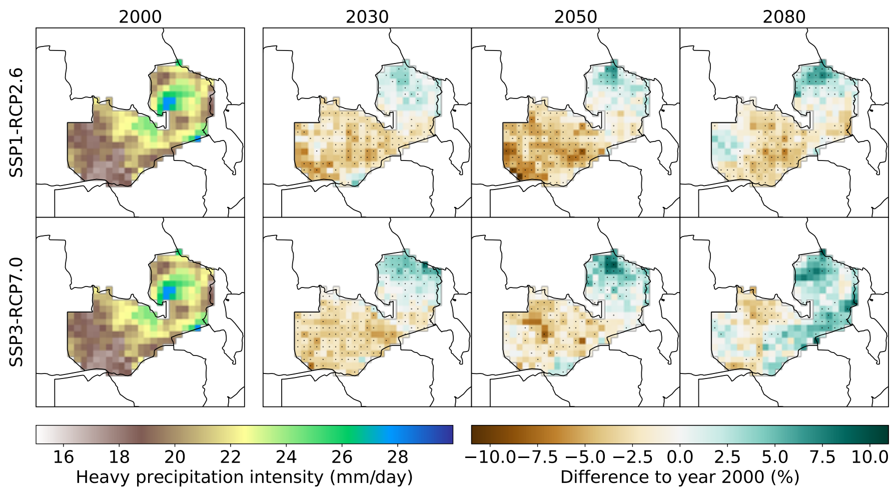

Figure 7: Projected change in heavy precipitation events in Zambia for SSP1-RCP2.6 and SSP3-RCP7.0

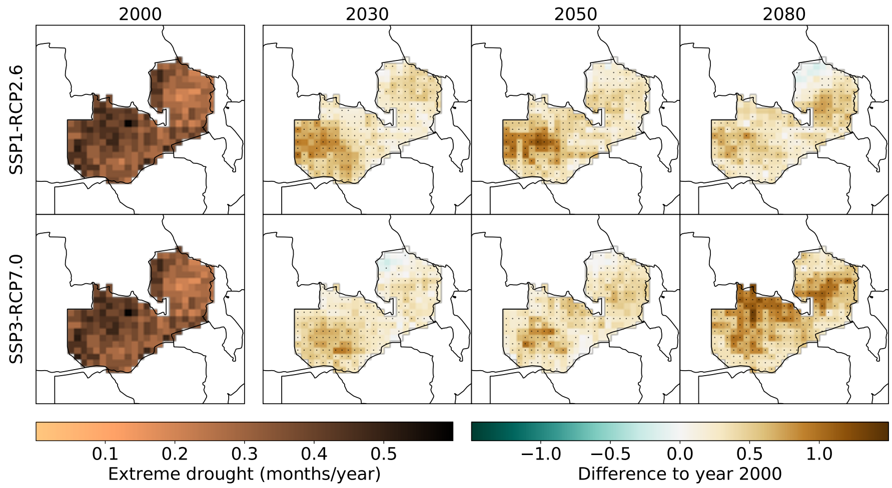

Figure 8: Projected change in extreme drought measured in the Standardized Precipitation Index (SPI) in Zambia for SSP1-RCP2.6 and SSP3-RCP7.0; The left map shows how many months per year an SPI of −2 is surpassed, which defines an extreme drought. The maps to the right show projected changes in SPI relative to the year 2000

The change in extreme drought, however, indicates an increase all over the country. The Standardized Precipitation Index (SPI) is a relative measure of accumulated dry conditions (here we show the SPI over 6 months). Extremely dry months are defined by an occurrence of approximately once every 3 to 4 years. Projections show about a tripling of these extremely dry months, with the strongest increase in central Zambia under SSP3-RCP7.0 (Figure 8). Overall, these trends in extreme indicators show a shift towards more intense climate conditions both in terms of dry as well as wet conditions.

Summary

Climate models project a robust trend towards increasing temperatures all over Zambia with the south-western part showing the strongest increase. Projections of mean precipitation indicate high spatial variations within the country. The southern and central parts of the country, which are already today drought prone, are projected to experience a decrease in precipitation with ongoing climate change. Projections of extreme drought, however, indicate an increase all over the country. Overall, these trends in extreme indicators show a shift towards more intense climate conditions both in terms of dry as well as wet conditions.

Box 2: Data and methods for the assessment of climate impacts in Zambia

The analysis builds on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which provides bias-adjusted climate projections as well as impact projections. Future climate projection data simulated by Global Climate Models (GCMs) is obtained from ISIMIP3b. Historical simulations cover the years 1850–2014 and future projections cover the years 2015-2100. Two greenhouse gas emission concentration scenarios are included. While SSP1-RCP2.6 represents the low emissions scenario, SSP3-RCP7.0 represents the high emissions scenario. W5E5 is the observational reference dataset used for bias adjustment and statistical downscaling of ISIMIP3b. The GCMs included in ISIMIP3b are IPSL-CM6A-LR, GFDL-ESM4, MPI-ESM1-2, MRI-ESM2-0 and UKESM-0-LL. These five GCMs were selected from the larger CMIP6 (phase 6 of the Coupled Model Intercomparison Project) ensemble based on criteria including data availability, model performance and climate sensitivity (Lange, 2021).

3. Climate change impacts on agriculture

Climate change impacts Zambian agricultural production in various ways, such as through changes in modal conditions, seasonal changes and extreme events. Extreme events increasingly cause crop losses (Cottrell et al., 2019), for example related to droughts (Kim et al., 2019), heat (Liu et al., 2019; Zampieri et al., 2017) or a combination of multiple hazards (Matiu et al., 2017). Dry conditions reduce the amount of water available for crops, leading to yield losses, particularly if water is not sufficiently available during critical development stages in the growing season. More intense rainfall and excessive rain, on the other hand, contribute to floods and higher levels of soil erosion, which in turn reduces soil fertility and can lead to a loss of topsoil.

Seasonal changes in climate can affect agriculture as warming trends lead to shortened life cycles of major crops (Kerr et al., 2022; Wang et al., 2009). Modal changes, such as the shift in climatic envelopes, can alter the crop suitability in certain areas and lead to shifts in growing areas (Chemura et al., 2020a; Kummu et al., 2021; Travis, 2016). Moreover, the distribution of pests and pathogens changes with increasing warming and can potentially lead to drastic harvest losses, which has contributed to high levels of food insecurity in Zambia in the past (IPC, 2021).

All in all, there is a complex interplay of climate drivers on agriculture, which has wide-ranging consequences for societies. For example, loss of arable land and the degradation of soil quality can lead to the expansion of arable land with potentially arising conflicts over land, water resources and biodiversity-rich areas. Zambia's vegetation has experienced profound disturbances in previous years, primarily through the expansion of smallholder farming and charcoal production (WWF, 2021). This in turn negatively effects water resources and availability for agriculture.

Smallholder farming systems are most prevalent in Zambia. Approximately 90 % of farmers are small-scale farmers (International Trade Administration, 2023) and are disproportionally vulnerable to climate change (Donatti et al., 2019; Kerr et al., 2022; Morton, 2007). The livelihoods of smallholder farmers mostly depend on rainfed agriculture so that changes in rainfall, temperature and the occurrence of extreme events directly affect their income, food security situation and well-being (Harvey et al., 2014; Morton, 2007; Vignola et al., 2015). Moreover, smallholder farmers have limited capacities to adapt to climate change for various reasons, such as lacking political, infrastructural and institutional support as well as limited access to inputs, credits and viable markets (Kerr et al., 2022; Mbow et al., 2019). Also, insecure land tenure rights can constrain farmers' ability to adapt to climate change (Murken & Gornott, 2022). The negative impacts of global warming on agriculture and the high vulnerability of smallholder farmers further jeopardize their food and nutrition security (Wheeler & Von Braun, 2013).

As described, climate change affects agriculture in Zambia in many ways. In the following sub-chapters, we focus on three aspects. First, we describe how climate change is projected to impact sorghum yields in Zambia (chapter 3.1). Second, we show how climate change alters the areas that are suitable for crop production in Zambia, focusing on sorghum, maize and groundnuts (chapter 3.2). Given the high importance of water availability for agricultural production, biodiversity and energy security in Zambia, chapter 3.3 assesses how climate change is projected to change water availability in future. For this analysis, we focus on the Kafue Catchment; and the Zambezi Catchment in the Southern Province of Zambia.

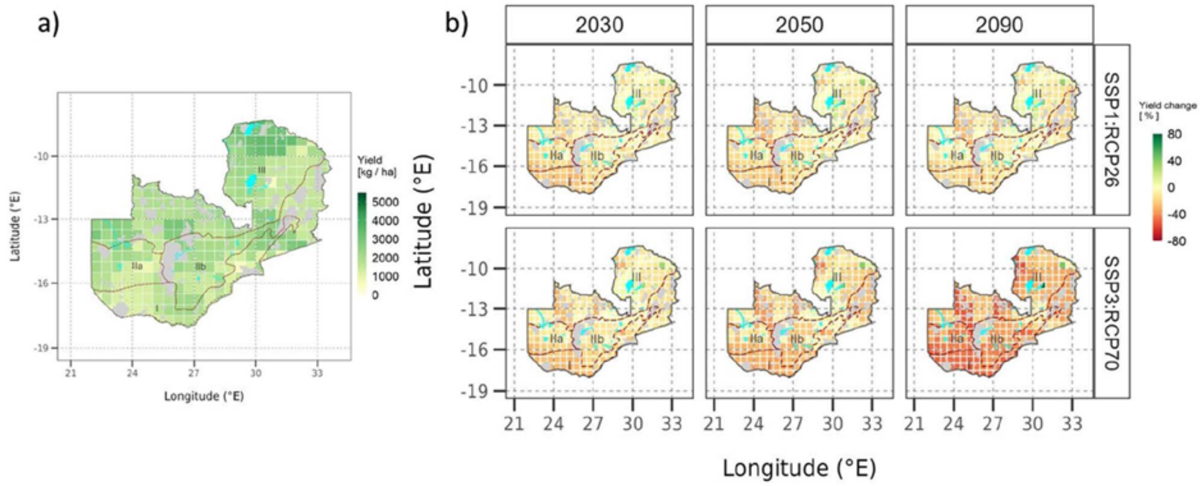

Figure 9: a) Current sorghum yields in kg/ha and b) projected future sorghum yield changes in % in Zambia at 0.5 ° grid under the low emissions scenario SSP1-RCP2.6 (top row) and the high emissions scenario SSP3-RCP7.0 (bottom row) for periods of 20 years centered around 2030, 2050, and 2090; The projections were calculated based on the process-based crop model DSSAT (see Box 4)

3.1 The impact of climate change on sorghum yields

Sorghum is a major starchy food crop in Zambia and plays a vital role in providing nutrient-dense food, particularly for poorer parts of the population (World Bank Group, 2018). Since 70 % of cropland in Zambia is used for maize production, producing sorghum can contribute to crop diversification, which makes farmers less vulnerable to both climatic as well as market shocks. Sorghum is produced all over Zambia with national average yields for smallholder farming systems of ca. 730kg/ha (from 2006 and 2015, ZamStats, 2022). The northern, north-western, central and eastern regions have vast areas with high sorghum yields (>3000 kg/ha) under current climate conditions. The Western, Southern and Muchinga Provinces have areas with the lowest sorghum yields in Zambia (Figure 9). Yields of sorghum are far below the yield potential that would be obtainable under current environmental conditions and the genetic characteristics of sorghum varieties that are planted in the country. The highest production intensity can be found in the Southern and Western Provinces of the country even though potential yields are highest in the northern parts of the country where rainfall amounts tend to be higher.

Climate change projections show a mostly negative impact on sorghum yields in Zambia with stronger yield losses under the high emissions scenario (SSP3-RCP7.0) than under the low emissions scenario (SSP1-RCP2.6). Mean yield losses for the whole country are between 5.3 % (SSP1-RCP2.6) and 7.2 % (SSP3-RCP7.0) by around 2030, 5.8 % to 12.2 % by 2050 and 4.5 % to 28.0 % by 2090. The impact of climate change on sorghum yields shows spatial and temporal disparities with most losses projected in the south of Zambia, which has currently the highest production intensity areas for sorghum. In agro-ecological zone I and IIa (see Figure 1), yield losses are projected between 9 % and 36.8 % by the end of the century. The lowest losses are projected for agro-ecological zone III (Figure 10).

