Federal Ministry for Economic Cooperation and Development

Potsdam Institute for Climate Impact Research

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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2020

A report prepared by the Potsdam Institute for Climate Impact Research (PIK) in cooperation with HFFA Research GmbH for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ). The report aims to contribute to Ethiopia's NDC implementation and to the objectives of the NDC Partnership.

In contribution to:

NDC PARTNERSHIP

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

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Acknowledgements

This work was commissioned and financed by the German Ministry for Economic Cooperation and Development (BMZ), which is gratefully acknowledged. The authors would also like to thank all reviewers for their contribution to this study, in particular at the Ethiopian Environment and Forest Research Institute (EEFRI), the Ethiopian Agricultural Transformation Agency (ATA), the National Disaster Risk Management Commission (NDRMC), the Ethiopian Ministry of Agriculture (MoA) and the Ethiopian Environment, Forest and Climate Change Commission (EFCCC) as well as at BMZ and at the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The authors are especially grateful to the colleagues from GIZ's Climate Policy Support Programme Enrico Grams, Lena Klockemann and Elisa Romanato for coordinating the overall study and stakeholder engagement process as well as providing valuable inputs. Further, the authors would like to thank Dorothée Merkl, Till Serafimov, Magnus Schmid, Melaku Tadesse, Ulrich Mueller and Karin Allgöwer from the GIZ Ethiopia office for providing overall support throughout the study process and assisting in the engagement of Ethiopian stakeholders. The study greatly benefitted from two workshops held in Addis Ababa with stakeholders from the Ethiopian government, academia, civil society and international organisations working on climate change and agriculture. The lively discussions on the study approach and content resulted in insightful recommendations. Furthermore, the authors would like to thank all individuals interviewed for their time and the valuable information they provided.

Author's contributions

Christoph Gornott and Lisa Murken coordinated and edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Christoph Gornott designed the study and contributed to Chapter 3, while Lisa Murken conducted key informant interviews and contributed to Chapters 5-10. M. Rocío Rivas López performed the climate analysis in Chapter 1, under the guidance and with significant input from Stephanie Gleixner and Jascha Lehmann. Abel Chemura analysed climate impacts on crop yields and crop suitability in Ethiopia, leading on to Chapter 3 and contributing to Chapters 7 and 8 with biophysical adaptation assessments. Iulii Didovets conducted the hydrological analysis for Chapter 2, supported by Hagen Koch and Stefan Liersch. Sophia Lüttringhaus, Matti Cartsburg and Steffen Noleppa conducted the micro-level cost-benefit analyses in Chapters 6, 7, 8 and 9. Felicitas Röhrig contributed to Chapters 9 and 10. Julia Tomalka contributed to Chapter 6 and provided overall research support. Bernhard Schauberger performed statistical analyses on the link between weather and crop yields and contributed to Chapter 3 and Chapter 10. Roopam Shukla conducted the spatial vulnerability analysis in Chapter 4, with the support of Amsalu W. Yalew. In addition, Amsalu W. Yalew conducted the economic analysis in Chapter 6 and contributed the economic analysis of climate impacts on the agricultural sector to Chapter 3. All authors contributed to Chapter 11 on uncertainties.

Suggested citation:
Murken, L., Cartsburg, M., Chemura, A., Didovets, I., Gleixner, S., Koch, H., Lehmann, J., Liersch, S., Lüttringhaus, S., Rivas López, M. R., Noleppa, S., Roehrig, F., Schauberger, B., Shukla, R., Tomalka, J., Yalew, A. & Gornott, C., (2020). *Climate risk analysis for identifying and weighing adaptation strategies in Ethiopia's agricultural sector*. A report prepared by the Potsdam Institute for Climate Impact Research for the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development, 150 pp. DOI: 10.2312/pik.2020.003

Abstract

Climate change increasingly affects Ethiopia's agricultural sector, with droughts and precipitation variability challenging farmers' livelihoods and economic prospects. Effective adaptation is needed to mitigate climate risks, which is recognised in national adaptation policy plans. Yet, for Ethiopia only limited information on climate risks is available, on which sound adaptation decisions can be based. This study aims to address this gap, providing a comprehensive climate risk analysis for Ethiopia's agricultural sector. Driven by three global climate models (GCMs) under two climate change scenarios, RCP2.6 and RCP8.5, we use impact models to analyse future trends in temperature, precipitation, climatic extremes, water availability, crop yields and crop suitability. The models used range from an eco-hydrological model, semi-statistical and process-based crop models, suitability models based on machine learning to economic models, using net value of production and cost-benefit approaches. We also assess the spatial vulnerability patterns to climate change in Ethiopia, using an indicator-based approach. The main crops considered in this analysis are maize, teff, sorghum and wheat as well as coffee as a cash crop. Based on information regarding expected climate change impacts, we selected adaptation strategies for assessment of their overall feasibility and suitability for Ethiopia. The assessment was carried out employing a multi-criteria framework, with nine indicators ranging from biophysical and economic performance to soft assessment indicators. Using the impact and economic models, we analysed the potential of the selected strategies to cost-effectively mitigate climate risks, which was complemented by expert- and literature-based assessments, informed by semi-structured key informant interviews, an expert survey and two stakeholder workshops.

The results show that temperature will increase with higher emissions, moderately under the low emissions scenario (average increase of 1.8° until 2090) and more strongly under the high emissions scenario (average increase of 4.6° until 2090), compared to pre-industrial temperatures around 1870. For precipitation, models predict a rise under the high emissions scenario by the end of the century and no significant change under the low emissions scenario, with high regional variation in results. Both temperature and precipitation extremes are projected to increase, with the diverse regions and agro-ecologies of Ethiopia differently affected. As regards water availability for agriculture, river discharge of the Blue Nile is projected to increase in the future under both emissions scenarios, with monthly projections indicating a potential prolongation of the wet period in Ethiopia. Climatic conditions substantially affect crop production in Ethiopia, the projected changes translate into modelled shifts in suitability patterns for different crops, with net suitability for maize, wheat and teff decreasing, while the overall suitability to grow sorghum will increase. Further, crop models predict maize yield increases at national level by mid-century, although some zones are projected to experience losses. The vulnerability assessment showed that zones with very high vulnerability to climate change are located mainly in Dire Dawa, Gambela, Somali, Oromia and SNNP regions, which is driven by factors, such as lack of input use and exposure to heat extremes, particularly in the pastoralist regions. To cope with those projected impacts, a wide range of adaptation strategies are suitable. Selected adaptation options analysed in this study indicate that agroforestry interventions and improved fodder and feed hold particular potential for adapting Ethiopian agriculture, with irrigation, insurance and improved crop management as necessary complements. Generally, combinations of adaptation strategies appear most useful and active stakeholder engagement as well as participatory approaches are needed to ensure feasibility and long-term sustainability of adaptation strategies.

Keywords: climate change adaptation, climate impacts, climate risk, agriculture, Ethiopia, biophysical modelling, cost-benefit analysis, multi-criteria analysis

Table of Contents

List of tables

List of figures

List of abbreviations

AEZ	Agro-ecological Zone
AMPLIFY	Agricultural Model for Production Loss Identification to Insure Failures of Yields
APSIM	Agricultural Production Systems Simulator
ASAL	Arid and Semi-Arid Lowlands
ATA	Agricultural Transformation Agency
BCR	Benefit-cost Ratio
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry for Economic Cooperation and Development)
CBA	Cost-benefit Analysis
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CIMMYT	International Maize and Wheat Improvement Center
CMIP5	Coupled (climate) Model Intercomparison Project
CRGE	Ethiopia's Climate Resilient Green Economy Strategy
CSA	Central Statistics Authority of Ethiopia
CV	Coefficient of Variation
ETB	Ethiopian Birr
ECMWF	European Centre for Medium-Range Weather Forecasts
EEFRI	Ethiopian Environment and Forest Research Institute
EFCCC	Ethiopian Environment, Forestry and Climate Change Commission
EIAR	Ethiopian Institute for Agricultural Research
ERA-Interim data	the European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis data
EVI	Enhanced Vegetation Index
FAO	UN Food and Agriculture Organization
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit
GRDC	Global Runoff Data Centre
GVP	Gross Value of Production
HARITA	Horn of Africa Risk Transfer for Adaptation
ICRAF	World Agroforestry Centre
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace (Climate model)
IRR	Internal Rate of Return
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project

JICA	Japan International Cooperation Agency
LCU	Local Currency Unit (here Ethiopian Birr)
MoA	Ethiopian Ministry of Agriculture
MoWIE	Ethiopian Ministry for Irrigation, Water and Energy
NAP	National Adaptation Plan
NAPA	Climate Change National Adaptation Programme of Action
NDC	Nationally Determined Contribution
NDRMC	National Disaster Risk Management Commission
NDVI	Normalized Difference Vegetation Index
NPK	Nitrogen, Phosphorous, Potassium
NPV	Net Present Value
NVP	Net Value of Production
PSNP	Productive Safety Nets Programme
RCP	Representative Concentration Pathway
RWH	Rainwater Harvesting
SDGs	Sustainable Development Goals
SLMP	Sustainable Land Management Program
SNNP	Southern Nations, Nationalities and People's Region
SRTM	Shuttle Radar Topography Mission
SWIM	Soil and Water Integrated Model
WFDEI	WATCH Forcing Data methodology applied to ERA-Interim data
WFP	World Food Programme
WII	Weather Index Insurance

Introduction

Adaptation to climate change is a key challenge for African nations, which they have recognised in their plans submitted under the Paris Agreement, such as in their respective Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). All NDCs submitted by African countries contain adaptation content and highlight the importance of adaptation action along with mitigation efforts (AfDB, 2019). Yet, little guidance on how to operationalise adaptation goals exists. As part of their international commitments, countries seek to develop and implement adaptation policies and investment plans. Ethiopia's Climate Resilient Green Economy Strategy (CRGE) is one such example. Yet, many countries including Ethiopia need better information on climatic risks to develop evidence-based adaptation policies. Lack of such information may affect designing adaptation policies and implementing adaptation strategies and could eventually lead to inefficient allocation of scarce public resources. Comprehensive climate impact assessments play an important role in filling this gap. They can generate information on future climatic impacts on a range of economic sectors under different greenhouse gas (GHG) emissions scenarios and enable decision-makers to design adaptation strategies and take investment decisions based on comprehensive risk assessments.

Climate risk analyses provide information on future climatic impacts on a range of economic sectors under different emissions scenarios. This can support decision-makers in designing adaptation strategies and taking investment decisions.

This is what this study seeks to provide for the context of Ethiopia. It combines climate impact assessment with economic and multi-criteria analysis to evaluate adaptation strategies best fit for Ethiopian agriculture under different climate scenarios. A better understanding of projected climate impacts and of possible adaptation benefits and risk-transfer solutions is important to guide, incentivise and accelerate public and private sector investments for a climate-resilient agricultural development. The need for scientific evidence does not stop with impact assessments, but also concerns accessible tools to assess costs and benefits of potential adaptation strategies. Therefore, scientific assessments can support countries, such as Ethiopia to gain access to local and international climate finance, which is crucial for implementing their adaptation strategies. Consequently, this study seeks to inform actors ranging from the public to the private sector on how to underpin decision-making for climate change adaptation. To ensure sustainability and suitability of the study approach and deliver tailored policy advice, Ethiopian stakeholders from government, civil society, academia and the private sector were consulted from the onset, with the aim to maximise the value of the study findings for Ethiopian policy-making and to co-create recommendations.

The main focus of this climate risk study is on the agricultural sector, which is the key economic sector in Ethiopia in terms of its importance for rural livelyhoods. In 2018, agriculture (including forestry and fisheries) accounted for about 31.1% of Ethiopia's GDP, although the share has been declining over the past years (World Bank, 2019a). The agricultural sector is the second most important contributor to Ethiopia's GDP, after services (ca. 36.5%) and before industry (ca. 27.3%) (World Bank, 2019c). Agricultural exports are increasing overtime. In 2016, they made up 84% of merchandise exports (World Bank, 2019c). This highlights the importance of livestock and export cash crops for Ethiopia, especially coffee. The sector also plays a key role for employment in the country, with an estimated 72% of the population depending on agriculture for their livelihoods (FAO, 2018). This study in particular focused on the four most important cereal crops in Ethiopia: teff, maize, wheat and sorghum (see Table 1).

This climate risk study focuses on Ethiopia's agricultural sector, which contributes almost one third to Ethiopia's GDP. Many rural livelihoods critically depend on agriculture.

Table 1: Main cereal crops in Ethiopia and the four main agricultural regions (average of 2014-2016).

Geographic Area	Crop	Area ('000 ha)	Yield (tons/ha)	Irrigated Area (%)	Price (USD/ton)
Ethiopia	Teff	2967	1.60	0.32	709
	Wheat	1675	2.58	0.35	484
	Maize	2121	3.50	1.50	327
	Sorghum	1857	2.41	0.86	439
Tigray	Teff	172	1.34	0.87	732
	Wheat	106	1.85	1.32	482
	Maize	64	2.41	1.35	368
	Sorghum	239	2.71	0.48	429
Amhara	Teff	1125	1.63	0.35	679
	Wheat	543	2.29	0.19	507
	Maize	517	3.62	0.95	346
	Sorghum	657	2.23	0.50	456
Oromia	Teff	1413	1.65	0.19	707
	Wheat	882	2.87	0.24	450
	Maize	1133	3.61	0.99	315
	Sorghum	740	2.53	0.63	439
SNNP	Teff	232	1.36	0.52	678
	Wheat	133	2.51	0.10	477
	Maize	319	3.22	3.12	278
	Sorghum	107	2.13	0.59	353

Source: Authors' compilation from various reports by Central Statistical Agency of Ethiopia (CSA).

Agriculture in Ethiopia is at the centre of both climate change impacts and climate change causes: Due to its reliance on weather conditions, it is one of the sectors most sensitive to climate change, while at the same time contributing to global GHG emissions, although this is much less so for smallholder agriculture. The Ethiopian agricultural system can be characterised by predominantly rainfed smallholder mixed farming. Only 2% of smallholder farmers' land is estimated to be irrigated in Ethiopia (FAO, 2018).

Ethiopia is characterised by high ecological and climatic diversity, which influences crop production patterns.

Crop production patterns and levels vary considerably across Ethiopia. They are affected by agro-ecological conditions, which in turn are highly influenced by altitude. Figure 1 shows the five major agro-ecological zones (AEZs) in Ethiopia, which we used as a basis for our analysis. These are Humid Lowlands Moisture Reliable, Moisture Sufficient Highlands – Cereals, Moisture Sufficient Highlands – Enset, Drought – Prone Highlands and Pastoralist – Arid Lowland Plains[1]. As the maps show, many regions span across different elevation levels and AEZs. In the eastern part of the country, the Afar and Somali regions mostly have low elevation levels and are dominated by pastoral agricultural systems. Regions, such as SNNP, Oromia, Amhara and Tigray, however, cover both highlands and lowlands, with diverse agro-ecological settings and agricultural uses. Population density is highest in the highlands and around major urban centres, such as Addis Ababa, Dire Dawa and Bahir Dar, but also around Sidama and Gurage zones.

[1] It is important to note here that we are aware of different classification of AEZs in Ethiopia. We, however, focused on the five common AEZs to limit our analysis to more meaningful units.

Figure 1: The map shows the elevation levels in Ethiopia and the ten administrative regions as well as five key AEZs, major cities and water bodies. Four exemplary climate diagrams are added to show some of the diverse climate regimes in Ethiopia. Note that the climate diagrams display temperature and precipitation values that are averaged over approximately 50kmx50km. Especially in areas with high differences in altitude, the climate in areas within the grid might differ significantly.

The Moisture Sufficient Highlands – Cereals host the majority of smallholder farmers, accounting for 59% of all farm area. About 27% of the total area cultivated is found in the Drought – Prone High lands, whereas the lowland and pastoralist areas are less important for smallholder farming, as they are largely inhabited by pastoralists and agro-pastoralists (Taffesse, Dorosh, & Gemessa, 2014).

The Landscape Approach

The landscape approach can be broadly defined as "a framework to integrate policy and practice for multiple land uses, within a given area, to ensure equitable and sustainable use of land, while strengthening measures to mitigate and adapt to climate change" (Reed, Deakin, & Sunderland, 2015). According to the Wageningen Center for Development Innovation, the landscape approach aims at a spatial integration of economic sectors and value chains into a network of overlapping ecological, economic and sociocultural elements (van Oosten, 2015). In this way, the landscape approach addresses increasingly competing demands on land including for agriculture and the mitigation of climate change, and counters the traditional fragmentation of development processes into independent units (Sayer et al., 2013). A key aspect of the landscape approach are multi-stakeholder dialogues: In order to manage the complexity inherent to physical landscapes as well as its multiple uses, all relevant stakeholders need to be taken into account and brought to the table, starting from the local communities of a given physical landscape.

Even though this study focuses primarily on the crop agriculture sector, the analysis can also offer insights to other economic sectors, value chains and natural resource systems, for instance forestry, livestock, water, energy and infrastructure. The projected climate change is expected to impinge on all of the aforementioned sectors that bear inter-linkages and spill-over effects across sectors and scales. Therefore, where possible, a landscape approach was considered in order to highlight the interconnectedness and the multiple uses of natural resources as well as potential user trade-offs due to competing demands. This is of special importance given Ethiopia's highly diverse and rich topography, climatic conditions and natural resource endowments. In addition, administrative boundaries of the key agricultural areas in Ethiopia were used for reporting findings, to facilitate policy-making and adaptation planning as well as implementation at regional and zonal levels.

In this study, we present a comprehensive analysis of climate risks that Ethiopia's agricultural sector is facing. Based on projected climate impacts, adaptation strategies are evaluated and recommendations for action are given.

The present study provides an in-depth analysis of climate risks for selected crops in Ethiopia, along with recommendations for adaptation and risk-transfer measures. Chapters 1-4 look at the impact dimension of climate change in Ethiopia, which then feed into the action (or adaptation) dimension in Chapters 5-10:

- Chapter 1 gives an overview on future climate change impacts in Ethiopia, which are derived from Global Climate Model (GCM) results for two climate scenarios, RCP2.6 and RCP8.5.
- Chapter 2 analyses changing water availability for agricultural production and electricity generation under climate change.
- Chapter 3 provides a comprehensive overview of climate change impacts on the agricultural sector in Ethiopia, ranging from the importance of weather influences on yields, projected yields and shifting crop suitability under climate change to economic impacts of climate change on crop production.
- Chapter 4 provides an analysis of spatial vulnerability in Ethiopia, which is based on a combination of climatic and socio-economic indicators. This is meant to indicate particularly vulnerable administrative zones of Ethiopia, where crop agriculture is most important.
- Chapter 5 presents the assessment framework and methodological approach for evaluating the usefulness of different adaptation strategies under climate change in Ethiopia, spanning from biophysical, economic to soft assessment indicators.
- Chapters 6 to 10 assess selected adaptation strategies. Chapter 6 presents the assessment of irrigation; Chapter 7 evaluates improved crop management; Chapter 8 analyses agroforestry; Chapter 9 considers improved fodder and feed management; Chapter 10 assesses crop insurance solutions for Ethiopia's agricultural sector.
- Chapter 11 discusses sources of uncertainty and presents limitations of the study to facilitate interpretation of results.
- Finally, a conclusion synthesises the study's results and policy recommendations are given. The results are meant to inform and support government-, non-profit- and private sector stakeholders in prioritising and designing their adaptation investments.
- A complimentary climate risk profile for Ethiopia provides information on climate risks to other sectors, such as health, water, biodiversity and infrastructure.

PART I - CLIMATE CHANGE IMPACTS

In the first part of this climate risk study, we analyse current and projected impacts of climate change on agriculture in Ethiopia.

Chapter 1 – Changing climatic conditions

To identify changes of future climatic conditions in Ethiopia, this chapter analyses several indicators concerning temperature and precipitation under two global climate scenarios. Projected climate data was analysed to show the range of possible future climatic conditions by 2030, 2050 and 2090. To cover the full range of climate change projections, the climate change impacts were examined for the scenarios RCP2.6 and RCP8.5, which are the lowest and highest CO_2 emissions scenarios covered in the Intergovernmental Panel on Climate Change (IPCC) reports. RCP2.6 represents a scenario that is likely below 2°C above pre-industrial temperatures (IPCC, 2014a) and is thereby in line with the goals of the Paris Agreement. RCP8.5 is a high emissions scenario and refers to the “without climate policy” scenario.

We analysed two emissions scenarios, which cover the range of possible CO_2 emissions pathways: one scenario is in line with the Paris Agreement (RCP2.6), the other scenario represents a world without climate policy (RCP8.5).

RCPs - representative concentration pathways

The standard set of scenarios used in the 5th Assessment Report of the IPCC (2014a) are the four pathways RCP8.5, RCP6.0, RCP4.5 and RCP2.6. Each RCP defines a specific emissions trajectory and subsequent radiative forcing. The RCPs are labelled after the additional radiative forcing level reached in the year 2100 relative to pre-industrial times (+2.6, +4.5, +6.0 and +8.5 W/m², respectively). Each RCP is consistent with a socio-economic pathway. RCP2.6 is in line with the Paris Agreement and assumes that through policy intervention, greenhouse gas emissions are reduced drastically and almost immediately, leading to a slight reduction of today's levels by 2100. The scenario without climate policy – RCP8.5 – assumes more or less no interventions and thus undiminished emissions (van Vuuren et al., 2011; Wayne, 2013).

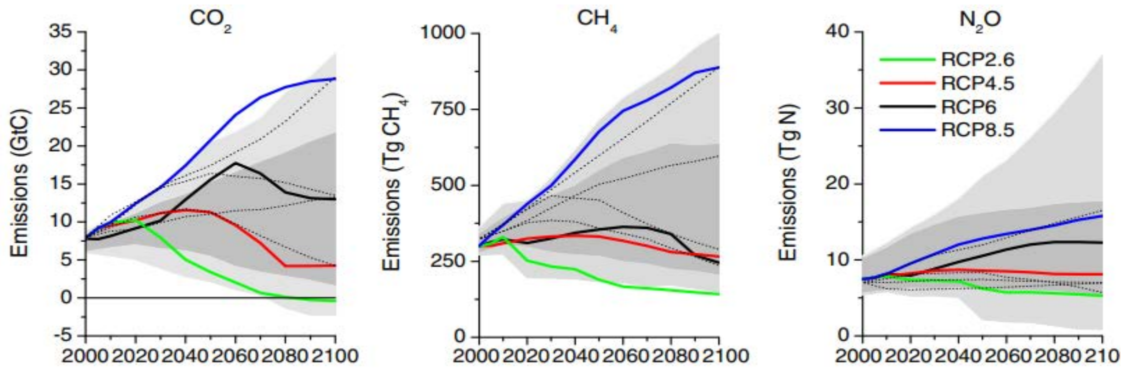


Figure 2: Emissions of main greenhouse gases across the RCPs. Grey area indicates the 98th and 90th percentile (van Vuuren et al., 2011).

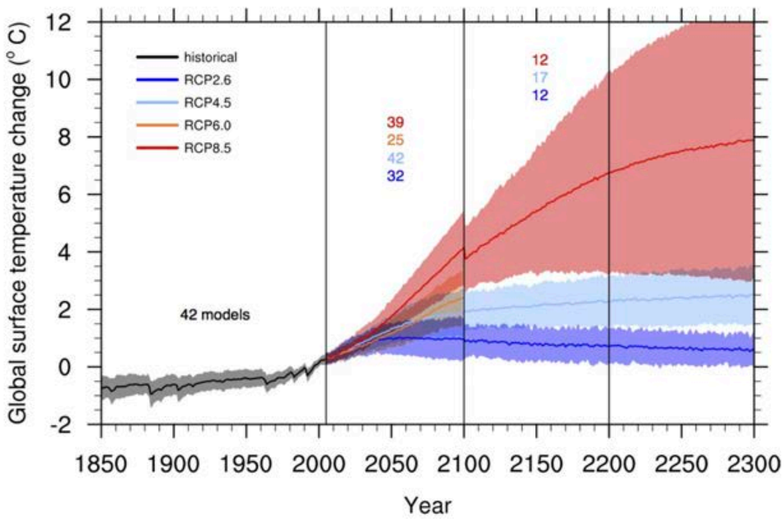


Figure 3: Multi-model mean global annual mean surface air temperature (relative to 1986-2005) for each RCP (IPCC, 2014a).

What drives Ethiopia's climate

Ethiopia's landscape spans across different elevation levels. In the highlands, temperatures are generally lower and precipitation is higher as compared to the lowlands.

Ethiopia is located in equatorial and subequatorial climate zones, where altitude and the inter-tropical convergence zone (ITCZ) play an important role in determining the regional climate of the country. Generally, higher elevations are associated with lower temperatures and higher precipitation, which increases with altitude until about 2,000 metres (Dinku et al. 2008). The seasonal cycle of precipitation shows strong regional differences within Ethiopia. The western part of the country receives most of Ethiopia's annual precipitation and experiences a unimodal precipitation regime (one major rainy season). The southeastern part of the country is more arid and has a bimodal pattern (two rainy seasons and one or two dry periods). These precipitation patterns are influenced by complex interactions between the location of the ITCZ, which crosses Ethiopia twice a year, and surface wind patterns induced by sea surface temperatures (SST) (Griffiths, 1972; Segele et al., 2009; Yang et al. 2015; Nicholson, 2016). Tropical SST patterns like the El-Niño Southern Oscillation (ENSO) or the Indian Ocean Dipole (IOD) influence the atmospheric circulation and therefore the inter-annual variability of precipitation over East Africa (Endris et al., 2015; Gleixner et al., 2016). These patterns have been connected to the occurrence of severe droughts in the country, like the ones experienced in 1959, 1973-4, 1984-5, 1995, 2003, 2006 and 2015 (Levine, D., 2006; Philip et al., 2018).

1.1 Data and method

The basis for the evaluation of the current and near-past climate in this study is the observational climate dataset EWEMBI (Lange, 2019). EWEMBI is a dataset based on simulations from global weather models combined with satellite data and weather station observations and therefore covers the entire globe at 0.5° horizontal (corresponding to approximately 50km x 50km at the equator) and daily temporal resolution from 1979 to 2016. Data sources of EWEMBI are ERA-Interim reanalysis data (ERAI; Dee et al., 2011), WATCH forcing data methodology applied to ERA-Interim reanalysis data (WFDEI; Weedon et al., 2014), eartH2Observe forcing data (E2OBS; Calton et al., 2016) and NASA/GEWEX Surface Radiation Budget data (SRB; Stackhouse Jr. et al., 2011). The SRB data were used to bias-correct E2OBS shortwave and longwave radiation (Lange, 2018). EWEMBI was compiled to support the bias adjustment of climate data, which drive the impact assessments carried out in phase 2b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b; Frieler et al., 2017). The ISIMIP assessments contributed to the 2018 IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways.

Different datasets were used for the analysis, including from the Inter-Sectoral Model Intercomparison Project (ISIMIP). The impact models were driven by three global climate models. Using multiple models produces more reliable results than single-model approaches.

The past and future climate data simulated by Global Climate Models (GCMs) was also obtained from ISIMIP2b. The data was bias-adjusted with EWEMBI. Historical simulations cover the years 1861-2005 and projected simulations (under greenhouse gas emissions scenarios) cover the years 2006-2099. The GCMs[2] included in ISIMIP2b are: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M and MIROC5 (Frieler et al., 2017). IPSL-CM5A-LR was initially included in this study. However, IPSL has a very strong dry bias in Ethiopia. This bias makes the applied bias-adjustment method (Lange, 2018) unsuitable for this model in this region and leads to unrealistically high values in the future (more than 5000 mm of annual total precipitation). Therefore, the model has been removed from the ensemble of this study's analysis.

The indicators analysed in this study are: the annual average mean air temperature, annual number of very hot days (maximum temperature

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

Many different climatic indicators related to temperature and precipitation were analysed for this study.

above 35°C), very hot nights or tropical nights per year (minimum temperature above 25°C), annual average precipitation, number of days with heavy precipitation (exceeding the 95th percentile calculated from EWEMBI for 2007) and very heavy precipitation per year (exceeding the 99th percentile of EWEMBI in 2007) and precipitation and temperature in different seasons along the year considered relevant for agriculture.

Since multi-model means usually show more robust results than single model results, most of the results in the following chapters are averages over the three models. However, one should take into account that the models show a range with the corresponding uncertainty associated (see uncertainty Chapter). Along this report, climate change analyses are based on a 20-year average[3], meaning that the mean annual temperature in e.g. 2030 is calculated as average over the mean temperature between 2020 and 2039. The reference for the pre-industrial time is the climate in 1870 (1861-1880). The present climate, used as baseline in this study, refers to the climate in 2007 (1997-2016). The projected climate data is evaluated for the periods 2030 (2021-2040), 2050 (2041-2060) and 2090 (2081-2099)[4]. When referring to the changes in the future, the computations have been done for each of these three periods in relation to firstly the baseline (2007) and secondly to 1870 for each model and scenario (the comparisons to 1870 can be found in Table 3 for temperature and in the supplementary material for the rest of the indicators).

1.2 Present climatic conditions[5]

Ethiopia currently experiences an annual average temperature of 23°C, with a minimum of 11.9°C found in the Amhara region and a maximum of 30.8°C in the Northeast of the country. In the past, Ethiopia had an average number of very hot days per year of ~57 days and 8 very hot nights on average. However, Ethiopia shows high spatial variation in climate, so regional differences are also very important. Generally, regions with lower altitude experience higher average temperatures and extreme temperatures more frequently than regions with higher altitude[6]. Tropical nights do not happen very often in higher altitude regions.

There are large regional differences in Ethiopia's climate.

The annual mean total precipitation is 900 mm per year, with the lowest amount (around 100 mm.) found in the northeastern part of the country (Afar Triangle) and the maximum amount in the western part (above 1,900 mm.).

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

4 When referring to the changes in the future, the computations have been done for each of these three periods in relation to: firstly the baseline (2007) and secondly to 1870 for each model and scenario (the comparisons to 1870 can be found in the tables included in this document for temperature and in the supplementary material for the rest of the indicators).

5 Further figures and data for the whole of this chapter can be found in the supplementary material.

6 For values regarding the different regions, please refer to the supplementary material.

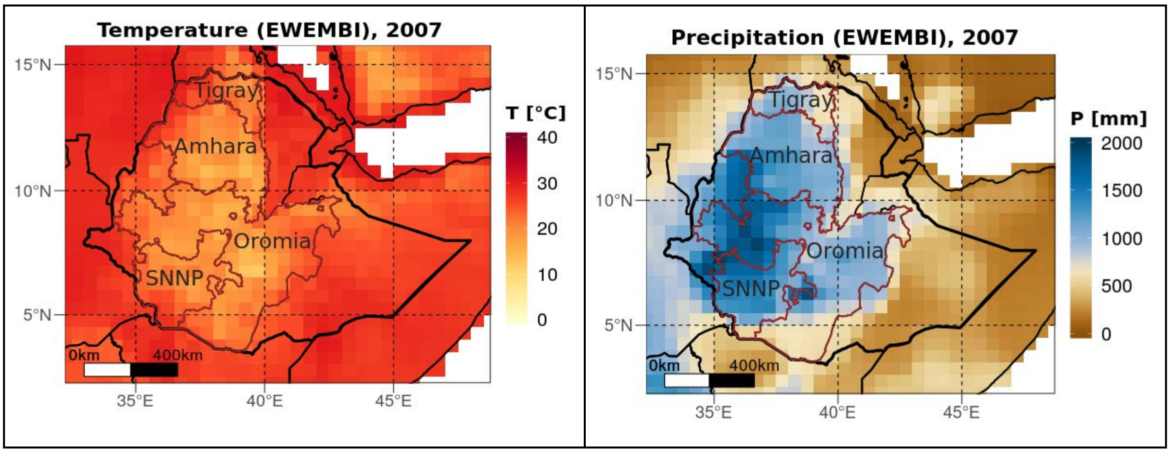


Figure 4: Mean annual temperature (left) and annual precipitation sum (right) in 2007 (1997-2016) over Ethiopia.

1.3 Past Climate Change

Temperature and heat extremes are rising in Ethiopia: from 1990 to 2007, mean air temperature increased by almost half a degree Celsius.

During the recent past (changes from 1990 to 2007), annual average and extreme temperature indicators showed a robust rise over Ethiopia. The mean air temperature increased by almost half a degree Celsius and the number of very hot days also saw a general increase of around 37% (~15 days per year) in Ethiopia from 1990 to 2007. SNNP is the region that experienced the highest change, with about 11 additional very hot days above 35°C per year, and the central mountainous regions (Amhara and Oromia) saw the lowest change (an additional 6 very hot days per year).

Annual precipitation decreased over Ethiopia by about 7% on average. However, the picture is slightly different for the main agricultural regions, where only Oromia saw a precipitation decrease (as average over the region) in the past, whereas the other three regions experienced a slight increase in precipitation. EWEMBI shows a decreasing trend in days with heavy precipitation from 1990 to 2007 over the whole of Ethiopia of 6% or 4 days per decade. While in Oromia and SNNP, the number of heavy precipitation days per decade decreased by 15 days (e.g. 96 days in 1990 vs. 81 in 2007 in SNNP and roughly 68.5 days vs. 83.5 in Oromia), in Amhara and Tigray, it increased by 7.5 and around 10 days respectively (84 days in 1990 vs. ~77 in 2007 in Amhara and 74 vs 64 in Tigray respectively for the same periods). For the very heavy precipitation events, the regional patterns of change from 1990 to 2007 are analogous to the heavy precipitation ones, however, of lower magnitude with a decrease of 4 and 3 days in SNNP and Oromia regions respectively and an increase of 2.5 days in Amhara and almost 5 days in Tigray in 2007, with reference to 1990. Figure 5 shows the heavy precipitation extreme threshold in 2007, with Table 2 giving the regional values.

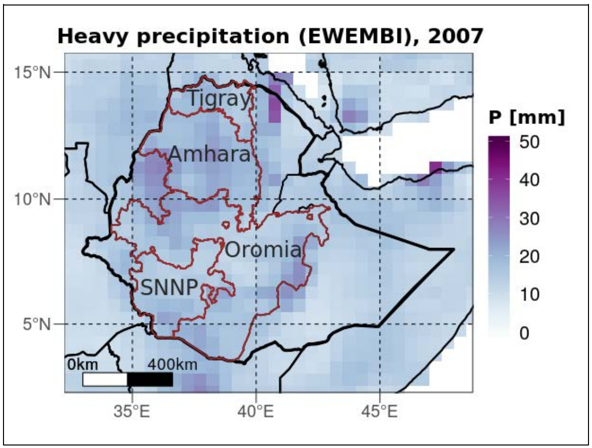


Figure 5: Daily heavy precipitation extreme threshold in 2007 (average 16.6 mm over the whole of Ethiopia) (EWEMBI).

Table 2: Regional values for heavy and very heavy precipitation from 1997-2016.

Region	Heavy precipitation (95th percentile)	Very heavy precipitation (99th percentile)
Ethiopia	16 mm	30 mm
Amhara	20 mm	35 mm
SNNP	16 mm	28 mm
Oromia	17 mm	30 mm
Tigray	17 mm	30 mm

Note that Oromia and Tigray show very similar extreme precipitation thresholds, which are rounded.

1.4 Projected Climate Change

Confidence in projected trends of extreme events depends on the region, season and type of extreme event. It is virtually certain that increases in the frequency and magnitude of warm daily temperature extremes will increase on a global scale. According to the IPCC (IPCC, 2014a), global surface temperature is projected to rise over the 21st century under all assessed emissions scenarios. It is likely that temperatures over land will rise faster than the global average, particularly in the more arid regions, and that the rate of increase in minimum temperatures will exceed that of maximum temperatures. The IPCC also states that it is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. In regions of high or complex topography, such as the Ethiopian Highlands, downscaled projections indicate likely increases in precipitation and extreme precipitation by the end of the 21st century (Niang et al., 2014).