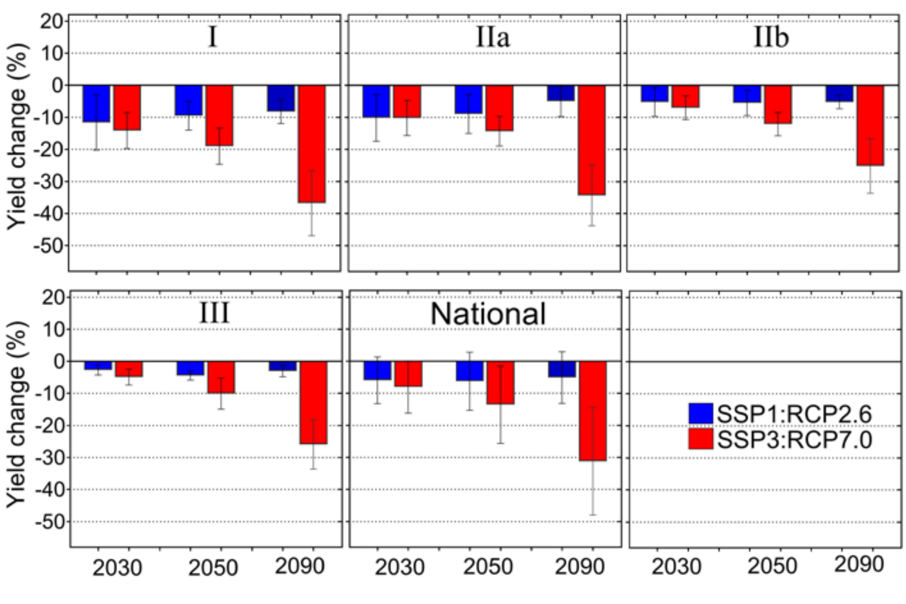

Figure 10: Projected future sorghum yield changes in percent for the four agro-ecological zones in Zambia under the low emissions scenario SSP1-RCP2.6 (blue) and the high emissions scenario SSP3-RCP7.0 (red) for periods of 20 years centered around 2030, 2050, and 2090; the error bars show the model range of 5 Global Circulation Models used as input for the process-based crop model DSSAT

Box 3: Model certainty and confidence in the results

Our model results show a high agreement between observed (ZamStats, 2022) and modelled sorghum yields indicating a high model performance: The average sorghum yield for smallholder farming systems in Zambia from 2006 and 2015 was 729kg/ha and our model estimates this at 753kg/ha. Moreover, our projected sorghum yield losses of up to 30 % under the high emissions scenario (SSP3-RCP7.0) around the end of the century are in line with other studies showing projections for sorghum in the region under A2 storylines of 27 % to 38 % (Lobell & Field, 2007) and 5 % to 35 % (Adhikari et al., 2015).

Summary and discussion of the results

The analysis reveals mostly negative impact on sorghum yields with most losses projected in the south of Zambia, which has currently the highest production intensity areas for sorghum. Both water availability and temperature effects explain the changes in sorghum yields, with increasing temperatures having more significant impacts than the projected changes in precipitation. This explains why sorghum yields are projected to decrease even for areas where rainfall is projected to remain the same or increase slightly with ongoing climate change (chapter 2.2). However, sorghum yields in Zambia are not only affected by dry conditions, but also by water logging. Excessive moisture in the root zone and flooding are detrimental to sorghum growth and yields, especially if they occur during the early stages of its growth (Chadalavada et al., 2021). Despite the projected sorghum yield decreases with ongoing climate change of about 5.8 % to 12.2 % by mid-century and the detrimental effect this potentially has on the food and nutrition security of households in Zambia, it should be noted that this decrease is nevertheless only about half of the projected decrease in maize yields, which is about 21 % to 35 % (Hachigonta et al., 2013; Siatwiinda et al., 2021).

Box 4: Methodology of process-based modelling

To analyse climate change impacts on sorghum production, we use the process-based crop model Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2019; Jones et al., 2003). DSSAT is a modular modelling framework based on biophysical processes in farming systems, with many plant, soil and management modules for a diverse range of crops, soil processes and range of management controls. It simulates several key underpinning plant physiological processes and plant growth on a daily time step in response to daily input of weather data, soil characteristics and crop management actions. The simulated processes include phenological development, biomass accumulation, yield formation, soil moisture and nutrient status against agricultural management practices. In this study, we used DSSAT version 4.8, with Crop Environment Resource Synthesis (CERES)-sorghum as the crop model, CENTURY model to simulate soil C and N dynamics, and the Ritchie soil–water balance model. The model was parameterized and calibrated for using gridded information obtained from local (ZamStats, 2022) and global data sources.

This is in line with findings from Ngoma et al. (2021) showing that maize will be most impacted by climate change compared to other cereals, root crops, cotton and tobacco in Zambia. This confirms that sorghum is indeed a comparably more resilient crop, as it will suffer less yield losses compared to other crops, such as maize.

3.2 Changes in areas suitable for crop production

Crop suitability modelling allows to identify how the areas suitable for crop production will alter with ongoing climate change. We applied crop suitability models to assess the current suitability of sorghum, maize and groundnut and how their suitability will change throughout the 21st century due to changes in climatic conditions. Crop suitability refers to the ability of land to sustain a crop throughout its growing cycle, given the prevailing climatic and biophysical conditions (Chemura et al., 2020b). Crop suitability models assume that biophysical and climatic factors are vital for crop production, which is valid for rainfed agriculture. Due to its relevance for subsistence farmers, we focus on small-scale production in our analysis.

The three crops maize, sorghum and groundnuts were selected together with stakeholders (chapter 1 in SI). Maize was selected as it is the primary food crop in Zambia (Chapoto et al., 2015) and grown on 70 % of cropland in Zambia. As maize is dominating agricultural production, sorghum production could play an important role for crop diversification. Sorghum provides nutrient-dense food, particularly for poorer parts of the population (World Bank Group, 2018). Groundnut was selected as it is a major source of protein in Zambian diets. The legume crop plays an important role due to its nutritional and economical value (Bioversity International & CIAT, 2020).

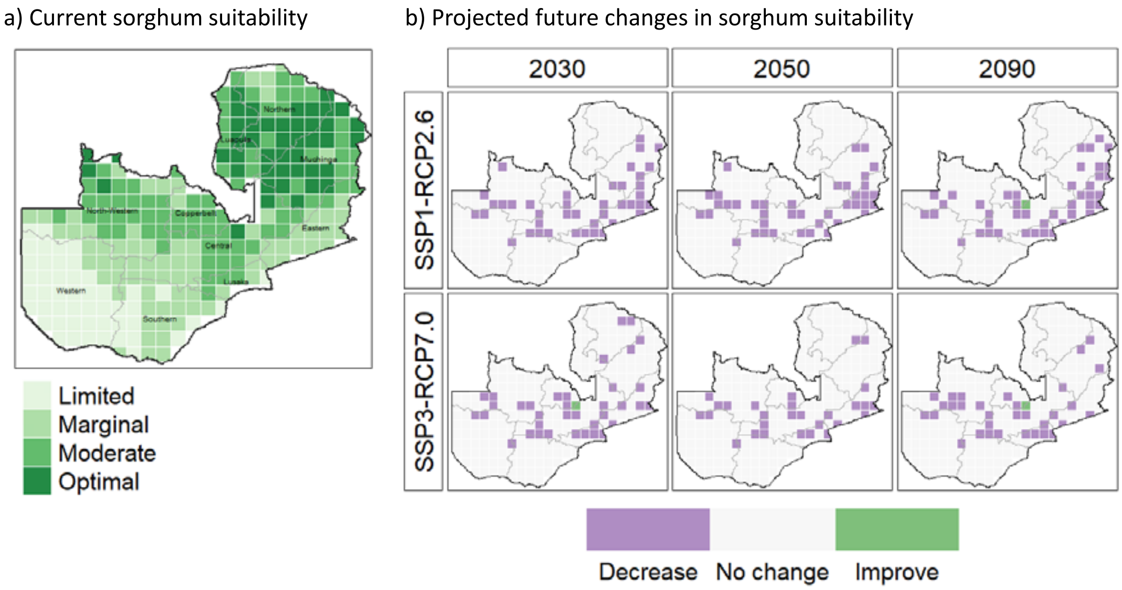

Figure 11: a) Current suitability of sorghum production; b) projected future change in sorghum suitability in Zambia at 0.5 ° grid under the low emissions scenario SSP1-RCP2.6 (top row) and the high emissions scenario SSP3-RCP7.0 (bottom row) for periods of 20 years centered around 2030, 2050 and 2090

Crop suitability for sorghum production

Sorghum production is currently suitable in around 50 % of the total crop land area in Zambia. Even though the largest share of suitable areas for sorghum production is in Copperbelt, Luapula, Muchinga and Eastern Provinces (Figure 11a), sorghum is mostly produced on less marginal areas in Central and Southern Provinces. This confirms the importance of sorghum for agricultural production under less favourable climatic conditions on marginal areas.

> Sorghum is a crop that is able to grow under less favorable conditions on marginal areas. With climate change, the northern parts remain highly suitable for sorghum production, whereas the southern parts remain largely unsuitable throughout the century. The biggest decreases in suitability are projected for eastern and central Zambia.

With climate change, a net reduction in suitable areas for sorghum production between 28 and 35 % is projected by mid-century on the national level. However, the model suggests no significant changes in suitability for the northern and southern parts of the country. The northern parts of the country are projected to remain highly suitable for sorghum production throughout the century. Southern Zambia, on the other hand, will remain largely unsuitable for sorghum production. The areas in the Southern Province – therefore – do not show strong decreases as suitability is already low under current climatic conditions.

In the central and eastern parts of the country, the model suggests a decrease in suitable areas for sorghum production. Under current climatic conditions, Eastern Province has the largest areas with suitable crop production. Here decreases in suitable areas are projected within the range of 40 % to 60 % by mid-century – resulting in the largest decreases in suitable areas in absolute terms. Strong decreases are also projected in Central Province.

Box 5: Methods of the crop suitability assessment

Crop suitability assessments are based on the understanding that the biophysical parameters (e.g. soil organic carbon) and climatic variables (e.g. total amount of precipitation received in the growing season) play an important role in determining crop production. A suitability model, therefore, uses these variables to create a crop-specific score for each time period and location depending on how the variables meet the crop requirements or conditions in known current production areas (Evangelista et al., 2013). The crop production data is split into four bins (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 then corresponds to areas 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. Running the model based on current and projected climate data from the ISIMIP data base allows for an analysis of changes in the potentially cultivatable arable land under climate change. The models are evaluated using leave-one-out cross validation, balanced accuracy and the multi-class area under the receiver operating curve.

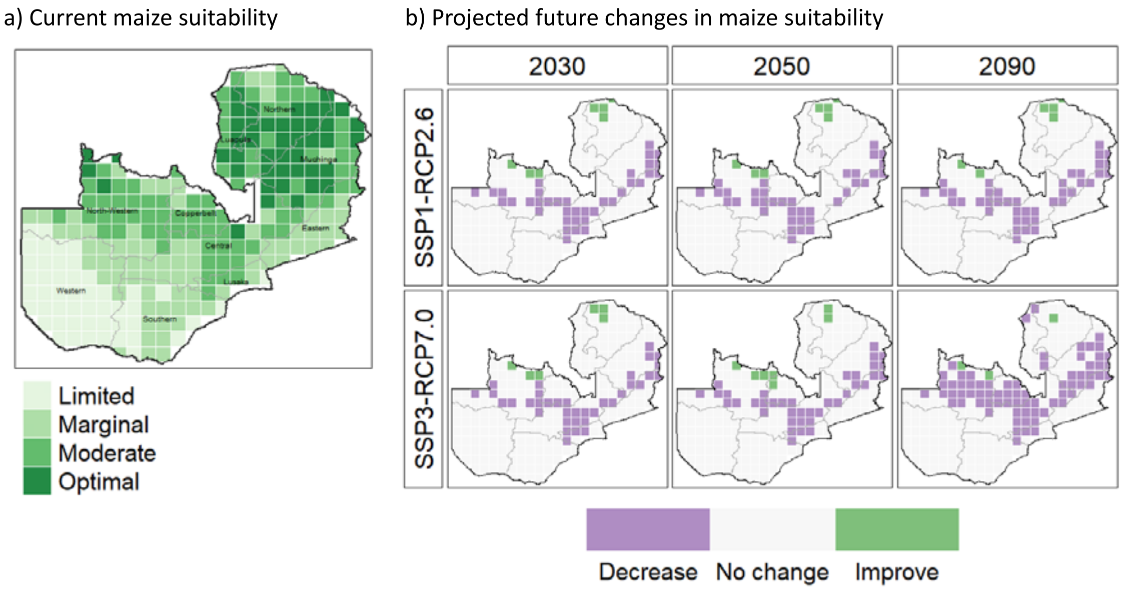

Figure 12: a) Current suitability of maize production; b) projected future change in maize suitability in Zambia at 0.5 ° grid under the low emissions scenario SSP1-RCP2.6 (top row) and the high emissions scenario SSP3-RCP7.0 (bottom row) for periods of 20 years centered around 2030, 2050 and 2090

Crop suitability for maize production

Under current climatic conditions, maize is suitable in around 45 % of total crop land area with the largest share of highly suitable areas in Luapula, Muchinga and Northern Provinces (Figure 12). Most maize is currently produced in Central and Southern Province. However, Southern Province together with Western Province are least suitable for maize production under current climatic conditions.

Overall, the model suggests a net reduction in suitable areas for maize production between 35 and 37 % in Zambia until mid-century due to changes in climatic conditions. The decrease in suitable areas becomes stronger in case of the high emissions scenario (SSP3-RCP7.0) towards the end of the century.

> There is a northwards-shift in suitability for maize production. The south remains unsuitable for maize production whereas the north remains or becomes more suitable. The strongest absolute reduction in suitable areas are projected for Central Province.

Southern and Western Provinces are projected to remain largely unsuitable for maize production throughout the 21th century. Central Province has currently the largest suitable areas for maize production. It is expected to face considerable decreases above 70 %, which results in the highest absolute decreases in suitable area. Most relative decreases are projected for Eastern Province and Lusaka. Under current management practices, the model suggests that these provinces will largely become unsuitable for maize production.

Whereas, the model suggests varying changes in suitability in the North-Western Province depending on the scenario, the Northern Province shows slight increases in maize suitability. Luapula is projected to remain highly suitable for maize production.