Temperature and heat extreme projections

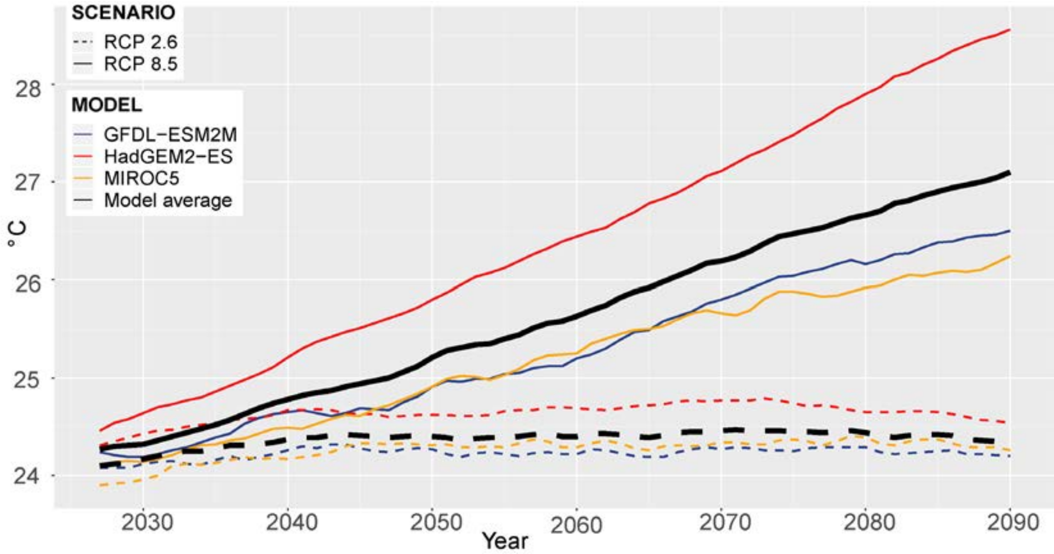


Figure 6: Projected mean annual temperature over Ethiopia for two scenarios and three climate models. The graph shows the 20-year moving average.

Temperatures are projected to further rise in Ethiopia with progressing climate change. Depending on the scenario, the mean annual temperature in Ethiopia is projected to increase by between 1.8°C (RCP2.6) and 4.6°C (RCP8.5) until end of the century, compared to pre-industrial temperature levels.

ISIMIP models project an increase in temperature under both scenarios and in all periods (2030, 2050, 2090) with very high confidence (all models agree on the same signal of change) in reference to 2007 (see Table 3). Figure 6 shows the 20-years moving average of the annual mean temperature over Ethiopia from the different GCMs. A linear steady average rise of 0.05°C per year along 2017-2090 is shown by every model under RCP8.5, while under RCP2.6 after a mean increase in temperature of +0.02°C per year until mid-2040, a stabilisation until the end of the 21st century is projected, which is a consequence of the GHG emissions driving this scenario (that also stabilise). The average of the model ensemble indicates an average increase over Ethiopia from approximately 1.6°C (2030) to 1.9°C (2050) under RCP2.6 and from 1.9°C (2030) to 4.6°C (2090) under RCP8.5, compared to the pre-industrial climate. When only considering single model results, a broader range of possible future temperature increases over Ethiopia (geographical average) is projected, ranging from 1.4°C (2030) to 2.3°C (2090) under RCP2.6 and from 1.6°C (2030) to 6.4°C (2090) under RCP8.5. Under RCP2.6, the highest temperatures are reached by 2050, which again follows from the stabilisation of GHG emissions around mid-century. Spatially, the averages of the ISIMIP models do not show significant differences in mean temperature changes across Ethiopia for the future periods and scenarios RCP2.6 and RCP8.5.

Table 3: Projected mean annual temperature and absolute differences in Ethiopia for the 20-year periods averages (2030, 2050, 2090) in relation to 2007 (1997-2016) and 1870 (1861-1880) for RCP2.6 and RCP8.5[7].

Year	Scenario	Temperature [°C]	Temperature diff. [°C] with ref=2007	Temperature diff. [°C] with ref=1870
1870	Hist.	22.2		
2007	Hist.+RCP2.6	23.2		1.0
2007	Hist.+RCP8.5	23.2		1.0
2030	RCP2.6	23.8	0.6	1.6
2030	RCP8.5	24.0	0.8	1.8
2050	RCP2.6	24.1	0.9	1.9
2050	RCP8.5	24.8	1.6	2.6
2090	RCP2.6	24.0	0.8	1.8
2090	RCP8.5	26.8	3.6	4.6

Models show that very hot days and tropical nights are likely to increase in the future, which will affect the lowlands and pastoral areas most.

Very hot days (with maximum temperature above 35°C) and tropical nights (with minimum temperature above 25°C) are projected to increase under all scenarios and periods (2030, 2050, 2090), both in frequency and severity (see Figure 8 and Figure 10), with pastoralist areas being the most affected. Averaged over Ethiopia, the model simulations show an increase in the number of very hot days per year of up to 17 days (by 2050) under RCP2.6 and up to 94 days (by 2090) under RCP8.5 in comparison to present day conditions. The projected increase in tropical nights is less than the increase in very hot days. Tropical nights are projected to increase by up to 9 nights (RCP2.6 by 2050) and 75 nights (RCP8.5 by 2090) respectively. Both indicators affect mostly the lowlands of Ethiopia, with higher intensity in the Danakil depression and in the south-eastern pastoral lands.

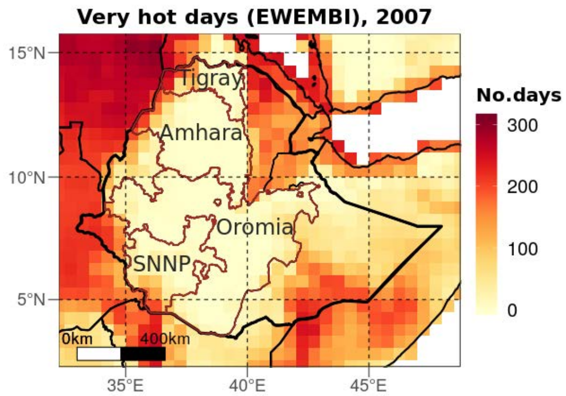


Figure 7: Average number of very hot days (temperature above 35°C) per year in 2007, as indicated by EWEMBI.

7 Slight deviations in the temperature differences with regard to the historical temperature may occur due to rounding.

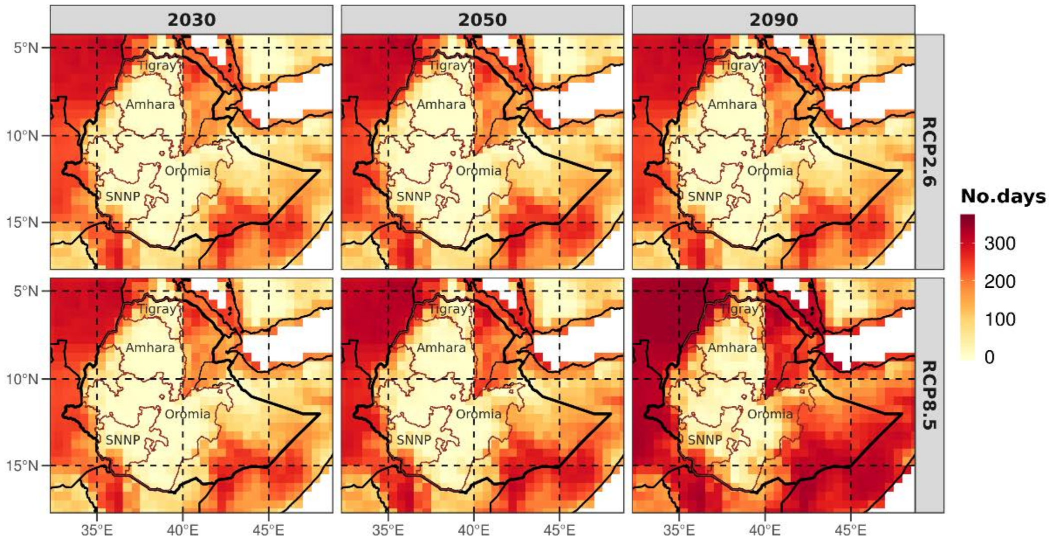


Figure 8: Average number of very hot days (temperature above 35°C) per year in 2030, 2050 and 2090 under scenario RCP2.6 and RCP8.5. Results are averages over the three ISIMIP models.

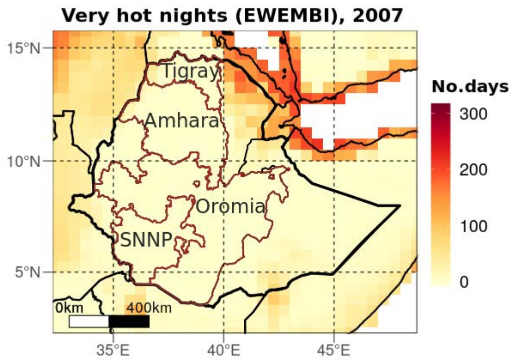


Figure 9: Average number of tropical nights (temperature above 25°C) per year in 2007, as indicated by EWEMBI.

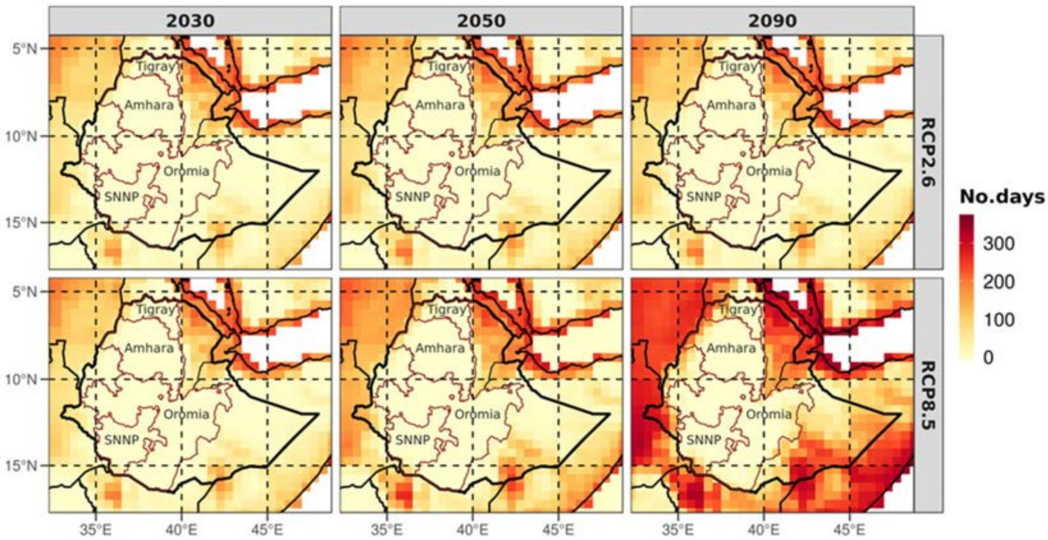


Figure 10: Average number of tropical nights (temperature above 25°C) per year in 2030, 2050 and 2090 under scenario RCP2.6 and RCP8.5. Results are averages over the three ISIMIP models.

Precipitation projections

Precipitation projections are much more uncertain than temperature projections and differ widely across regions. In the low emission scenario, no precipitation trend is detected, while for the high emission scenario, a precipitation increase after 2040 is projected.

Generally, there is much less confidence in projected precipitation changes than in temperature changes, as differences between models and scenarios are larger. The three ISIMIP models do not show a robust trend in average Ethiopian precipitation under RCP2.6, but they agree on a projected increase in annual average Ethiopian precipitation under RCP8.5 after 2040. Therefore, the ensemble average shows a positive precipitation trend under RCP8.5 and no precipitation trend under RCP2.6.

Projected precipitation levels differ across regions: Generally, the projections show different precipitation changes for the northern regions (Amhara and Tigray) and the southern regions (SNNP and Oromia). The northern regions show a slight decrease in precipitation throughout the 21st century under RCP2.6 and an increase under RCP8.5. The southern regions do not have a clear trend under RCP2.6. Under RCP8.5 the South of Ethiopia is drying until the middle of the 21st century and then annual precipitation increases (see Figure 11).

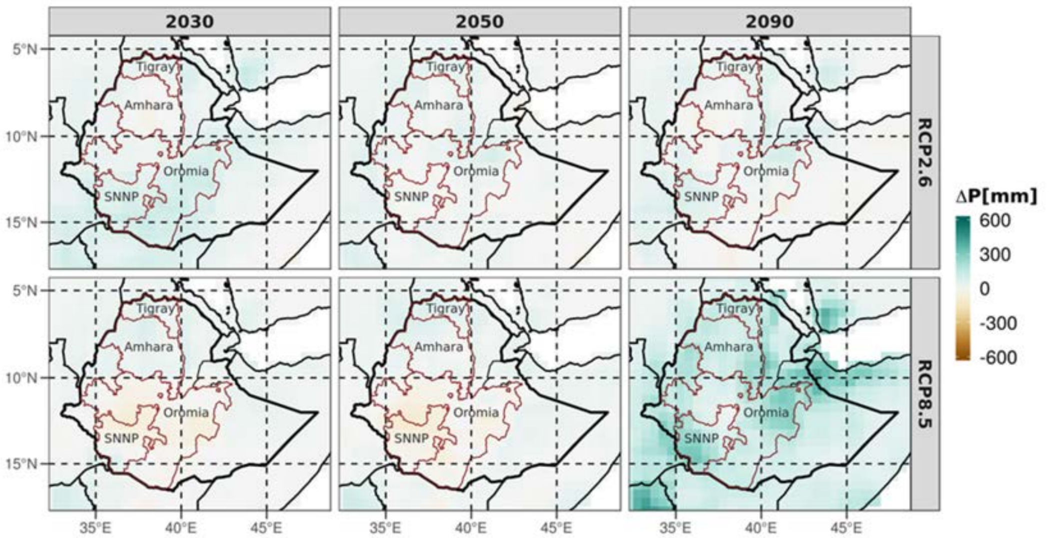


Figure 11: Annual average precipitation difference in 2030, 2050 and 2090 in relation to 2007 under RCP2.6 (top) and RCP8.5 (bottom) projected by the multi-model mean.

Extreme precipitation events are projected to increase with climate change, especially in the south-western quadrant of Ethiopia.

In addition to projections for average changes in precipitation, future precipitation extremes are particularly relevant for agriculture. Under a warmer climate, extreme precipitation events like days with heavy precipitation (exceeding the 95th percentile indicated by EWEMBI for 2007) and very heavy precipitation (exceeding the 99th percentile indicated by EWEMBI for 2007) are expected to increase. Figure 5 shows the heavy precipitation extreme threshold in 2007, upon which the analysis of future precipitation extremes is based. Over Ethiopia, mostly the southwestern quadrant of Ethiopia is projected to be affected by increasing precipitation extremes (see Figure 12). The average increase in the days with heavy precipitation across Ethiopia (95th percentile over Ethiopia of 16.6 mm) ranges from 9 to 15 days (by 2030) as average per decade under RCP2.6 and from 7 to 41 days under RCP8.5. The change in heavy and very heavy precipitation extremes is projected to occur with similar distribution and only slightly different magnitudes of change.

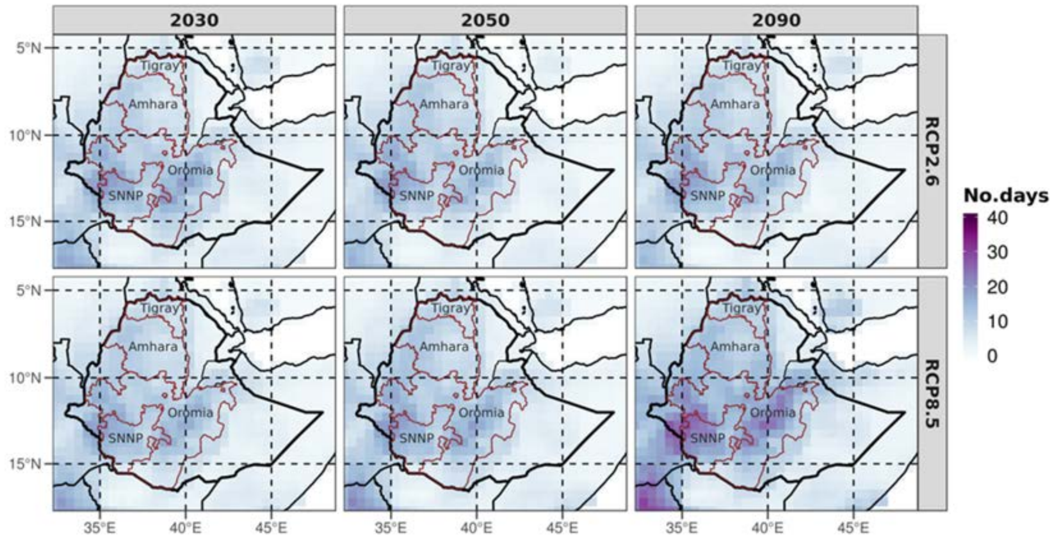


Figure 12: Number of days with heavy precipitation per year under scenarios RCP2.6 (top) and RCP8.5 (bottom) for 2030 (left), 2050 (middle) and 2090 (right), projected by the ISIMIP multi-model mean.

Besides extreme precipitation events, projected precipitation during the main agricultural seasons is of high importance for farmers. During the main rainy season (from the end of February to the end of September), Ethiopia receives 80% of its annual precipitation (~90% in Tigray, ~88% in Amhara, ~79% in Oromia and 74% in SNNP), thus covering the main agricultural period (sowing, growing and harvesting). Therefore, the projections show similar patterns as for the average annual precipitation. More information in relation to the main rainy season can be found in the supplementary material.

Chapter 1 Summary

Historical and present climate
• Ethiopia has an average mean annual temperature of 23.0°C, reaching higher temperatures in the northeastern part of the country, and lower ones in Amhara region. • Mean annual precipitation ranges from around 100 mm in the northeast of the country to above 1,900 mm in the highlands. • Ethiopia currently experiences about 57 very hot days per year (maximum temperature above 35°C), on average, and about 8 very hot nights (minimum temperature above 25°C).
Projected climatic changes
• Mean annual temperature is projected to increase by 1.6°C until 2030, by 1.8°C until 2050 and by 1.9 until 2090 under RCP2.6, and by 1.8°C until 2030, by 2.6°C until 2050 and by 4.6°C until 2090 under RCP8.5, compared to pre-industrial levels. • Projected precipitation changes are uncertain, but models agree on a precipitation increase during the second half of the century under RCP8.5. • The number of very hot days and tropical nights per year is projected to increase considerably, especially under RCP8.5 and by the end of the century. Over Ethiopia, the average of very hot days would increase from 12 to 16 under RCP2.6 by 2050 and from 20 to 94 under RCP8.5 by 2090. The number of very hot nights would increase seven times per 20-year period on average under RCP2.6 and from 7 to 59 under RCP8.5 by 2090. • Extreme precipitation events are projected to increase slightly, with a maximum of four heavy precipitation events per period under RCP8.5 by 2090 and two additional very heavy precipitation events for the same period and scenario.

Chapter 2 – Changing water availability for agricultural production

Ethiopia is the second most populous country on the continent with around 105 million people (World Bank, 2018) and plays a prominent socio-economic and geopolitical role in the region. The country is well known as Water Tower of Africa with 12 river basins, 22 lakes and groundwater resources, which deliver about 2.6 billion m^3 water per year. Future development and variability of water resources can affect the economy with a growing energy and water demand in different sectors like agriculture, industry, transportation etc. in the region (Degefu, He, & Zhao, 2015; Liersch et al., 2018).

For the assessment of climate change impacts on water resources for agricultural production in Ethiopia, an eco-hydrological model SWIM (Soil and Water Integrated Model) (Krysanova et al., 2000) was used. In this study, for the hydrological part, we have focused on two river basins: the Blue Nile and the Awash basin (Figure 13), as crop land covers large parts of these basins, which gives them an important role in the country's economy. The Blue Nile is one of the two major tributaries of the Nile, which originates at Lake Tana in the Ethiopian Highlands. The catchment is located in the northwestern part of the country (Taye & Willems, 2012). It covers a total area of 296,000 km^2 and it is one of the major sources which contributes 55-65% of flow to the Nile (Liersch et al., 2018). The Awash River, with a total area of 110,000 km^2 and a length of 1,200 km, is another major river in Ethiopia. It falls entirely within Ethiopia's boundaries. The river originates in the high plateau near Ginchi town, located west of Addis Ababa, and terminates in the Lake Abbe on the border to Djibouti (Taddese, Sonder & Peden, 2003).

For the hydrological analysis, the eco-hydrological model SWIM was used and two river basins were studied, the Blue Nile basin and the Awash River basin.

2.1 Input Data and Hydrological Modelling

To set up the SWIM model, a number of data and information was collected and converted into appropriate format. A digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) (CGIAR-CSI, 2017) with 90 m resolution. Soil parameters were derived from the Harmonised World Soil Database (HWSD v1.2) (FAO et al., 2012). The land use data is retrieved from World Land Cover BaseVue 2013 developed by MDA (MDA BaseVue, 2019) with 30 m resolution, but aggregated to 90 m. The SWIM model was set up, calibrated and validated using daily and monthly data for a number of gauges in the Blue Nile and Awash River basins. The river discharge was provided by the Global Runoff Data Centre (GRDC, 2017).

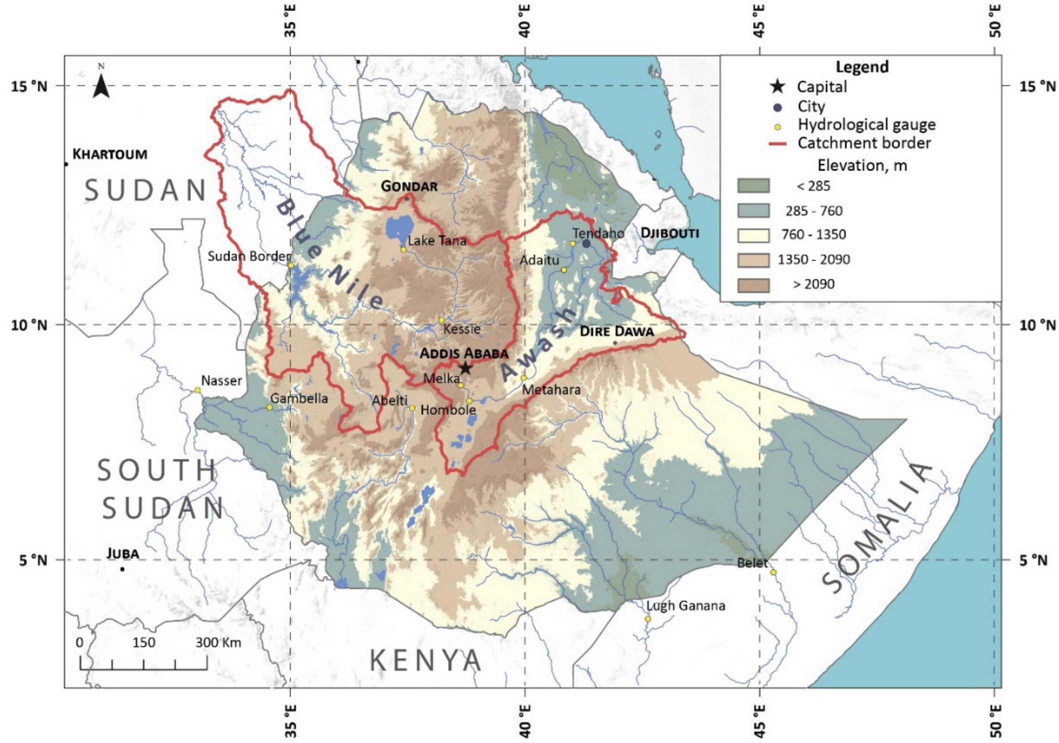


Figure 13: Study areas: The Blue Nile and Awash River basins.

Although the main goal was to assess the climate change impact on the hydrological cycle without changes in water management and land use, existing and planned reservoirs were also included in the modelling process in both basins, as a second analysis. Land use was considered as stable over the years.

2.2 Results and discussion

For the analysis on future water availability under climate change, the hydrological model was driven by two emissions scenarios (RCP2.6 and RCP8.5) with the input of three global climate models until the end of the 21st century.

After model calibration and validation for both basins, the hydrological model was driven by two climate scenarios (RCP2.6 and RCP8.5) with the input of three GCMs until the end of the 21st century. The results of calibration and validation of the model and agreement of different climate models for the historical period for the Blue Nile and Awash River basins are presented in the supplementary material. The absolute and relative changes of the river discharge were analysed for both basins. Results for the Sudan border (Blue Nile) gauge are presented in this section, results for the Awash basin are presented in the supplementary material. For the assessment of the river discharge changes, the simulation period was divided into the reference period from year 1986 to 2005 and three future periods (P1: 2021-2040, P2: 2041-2060 and P3: 2080-2099). The assessment of changes was based on periods instead of single years to avoid the variability of climate (year to year) and to get a robust signal for the future conditions in general. Initially, the IPSL-CM5A-LR model was also included in the assessment. However, while conducting the analysis, a strong deviation in precipitation for the Blue Nile basin was detected. Similar results have been found in previous studies (Liersch et al., 2018; Teklesadik et al., 2017) and it was thus decided to exclude this model from the assessment of climate change impacts on the hydrological cycle. Some examples of the bias of the IPSL model are presented in Chapter 11.

Average annual river discharge projections

Figure 14 and Figure 15 show the 11-years moving average of the projected mean annual discharge for the Sudan border gauge (Blue Nile) under RCP2.6 and RCP8.5 until the end of the century. Grey areas indicate the three future periods and the reference period. The mean of changes among the models shows an increase in all periods of up to 11% under RCP2.6. Similar changes occur under RCP8.5 in the first (P1) and second (P2) future period with an increase of mean annual discharge by 11%. In the last future period (P3), the river discharge is observed to increase by 45%, where the MIROC5 model gives the highest changes.

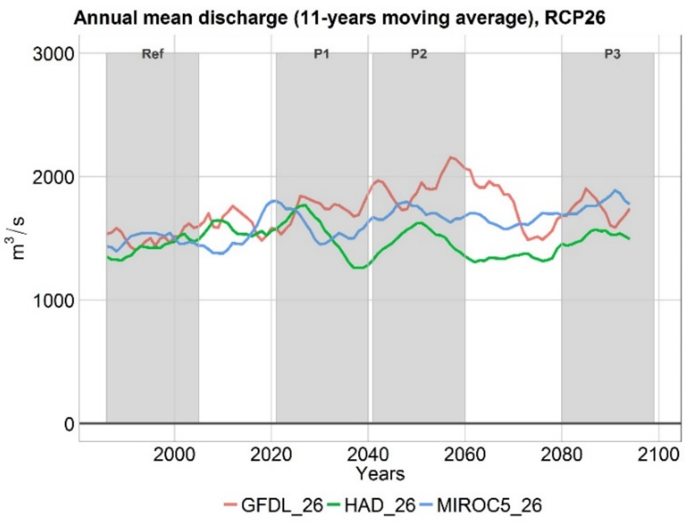


Figure 14: Annual mean discharge at the Sudan border gauge (11-years moving average) under RCP2.6.

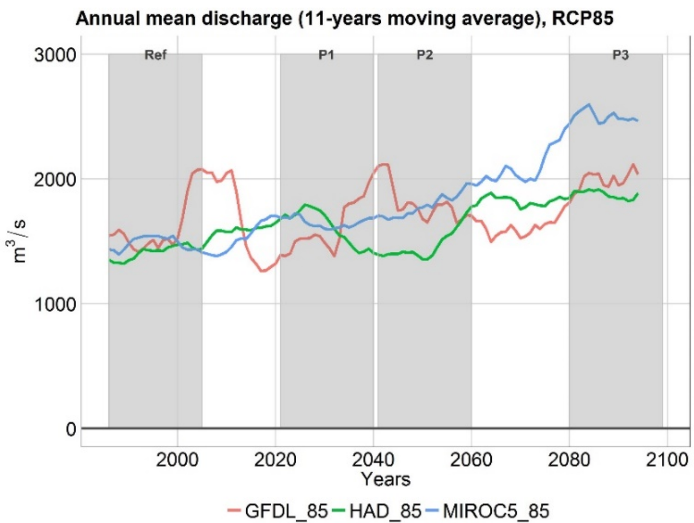


Figure 15: Annual mean discharge at the Sudan border gauge (11-years moving average) under RCP8.5.

To have a better understanding of the origins of changes, the results for each climate model were analysed independently, i.e. analysing the results from each model individually. The MIROC5 model shows the highest changes of mean annual river discharge towards the end of the century under RCP8.5. In the first period, river discharge increases by 11%, in the second by 18% and in the last period by 69%. The GFDL model shows the highest increase (by 36%) in the second future period compared to other future periods and models under both RCPs. In general, all projections of mean annual discharge show wetter conditions in all future periods compared to the reference under RCP2.6 and RCP8.5 for the Blue Nile basin. In the Awash River basin, no significant changes were found in annual mean discharge for all future periods under both RCPs, except for the last period under RCP8.5, where the river discharge increases by 32%.

For the Blue Nile basin, wetter conditions are projected in all future periods and for both emissions scenarios, compared to the current situation.

Average monthly discharge projections

The seasonal changes of river discharge at the Sudan border gauge (Blue Nile basin) for three future periods compared to the reference period under RCP2.6 and RCP8.5 are presented in Figure 16 and Figure 17. Absolute changes are presented in red and blue colours, where solid lines are the multi-model mean and the dashed area shows the model spread. The relative values are presented in red lines, which indicate the multi-model mean, and grey dashed areas for the model spread.

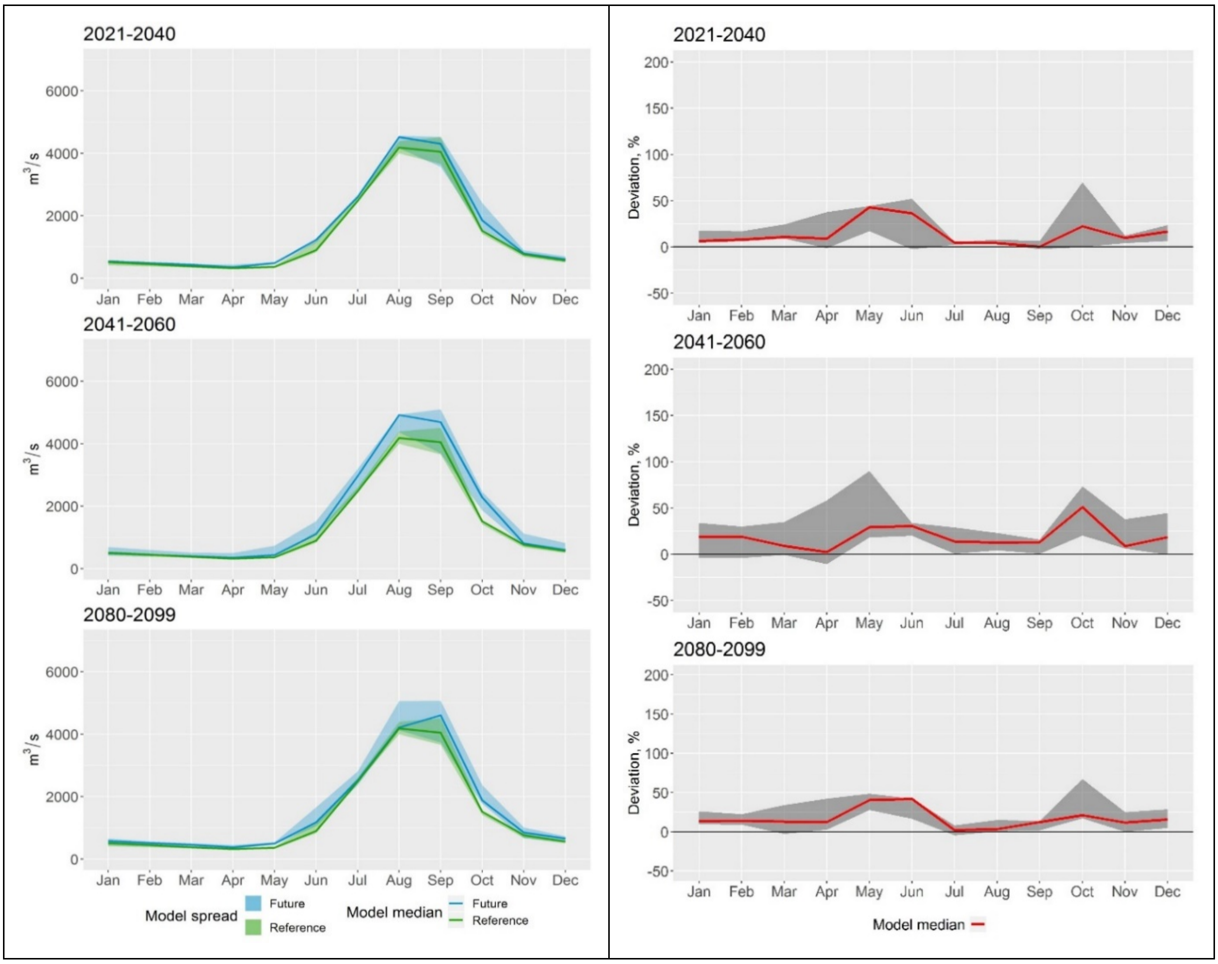


Figure 16: Absolute (left) and relative (right) mean monthly discharge changes of the river discharge at the Sudan border gauge (Blue Nile basin) for three future periods, compared to the reference period under RCP2.6.

The results show a stable increase in monthly river discharge throughout the year in all future periods under RCP2.6. The highest changes are observed in May, June and October in all future periods and can reach up to 51%. The lowest changes are projected from July to September in the first future period (P1) and in July and August in the last future period (P3). However, in the second future period, the lowest increase is projected in early spring. An increase in May-June at the beginning of the wet period and in October – end of the period – means a prolongation of the wet period in the future. Despite a steady increase in annual mean temperature until the end of the century, there is no strong trend between different future periods with regard to increases or decreases of river discharge under RCP2.6 until the end of the century.

The monthly river discharge in all future periods was also analysed for both emissions scenarios.

The GFDL model projects the highest increase of the monthly river discharge among the models, especially in the second future period (P2), similar to annual river discharge. The lowest changes have been projected for the MIROC5 model in the first two periods, where changes could be even negative.