Crop suitability for groundnut production

On the national level around 40 % of the total crop land area is suitable for groundnut production under current climatic conditions. The largest share of suitable areas for groundnut production can be found in Copperbelt, Muchinga, Luapula and North-Western (Figure 13). Most production areas for groundnut are currently in Central and Southern Provinces.

> Model projections show no significant changes for groundnut suitability on the national level with on-going climate change.

On the national level, the model projections suggest no significant changes in crop suitability for groundnut under both emissions scenarios. For large parts of the country – also the provinces with the currently largest production areas for groundnuts – the climatic conditions to grow groundnuts are projected to reflect current patterns. There is a tendency towards a northward shift in groundnut suitability: Slight increases are projected for Luapula and Northern Province, whereas areas in Western Province and Muchinga are projected to experience moderate decreases in groundnut suitability.

Summary and discussion of results

The crop suitability analysis shows how the areas suitable for sorghum, maize and groundnut production alter with ongoing climate change in Zambia. The results show a net reduction in suitable areas for maize and sorghum production and no significant change in groundnut suitability with climate change. Moreover, there is a northward shift in crop suitability for maize, sorghum and groundnuts. Northern parts of Zambia are more suitable for sorghum, maize and groundnut production than the southern parts of Zambia and climate change is going to intensify this pattern.

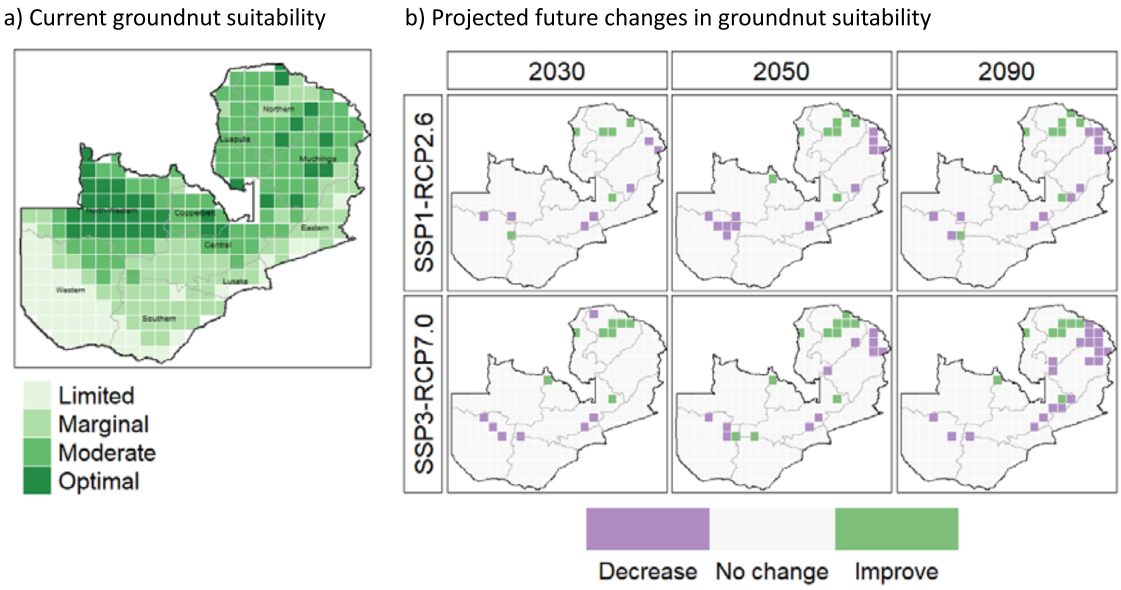

Figure 13: a) Current suitability of groundnut production; b) projected future change in groundnut suitability in Zambia at 0.5 ° grid under the low emissions scenario SSP1-RCP2.6 (top row) and the high emissions scenario SSP3-RCP7.0 (bottom row) for periods of 20 years centered around 2030, 2050 and 2090

To better compare crop suitability of maize, sorghum and groundnuts, we only focus on small-scale production in our analysis. However, the three crops differ considerably in terms of current management practices and agronomic production systems. Whereas sorghum is almost entirely grown by small-scale farmers, maize and groundnuts are grown by large-scale farms to a large extent, which have more means to produce crops also on less favourable land by using e.g. irrigation. The results are therefore not directly transferrable to large-scale production systems.

This analysis focuses purely on biophysical and climatic conditions and assumes that current management practices remain constant over time. This assumption allows to extract climatic influences on crop suitability and reduces the overall uncertainties of future projections for crop suitability. This assumption needs to be considered for the interpretation of the results. The presented results show how climate change influences the areas that are suitable for crop production, if no adjustments were made in e.g. agronomic management practices or in agricultural policies. However, implementing climate adaptation and sustainable intensification measures can substantially increase yields (Silva et al., 2023) and suitable areas for crop production. The results, therefore, highlight the importance of taking timely and effective adaptation measures to mitigate the negative impacts of climate change on crop suitability.

The specific policy recommendations that can be derived from these results, depend on the policy objectives and priorities. Promoting crop production on suitable areas can optimize yields. It can improve the food security situation of households and increase their incomes. To foster economic growth in the agricultural sector, crops should be promoted on land that is most suitable for a specific crop. However, certain crop production is advisable on marginal areas – particularly from a food security point of view. Sorghum is an important cereal crop in Zambia and performs well even under unfavourable climatic conditions. It plays an important role in enabling and sustaining agricultural production on marginal land that is not or will no longer be suitable for more demanding crops with ongoing climate change. Sorghum production on marginal land can therefore contribute to improving food security in subsistence-based farming systems to support social protection and poverty alleviation. Moreover, environmental aspects need to considered in agricultural and climate polices. Agricultural expansion into forest land or biodiversity-rich areas should be avoided due to high environmental and social costs. Instead, sustainable agricultural intensification measures on both, suitable and marginal land, should be promoted.

3.3 Changes in water availability

Sufficient and timely water availability is not only key for agricultural production, but also for the energy security of the country and for maintaining and promoting resilient ecosystems. Particularly the southern parts of the country are already today confronted with recurring droughts and climate change is further aggravating variations in water availability through more extreme dry and wet conditions (Chapter 2 and Tomalka et al., 2022). Moreover, Zambia's vegetation, especially forests have been affected by degradation from human activities mainly through smallholder farming and charcoal production (WWF, 2021), putting the country's water resources and biodiversity further at risk. Due to population growth and linked expansion of arable land, over-allocation of water and water-user conflicts (Funder et al., 2010; Marcantonio et al., 2018) can be expected to increase in future. This underlines the need for sustainable water and landscape management practices. As Zambia is estimated to hold about half of the surface and underground water resources of Southern Africa (Hamududu & Ngoma, 2019), integrated

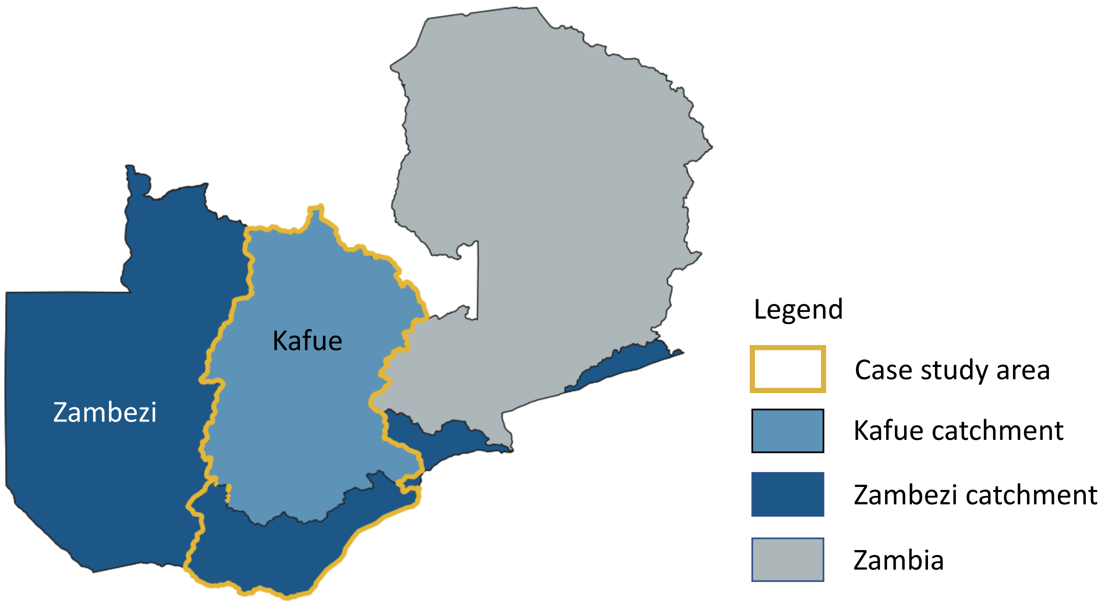

Figure 14: Case study area for the water balance analysis

water resource management also plays an important role from a regional perspective.

In this study, we analyse climate impacts on water availability in the Kafue Catchment; and the Zambezi Catchment in the Southern Province (Figure 14) and assess the implications for the irrigation potential. The case study area was selected based on stakeholder priorities. Whereas in practice, water availability will largely be determined by increasing water demand due to population and economic growth, water use allocations and transboundary water use, we deliberately disregard these factors – allowing us to disentangle future climatic drivers on water availability.

For the analysis, we compare water inflows to water outflows to estimate the overall water balance which determines the irrigation potential for the case study area. Therefore, the three components of the water balance equation are assessed, namely crop water demand, irrigation water need and water availability. The current state of these components and the projected changes with ongoing climate change for different global warming levels (GWL, chapter 2 in SI) are described in the following paragraphs.

Average crop water demand

The crop water demand (CWD) estimates the amount of water required for an optimal growth under well-watered conditions. It is currently highest in the south of the catchment (Figure 15), where temperatures are overall higher and rainfall is comparably lower (SI chapter 3). Under climate change, the crop water demand is projected to increase for all considered global warming levels. The increase is projected to be highest in the south, with up to 10 % under a 3 °C global warming. These changes closely follow projected temperature changes (SI chapter 3).

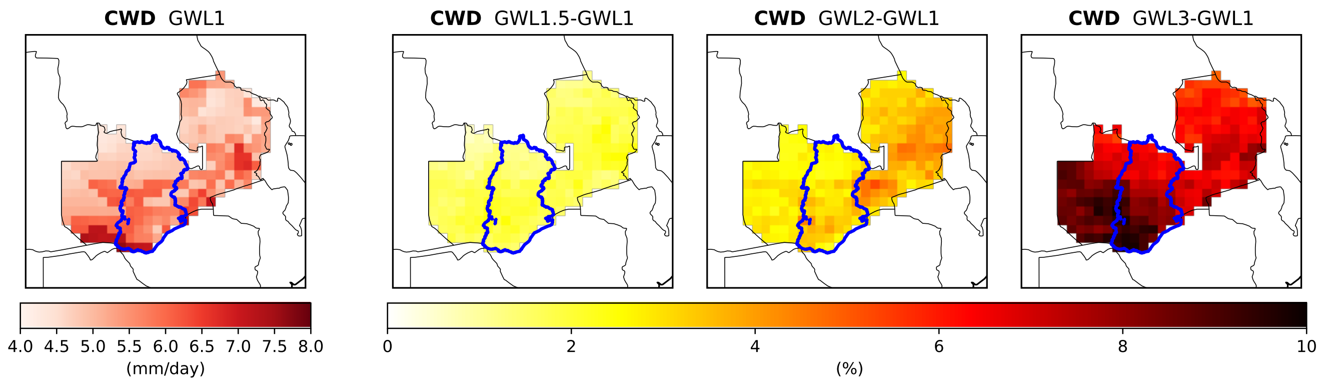

Figure 15: Average Crop Water Demand (CWD) between November and April in Zambia at a global warming level (GWL) of 1 °C (left), representing current conditions, and the change from GWL 1 °C to GWLs 1.5 °C, 2 °C and 3 °C

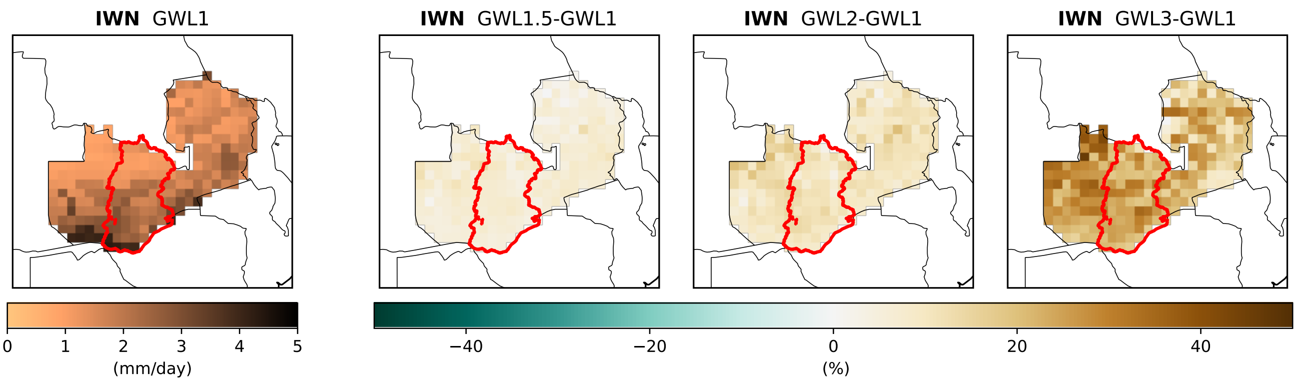

Figure 16: Average Irrigation Water Need (IWN) between November and April in Zambia at a global warming level (GWL) of 1 °C (left), representing current conditions, and the change from GWL 1 °C to GWLs 1.5 °C, 2 °C and 3 °C

Average irrigation water need

The irrigation water need (IWN) is the additional water amount required to reach optimal growth conditions for crops. Currently, IWN shows a similar pattern as the crop water demand (CWD), with the need for irrigation being higher in the south of the catchment (Figure 16). Overall, the irrigation water need is positive and in a magnitude of about half of the crop water demand. This means that already today, rainfall cannot meet the water demand of crops in the case study area so that irrigation would be needed. Projected changes in the IWN show an increase throughout the whole case study area with no clear spatial pattern.

Average water availability

Water availability in the excess water from precipitation and currently mostly reflects the precipitation pattern (SI chapter 3), with more water available in the north of the catchment (Figure 17). Projections show a decrease in water availability of about 15 % to 25 % under 3 °C global warming in the case study area. A smaller part in the south of the case study area shows an increase in water availability. However, this area is also where projections show a higher demand for water as shown by the crop water demand (CWD) and the irrigation water need (IWN) in this area.

When aggregated over the whole catchment, the time-series of these three water balance components clearly shows an overall increase in water and irrigation demand and a decrease in the water supply (Figure 18). The spread of the model simulations shows that there is strong model agreement on the increase on the demand side, which is mostly driven by the increase in temperatures with ongoing climate change. The supply side of the equation is, however, driven to a stronger degree by changes in projected precipitation. The model agreement here is lower and projected changes are smaller.

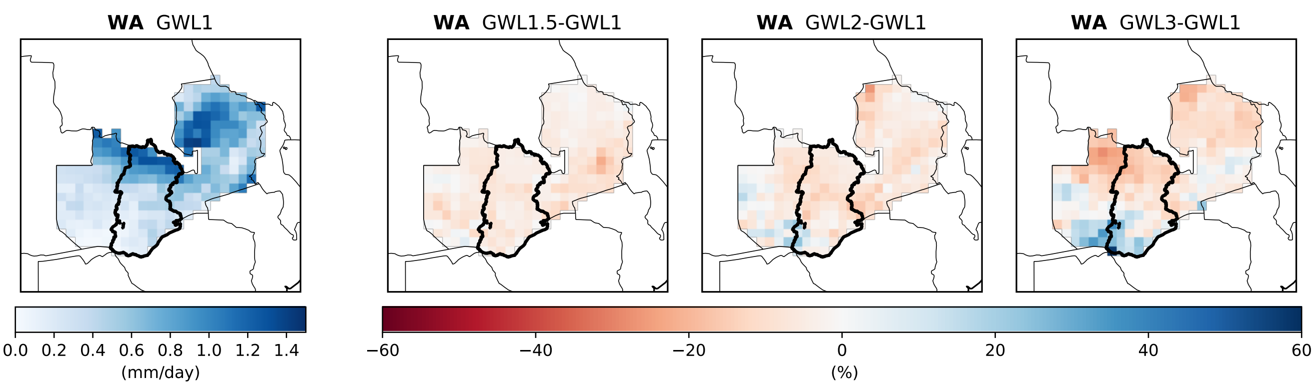

Figure 17: Average Water Availability (WA) between November and April in Zambia at a global warming level (GWL) of 1 °C (left), representing current conditions, and the change from GWL 1 °C to GWLs 1.5 °C, 2 °C and 3 °C

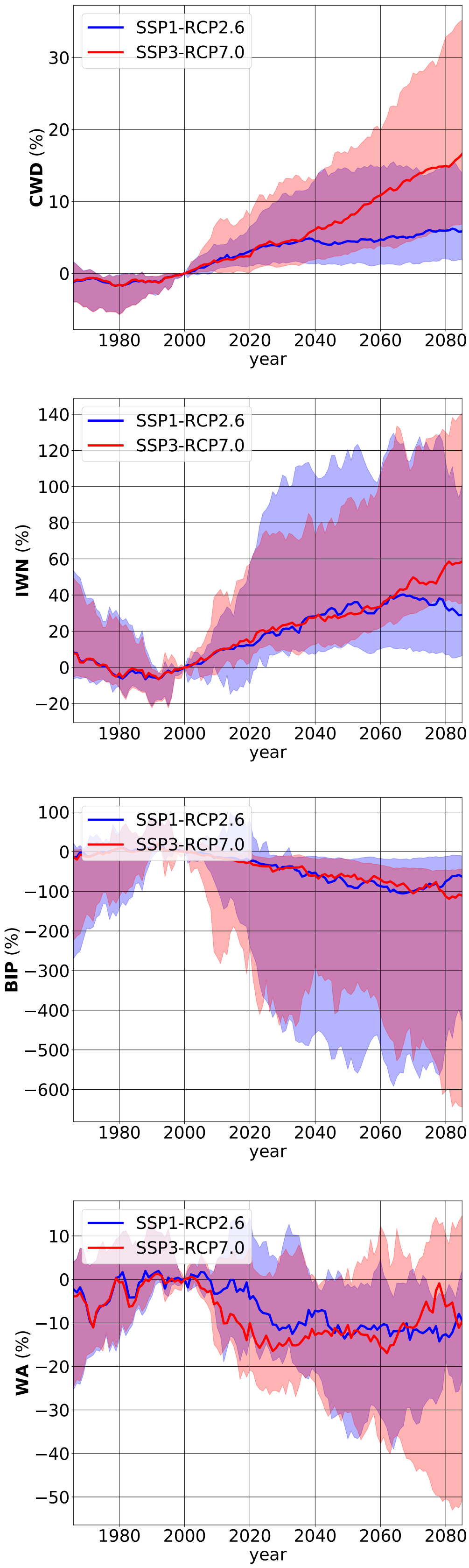

Figure 18: Changes in the basin-wide Crop Water Demand (CWD), Irrigation Water Need (IWN), Water Availability (WA) and the Basin Irrigation Potential (BIP) of the case study area between November and April in reference to the year 2000 for the low emissions scenario SSP1-RCP2.6 (blue) and the high emissions scenario SSP3-RCP7.0 (red). The shading shows the full range of the 10 model simulations per scenario (two hydrological models based on data from five global climate models)

Basin Irrigation Potential

The Basin Irrigation Potential (BIP), which is the balance of water supply and demand, shows a clear decrease in the future with high model agreement (Figure 18, third panel from the top). The simulated absolute values of BIP are already negative at current conditions under a global warming level of 1 °C (not shown), which indicates that even with a fully developed irrigation system, the current water demand could not be met. This situation will worsen in the future – a development that is mostly driven by increased water demand due to rising temperatures.

Summary and discussion of results

The water balance analysis shows an increase in water demand due to rising temperatures with ongoing climate change. At the same time, most simulations show a decrease in water availability in the case study area. As a consequence, the potential for irrigation will be further reduced in future. These findings are in line with Hamududu & Ngoma (2019) who found no change to slight gains in water resources available for northern basins, but reduction for Zambezi, Kafue and Luangwa River.

These purely bio-physical climate change impacts on water availability interplay with socio-economic developments in the case study area. Due to population growth, per capita water availability per year is projected to decrease by 75 % until the end of the century (Tomalka et al., 2022). Moreover, water allocation for domestic, industrial, agricultural and other uses will determine the availability of water for different user groups. By law, domestic water use is prioritized over agricultural water use (Government of Zambia, 2011). In case of water shortages, water for irrigation might not be provided – even if available in theory. Water shortages can lead to conflicts over water as shown for case studies in southern Zambia (Funder et al., 2010; Marcantonio et al., 2018). Moreover, there are barriers for implementation of irrigation schemes in Zambia (Hamududu et al., 2017). Around 7 % of irrigable land in Zambia is actually irrigated (Ministry of National Development Planning, 2017). Among smallholder farmers, irrigation is largely informal and applied mainly in close proximity to water sources for fruits and vegetables (Hamududu & Ngoma, 2019). Large-scale irrigation schemes might thus not be easily accessible for the majority of smallholder farmers who currently practice rainfed agriculture (MoA & MFL, 2016). Hence, water resources and land management need to take account of multiple user groups and the local context – promoting more water-efficient irrigation technologies (Hamududu & Ngoma, 2019), region-specific drought and heat tolerant crops and sustainable agricultural practices amongst others (Ngoma et al., 2021).

Box 6: Data and methods for water-balance modelling

For the water balance modelling approach, we analyse changes in crop water demand (CWD), irrigation water needs (IWN), water availability (WA) and Basin Irrigation Potential (BIP) at the level of the case study area (i.e. the Kafue Catchment; and the Zambezi Catchment in the Southern Province) considering climate change projections. The water balance is given by:

BIP = WA − IWN = WA − (CWD − ET)

CWD estimates the amount of water required for an optimal growth under well-watered conditions. It is approximated by potential evapotranspiration. IWN is the additional water amount required to reach these optimal conditions. It is approximated by the difference between potential (ET0) and actual evapotranspiration (ET). WA is the excess water from precipitation, and it is approximated by runoff. BIP is a measure of water availability in excess or deficit of IWN that has the potential to be stored and used for irrigation. It is calculated as the difference between WA and IWN. If WA is greater than IWN, it is assumed that the basin can potentially meet its irrigation needs through the development of its water resources and vice versa. The analysis does not consider changes in groundwater availability but assumes water storage to be constant in the long run. The analysis is carried out for the main rainy season from November to April, when the bulk of water supplies becomes available and could be stored for irrigation purposes. The underlying dataset for all these indicators is the output from the global hydrological models H08 (Boulange et al., 2023) and WaterGAP 2−2c (Müller Schmied et al., 2021) from the ISIMIP3b phase. The climate data feeding into the hydrological models is the ISIMIP3b climate data from 5 GCMs under two climate change scenarios, which are described in the climate section. Instead of analysing changes for certain time steps under the different climate change scenarios, we analyse changes on different global warming levels (SI chapter 2).

4. Adapting to climate change impacts

The large gaps between potential yields and actual yields in Zambia (Djurfeldt et al., 2019; Sadras et al., 2015; ZamStats, 2022) demonstrate the importance of agronomic practices and production circumstances on crop yields in Zambia and underline the potential of climate adaptation options. As projections show a decrease in sorghum yields (chapter 3.1) and crop suitability (chapter 3.2) with ongoing climate change, there is a need for sustainable intensification and adaptation measures that can increase production and buffer climate shocks while minimizing environmental degradation.

Possibilities to adapt to climate change in agriculture are manifold. They range from sustainable intensification measures, e.g. through the sustainable use of fertilizer and improved cultivars, to infrastructural and technological measures and nature-based adaptation solutions. Examples for the latter are the adjustment of planting dates, agricultural diversification to spread risks in case of harvest losses, water and soil management practices, water harvesting, agro-ecological approaches, mixed systems or agroforestry (Berrang-Ford et al., 2021; Kerr et al., 2022). Apart from these field-level adaptation options, several institutional measures can contribute to risk reduction. By providing tailored climate information such as early warnings, climate services can facilitate the implementation of adaptation options. Spreading risks through livelihood diversification or migration, increasing adaptive capacity through community-based adaptation (Ensor et al., 2018) or integrated approaches addressing climate adaptation and mitigating simultaneously (Harvey et al., 2014) are also possibilities to reduce climate-related risks in agriculture. In light of the complexity of climate impacts, a meaningful combination and integration of different adaptation options considering the local context, intersectoral and gender aspects, the diversity of involved actors and co-benefits with climate mitigation is therefore crucial for effective adaptation responses.

In this study, we analyse two adaptation options that could contribute towards reducing the risks in agriculture: **conservation agriculture** and **early warning systems**. The selection process of the two adaptation options was done jointly together with the Zambian Ministry of Agriculture and was informed by stakeholder priorities as identified during the kick-off workshop (see SI chapter 1 for more information on the selection process of adaptation options). The two adaptation options are not meant to provide silver-bullet solutions but should be interpreted as two possible adaptation options within the wider context of building climate-resilient agri-food systems.

Given the different nature of the two adaptation options (field-level adaptation measure vs. institutional adaptation measure), we used different methods for the evaluation. Whereas chapter 4.1 focuses on the risk-mitigation potential of conservation agriculture based on biophysical crop modelling, chapter 4.2 provides an economic assessment of costs and benefits of early warning systems, focusing on the Participatory Integrated Climate Services for Agriculture (PICSA) approach. Additionally, both adaptation options are evaluated in terms of gender aspects and possible financing options.