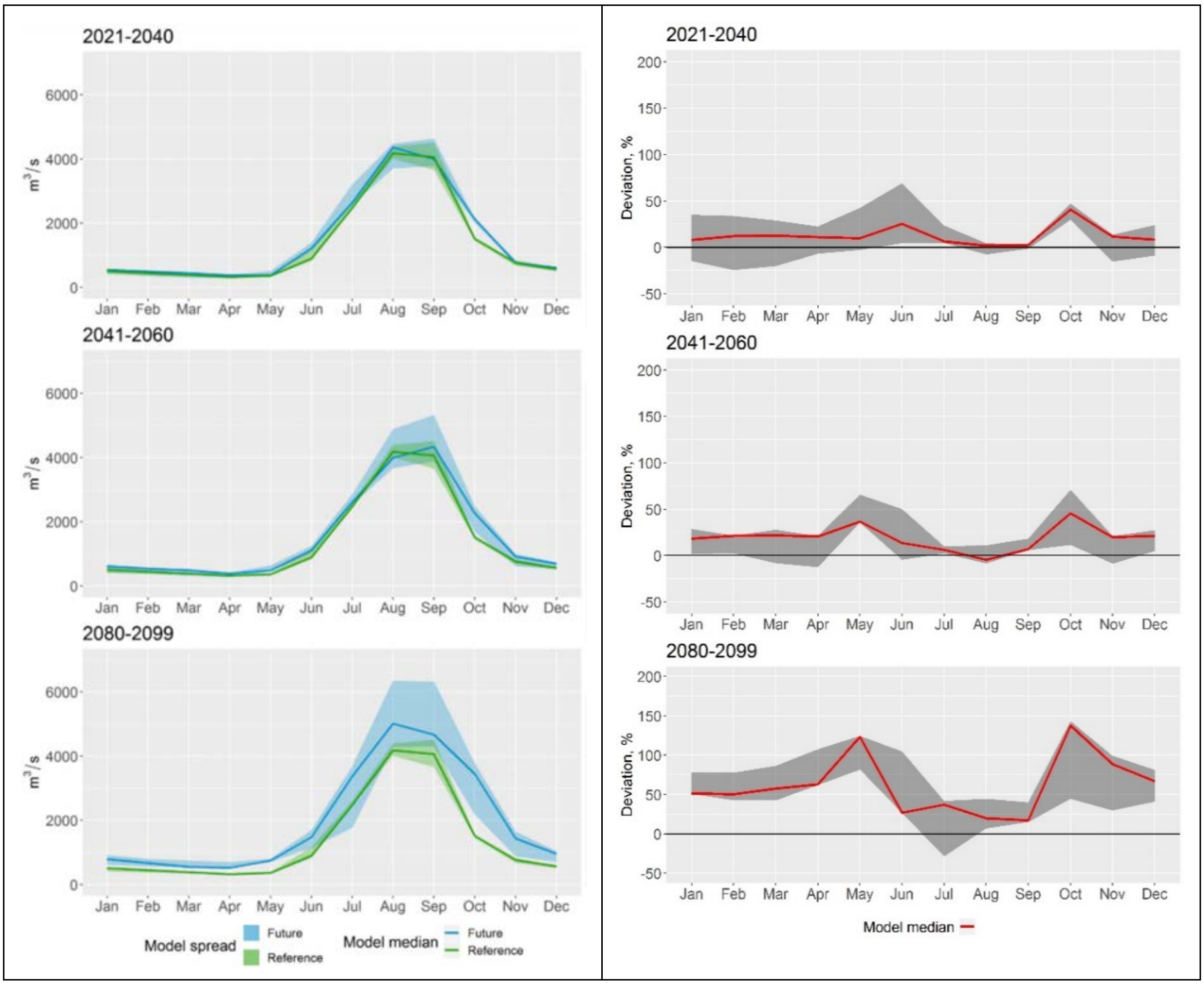


Figure 17: Absolute (left) and relative (right) mean monthly discharge changes of the river discharge at the Sudan border gauge (Blue Nile basin) for three future periods compared to the reference period under RCP8.5.

The multi-model mean changes in monthly river discharge under RCP8.5, compared to the reference period, are projected to increase during all seasons and all future periods, except August of P2 (Figure 17). Similar to RCP2.6, the highest changes under RCP8.5 occur in May-June and October in all future periods. At the same time, the changes under RCP8.5 are higher compared to RCP2.6. Further, there is an increasing trend towards the end of the century, as can be seen for the last period (P3), where all values of change are above 17% and the changes in height reach up to 137% (October, P3).

However, despite the multi-model mean showing an increase of river discharge in all future periods in all months, the GFDL model shows a decrease in the first future period (P1) during winter and summer months of up to 24%. In the last two periods, the GFDL model projects an increase of river discharge for the majority of months.

Regarding changes in the Awash River basin at the Hombole gauge, similar to the Blue Nile, the multi-model mean of monthly river discharge shows an increase of river discharge in June and October in all periods under both RCPs (see supplementary material). However, in the first period (P1), monthly river discharge is projected to decrease in autumn (except October) and winter under both RCPs.

In sum, the two river basins analysed for this study are projected to see higher water availability in the future. This additional water could be used for irrigation, but water demand for irrigation could also rise under future climate change.

Taken all together, the projected changes of annual river discharge in the two Ethiopian river basins analysed show an increase in all future periods, which means an increase of water availability in general and in particular for the agricultural sector. Moreover, seasonal changes show a higher water availability during the year, especially in May-June, which can be beneficial for irrigation in the region. On the other hand, an increase in October may cause post-harvest losses. In addition, such increases in these months mean a prolongation of the wet period of the year in all future time periods under both RCPs. At the same time, results show an increase of potential evapotranspiration until the end of the century with no trend in actual evapotranspiration, which means an increase in water demand for irrigation (see supplementary material).

Electricity production

Potential for electricity production from hydropower is projected to increase in the future, for both emissions scenarios.

In this study, together with the assessment of the river discharge changes until the end of the century, the electricity production of hydropower plants in the basins under study was considered. The multi-model mean of annual average electricity production of the Koka (Awash 1) hydropower plants under RCP2.6 and RCP8.5 is presented in the supplementary material. The potential electricity production is projected to increase in all future periods under both RCPs. Changes under RCP8.5 are higher, compared to RCP2.6, and reach up to 30% in the last future period (P3).

Changes in the multi-model mean of 90th percentile monthly electricity production for the Koka (Awash 1) hydropower plants show an increase from May to September of more than 7% and from July to August - for more than 31% in all future periods under both RCPs. The highest changes under RCP2.6 and RCP8.5 occur in the last period and are always positive during the year. For the rest of the months under both RCPs no significant changes were found (see supplementary material).

Chapter 2 Summary

Main findings for changes in water availability
• For the Blue Nile basin, the multi-model mean of average annual discharge projections increases in all future periods under both RCPs, with the projected increase ranging from 10% to 45%. • For the Awash River basin, the changes of the multi-model mean of average annual river discharge show an increase of up to 32% under RCP8.5 until the end of the century. • The multi-model mean shows an increase of monthly river discharge in all periods for the majority of months under both RCPs. The changes under RCP8.5 towards the end of the century are higher compared to other periods and RCPs. • The highest changes are projected in May-June and October under both RCPs, which could be an indicator of prolongation of the wet period and more water available for irrigation in the region in the future. • An increase of the river discharge in the Blue Nile basin means a higher water availability for agriculture in all three future periods under both RCPs. • An increase of potential evapotranspiration towards the end of the century can lead to higher water demand for irrigation.

Chapter 3 – Climate impacts on agricultural production

Most of the crops in Ethiopia are produced by smallholder farmers, with low input use and without irrigation technologies.

The agricultural system in Ethiopia is diverse including food crops, cash crops and livestock. Crop production is mainly based on rainfed, low-input smallholder agricultural systems. Spatially, agriculture is distributed across the various heterogeneous agro-climatic zones, which in turn are highly influenced by different elevation levels. Production patterns thus follow a climate gradient influenced mainly by altitude. Precipitation distribution varies over the diverse AEZs: It ranges from around 1,900 mm in the humid highlands to about 100 mm in the drylands in Afar and Somali regions. Mean annual temperature follows a reverse trend of being cooler in the highlands and warmer in the dry areas (Conway & Schipper, 2011; FAO, 2011). Consequently, agricultural production follows these climatic patterns, as agricultural activities are practiced in areas for which they are most suitable. Areas of high agricultural potential have coincided with high rural population densities and resultant land pressure, especially in the *weyna dega* and *dega* zones, which are best suited for production of the main staple crops in Ethiopia (Chamberlin & Schmidt, 2014)[8]. In addition to these patterns for crop production, agricultural production is also influenced by climatic extremes, such as droughts and heavy precipitation.

The variation in crops yields in Ethiopia can be explained by differences in weather conditions and soil fertility as well as limited use of agricultural inputs.

Drivers of crop yield variation in the country are weather variables, soil fertility and use of agricultural inputs, which is often very limited. The relative contribution of each of these factors to yield formation and variance of major crops varies over time and space. The relative climatic risk to crops differs between different areas, crops and years, with notable divergence between aggregate, regional and local drivers of crop production. Yet, for this analysis, we focus on biophysical drivers, which can be analysed employing a range of different climate impact models. Some of the main agricultural crops in Ethiopia are maize, teff, sorghum, wheat and barley, together with common beans and other pulses. For our analysis, we focus on maize, teff, sorghum and wheat, as in combination they make up about 80% of arable land area in Ethiopia and are the major staple crops.

Maize (*Zea mays*) is the most important staple food in terms of caloric intake, number of farmers/rural households and production volume in Ethiopia (Abate et al., 2015). As such, maize has a long history of production. The growing periods for maize depend on local conditions and can vary between 70 and 210 days, depending on crop genetics, production system, agronomic management and weather conditions. Teff (*Eragrostis tef* (Zucc) Trotter) is also an important crop in Ethiopia, being planted on the largest area and coming second in terms of production volume (Haileselassie et al., 2016). Teff is mostly suitable in the highlands, but is widely grown in Ethiopia across various climatic zones. It prefers annual precipitation above 750 mm and temperatures between 10 and 27°C (FAO, 2011). Sorghum (*Sorghum bicolor*) is another main crop that takes 90-120 days to mature with the grain being used for both food and feed. Sorghum is more adapted to adverse weather conditions than maize, teff and wheat and thus has a wider potential production area in Ethiopia than the other crops. Finally, wheat (*Triticum aestivum*) also belongs to Ethiopia's major crops, being produced by about 35% of smallholder farmers on 17% of the total arable area in Ethiopia, mainly in the highlands. Wheat can be harvested 90-150 days after planting.

We analysed four crops in this study: maize, teff, sorghum and wheat. They are major staple crops and important for food security.

[8] The *weyna dega* zones or subtropical zones include the highland areas with elevation levels between 1830-2440 m and the *dega* zones include all zones above 2 440 m.

3.1 Weather signal and crop yields in Ethiopia

Two crop models were used to assess the impact of climate change on crop yields in Ethiopia, a statistical model and a process-based crop model.

To elicit the share of crop yield variation that is caused by variance in weather or other factors we apply two distinct models. The first is a statistical model, AMPLIFY (Agricultural Model for Production Loss Identification to Insure Failures of Yields) (Gornott & Wechsung, 2016; Schauberger, Gornott, & Wechsung, 2017) which relates changes in weather variables to changes in crop yields and thus requires only little information on the agricultural system in Ethiopia, while being able to separate the yield variation induced by weather from variation induced by other (agronomic) factors. The second model is a process-based crop production simulator, APSIM (Agricultural Production Systems sIMulator) (Holzworth et al., 2014) which simulates plant growth and yield formation on daily time step, thus allowing for a testing of adaptation strategies and long-term crop yield projections under climate change. The results for APSIM are presented in the next section.

For the AMPLIFY model, exogenous variables are different weather indices measured during the growing season. The model quality is measured by reproduction of the observed yield time series on national level, with an additional out-of-sample quality test. Input data are precipitation, mean temperature and potential evapotranspiration (PET), split between the vegetative and the reproductive parts of the growing season. The split between these two parts is defined by the month when 50% of the total growing-season GDD[9] are reached. This split is necessary, as climatic influences between the two parts may differ. All weather data are derived from ERA-Interim (Dee et al., 2011) and are summarised to monthly aggregates from daily values.

Climate has a substantial impact on crop production in Ethiopia: on national average, weather explains 55-89% of the yield variability from year to year.

The analysis with AMPLIFY shows that climate has a substantial impact on crop production in Ethiopia. On national average, weather explains 55-89% of the year-to-year yield variability, which is confirmed by the process-based model APSIM (see next section). This is evidenced by a co-variation of crop yields with the variations of weather for maize, sorghum, wheat and teff (Figure 18). Strong losses in crop yields (e.g. in 2009 for maize and sorghum or 2012/2014 for wheat) are accompanied by abnormal weather phenomena, which are likely to occur more frequently in a future with climate change. Water provision, in particular, is a major determinant of agricultural performance. For teff, a reasonable connection with weather could not yet be established (evidenced by the low out-of-sample performance; panel 18d in Figure 18). This may likely be due to discrepancies in growing seasons between the regions, which are not reflected in the national cropping calendars provided by the FAO, undocumented variation in management inputs or data issues inherent in the time series.

9 Growing Degree Days, the sum of daily temperatures above a threshold of 0°C for teff and wheat and 8°C for maize and sorghum.

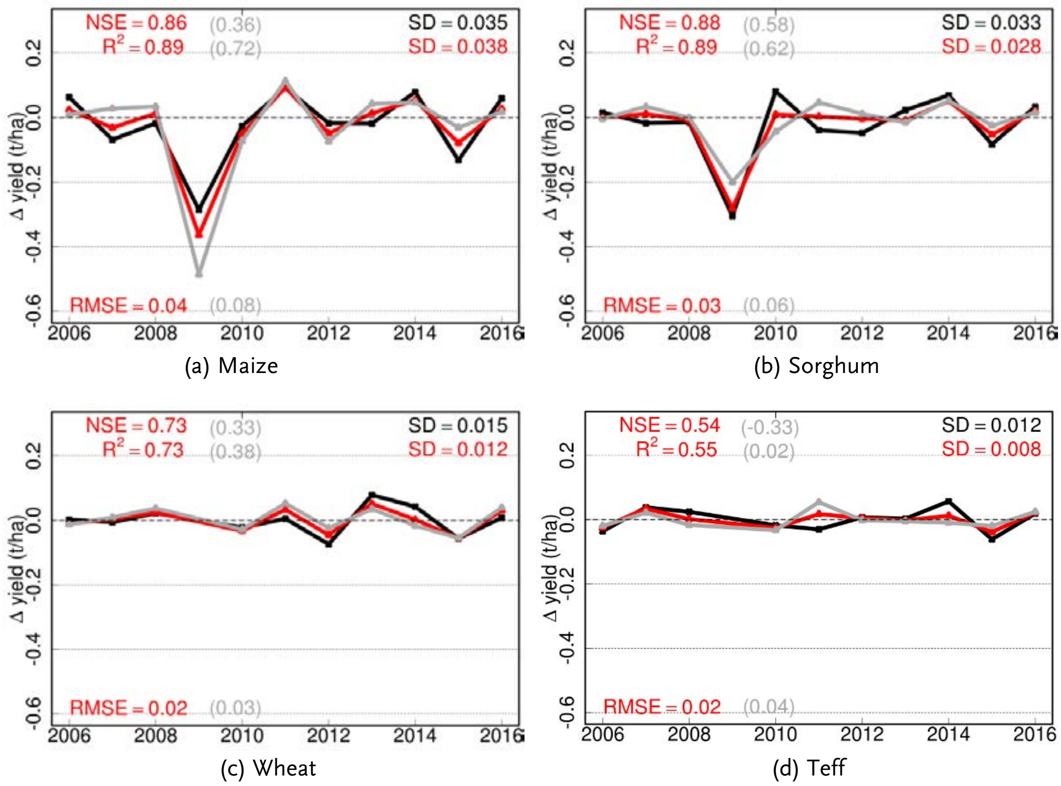


Figure 18: Co-variation of nationally averaged crop yields with weather in Ethiopia for (a) maize, (b) sorghum, (c) wheat and (d) teff. Time series of yield anomalies (the deviation of the expected yields, in t/ha) are shown between 2006 and 2016. Black lines are observed yield anomalies, red lines are modelled yields estimated with the full observed data set and grey lines are modelled yields estimated out-of-sample. NSE (Nash–Sutcliffe model efficiency coefficient), R^2 and RMSE (Root Mean Square Error) indicate model performance, once for the full model (red) and once for the out-of-sample model (grey). SD denotes standard deviation for observed (black) and modelled yields (red).

3.2 Yield loss assessment with process-based modelling using APSIM

The process-based crop model APSIM was used for projecting maize yields. APSIM simulates maize growth, based on weather data, soil characteristics and information on crop management.

To simulate maize yield losses, the process-based crop model APSIM was applied for the period 2006-2016. Maize was chosen for the analysis, as good data was available and due to its high importance for Ethiopian agriculture. The simulations were run using the APSIM-Maize module. The APSIM-Maize module simulates the plant physiological processes in maize growth and grain development on a daily time step in response to daily input of weather data (CHIRPS for precipitation and WFDEI for temperature), soil characteristics (ISRIC Grids for soil profiles) and crop management actions (from field survey data, published papers and national agricultural survey reports).

Planting windows, maize varieties, planting density and nitrogen fertiliser rates were the key management inputs that varied for each zone. Each year, the simulated crop was planted after sufficient first rains in a planting window. This planting window is determined by the agronomic profile of each respective zone. To determine the yield changes under climate change, projected climate data from the ISIMIP project was used. We averaged precipitation, temperature and radiation for each day over the entire zone to align those parameters with the spatial scale of modelling.

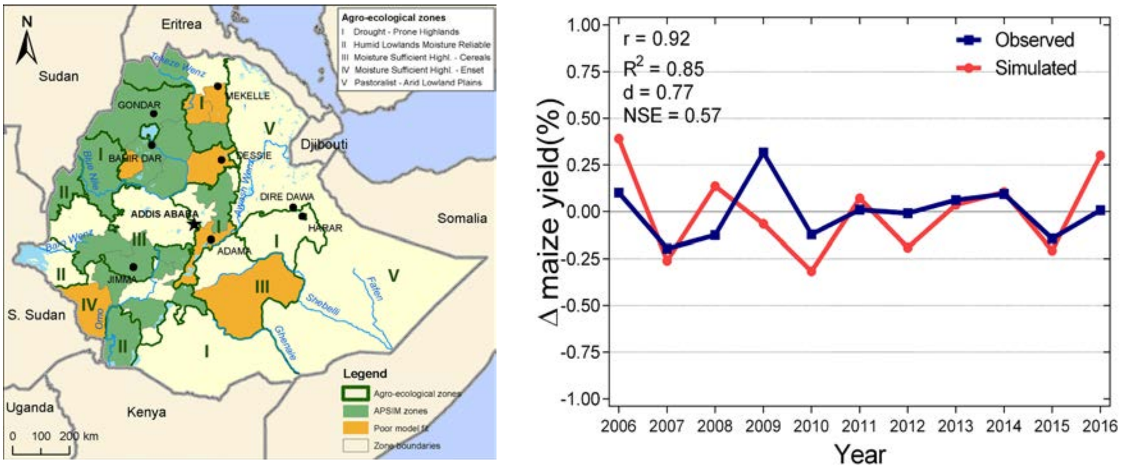


Figure 19: (a) Distribution of APSIM model fitting zones (b) De-trended anomalies of time series of maize yields for Ethiopia, 2006 and 2016 from APSIM model.

Current trends in maize yield in Ethiopia

Maize yields vary a lot in Ethiopia from year to year and from region to region.