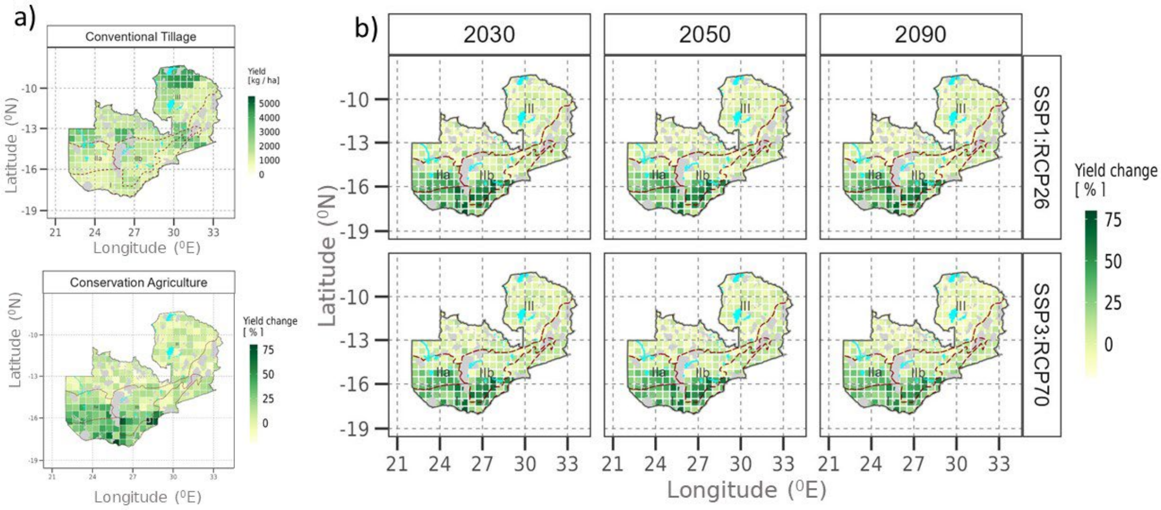

Figure 19: The grid-level spatial distribution map of a) projected sorghum yields in kg/ha under current climatic conditions with conventional tillage (top) and with conservation agriculture (bottom). b) shows changes in sorghum yield in % with conservation agriculture under the low emissions scenario SSP1-RCP2.6 (top) and the high emissions scenario SSP3-RCP7.0 (bottom) for periods of 20 years centered around 2030, 2050, and 2090

4.1 Conservation agriculture

Conservation agriculture (CA) is a promising adaptation and sustainable intensification measure, defined as the bundle of practices involving minimum soil tillage, optimum organic ground cover with crop residue or cover crops and proper crop rotations (FAO, 2019). Many potential environmental, economic and production benefits of CA have been reported widely across different systems and climatic gradients (Devkota et al., 2022; Jat et al., 2020; Mupangwa et al., 2017; Ngwira et al., 2014). In Zambia, CA is an integral part of agricultural policies aimed at facilitating soil fertility, crop productivity, household incomes, food and nutrition security improvement, mitigating adverse impacts of climate change as well as diversifying crop production (Abdulai, 2016). Field experiments have shown that CA can nearly double crop yields in long term experiments compared to conventional farming practices (Komarek et al., 2019; Mupangwa et al., 2017; Thierfelder et al., 2013; Thierfelder & Wall, 2009). Despite the overwhelming evidence on the positive effects of CA on crop yields, scaling it across regions from field experiments has been a challenge, including in Zambia (Ndah et al., 2018; Westengen et al., 2018). In Zambia, the adoption of conservation agriculture remains generally low and seems constrained by inadequate access to finance, input and output markets and capacity building. However, the adoption rate varies depending on the specific agricultural practice. Whereas, 59 % of smallholder farmers practice crop residue retention, only 7.8 % of smallholder farmers practice minimum soil disturbances. Crop rotations with legumes are used by 8.5 % of farmers (The World Bank, 2019).

In regions with heterogeneous environmental and crop management systems, the response of crop yield, yield stability and profitability to CA are variable (Pittelkow et al., 2015; Sun et al., 2020). Therefore, a spatially explicit assessment of yield responses to CA in Zambia is needed. Behind this background, we apply a gridded crop modelling approach to provide a better understanding of the performance of CA across space and time to avoid mal-adaptation and enhance more targeted agronomic recommendations and sustainable intensification investments. In addition, we also provide an assessment of potential performance of CA as an adaptation measure under projected climatic conditions in the country. Based on the process-based model DSSAT (Box 4), we simulate the effect of conservation agricultural practices on sorghum yields in Zambia focusing on minimum soil disturbances. The input data, protocol and adjustments needed to simulate CA in DSSAT across grids in Zambia are detailed in SI chapter 4.

Under current climatic conditions, adopting CA practices would result in an increase in sorghum yields of 11 % compared to conventional tillage at the national level. The greatest increases in sorghum yields would be expected in the currently dry prone areas in southern Zambia. Here an increase of 30.7 % could be achieved in the agro-ecological zones I and an increase of 26.5 % in agro-ecological zone IIa. In contrast, yields in agro-ecological zone III would not show significant changes in yields (i.e. <5 %) by mid-century (Figure 19).

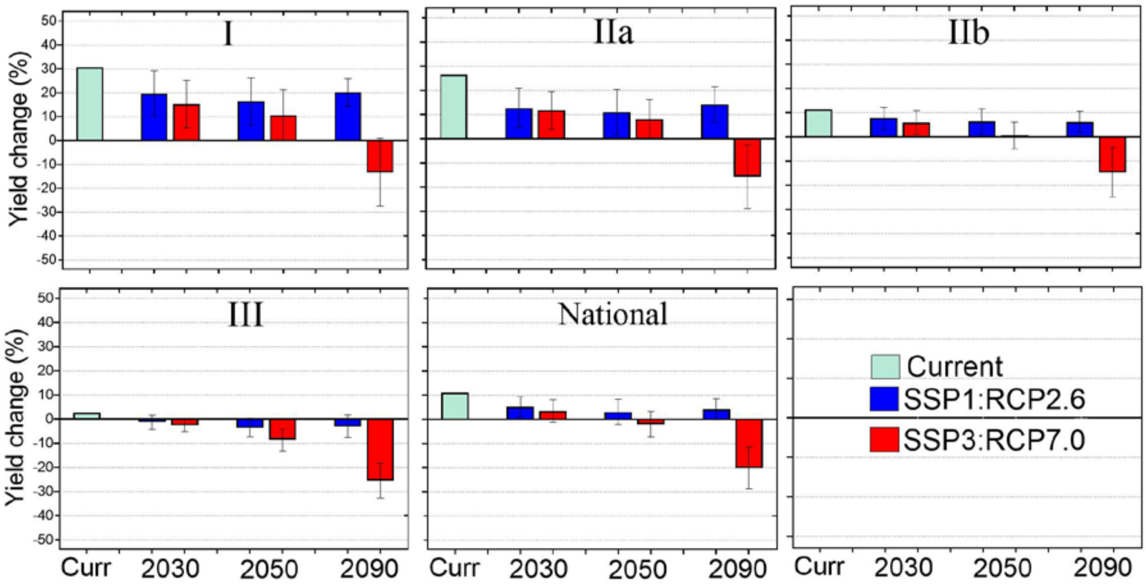

Figure 20: Climate impact buffering potential of conservation agriculture in Zambia: Current and future projected sorghum yield changes in % with conservation agriculture for the four agro-ecological zones in Zambia under the low emissions scenario SSP1-RCP2.6 (blue) and the high emissions scenario SSP3-RCP7.0 (red) for periods of 20 years centered around 2030, 2050, and 2090; the error bars show the model range of 5 Global Circulation Models used as input for the process-based crop model DSSAT

Future climate impact projections on sorghum yields with conservation agriculture show spatial and temporal differences within Zambia. The climate impact buffering potential of conservation agriculture is highest in the agro-ecological zones I, IIa and IIb. This corresponds to the yield responses under current climate, i.e. particularly the currently and future dry regions in southern Zambia would benefit from conservation agriculture.

The climate change buffering potential of conservation agriculture is highest in the near future and decreases with time, particularly under the high emissions scenario SSP3-RCP7.0 (Figure 20). In the near-future, conservation agriculture can buffer climate change impacts and even increase sorghum yields. Towards the end of the century with increasing climate change impacts, the model projections indicate that conservation agriculture might not be sufficient anymore to mitigate these impacts. Whereas conservation agriculture has high potential to improve soil quality and thus water availability, the model projections suggest that this adaptation measure is not sufficient in terms of counteracting the strong temperature increases towards the end of the century.

Financing options

Overall, conservation agriculture is practised by more than 300 000 smallholder farmers in Zambia (translates to 8.3 % of smallholder farmers; The World Bank, 2019), covering an estimated 330 000 hectares of land. The implementation of conservation agriculture practices can vary depending on different factors such as awareness, access to technical support and availability of resources. A project by FAO & UNDP (2020) estimated the total cost for 268 137 farmers practicing conservation agriculture to be US $14 511 974.59, resulting in an annualized unit cost of US $10.82. Thus, given this annualised unit cost and the 91.7 % of farmers who are not yet practicing conservation agriculture in Zambia, the estimated annualised investment potential (herein referred to as financing need) is approximately US $ 35.7 million per year to realize that all smallholder farmers in Zambia are practicing conservation agriculture (GIZ, 2023). Three financing options were identified that are particularly suitable for financing the implementation of conservation agriculture:

1. National Climate Fund or National Financing Vehicle (NFV)

A National Climate Fund or NFV is a national financial facility providing finance, from both international and domestic sources, in the form of grants, concessional loans, equity investment, etc. to initiatives that aim to strive towards mitigation and/or adaptation activities. NFVs have the advantage of (a) creating stronger alignment with national priorities, (b) reducing barriers to access climate finance for smaller organisations that do not have the capacity to access international climate finance directly, (c) the rapid deployment of climate funds into projects in sectors of strategic national importance. Zambia is currently developing a robust NFV to support the process of institutionalising a climate resilient economy. Zambia's NFV will be operated as a climate fund and could play a catalytic role for both promoting conservation agriculture as well as enhancing early warning systems. Furthermore, the facility can unlock a wide range of financing from public and private as well as domestic and international sources.

2. TerraFund

TerraFund is an innovative climate finance instrument developed under the *Global Innovation Lab for Climate Finance* to provide loans to small and medium-sized enterprises (SMEs) working in land restoration in Africa, South Asia, and Latin America. The SMEs participating in this program are eligible to apply for credit from the TerraFund at discounted interest rates to incentivize the SMEs to boost their social and environmental impact by working closely with smallholders. In Zambia, four locally led community organisations and entrepreneurs were part of the 100 project cohorts selected under the TerraFund for the AFR100 initiative – Mooto Cashew Suppliers, Schools and Colleges Permaculture (SCOPE) Zambia, Solidaridad (Zambia), and WeForest Zambia. Thus, TerraFund combines an accelerator program with credit and tailored capacity building to land restoration SMEs under four relevant clustered categories (agroforestry, agricultural inputs such as organic fertiliser, beekeeping, and timber products) that are too small for commercial banks and too large for microfinance (GIZ, 2023).

3. Sale of Carbon Credits

A carbon credit is a tradeable certificate that represents the right to emit one metric ton of carbon dioxide (CO2) or the equivalent amount of another greenhouse gas (such as methane, nitrous oxide, etc.), called a carbon dioxide equivalent (CO2-eq). Carbon markets aim to turn emission reductions and removals into tradable assets and can be a powerful tool to tackle land and ecosystem degradation. Government-imposed carbon pricing policies, whether through an emissions trading system (ETS) or a carbon tax, offer economically efficient approaches for countries to transition to a low-carbon economy. These policies create incentives for entities affected by the pricing mechanism to seek out the most cost-effective methods of reducing emissions (GIZ, 2023). However, Zambia currently lacks officially established frameworks for carbon markets. In December 2022, the Zambian government introduced interim guidelines for carbon trading. These guidelines aim to govern the entire process of managing the carbon market, encompassing approval, implementation, and regulation of carbon projects. The government is presently in the process of revising the regulations for carbon credits as part of the Climate Change Bill, which is scheduled to be enacted in 2023 (Government of Zambia, 2022). There are also private organizations, such as Community Markets for Conservation (COMACO) and BioCarbon, which are actively involved in the carbon offset market. COMACO has successfully established an international trade in carbon credits generated in Zambia. Buyers like Shell's Nature Based Solutions engage with COMACO to purchase these credits. COMACO operates by compensating local farmers and rural residents whose agricultural land and forest reserves are utilized to generate verified carbon credits (COMACO, n.d.).

However, carbon offsets are criticized for many reasons. Several studies have demonstrated that carbon offset projects frequently overestimate carbon emission reductions. This can occur either due to inflated deforestation rates in the crediting baselines compared to counterfactual estimates based on synthetic controls (West et al., 2020), or by awarding a significant number of offset credits to forest projects with carbon stocks surpassing regional averages (Badgley et al., 2022). In addition, some authors criticize climate offset projects for encroaching on the lands of indigenous and local communities whose rights are not secured. The dynamics of carbon trading, where powerful actors profit at the expense of disempowered communities in the North and South, is often referred to as neocolonialism (Bachram, 2004; Bumpus & Liverman, 2011; Sultana, 2022).

Gender aspects

Conservation agriculture (CA) interventions are not gender-neutral (Milder et al., 2011). According to research conducted in Zambia and Zimbabwe, male-headed households had higher chances of adopting CA than female-headed households, since men had better access to finances, land and other farming inputs (Kristjanson et al., 2017; Makate et al., 2017; Ng'ombe et al., 2017). A study from Zambia demonstrates that the division of labour within CA affects men and women differently. For example, crop residue retention in CA basins reduced labour requirements for women and children during pre-tillage, however, labour requirements increased for women more than for men during basin digging and hand hoe weeding. The authors attribute this difference to the fact that the performance of tedious small-scale tasks and the use of manual tools is typically assigned to women (Nyanga et al., 2012). In a similar way, field trials from Nepal showed that it was mostly women who absorbed increases in labour demand resulting from the adoption of CA, particularly where more labour for ploughing, sowing, and harvesting was required (Halbrendt et al., 2014). While CA practices can help to increase productivity and income, too often, women do not reap these benefits.