The trends in the spatial characteristics of maize yield in Ethiopia for each of the zones are illustrated in Figure 20. The distribution of the yield between 2006 and 2016 shows that there is significant year-to-year variation in maize yield, explained by changes in weather or management (or both). Generally, most of the zones are producing approximately the national average yield, with East Shewa having consistently high maize yield, while North Wollo, South Tigray and Wag Hemira zones for instance are low maize yield zones (Figure 20). Any climatic pressures in these low-maize-yielding zones will exacerbate the food security situation and may severely affect related livelihood systems. There is large variation in maize yields in many zones, especially in Awi, East Gojam, Guraghe, Illuababor, Gamo-Gofa, Kemashi, Metekel, Sidama and Western Tigray. These zones with high inter-annual variability in maize yield represent areas of high volatility and production risk under current climatic conditions.

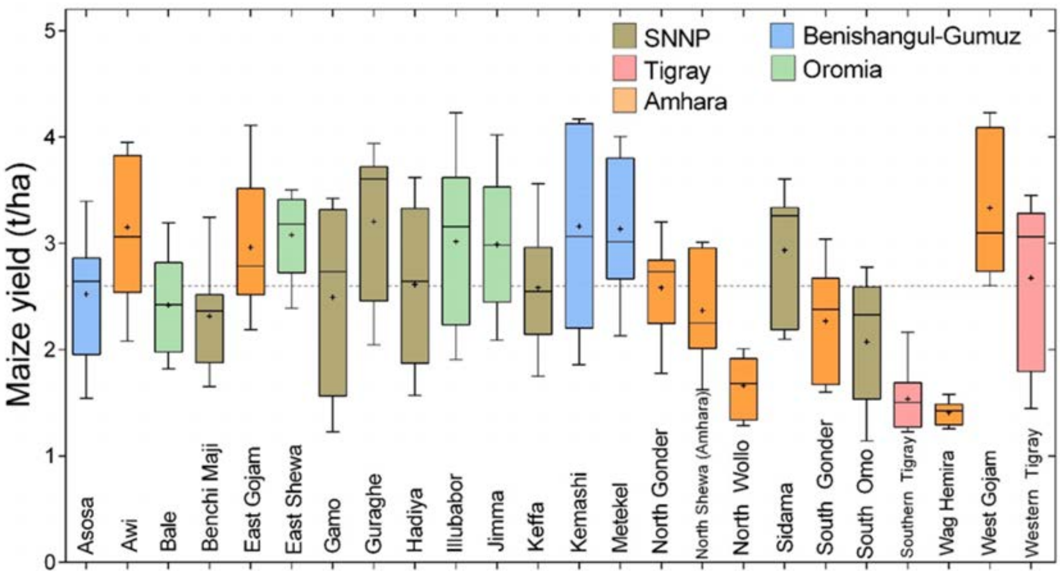


Figure 20: Current observed trends in maize yield for each zone. The dotted line is the long-term national maize yield average.

Projected maize yield changes under climate change

Using the 18 zones for which APSIM modelling was satisfactory, the daily weather forcing data in the model was replaced by the projected weather data from 01 January 2041 to 31 December 2060 for RCP2.6 and RCP8.5 from the three GCMs. The yield changes that are attributable to the projected changes in climate are shown in Figure 21, without CO_2 fertilisation effect. At national levels, the results show that there will be a yield increase of 5% under RCP2.6 and 1% under RCP8.5 in Ethiopia. These increases are driven by simulated maize yield increases in South Gonder, Jimma, East Gojam, West Gojam and Asosa (Figure 21). Six zones are projected to experience yield losses under climate change. These are Western Tigray, South Omo, North Shewa (Amhara), Metekel, Guraghe and Gamo-Gofa. While higher yield losses are projected under RCP8.5 than under RCP2.6, the pattern is less uniform for yield increases, with some areas experiencing higher increases under RCP2.6 and others under RCP8.5. The results show that maize yields in a further four zones will remain stable under climate change, i.e. within a 10% range of change only (from +5% to -5%), as indicated by the dotted red line.

Under future climate change, some zones are projected to experience maize yield decreases, whereas in other areas, the yield will increase.

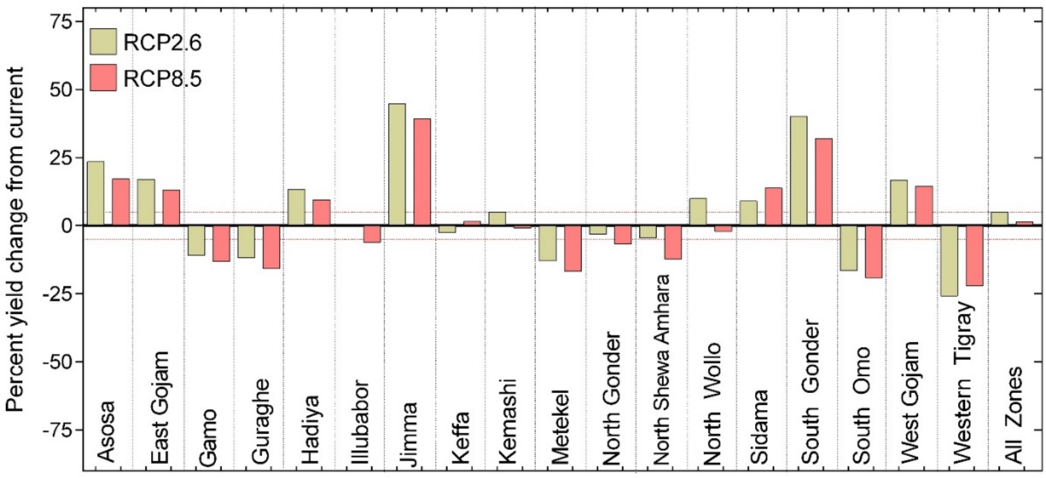


Figure 21: Climate change induced yield changes for selected zones in Ethiopia under the RCP2.6 and RCP8.5 scenarios, without CO_2 fertilisation. The red dotted lines represent the 10% window within which yield changes are considered stable.

3.3 Impact of climate change on crop suitability

Climate change not only affects crop yields, but also the suitability of areas to grow specific crops.

Besides weather influence on crop yields and projected yield losses under climate change, climatic changes also affect the suitability of an area to produce a certain crop. The biophysical ability of an area to produce a crop explains the spatial distribution of crop production in Ethiopia. With climate change, the suitability of an area to grow a specific crop can change to other regions or altitudes.

Given the strong influence of weather on the Ethiopian crop production, it is clear that the biophysical conditions are important determinants for the distribution of agricultural production in Ethiopia. Therefore, any changes in the climatic conditions affect crop suitability and production, with downstream impacts on food security, livelihoods and local, regional and national economic development. We have thus used suitability models to characterise the current suitability for maize, sorghum, teff and wheat in Ethiopia and to understand the crop suitability changes under different climatic scenarios. The variables used for the suitability modelling were obtained from daily weather data for the current and projected climatic conditions using the RCP2.6 scenario and RCP8.5 scenarios. The variables that were used for suitability modelling can be classified into precipitation, temperature and soil variables. Precipitation variables were total precipitation in the growing season, total precipitation received between sowing and harvesting, sum of precipitation in the crop-sowing month and a precipitation coefficient of variation between sowing and harvesting. Temperature variables were diurnal temperature range between sowing and harvesting, mean temperature in the growing season and mean temperature between sowing and harvesting. The soil variable was top soil organic carbon. These variables used are based on the conditions for the growing period of the various crops, as determined from the crop calendar of Ethiopia from FAO.

Before presenting the results of this analysis, it is important to note that not all of Ethiopia is currently suitable to produce crops. In fact, some 47% of the country, especially in the Somali and Afar regions, cannot produce any of the four crops analysed here, although those areas may of course produce other crops and be put to other agricultural use, such as pastoralism.

Results and discussion

Under present day conditions, the suitability of areas to produce maize, teff, sorghum and wheat differs across Ethiopia's agro-ecological zones.

Crop suitability modelling results show that the suitability of areas to produce maize, teff, sorghum and wheat in Ethiopia varies across different AEZs (Figure 22). Generally, the area share suitable for producing sorghum is highest in all AEZs, with the suitability for wheat production lowest at national level, but this varies across AEZs and administrative regions. Current production figures and areas cultivated do not correspond to the identified crop suitability in Ethiopia. Data shows that the largest area is put under teff production (28%), followed by maize (21%), with sorghum and wheat at 17% of the cultivated area.

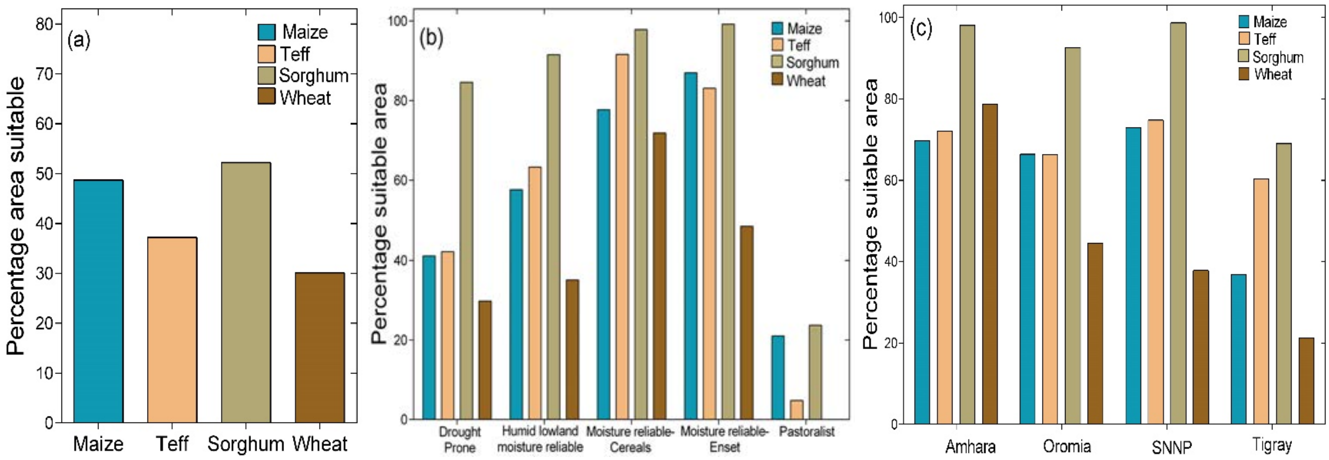


Figure 22: Current crop suitability according to (a) national (b) AEZs and (c) selected administrative regions under current climatic conditions.

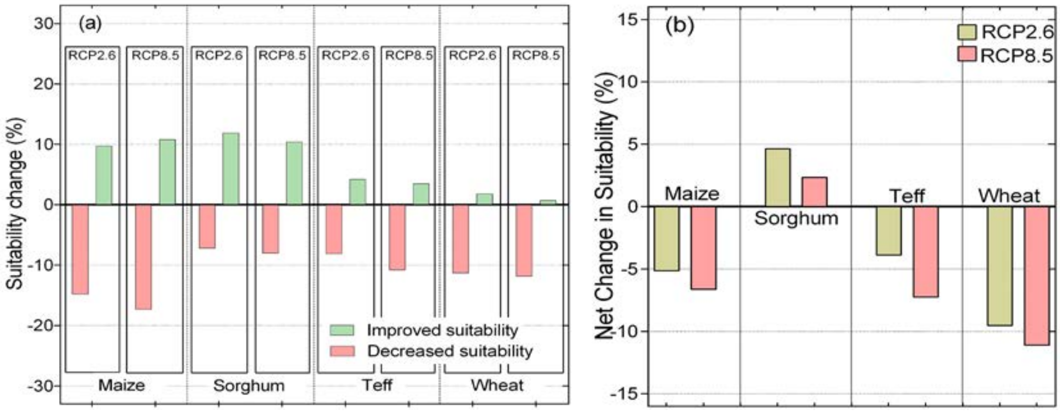


Figure 23: Impact of climate change on suitability of maize, teff, sorghum and wheat in Ethiopia under RCP2.6 and RCP8.5.

Maize suitability

By 2050, the model projects a net loss in maize suitability of 5% under RCP2.6 and 7% under RCP8.5 for the whole of Ethiopia. Amhara and Tigray will experience lower suitability, with suitability in SNNP increasing.

The results show that 49% of Ethiopia has potential for maize production under current climatic conditions. The majority of these suitable areas are in the Humid Lowlands Moisture Reliable, Moisture Sufficient Highlands – Cereals and the Moisture Sufficient Highlands – Enset AEZs (Figure 24). Two thirds of the Oromia region is currently suitable for maize production, while 70% of the Amhara region is suitable for maize. The largest proportion suitable for Maize can be found in the SNNP region (73%), while the lowest share is in the Tigray region with only 37% of the region modelled suitable for maize production under current climatic conditions. Under projected climate change, 15% (RCP2.6) or 17% (RCP8.5) of the area currently suitable for maize in Ethiopia will become marginal (or less suitable), while 10% (RCP2.6) or 11% (RCP8.5) of the area currently marginal for maize will become more suitable by 2050. Therefore, the modelling projects a net loss in maize suitability of 5% under RCP2.6 and 7% under RCP8.5 in Ethiopia (Figure 23). The largest proportion of the losses in suitability will occur in the Drought prone zone (28% for RCP2.6 and 30% for RCP8.5). For the Humid Lowlands Moisture Reliable AEZ, no change is projected under RCP2.6, but a net decrease in suitability for maize of 10% will occur under RCP8.5. The Moisture Sufficient Highlands – Cereals and the Moisture Sufficient Highlands – Enset regions are projected to see increased maize suitability by 2050. In terms of administrative regions, Amhara and Tigray are projected to lose a proportion of their currently suitable area for maize, with increases in suitability in the SNNP region (Figure 24).

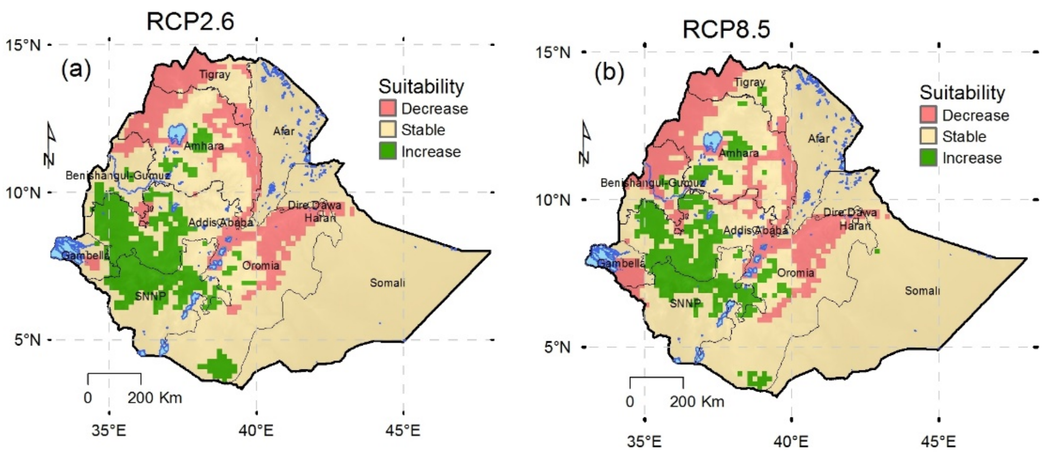


Figure 24: Projected impact of climate change on suitability of maize under (a) RCP2.6 and (b) RCP8.5 scenarios in Ethiopia by 2050.

Teff suitability

Model results show that 38% of the country is suitable for successful teff production under current conditions. The Moisture Sufficient Highlands – Cereals (92%) and the Moisture Sufficient Highlands –Enset (83%) are the most suitable AEZs for teff production in Ethiopia (Figure 25). The Humid Moisture Reliable Lowlands (63%) and the Drought – Prone Highlands (42%) have extensive areas that can meet the climatic production requirements of teff. Around three quarters of SNNP and Amhara are suitable for teff production, while about a third of Oromia and Tigray are suitable (Figure 25). Under the climatic conditions projected for 2050, a net loss in teff suitability in Ethiopia of 4% under RCP2.6 and 7% under RCP8.5 is projected (Figure 25). These losses will occur in the drought-prone regions and the Moisture Sufficient Highlands – Cereals AEZs, with small patches in SNNP, Oromia and Amhara projected to see increased teff suitability by 2050 (Figure 25).

The model projects a net loss in teff suitability in Ethiopia of 4% under RCP2.6 and 7% under RCP8.5 by 2050.

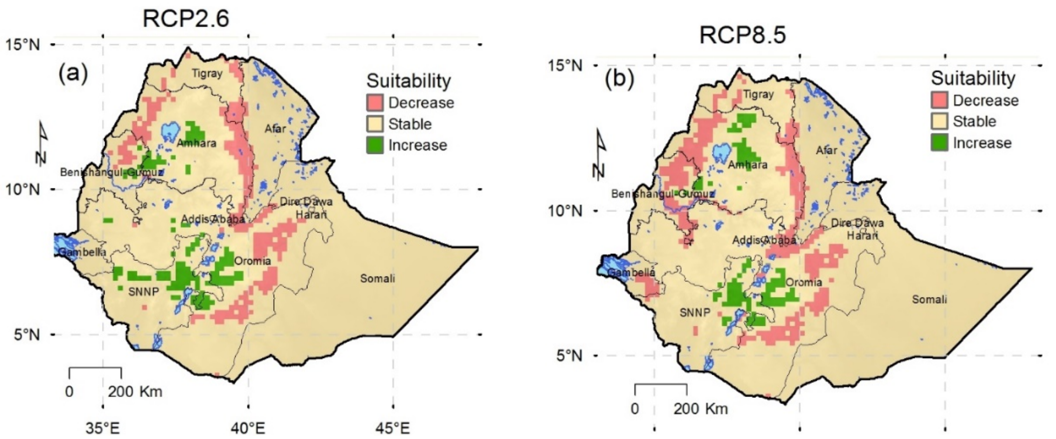


Figure 25: Projected impact of climate change on suitability of teff under (a) RCP2.6 and (b) RCP8.5 scenarios in Ethiopia by 2050.