Summary and discussion of results

The modelling results show that under current climatic conditions, adopting conservation agricultural practices would result in an increase in sorghum yields of 11% compared to conventional tillage at the national level. In the near-future, conservation agriculture can buffer climate change impacts and even increase sorghum yields. The greatest increases in sorghum yields would be expected in the dry prone areas in southern Zambia. These findings are in line with a study from The World Bank (2019). Thus, conservation agriculture can play a vital role in adapting to increasingly extreme and dry climatic conditions in Zambia. Behind the background of a projected reduction in the irrigation potential with climate change in parts of the country (chapter 3.3), this adaptation option can contribute to increasing plant available water without depleting surface or groundwater resources. Towards the end of the century with increasing climate change impacts, the model projections indicate that conservation agriculture might not be sufficient anymore to mitigate these impacts. Whereas conservation agriculture has high potential to improve soil quality and thus water availability, the model projections suggest that this adaptation measure is not sufficient in terms of counteracting the strong temperature increases towards the end of the century. Moreover, evidence suggests that the projected productivity increases due to conservation agriculture are not sufficient to avoid further expansion of arable land into forest land in Zambia, which underlines the need for complementary sustainable intensification measures and land management (The World Bank, 2019).

Many environmental, economic and production benefits of conservation agriculture have been reported making the adoption of conservation agricultural beneficial across different systems and climatic gradients (Devkota et al., 2022; Jat et al., 2020; Mupangwa et al., 2017; Ngwira et al., 2014). Apart from improved crop productivity and its positive impact on household incomes and thus food and nutrition security, conservation agriculture has a positive impact on biodiversity through diversifying crop production and enhancing natural biological processes above and below the ground surface. At the same time, conservation agriculture can contribute to climate change mitigation as reduced tillage and residue retention can potentially increase carbon sequestration (Richards et al., 2014). Therefore, adopting conservation agriculture also in areas with low projected yield increases can be recommended to foster sustainable agricultural intensification in Zambia.

However, benefits of conservation agriculture only manifest after some years as improving the soil structure and fertility are slow processes. Moreover, there are challenges in the implementation of conservation agriculture related to appropriate soil types, sufficiently available crop residues, weed control or the need for fertilizers. There are barriers to its implementation and the adoption of conservation agriculture in Zambia seems to be constrained by inadequate access to finance, input and output markets and capacity building (The World Bank, 2019). Guidance and experiences with conservation agriculture (Richards et al., 2014), leveraging existing financing options as well as a careful gender-sensitive design of conservation agriculture are therefore needed for a successful implementation.

4.2 Early warning systems

Early warning systems have a high potential for anticipating climate risks, such as droughts, and can therefore contribute to improving food security (Braimoh et al., 2018). An early warning system provides timely and effective information to avoid or reduce risks related to a hazard or to prepare for an effective response. It consists of several elements spanning from knowledge of hazards and vulnerabilities, a monitoring and warning service, dissemination and communication and response capabilities (Braimoh et al., 2018). The aim of an early warning system is thus not only to facilitate responses to impending hazards but also to facilitate both short-term and long-term risk reduction behaviour before a disaster arrives (Šakić Trogrlić et al., 2022). Evidence suggests that access to early warning systems and seasonal forecasts is critical to adopt better agricultural practices (Djido et al., 2021). Early warning systems are thus a key priority in national adaptation policies, such as in the NAPs or NDCs (Cullmann et al., 2020) or the Zambian 8th National Development plan (MoFNP, 2022). Nevertheless, Zambia has not reported to have a multi-hazard early warning system (Cullmann et al., 2020) yet, but national meteorological and hydrological services are in place.

There is a particular need to strengthen capacities to translate early warnings into early action (Cullmann et al., 2020). Therefore, we specifically focus on a participatory approach for climate and agricultural extension services that integrates climate information and weather forecasts to inform livelihood decisions of farmers. The Participatory Integrated Climate Services for Agriculture (PICSA, Box 7) combines historical climate data and forecasts with farmers' knowledge of what works in their own context, and then uses participatory planning methods to help farmers make informed decisions about their agricultural practices (Clarkson et al., 2022).

To evaluate the economic viability of introducing the PICSA approach in Zambia, we perform a cost-benefit analysis (CBA) at the farm level. A cost-benefit analysis allows evaluating the economic costs and benefits of adaptation options to climate change. Therefore, the expected costs and benefits of implementing a specific adaptation option are compared to the costs and benefits of a business-as-usual production system (Box 8 provides more information on the methodology). In this way, the analysis helps to identify adaptation options with high net economic benefits compared to a business-as-usual scenario. Based on a cost-benefit analysis, we evaluate the economic viability of introducing the PICSA approach for an average farmer in Zambia at the farm level. To assess the effect of PICSA, we compare two scenarios:

- **Baseline scenario:** In the baseline scenario, a small-scale farmer continues her/his farming activities without the adoption of PICSA.
- **Adaptation scenario:** In the adaptation scenario, it is assumed that PICSA training is implemented in Zambia and a small-scale farmer adopts suitable adaptation options for her/his production system. This scenario does not distinguish between different adaptation options, but assumes that the farmer choses the best suitable adaptation option for her/his production system.

Box 7: Participatory Integrated Climate Services for Agriculture (PICSA) approach

The Participatory Integrated Climate Services for Agriculture (PICSA) approach supports farmers to make informed decisions based on accurate, location-specific, climate and weather information. By participating in the PICSA program, farmers identify and explore locally relevant crop, livestock, and livelihood options as well as their risks with the support of PICSA trained field staff (Dorward et al., 2015).

The decision-making and planning process is supported by participatory tools and a joint analysis of relevant information. At the same time, PICSA strengthens the individual choices of farmers regarding how they may adapt their business to variable and changing climate conditions by using an 'options-by-context' approach. Here, farmers consider different options for adaptation using participatory decision-making tools so that they make their decision based on their very diverse contexts. Individual contexts of farmers are marked by features of their household size, available financial means, education, availability and access to land, soil types and soil fertility, livestock holdings and many more variables. Thus, farmers are implementing very different and diverse adaptation measures – depending on their individual economic and agro-ecological contexts (Dorward et al., 2015).

PICSA has already been applied successfully in at least 20 different countries, thereby training hundreds of thousands of farmers (Clarkson et al., 2022). Amongst the countries of implementation are also a number of sub-Saharan African countries, including Malawi (Independent Evaluation Unit, 2022b), Rwanda (Nsengiyumva et al., 2022), and Ghana (Clarkson et al., 2019). Evidence generated by evaluations focusing on Least Developed Countries found that PICSA had a statistically significant and positive impact in building adaptation capacity of farming households that face the risks of climate change and climate variability. Project beneficiaries were more likely to actively take seasonal forecasts into consideration when making farm decisions and were almost twice as likely to make crop diversification decisions and changes in crop activity (Independent Evaluation Unit, 2022a).

For these two scenarios, the market revenues and costs of the production system are extrapolated until 2050 under changing climate conditions considering the low emissions scenario (SSP1-RCP2.6) and the high emissions scenario (SSP3-RCP7.0). The costs applied in this scenario are based on a current piloting project which is run in two districts (Chipata and Petauke) in Zambia by GIZ and, as the supporting institution, the University of Reading. For the purpose of this CBA, in a first step, these costs were extrapolated based on a potential national-level roll-out to all extension workers in Zambia. In a second step, the costs were downscaled to the individual farmer, as presented in the following CBA.

A number of assumptions were made, which are detailed in SI chapter 5. They include:

- Climate change impacts on agricultural productivity were approximated by projections of sorghum yields under changing climatic conditions (chapter 3.1).
- Since PICSA has not yet been fully evaluated for Zambia, limited data is available. Therefore, data from other sub-Saharan African countries, particularly from Northern Ghana were applied as proxy for our calculations when necessary.
- We assume that the PICSA implementation builds upon existing structures in the Zambian agricultural sector, such as existing extension services.

Box 8: Methodology of the cost-benefit analysis

In the cost-benefit analysis (CBA) all expected costs and benefits are monetized that are associated with implementing a specific adaptation option over a certain period of time. The costs of implementing an agricultural extension approach, such as PICSA, includes costs for the training of experts and extension workers (fuel, accommodations, technology) as well as the opportunity costs for the extension workers and farmers participating in and leading workshops. The benefits derived from implementing PICSA are mainly concerning an increase in agricultural productivity due to the climate adaptation measures farmers have individually chosen and implemented for their farm. For a CBA, the costs and benefits of adaptation options that are linked to different time periods are discounted at an appropriate discount rate to take into consideration the timely value of money (Boardman et al., 2011). This is necessary, as we typically value current benefits (and costs) more than benefits in the (distant) future, which is integrated into the calculation by using a discount rate.

The results of the cost-benefit analysis suggest that employing PICSA in Zambia is highly beneficial in comparison to not employing it. Over time, it has a very positive net cash flow expressed per farmer participating in a PICSA training (Figure 21). Three economic indicators are commonly used as indicators for prioritisation in a CBA, leading to the following results for our specific case (Table 1):

- The Net Present Value (NPV) represents the discounted net benefit per farmer. The NPV is positive under both climate change scenarios and ranges between ca. 18 400 ZMW and 19 790 ZMW, depending on the climate change scenario. Hence, the present value of the cash flow is larger than the initial investment amount, making this investment worthwhile.
- The Internal Rate of Return (IRR) provides the discount rate at which the NPV is equal to 0. If the IRR is greater than the discount rate, the adaptation strategy is considered to be economically profitable (Boardman et al., 2011). Adapting to climate change in response to having participated in PICSA results in an IRR of 115 % under SSP1-RCP2.6 and 114 % under SSP3-RCP7.0. Under a global rentability perspective, any IRR higher than six percent can be considered a profitable investment. Hence, the high IRRs for the PICSA implementation are indicators for a project exceeding its target rate of return.
- The Benefit-Cost Ratio (BCR) represents the ratio between the discounted benefits and costs of an adaptation option. An adaptation option with a BCR value greater than 1 is considered to be economically profitable. The BCR for adopting PICSA is 3.83 under SSP1-RCP2.6 and 3.64 under SSP3-RCP7.0, which means that each USD invested in PICSA generates between 3.64 and 3.83 USD in benefits depending upon the climate scenario considered.

All three considered indicators of the CBA show that the investment in PICSA is highly economically beneficial.

	Adaptation under SSP1-RCP2.6	Adaptation under SSP3-RCP7.0
IRR	115 %	114 %
NPV	19 786 ZMW	18 402 ZMW
BCR	3.83	3.64

Table 1: Summary of major CBA indicators for switching from not employing PICSA to employing PICSA; the Net Present Value (NPV) represents the discounted net benefit; the Internal Rate of Return (IRR) provides the discount rate at which the NPV is equal to 0 and the Benefit-Cost Ratio (BCR) represents the ratio between the discounted benefits and costs of an adaptation option

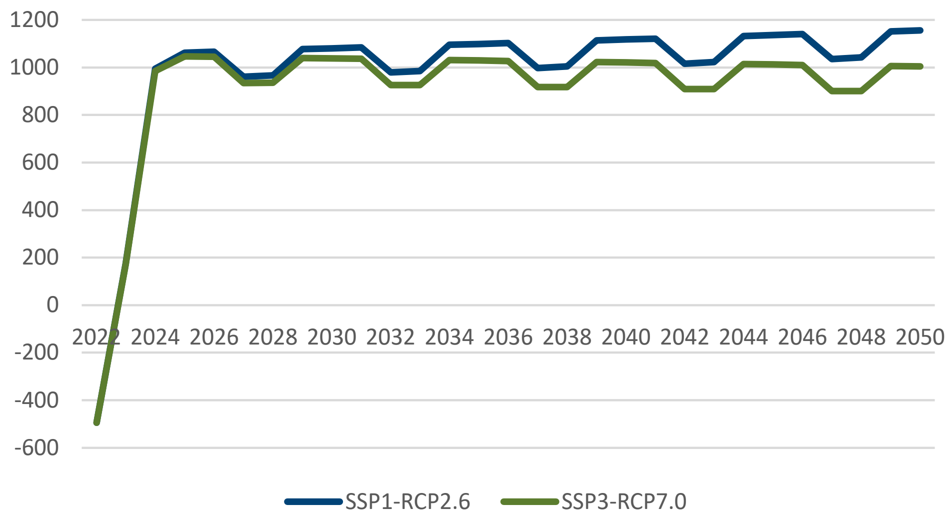

Figure 21: Net cash flow of the PICSA implementation for smallholder farmers in Zambia in Kwacha per farm beginning in the year 2022 until the year 2050 under the low emissions scenario SSP1-RCP2.6 and the high emissions scenario SSP3-RCP7.0

The net cash flow of the PICSA implementation for smallholder farmers in Zambia increases sharply with time and is already positive after merely one year (Figure 21). In the first year, there are implementation costs related to trainings of regional and national experts and extension workers, for logistics and for the planning of the workshops. Moreover, in the following years (year 2 and 5) there are costs due to refresher trainings of farmers and extension workers, which are detailed in SI chapter 5. Monetary benefits to farmers include an increase in income due to improved productivity after implementing climate adaptation measures through PICSA. This leads to an improvement of resilience of farmers toward changing climate conditions and thus constitutes an important variable in the safeguarding of their long-term livelihood. Additional to the net benefits from implementing PICSA in the first two years, the net benefit increases over time as the adaptation options buffer for negative climate change impacts in future, resulting in a relative increase in productivity over time. The net cash flow is higher under the low emissions scenario (SSP1-RCP2.6) that leads to lower yield reductions than the high emissions scenario (SSP3-RCP7.0).

> The initial investment needed to employ PICSA already becomes economically beneficial after one year with increasing returns in the future under both climate change scenarios. Each USD invested in PICSA generates between 3.64 and 3.83 USD in benefits depending upon the climate scenario considered.

Financing options

There are two suggested financing options suitable for financing early warning systems. First, the National Climate Fund or National Financing Vehicle (NFV), which is described in Chapter 4.1, and second, the Climate Risk and Early Warning Systems Initiative (CREWS), which is described below.

- Climate Risk and Early Warning Systems Initiative (CREWS)

CREWS is a pooled financing mechanism that aims to "significantly increase access to early warnings and risk information in Least Developed Countries (LDCs) and Small Island Developing States (SIDS)". CREWS is designed to have impactful action at three levels: at the country level through improvement of access to effective impact-based early warning systems; at the regional level through building regional institutions' capacities; and at the global level through increased coherence of investments in EWS (CREWS, 2021). In the context of Zambia, CREWS has not yet been initiated, however, the Government of the Republic of Zambia could receive support if the existing project proposal aiming at supporting the Southern African Development Community (SADC) in strengthening their EWS is approved in January 2024, as well as through utilizing CREWS accelerated support window (GIZ, 2023).

Gender aspects

Several studies emphasize the importance of gendered access to climate information services like weather forecasts and early warning systems (Alvi et al., 2021; Diouf et al., 2019; Partey et al., 2020). Ngigi and Muange (2022) for example show that women and men tend to use different dissemination pathways to receive information on weather forecasts or early warnings. Gumucio et al. (2018) highlight gender differences with regards to childcare and household responsibilities and their implications on the attentiveness and ability to listen to radio programs that broadcast early warnings.

While climate information and services are crucial to smallholder farmers, it is essential to carefully assess and understand the power imbalances that may affect individual and group ability to access, use and benefit from them (Nsengiyumva et al., 2022). The PICSA approach allows for the combination of farmers' traditional ecological knowledge with scientific information, and can also identify gendered differences in rural households (Mosso et al., 2022). Although men tend to dominate intra-household decision-making, there is evidence that approaches like PICSA have contributed to improving women's role in agricultural production and their position in households, partly due to their enhanced climate knowledge, and higher production and income levels (Gumucio et al., 2020). In Clarkson et al.'s (2017) monitoring and evaluation of PICSA trainings in Rwanda, many women and men reported greater confidence in building agricultural and non-agricultural enterprises and in discussing livelihood strategies with fellow farmers, with no significant gender differences. Another study on the results of PICSA also finds that disaggregating data according to gender alone finds very few significant differences, but as well emphasizes that considering additional socioeconomic variables such as headship and wealth and how they intersect with gender are important to assess (Nsengiyumva et al., 2022). Gumucio et al. (2020) also state that participation in climate services interventions improves women's management decisions, narrowing the gender equity gap. However, the authors emphasize the need to consider gendered communication preferences, with women using fewer communication channels than men.

Summary and discussion of results

The results of the Cost-Benefit Analysis suggest that PICSA is a highly cost-effective adaptation measure for farmers in the Zambian context. This confirms existing findings from the Independent Evaluation Unit of the Green Climate Fund, which also attests extraordinary benefits due to PICSA received by farmers (Independent Evaluation Unit, 2022a). As outlined in chapter 5 of SI, the analysis relies on several assumptions since PICSA has not yet been fully evaluated for Zambia and thus limited data is available. While the concrete economic impact might differ between agro-ecological zones as well as between individual farmers participating in the PICSA training, a general positive impact from coupling location-specific climate and weather information with locally adopted knowledge from farmers can be confirmed by this analysis. Also, this analysis underlines the relevance of strengthening farmers in developing their individual livelihood strategies targeted to their specific and contextual needs. Moreover, PICSA does not only inform farmers about climate conditions and expected changes but provides tools and guidance on how to apply this information for concrete adaptation actions on their farms to empower them through participatory tools for informed decision-making. The PICSA approach allows for the combination of farmers' traditional ecological knowledge with scientific information, and can also identify gendered differences in rural households (Mosso et al., 2022). There is evidence that approaches like PICSA have contributed to improving women's role in agricultural production and their position in households, partly due to their enhanced climate knowledge, and higher production and income levels (Gumucio et al., 2020).

5. Climate and Disaster Risk Financing

Although the adaptation measures identified above are highly beneficial and cost-effective, their implementation is unlikely to be sufficient to fully address the losses that Zambian farmers do (and will) face as a result of climate change. This is illustrated by the magnitude of the potential impacts associated with droughts and other climate-related disasters that have been estimated in previous studies. For example, a previous UNDRR study on Zambia (CIMA & UNDRR, 2019) found that, even under current climate conditions, an average of about 3.3 million people are expected to be directly affected by droughts and floods each year, and that this could rise to 7.0 million people per year by 2051–2100 (taking into account both socio-economic change and climate change under the RCP8.5 scenario). Similarly, the average annual economic losses from drought and flood impacts on the entire economy currently amounts to around $100 million and could rise to around $281 million in 2051–2100. Focusing on the agricultural sector, the average annual economic losses from drought and floods on crop production are currently estimated at around $31 million per year and could rise to $182 m in the second half of the century, with still further losses associated with livestock production. Looking specifically at maize and sweet potato, the UNDRR study also found that, even with full implementation of the adaptation measures it considered (relating to changing crop varieties), around 25 % of the expected annual losses in the 2051–2100 period would remain (CIMA & UNDRR, 2019). In practice, full implementation may be challenging, which would leave large expected losses in both the short and longer term.

Previous studies have shown that countries that recognise and plan for disasters such as droughts and floods, are able to respond to these crises much more quickly and effectively than countries that do not have such plans in place (Clarke & Dercon, 2016). In turn, a critical part of this planning is ensuring that countries have, at least in part, pre-arranged the financing they need to implement these plans. This pre-arranged financing (or disaster risk finance) can help cover both the costs associated with the immediate response to a disaster and/or the recovery of losses that may be incurred because of the disaster. The alternative to pre-arranged finance is to rely on 'ex-post' measures such as borrowing, which is very challenging in Zambia given the fiscal context, and/or humanitarian assistance, which is often inadequate and slow in responding to the needs of the affected. The term 'protection gap' is used to describe the difference between the costs and/or losses associated with the disaster and the amount of pre-arranged financing a country has organised.

There are a variety of mechanisms that countries can use to close the protection gap. A basic distinction exists between:

- Risk retention mechanisms – where the country remains responsible for meeting the necessary costs (i.e., the risk is retained) but has developed pre-arranged financial instruments, such as reserve funds, budget lines or contingent credit, to ensure that it can access funding quickly.
- Risk transfer mechanism – where the responsibility for providing financial resources in the event of a disaster is transferred to a third party, in exchange for a premium. In this way, risk transfer instruments redistribute the infrequent and potentially unmanageable total losses of a disaster event into an equivalent manageable annual cost (premium). Risk transfer instruments include a range of different insurance products as well as alternative risk transfer instruments such as catastrophe or disaster relief bonds.

Similar concepts can also be applied when considering how households and businesses respond to the impacts of disasters. While they could rely on borrowing after the event, they may also put aside contingency and reserves (risk retention) or access insurance (risk transfer).

In general, most analyses show that risk retention instruments are more cost effective for covering the costs associated with relatively low impact disaster events that happen more frequently (Clarke et al., 2017). By contrast, risk transfer instruments are generally considered to be more effective in providing finance for less frequent but more severe disasters. This is known as risk-layering.

Zambia has already taken some important steps to plan for and finance the impact of disasters. In the area of risk transfer, Zambia first obtained an insurance policy with the sovereign risk pool *Africa Risk Capacity (ARC)* for the 2020/2021 agricultural season to cover the impact of drought on maize production in parts of the country. The policy was subsequently renewed for the 2021/2022 and 2022/2023 agricultural seasons. The development partners provide assistance to cover part of the premium payment to ARC. It is worth mentioning that an integral part of this policy is the need to develop a contingency plan to determine how the pay-outs will be used: in the case of Zambia, the contingency plan includes both the scaling up of the existing social cash transfer scheme and the provision of food aid, emergency cash transfers and market-based interventions. Due to a major drought, this policy provided a pay-out of $5.4 m in 2022 for the 2021/2022 agriculture season. In addition, insurance solutions provide support to individual farmers and their households for drought and flood risk. The bulk of these policies are microinsurance policies. Most of this microinsurance is facilitated by the government, as part of its Farmer Input Supply Programme (FISP) insuring around 1 million smallholder farmers each year, but some microinsurance products in the form of crop insurance are accessible through smaller intermediaries with almost 9,000 farmers reached through aggregators like Micro Finance Institutions (MFIs) and agri-businesses in the 2022/2023 agricultural season. In addition, insurance is provided to commercial farmers – market estimates suggest this is taken out by around 600 farmers. There is also a fully subsidized index-based livestock insurance scheme that reached 5,000 farmers in the 2022/2023 agricultural season (GIZ, 2023b).

In the area of risk retention, Zambia's annual budget makes various provisions to support disaster response, including the "Disaster and Humanitarian Operations Management" programme by the Disaster Management and Mitigation (DMMU), to which around $1 million per year has been allocated, and the 'National Food Reserves Management' which is allocated to the Food Reserve Agency under the Ministry of Agriculture and receives on average around US$ 64 million per annum. Moreover, the government has a general contingency fund to cover a wide range of unforeseen and unavoidable costs.

In 2022, around 115 million Kwacha (around $6.8 million) from the Contingency Fund have been allocated to DMMU. Additionally, the National Disaster Relief Trust Fund (NDRT Fund) has the potential to be an important risk retention instrument in Zambia, however, currently it is not yet operational.

Despite all these instruments in place, there is still a substantial protection gap (GIZ, 2023a). Using the estimations of average annual losses as well as average annual amount of pre-arranged finance summarized in SI chapter 6, this analysis finds that the current protection gap for drought and flood risks amounts to 43 % in the agricultural sector and 82 % in the entire economy of the Government of the Republic of Zambia (GIZ, 2023a). When considering the recent changes in the FISP insurance cover for season 2022/2023, the protection gap would decrease to around 36 % and 80 % for the agricultural sector and the entire economy, respectively. A potential future NDRT Fund capitalisation of 50 % of the 2022 DMMU budget would also decrease the protection gap by roughly the same percentage points (GIZ, 2023a).

Understanding the size and characteristics of the protection gap is a critical component in the development of a climate and disaster risk financing (CDRF) strategy (GIZ, 2023a; Summit on a New Global Financing Pact, 2023). The aim of such a strategy would be to close the protection gap by determining the optimal mix of pre-arranged financing mechanisms that enable swift and effective responses to disasters. Building on the protection gap analysis (GIZ, 2023a), probabilistic modelling and analysis of costs associated with different pre-arranged finance instruments would need to be conducted to inform the risk layering within the planned CDRF strategy. On this basis, the priority instruments that Zambia intends to utilize to cover remaining gaps could be identified, as well as any recalibration of existing instruments that may be required could take place. Ideally, the CDRF strategy would consider both instruments and policy options relating to disaster-related liabilities of the government as well as those of households and businesses. It would also identify the relevant role of development and humanitarian actors, who in many cases are likely to continue to play a critical role in financing disaster recovery and response. In most other countries that have developed a similar strategy, the institutional initiative for developing and implementing such a strategy has come from the Ministry of Finance, but with key input in developing the strategy coming from those responsible for disaster risk management (in Zambia, the Disaster Management and Mitigation Unit (DMMU) within the Office of the Vice President) as well as subnational governments affected by disaster risks, the private sector (especially the insurance sector) and civil society. Strategies are often developed with the support of development partners.

Table 2 in the recommendation section summarises the key insights from the protection gap analysis (GIZ, 2023a) for Zambia's future CDRF strategy to close Zambia's protection gap.

6. Conclusion and policy recommendations

This study provides a comprehensive climate risk analysis for Zambia's agricultural sector and evaluates suitable adaptation options to promote climate-resilient agricultural intensification. Driven by ten Global Climate Models under two climate change scenarios, SSP1-RCP2.6 and SSP3-RCP7.0, we used climate impact models to analyse future trends in climatic conditions. Based on stakeholder priorities, we further analysed climate impacts on sorghum yields, crop suitability for sorghum, maize and groundnuts; and water availability in the Zambian Kafue Catchment and parts of the Zambezi Catchment. Together with stakeholders, we selected two adaptation options to assess the overall suitability to reduce climate impacts in the agricultural sector in Zambia: conservation agriculture and early warning systems. For this purpose, we considered aspects of risk mitigation potential, cost-effectiveness, financing and gender. The results have been complemented and cross-checked by expert- and literature-based assessments and two stakeholder workshops. Moreover, the study presents suitable financing options for the adaptation options and proposes a roadmap for managing residual risk through a climate and disaster risk financing strategy.

The study aims to offer in-depth evidence-based information for national and local decision-makers on current and future climate risks and to deliver tailored policy advice and promote the uptake of the study results. Therefore, the study was designed and conducted in close collaboration with stakeholders in key sectors such as agriculture, water and finance.