Sorghum suitability

Sorghum suitability is projected to rise with climate change: At national level, models project a net increase in sorghum suitability of 5% under RCP2.6 and 2% under RCP8.5 by mid-century.

Under current climatic conditions, 53% of Ethiopia has the potential for sorghum production. With the influence of climate change, a net increase in the areas suitable for sorghum of 5% under RCP2.6 and of 2% under RCP8.5 at national level is projected by 2050. This is because of projected increases in sorghum suitability in the Humid Moisture Reliable Lowlands, the Moisture Sufficient Highlands – Cereals and the Moisture Sufficient Highlands – Enset AEZs in parts of SNNP, Oromia, Gambella and Amhara regions (Figure 26). However, the northern and central parts of Ethiopia will experience reduced suitability for sorghum under climate change (Figure 26). Suitability in the drought-prone areas will decrease by 13% under RCP2.6 and 16% under RCP8.5 (Figure 26). These findings of a projected net increase in sorghum suitability in Ethiopia confirm that sorghum is both drought-resistant and tolerant of excess water, as these conditions are projected for Ethiopia. These characteristics indicate that it has a large climatic tolerance compared to other cereals.

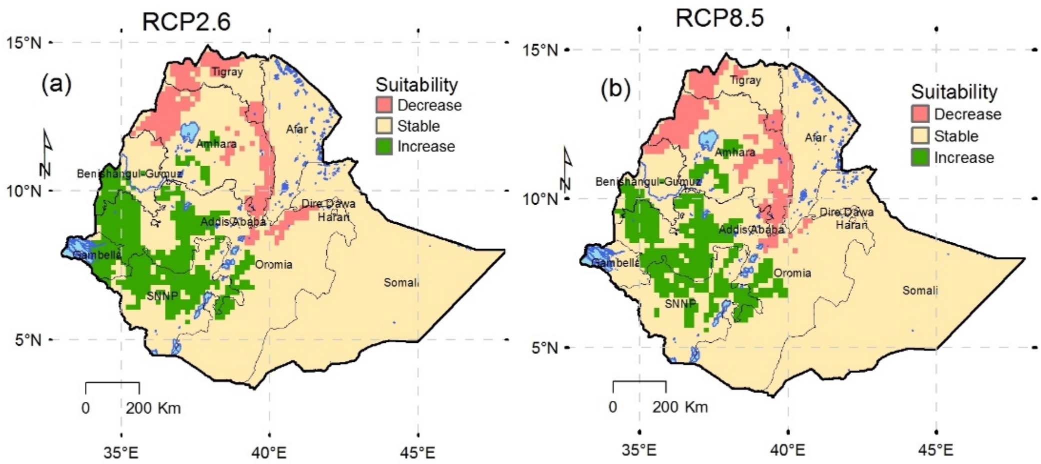


Figure 26: Projected impact of climate change on suitability of sorghum under (a) RCP2.6 and (b) RCP8.5 scenarios in Ethiopia by 2050.

Wheat suitability

Out of the four crops, the area suitable for wheat is the smallest: Only 31% of the country is suitable for wheat. The Moisture Sufficient Highlands – Cereals AEZ has the largest proportion suitable for wheat at 72%, followed by the Moisture Sufficient Highlands – Enset with 48% (Figure 27). In the Amhara region, 79% of the area is suitable for wheat production under current climatic conditions, while in Oromia, SNNP and Tigray the proportion is 45%, 38% and 31% respectively. Under climate change, the suitability for wheat will decrease by 9% under RCP2.6 and by 12% under RCP8.5 at national level, representing the largest losses in suitability for the four crops (Figure 23). The largest losses in suitability will occur in the Moisture Sufficient Highlands – Cereals and Moisture Sufficient Highlands - Enset AEZs, with more severe losses projected under RCP8.5. The Humid Lowlands Moisture Reliable AEZ is projected to see an increase in wheat suitability of 2% under RCP2.6, but these areas will turn marginal under RCP8.5 (-3%). These changes in wheat relate to the combined suitability of a range of wheat varieties of bread wheat, durum and emmer varieties grown in Ethiopia. Wheat is known to have low tolerance for heat and water stress associated with warmer environments and to require specific conditions for the different growth stages (Ortiz et al., 2008; White, 2001).

Out of the four crops analysed in this study, wheat will be most affected by climate change. Its net suitability is projected to decrease by 9% under RCP2.6 and by 12% under RCP8.5 until 2050.

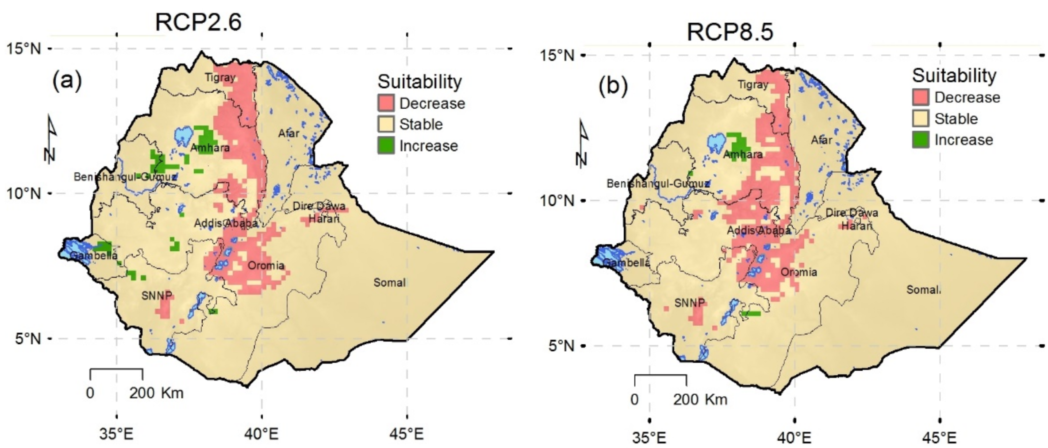


Figure 27: Projected impact of climate change on suitability of wheat under (a) RCP2.6 and (b) RCP8.5 scenarios in Ethiopia by 2050.

Suitability of multiple crops

Under current climatic conditions, 47% of Ethiopia is not suitable to produce any of the four crops analysed in this study.

Overlaying the suitability maps of maize, teff, sorghum and wheat showed that 47% of Ethiopia is not suitable, under current climatic conditions, for any of the four crops (Figure 28). It is noteworthy that out of the areas which are suitable for crop production, the greatest proportion is suitable for all the four crops (23%), followed by areas suitable for three crops (13%) and two crops (10%). Only 4% of the country is suitable for only one crop, which shows the crop diversity prevalent in Ethiopia. The Moisture Sufficient Highlands – Cereals and Moisture Sufficient Highlands – Enset AEZs have the largest proportions that are currently suitable for all of the four crops, with 50% and 36% respectively. In the Drought – Prone Highlands AEZ, 64% is suitable for at least one crop, 39% for at least two crops and 15% for at least three crops under current conditions. In terms of administrative regions, Amhara has the largest area currently suitable for four crops with 67%, followed by Oromia (38%) and SNNP (29%).

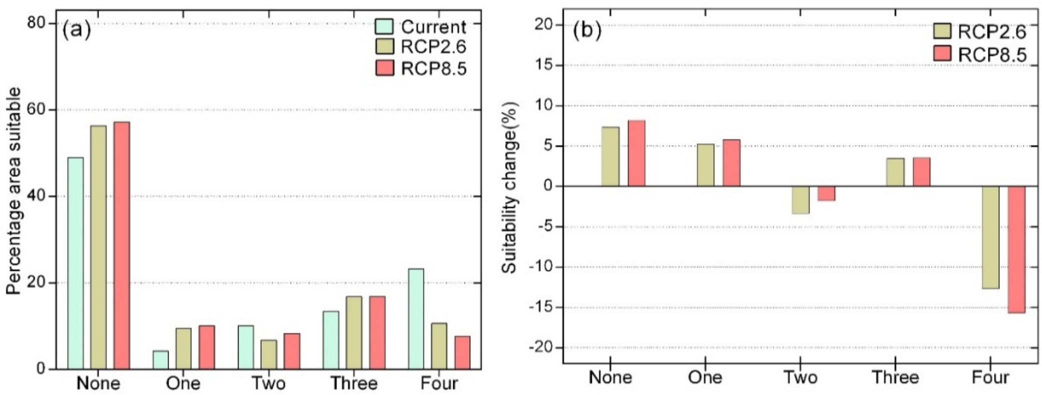


Figure 28: Suitability of multiple crops in Ethiopia under current and projected climatic conditions.

With future climate change, the areas in Ethiopia that are suitable to produce maize, wheat, sorghum and teff are projected to decrease by 13-16%, depending on the emissions scenario.

Under projected climate change, the area suitable for four or two crops will reduce, while the area that is suitable for three, one and none of the crops will increase (Figure 29). The proportion that is suitable for four crops will see the largest losses in multiple crop suitability, as these will be reduced by 13% (RCP2.6) and 16% (RCP8.5). Areas suitable for three crops will increase, as many areas lose suitability from four to only three crops (Figure 29). Due to climate change, there will be an increase of 7% (RCP2.6) or 8% (RCP8.5) of areas that are marginal for the production of any of the four crops in Ethiopia by 2050.

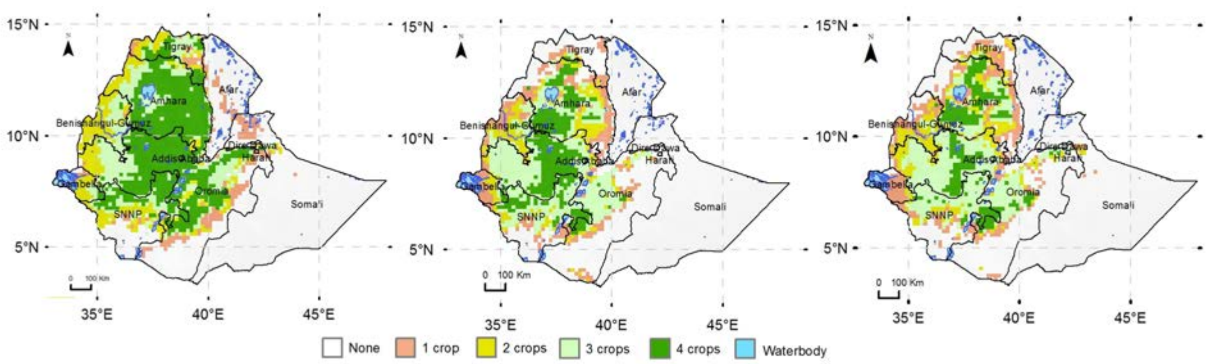


Figure 29: Distribution of suitability of multiple crops in Ethiopia under (a) Current, (b) RCP2.6 and (c) RCP8.5 climatic conditions in Ethiopia.

Further analysis of the effect of climate change on multiple-crop suitability in Ethiopia shows that the AEZs that will lose their suitability for producing multiple crops the most will be the Moisture Sufficient Highlands – Cereals and Moisture Sufficient Highlands – Enset. In these two regions, the suitability to produce all four crops is 50%, but this will reduce to 29% under RCP2.6 or 21% under RCP8.5. Furthermore, the area that is suitable for one crop in these two regions will increase from currently 7% to 17% under RCP2.6 or 19% under RCP8.5. In terms of administrative regions, changes in suitability for all four crops will occur mostly in the Amhara region, where decreases of 37% under RCP2.6 and 24% under RCP8.5 are projected (Figure 29). In the SNNP region, 8% (RCP2.6) or 19% (RCP8.5) will become less suitable for all of the four crops, while suitability for production of only two crops will increase by 4% (RCP2.6) or 10% (RCP8.5). In the Tigray region, the results show that suitability for two crops will decrease by 22% (RCP2.6) or 13% (RCP8.5).

3.4 Climate change impacts on coffee

Ethiopia is the country of origin of *Coffea arabica*, the most important coffee species in terms of production and trade. As a result, Ethiopia is the largest coffee producer in Africa, with the crop being the most important non-staple agricultural crop (Petit, 2007). As a result, coffee is very important for the country's economy, as it contributes significantly to export earnings, tax revenue and employs around 15 million people in the coffee value chain (Boansi et al., 2013; Moat et al., 2017). In addition, coffee is an important part of the Ethiopian culture and as such around half of the coffee produced in Ethiopia is consumed locally in exquisite ceremonies and in coffee shops, with the country being the leading consumer of coffee in Africa. To meet the international and domestic demand of Ethiopian coffee, coffee is cultivated on about half a million hectares, representing over 1% of all agricultural land in the country. Four major coffee production systems are practiced in Ethiopia: These are forest coffee (10%), semi-forest coffee (30%), garden coffee (50%) and plantation coffee systems (10%) (Amamo, 2014).

In Ethiopia, coffee prefers an altitude between 1,500 m and 1,900 m above sea level, precipitation above 1,400 mm well distributed over a seven month period and an average temperature from 15 to 26°C, without frost or excessive heat (Melke & Fetene, 2014; Taffesse, Dorosh, & Gemessa, 2013). Given the specific requirements, any changes in these conditions induced by climate change pose significant risks to the Ethiopian coffee sector and related livelihoods as well as the economy. The specific niches on which specialty coffee is produced can be impaired, as temperature and precipitation amounts and patterns change.

Coffee is one of Ethiopia's most important crops in terms of economic and cultural value. Climate change poses significant risks to Ethiopia's coffee production.

Coffee is very sensitive to the impacts of climate change as it is a perennial crop which is in the field throughout the year, experiencing the entire seasonal climatic cycle (Chemura et al. 2016). Minten (2014) has identified low productivity, quantity and quality inconsistencies and increasing pests and diseases as current climate-related risks to the coffee sector. Davis et al. (2012) as well as Moat et al. (2017) have characterised Arabica coffee as climate-sensitive and with little adaptive capacity due to its preference for specific climatic conditions. Therefore, in this study we quantified the exposure of coffee production in Ethiopia to climate change using an ensemble suitability modelling approach for current and projected climatic conditions until 2050. Coffee suitability is defined as the ability of an area to sustain the production cycle of coffee from establishment to harvesting as well as achieving required quality and quantity at current production costs, management and technology. This modelling provides an indication of how easy or difficult it will be to meet current production levels for coffee in Ethiopia under current and projected climatic conditions, assuming management and varieties remain the same.

Climate change impacts on coffee suitability

Using current climatic data, we identified the coffee belt in Ethiopia to be extending from the eastern states of Harari to the West, with the largest suitable area being in Oromia followed by SNNP and small suitable patches in Gambela, Benishangul-Gumuz and Amhara regions. This coffee belt strongly follows the altitude as the most suitable areas are in the high altitude areas. Under RCP2.6, 10% of current Ethiopian production areas will have decreased suitability for coffee production by 2050, while 7% of areas currently not suitable for coffee will become suitable, giving a net loss in suitability of 3% (Figure 30). Under the RCP8.5 scenario, a net loss of 8% at national level is projected, which is driven by a higher loss of areas suitable of 14% against new suitable areas of 6% (Figure 30).

Suitability modelling shows that by 2050, the area suitable for growing coffee in Ethiopia could decrease by 3% under RCP2.6 and by 8% under RCP8.5.

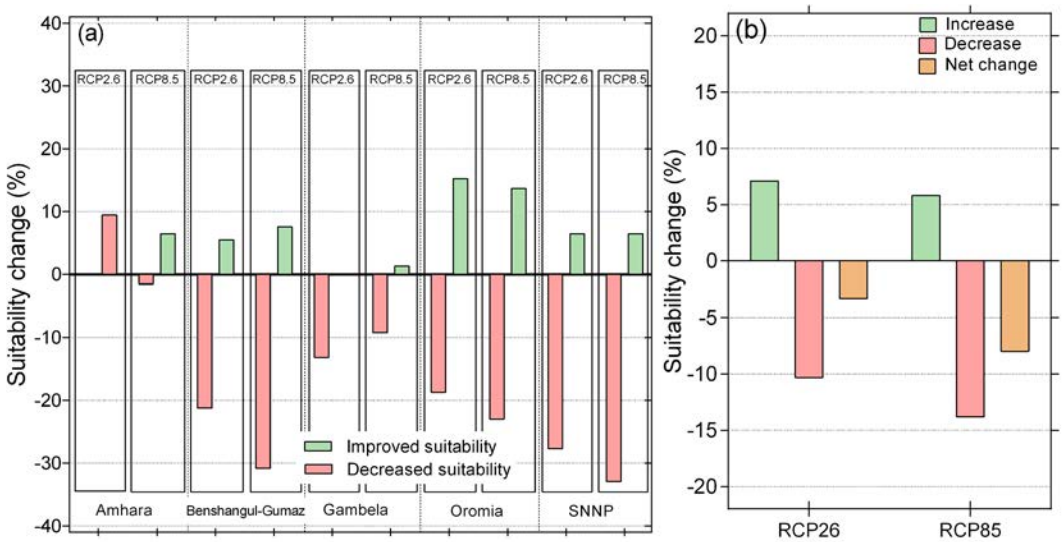


Figure 30: Impact of climate change on coffee suitability for (a) all regions and (b) main coffee producing regions.

The greatest losses in suitability are projected to occur in the SNNP region followed by Oromia, with increased suitability projected mostly in the southern and central parts of Oromia and patches of Amhara region. New coffee areas will emerge in the Amhara region under climate change, which provides opportunities for development of the crop in these areas. However, it will become more difficult to produce coffee in SNNP and in the eastern parts of Oromia region under both RCP2.6 and RCP8.5 (Figure 31). These suitability changes mean that the cultivation potential for coffee in Ethiopia will be reduced by 3% under RCP2.6 and by 8% under RCP8.5 by 2050.

As the climate changes, coffee production could become possible in areas that were formerly not suitable for growing coffee, for instance in Amhara region. However, other regions may lose their potential to grow coffee, such as SNNP and parts of Oromia region.