6.1 Conclusion

Changes in climatic conditions

Climate models project a robust trend towards increasing **temperatures** all over Zambia with the south-western regions showing the strongest increase. Projections of **mean precipitation** indicate high spatial variations within the country. The southern and central parts of the country, which are already today drought prone, are projected to experience a decrease in precipitation with ongoing climate change. Projections of **extreme drought**, however, indicate an increase all over the country. Overall, climatic trends in extreme indicators show a shift towards more intense climate conditions both in terms of dry as well as wet conditions.

Climate impacts on agriculture

These changes in climatic conditions have wide-ranging consequences for the agricultural sector in Zambia. In the case of **sorghum**, which has been a focus of this study, climate impact projections for sorghum yields show mostly negative impacts with stronger yield losses under the high emissions scenario than under the low emissions scenario. Mean sorghum yield losses for the whole country are between 5.8 % to 12.2 % by mid-century with spatial and temporal disparities. Most losses are projected in the south of Zambia, which has currently the highest production intensity areas for sorghum. Compared to the projected decreases in maize yield, which are expected to be between 21 % to 35 %, decreases in sorghum yield are considerably smaller. This confirms that sorghum is indeed a comparably more climate resilient crop.

Furthermore, climate change also affects the extent and distribution of suitable areas for crop production in Zambia. On the national level, the crop suitability analysis of small-scale production systems shows a net reduction in suitable areas for maize and sorghum production and no significant change in groundnut suitability with climate change on the national level. Moreover, there is a northward shift in crop suitability in Zambia. Already today, northern parts of Zambia are more suitable for sorghum, maize and groundnut production than the southern parts of Zambia and climate change is going to intensify this pattern. This partly contradicts with currently high production areas for sorghum and maize, which can be found in central and southern Zambia. The projection results solely focus on climatic impacts on crop suitability and show the projected changes in crop suitability if left unaddressed, meaning if no adjustments were made in agricultural management practices or agricultural policies.

Climate impacts on water availability

In addition, we provide a case study on climate change impacts on **water availability** in the Kafue Catchment and parts of the Zambezi, given the high importance of water availability – not only for agricultural production, but also for biodiversity and energy security in Zambia. The water balance analysis shows an increase in water demand due to rising temperatures with ongoing climate change. At the same time, most simulations show a decrease in water availability – leading to an overall reduction in the climate-related irrigation potential in future. In addition to climate change impacts, there are socio-economic developments related to population growth, water allocation or potential conflicts over water which strongly influence water availability in Zambia.

Climate adaptation options

The analysed climate change impacts on agriculture and water availability in Zambia underline the need for strong adaptation efforts to support the transformation towards a climate-resilient agricultural system in Zambia. These adaptation efforts may include sustainable intensification measures, infrastructural, technological and institutional measures, nature-based solutions and integrated approaches. As part of this study, we evaluate two potential adaptation options: conservation agriculture and early warning systems. These two adaptation options were selected based on stakeholder priorities and could contribute to a comprehensive portfolio of adaptation options.

Conservation agriculture is a farming system that promotes minimum soil disturbance, maintenance of a permanent soil cover and diversification of plant species. Adopting conservation agricultural practices in Zambia would result in an increase in sorghum yields of 11 % compared to conventional tillage at the national level under current climatic conditions. In the near-future, conservation agriculture can buffer climate change impacts and even increase sorghum yields, particularly in the dry-prone areas in southern Zambia. Thus, conservation agriculture can play a vital role in adapting to increasingly extreme and dry climatic conditions in Zambia. However, towards the end of the century and with increasing climate change impacts, the model projections indicate that conservation agriculture might not be sufficient anymore to compensate for climate impacts, particularly due to projected strong temperature increases. The findings suggest that conservation agriculture is a highly beneficial adaptation option with positive production, environmental and economic benefits that needs to be combined with other adaptation options to compensate against negative climate impacts. Suitable financing options for conservation agriculture include the National Climate Fund / National Financing Vehicle that is currently being established in Zambia, the TerraFund, as well as the sale of carbon credits.

Early warning systems have a high potential for anticipating climate risks, such as droughts, and can therefore contribute to improving food security. They facilitate responses to impending hazards and contribute to both short-term and long-term risk reduction behaviour. There is a particular need to strengthen capacities to translate early warnings into early action. In our analysis, we therefore focus on a participatory approach for climate and agricultural extension services that integrates climate information and weather forecasts to inform livelihood decisions of farmers – called PICSA (Participatory Integrated Climate Services for Agriculture). The results of the cost-benefit analysis show that employing PICSA in Zambia is highly beneficial. The initial investment needed to employ PICSA already becomes economically beneficial after one year with returns increasing in the future under both emissions scenarios. Each USD invested in PICSA generates between ca. 3.60 and 3.80 USD in benefits depending upon the climate scenario considered. Farmers, who participated in a PICSA training, can improve their productivity and income, which increases their resilience towards changing climate conditions and thus constitutes an important variable in the safeguarding of their long-term livelihood. Beyond this, there is evidence that approaches like PICSA have contributed to improving women's role in agricultural production and their position in households, partly due to their enhanced climate knowledge, and higher production and income levels. Suitable financing options for enhancing early warning systems include the National Climate Fund / National Financing Vehicle that is currently being established in Zambia as well as the Climate Risk and Early Warning Systems Initiative (CREWS).

6.2 Policy recommendation

Based on the presented findings of this climate risk analysis and in close consultation with various stakeholders and experts, policy implications and recommendations can be suggested. The policy implications of the results may differ depending on specific policy objectives and priorities. This study considers aspects regarding the climate risk mitigation potential and economic, financial and gender aspects. Adaptation design requires a careful balancing of these aspects and other policy objectives involving relevant stakeholders and political actors.

Crop diversification and locally adapted crops to take account of region-specific climate impacts

The current and projected climatic conditions influence the extent and distribution of suitable areas for crop production, which show strong regional differences within Zambia. Against this background, locally-adapted crops should be promoted that can better cope with the specific climatic conditions in the different agro-ecological zones within Zambia. Drought and heat-tolerant crop varieties can play a vital role in stabilizing and increasing agricultural production, particularly in drought-prone areas. Sorghum can grow also under unfavourable climatic conditions. It plays an important role for small-holder farming systems by enabling and sustaining agricultural production on marginal land that is not or will no longer be suitable for more demanding crops with ongoing climate change. Moreover, **crop diversification** can help to spread production and economic risks over a broader range of crops and can guard farmers against climatic and market shocks. Crop diversification contributes to enhancing food and nutrition security by providing more varied and healthier food, it can improve the economic potential of rural communities and can have agronomic benefits, such as improved pest management. Currently, maize input and output subsidies absorb a high share of agricultural budget in Zambia through the Farmer Input Support Program (FISP). Our study confirms that maize is projected to have stronger yield losses due to climate change than other crops. Promoting crop diversification and regionally adapted crops within the currently developed Comprehensive Agricultural Transformational Support Programme (CASTP) and the currently implemented Farm Block Development Programme would therefore contribute to better prepare for climatic risks in the agricultural sector in Zambia. Participatory, context-specific policies and investment planning is needed to promote locally-adapted agricultural production.

Region-specific and holistic adaptation planning

Planning for adaptation should be regionally specific, as different areas in Zambia will be impacted by climate change differently. **Conservation agriculture**, for instance, is particularly beneficial in drought-prone areas in Zambia. However, conservation agriculture has proven to have positive environmental and economic benefits, making the adoption of conservation agriculture also useful in other parts of the country. Several criteria related to environmental, economic, social and climate mitigation effects should therefore be considered and balanced when prioritizing adaptation options and informing investment decisions on the local scale. Developing adaptation strategies therefore must be conducted in cooperation with multiple stakeholders in a multi-level governance approach. **Differing social characteristics** such as gender, age, education and health can substantially shape farmers' vulnerability and therefore their exposure to climate impacts. Taking these characteristics into consideration is an important prerequisite for the implementation of adaptation options, to avoid mal-adaptive outcome and fully leverage the great potential climate change adaptation at farm-level can hold to build resilience across farming communities. In a holistic system approach, single adaptation options need to be combined and integrated to **foster synergies between adaptation options** and consider intersectoral aspects. Sustainable agricultural intensification measures, integrated land use planning, and sustainable management of natural resources are needed to adapt to climate change, increase productivity and food and nutrition security while halting the expansion of arable land into forest land and biodiversity-rich areas in Zambia.

Coupling location-specific climate information with local knowledge for actionable early warning systems

The Participatory Integrated Climate Services for Agriculture (PICSA) approach supports farmers in coupling location-specific climate information with both local knowledge and new innovations, and strengthens them in developing their individual livelihood strategies, targeted to their specific and contextual needs. PICSA contributes towards increasing productivity and income of farmers and constitutes an important variable in the anticipation of short-term climatic risks and in safeguarding their long-term livelihood. The PICSA approach has been piloted in two districts in Zambia. Our findings suggest that a nation-wide implementation of PICSA would be a highly cost-effective investment towards making farmers more resilient to climate change in Zambia (each USD invested in PICSA generates between ca. 3.60 and 3.80 USD in benefits). PICSA would support the implementation of the NAP and NDC as well as Zambia's 8th National Development plan, in which development of EWS are mentioned as national priority.

Integrated water and land management to adapt to decreasing water availability with climate change

Climate change coupled with socio-economic factors, such as population growth and economic development, will further add pressure on Zambia's water resources. With decreasing water availability, a trend towards increasing droughts and more extreme climatic conditions, the potential for large-scale irrigation will be further reduced in the future. To address water shortages in Zambia, **integrated land and water resources management** should be a priority for agricultural development planning and should hence be mainstreamed in climate adaptation activities. That requires to balance multiple user needs for agricultural, energy, ecology, industrial and domestic purposes to avoid potential conflicts over water. As part of integrated water resources management, **promoting water use efficiency and investments** in sustainable water capture, storage and transfer, such as **rainwater-harvesting** can play a vital role. Furthermore, nature-based solutions and sustainable agricultural practices can ensure that water resources are used sustainably while at the same time protecting nature conservation and forest areas in Zambia. The principles of integrated water resources management should be integrated in the currently implemented Farm Block Development Programme and the currently developed Irrigation Master Plan and involve mandated institutions.

Designing gender-responsive adaptation strategies

The design of adaptation strategies needs to be inclusive. All community groups and income strata, including women and marginalized groups, should be engaged at all planning and implementation stages and levels, for instance through community conversation sessions. Women and other marginalised groups need to be moved to the centre of these processes, both as a target group and leaders of action, so that agricultural systems can be transformed towards greater gender equity, inclusion and climate resilience. For this to materialise, gender-disaggregated data and gender-sensitive approaches can help design gender-responsive adaptation strategies.

Financing adaptation measures

The GRZ is currently in the process of establishing a National Climate Fund that is able to bundle climate finance from various domestic, international, public and private sources and disburse it to a broad range of initiatives promoting climate change mitigation and/or adaptation in Zambia. It is advisable for the National Climate Fund to, among other adaptation measures, actively promote conservation agriculture and strengthen early warning systems (both MHEWS and the PICSA approach) to increase resilience in the agricultural sector. Moreover, partnering with the TerraFund to scale up existing and promote new initiatives, continuing efforts to establish strong and reliable carbon credit regulations, and promoting exchanges with CREWS can be highly beneficial in unlocking (additional) financial support for climate adaptation.

Developing a climate and disaster risk finance strategy

Recognizing that Zambia's agricultural sector (and the rest of the economy) is likely to face growing climate risks even with the full application of adaptation strategies, the government should prioritize the development of a climate and disaster risk financing and insurance strategy. This would allow to identify the disaster risk finance needs that the sector/country will continue to face and the respective roles of risk retention and risk transfer instruments, alongside the role of humanitarian response. To ensure effective implementation, strong institutional coordination and capacity building are essential: such a strategy should ideally be led by the Ministry of Finance and National Planning while drawing on the experiences and input of DMMU, the private sector insurance industry and civil society organizations. **Engaging with the Global Risk Modelling Alliance (GRMA)** hosted by the InsuResilience Solutions Fund is also highly recommendable as a successful application would unlock grant-funded modelling and data support according to the needs of the Government of the Republic of Zambia. Table 2 summarises the key insights for Zambia's future CDRF strategy to close Zambia's protection gap.

Strengthening science-policy interface

Research and development are at the core of innovative and climate-resilient agriculture. Regular investments into national research institutes and national meteorological and hydrological institutions and statistical services need to be upscaled. Increasing data availability and quality on which evidence-based decisions are built upon is key. Moreover, adaptation research should be mainstreamed into extension services and university curricula.

Risk	Risk retention	Risk transfer
Drought	Develop and implement risk retention instruments including: ■ National Disaster Relief Trust Fund ■ Contingent credit ■ Climate resilient debt clauses[1]	■ Continue to expand coverage of agricultural microinsurance. ■ Work with development partners to explore opportunities for greater protection through ARC (i.e., increase the ceding percentage). ■ Encourage the uptake of ARC Replica and/or expand coverage of ARC. ■ Explore need/opportunity to optimise balance of risk transfer and risk retention mechanisms (once these are established).
Flood		■ Explore the development of private insurance market products for flood risk in buildings. ■ Continue to expand coverage of agricultural microinsurance. ■ Explore sovereign solutions, with a potential focus on property assets.

Table 2: Opportunities to close Zambia's protection gap

1) Climate resilient debt clauses are a more recent proposal/instrument. Following a disaster event, interest and principal repayments are suspended (while suspended payments would accrue interest) for a period of time (potentially up to 2 years). This allows the country to use the financial resources to cover response and recovery efforts.

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