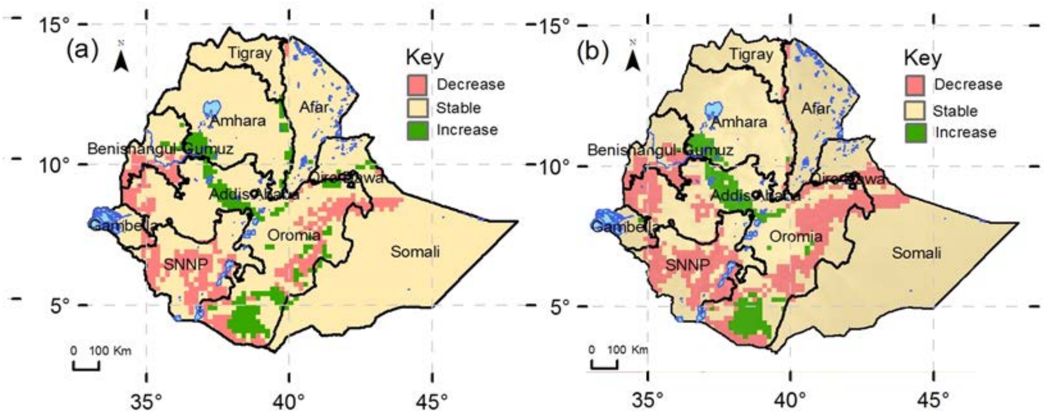


Figure 31: Suitability changes for coffee in Ethiopia under (a) RCP2.6 and (b) RCP8.5.

3.5 Economic impacts on crop production under climate change

The study analyses the economic impacts of climate change on crop production for selected zones in Ethiopia and under two emissions scenarios.

We analysed the economic aspects of climate change impacts on agriculture using an income (production) accounting approach. The approach links the changes in biophysical attributes (acreage and yield) to changes in economic values of crops under different scenarios. The conceptual framework is depicted in Figure 32.

To assess the economic impacts of climate change on crop production, the economic value of production under climate change scenarios (without adaptation) is compared with the current (baseline/BAS) value of production. Climate change scenarios are then further sub-divided on the basis of the emissions scenario (RCP2.6 and RCP8.5) and the impact channel (yield changes). Climate change may influence and result in changes in crop area suitability (eventually affecting the average crop yields) and crop yields. For our analysis, we focus on the impact on crop yields, although changes in area suitability may also significantly affect the production potential of crop agriculture in Ethiopia. We then conducted a comparative static analysis (i.e. with-climate change or without-climate change scenario) using a gross value of production (GVP) and a net value of production (NVP) approach.

In Chapter 6 of this study, we also conduct an economic analysis for irrigation as adaptation strategy as well as micro-economic cost-benefit analyses for some additional adaptation strategies.

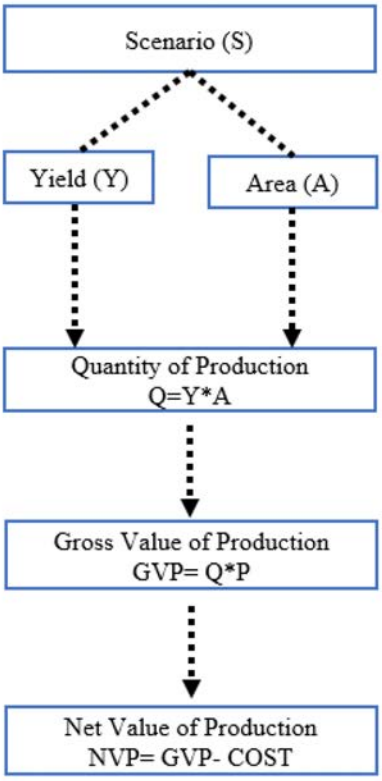


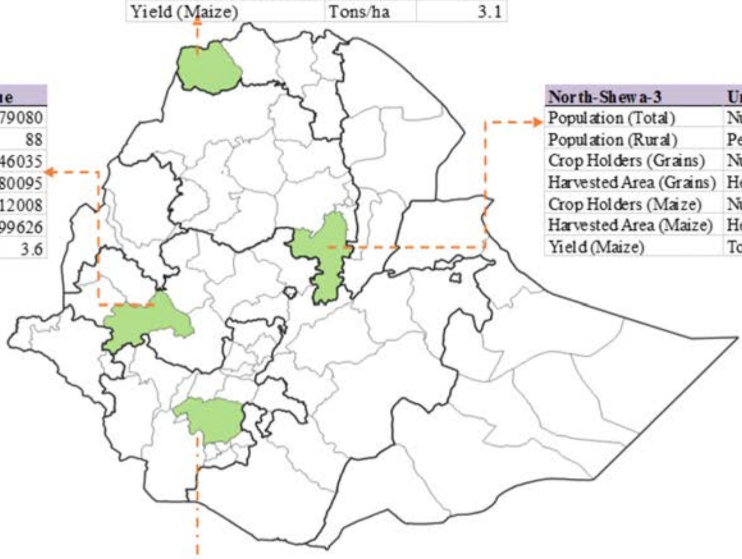
Figure 32: Conceptual framework for the economic analysis.

The economic analysis takes up the crop yield model results. It quantifies the economic losses due to projected maize yield losses in selected areas of Ethiopia.

In Figure 34, the costs of production (COST) include only variable costs. Thus, land, capital and other fixed costs are not accounted for. The production cost is constructed based on the unit costs obtained from the empirical literature and statistical reports. As we focus on rural smallholder agriculture, we took the rural agricultural labour wages to be equal to 50% of urban agricultural labour wages obtained from ILOSTAT (2017). We assumed one person working on a hectare of cropland for the *meher* harvesting season (six months from June to November). The prices of fertiliser per ton are extracted from Rashid et al. (2013) and IFDC (2012). Indigenous seeds are valued at product prices. Because local seed prices were not available for Ethiopia, we assumed that prices for improved seeds are 75% higher than the prices of indigenous seeds. Unit costs of irrigation and pesticides are extracted from the literature, such as Gebreegziabher et al. (2013) and Makombe et al. (2007). Insurance premiums and premium rates are taken from Araya et al. (2011). Only costs pertaining to irrigation (in the case of irrigation as adaptation) will be altered in the respective scenarios. The rest of the cost items will remain the same in different scenarios. The irrigation costs are mostly relevant for the adaptation analysis in the adaptation part of this study. Figure 33 shows the four zones that were selected for the economic analysis. For those four zones, good yield data was available and the crop model APSIM projected yield losses under future climate change.

Western-Tigray	Unit	Value
Population (Total)	Number	418756
Population (Rural)	Percent	74
Crop Holders (Grains)	Number	87632
Harvested Area (Grains)	Hectare	191579
Crop Holders (Maize)	Number	61089
Harvested Area (Maize)	Hectare	4013
Yield (Maize)	Tons/ha	3.1

Illubabor	Unit	Value
Population (Total)	Number	1579080
Population (Rural)	Percent	88
Crop Holders (Grains)	Number	346035
Harvested Area (Grains)	Hectare	280095
Crop Holders (Maize)	Number	312008
Harvested Area (Maize)	Hectare	99626
Yield (Maize)	Tons/ha	3.6



North-Shewa-3	Unit	Value
Population (Total)	Number	2171594
Population (Rural)	Percent	85
Crop Holders (Grains)	Number	481155
Harvested Area (Grains)	Hectare	556416
Crop Holders (Maize)	Number	155625
Harvested Area (Maize)	Hectare	6490
Yield (Maize)	Tons/ha	2.6

Gamo-Gofa	Unit	Value
Population (Total)	Number	1948636
Population (Rural)	Percent	85
Crop Holders (Grains)	Number	369236
Harvested Area (Grains)	Hectare	142889
Crop Holders (Maize)	Number	194895
Harvested Area (Maize)	Hectare	51443
Yield (Maize)	Tons/ha	3.4

Figure 33: The four zones selected for macro-economic analysis: Illubabor, Gamo-Gofa, North-Shewa and Western Tigray.

Baseline Scenario

The baseline data (harvested area, yield, share of irrigated area and product prices) per crop by geographic area are presented in the supplementary material. It shows that at national level, teff stands first in terms of harvested area. Nonetheless, teff is the least productive crop (expressed in terms of the crop yield in tons per ha) among the four crops. Yet, the economic value of teff is very important because of its high price. At all administrative levels (i.e. national, regional and zonal), maize is the crop where irrigation is most used as compared to the other three crops analysed in this study.

In Figure 34, the baseline production cost structure for maize is presented for selected administrative zones. Note that the baseline cost structures do not include insurance premiums, as the latter are not common yet. A similar figure for regions and other cereal crops covered in this study is given in the supplementary material.

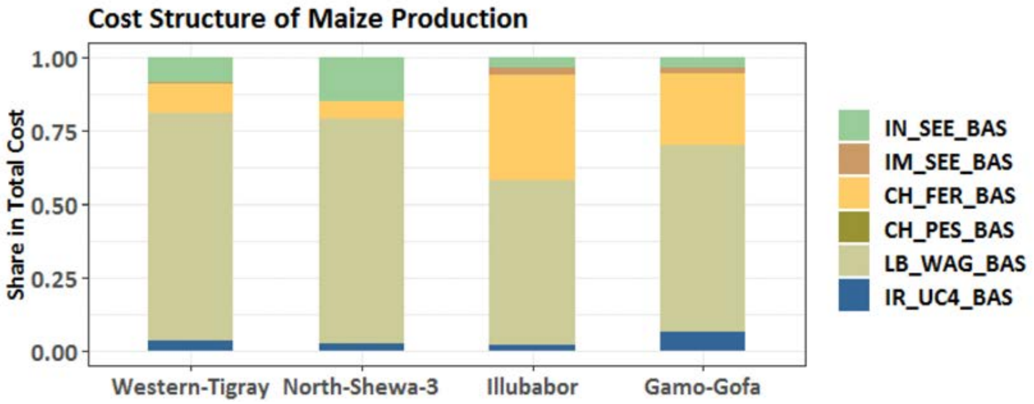


Figure 34: Structure of current maize production costs in different zones. Cost items represent costs in the baseline (BAS) scenario of indigenous seeds (IN_SEE), improved seeds (IM_SEE), chemical fertilisers (CH_FER), chemical pesticides (CH_PES), labour wages (LAB_WAG), and irrigation associated with high unit costs (IR_UC4). Note that the insurance premiums are not included in the baseline cost structure as they do not exist.

An analysis of the cost components of maize production in Ethiopia reveals that 1) smallholder maize production is labour intensive; 2) especially in the northern half of the country input use is low and 3) irrigation expenditure is low, since it is rarely used as of yet.

The cost structures tell three important messages. First, maize production by rural smallholder farmers is generally labour intensive. Second, the share of harvested area applying modern agricultural inputs (fertilisers, irrigation and improved seeds) highly varies across administrative regions. The use of improved seeds and chemical fertilisers seems low in the northern half of the country, as indicated in the cases of Western-Tigray (Tigray) and North-Shewa (Amhara). It is important to bear in mind that the costs of fertiliser depend not only on the total area fertilised, but also on the fertiliser intensity (tons of fertilisers per hectare of land). And third, because of the negligible share of irrigated land, the costs of irrigation are minuscule and are not even visible in the total cost structure, when we take the minimum unit cost of irrigation (not presented in this study).

Economic consequences of climate change impacts on crop production

As mentioned earlier, climate change can impact crop production in two ways: through changes in area suitability and/or directly through changes in yield. We attempt to analyse the economic effects through the yield impact channel. The projected maize yield changes under RCP2.6 and RCP8.5 are taken from biophysical model results (section 3.2 of this chapter). The impacts of climate change refer to the changes in future yields (in the 2050s), relative to the present yields. The results under any climate change scenario compared with the baseline scenario represent the costs of climate change or the costs of inaction.

We analyse the economic consequences of maize yield changes in four administrative regions, where the APSIM model performance was good and where they would represent the regional and agro-ecological variations in the country (see Figure 33). The four zones are Western-Tigray (Tigray region), North-Shewa-3 (Amhara region)[10], Illubabor (Oromia region) and Gamo-Gofa (SNNP region). The selected set of zones also represents the three main crop AEZs: Drought – Prone Highlands (Western-Tigray and North-Shewa-3), Moisture Sufficient Highlands – Cereals (Illubabor) and Moisture Sufficient Highlands – Enset (Gamo-Gofa). Further, the selected zones cover north (Western-Tigray), central (North-Shewa-3), west (Illubabor) and south (Gamo-Gofa) Ethiopia.

Maize cultivation is very common in the southern half of the country (e.g. Illubabor and Gamo-Gofa) and has a higher gross value compared to the

[10] Number three in 'North-Shewa-3' stands for the numerical code of Amhara region to distinguish it from a neighbouring North-Shewa zone in Oromia region, which would be 4.

northern half of the country (e.g. Western-Tigray and North-Shewa-3). This also implies that maize is a main staple crop in the southern part of Ethiopia.

On the other hand, the projected yield changes show that maize yields will decline in the four study zones. Therefore, for a given projected negative yield change for maize, the economic impacts will be higher in zones in the Oromia and SNNP regions, as depicted in Figure 35, compared to zones in Tigray and Amhara. The GVP losses are particularly high in the two zones in the southern half – Gamo-Gofa and Illubabor.

The two zones Illubabor and Gamo-Gofa in the southern half of Ethiopia will experience particularly high economic losses due to climate change impacts on crop production, as compared to zones in the northern half of the country.

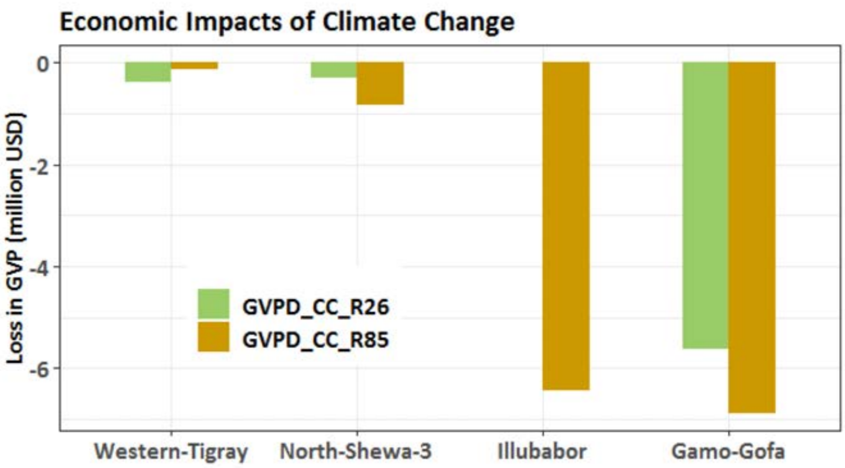


Figure 35: Gross value of production (GVP) losses in different zones, due to maize yield changes (D) under climate change (CC) under RCP2.6 (R26) and RCP8.5 (R85). Note that with no yield changes projected for Illubabor under RCP2.6, no economic impacts are expected.

Importantly, economic impacts of climate change are not only influenced by yield changes. They are also influenced by the baseline crop area harvested (representing the importance of the crop) and zone-specific crop prices (representing the demand side).

Due to these combined factors, out of the four sample zones, Gamo-Gofa and Illubabor observe the biggest impacts, 6.8 and 6.4 million USD respectively under the RCP8.5 scenario. The high impacts in Gamo-Gofa under both climate change scenarios can be explained by both relatively high expected yield decline (11% under RCP2.6 and 13% under RCP8.5) and current size of harvested area (ca. 54 thousands ha). In Illubabor, as per the APSIM model simulations, no yield changes are expected under RCP2.6. However, yields in the same zone may decline by 6% under RCP8.5. Consequently, Figure 35 above shows no economic losses under RCP2.6, but a gross value loss equivalent to 6.43 million USD under RCP8.5 for Illubabor. The simulated yield losses are projected to be 7% under RCP2.6 and 3% under RCP8.5 in the Western-Tigray zone which, combined with the importance of the crop in the zone (ca. 5 thousand ha harvested area), imply expected gross value losses of ca. 0.38 and 0.14 million USD under RCP2.6 and RCP8.5. The gross value losses in North-Shewa of Amhara region are calculated to be around 0.31 and 0.82 million USD under RCP2.6 and RCP8.5, respectively.

These projected economic value changes come with uncertainty that emanates from the biophysical inputs used, the biophysical models and the economic parameters and data. Regardless of this, however, the results and the discussion in this section highlight that crop yield changes and their economic consequences (which also depend on prices of crops) vary across geographic areas and crops. Therefore, such differences shall be considered in designing adaptation planning in Ethiopian agriculture.

3.6 Climate change impacts on livestock and fodder

While this study focuses on the crop sector, analysing climate change impacts on livestock in Ethiopia also has great policy relevance. This section thus provides a short synthesis of the context and highlights the potential risks posed by climate change to the Ethiopian livestock sector. The discussion below is largely based on the available literature, which also recognises the importance of livestock for rural livelihoods in Ethiopia.

The Ethiopian livestock sector

The climate risk analysis concentrates on crop agriculture. Nonetheless, livestock remains very important in Ethiopia and the impacts of climate change on livestock production should also be analysed.

Ethiopia has the largest livestock population among African countries. According to a national livestock sector analysis from 2017, the national herd is currently composed of 55.2 million cattle, 29 million sheep, 28 million goats, 4.5 million camels and around 50 million poultry (Shapiro et al., 2017). Livestock systems in the country can be roughly categorised into lowland grazing systems on the one hand, and precipitation deficient and precipitation sufficient mixed farming systems in the highlands on the other hand. Across these systems, cattle is the dominant species for 70-90% of livestock holding households, and around 70% of cattle and 59% of sheep are kept in the highland mixed farming systems. Goats and camels on the other hand are stronger represented in the lowland grazing systems, with 71% of goats and 100% of camels being kept in the lowlands (Shapiro et al., 2017).

According to the FAO and other sources, demand for livestock and livestock products is expected to increase considerably in the future.

Increasing demand for livestock products has triggered a steady expansion of Ethiopia's livestock herd since the early 2000s. In addition, current projections of the country's human population to nearly double by 2050 (from about 100 million in 2018 to ca. 190 million in 2050) and fast economic growth will likely result in a continuously increasing demand for high-quality foods, including meat, dairy and other livestock products. According to FAO estimates, demand for beef, milk, poultry, eggs, mutton and goat (combined) is projected to increase by 53%, 783%, 179%, 88% and 174% respectively, between 2010 and 2050 in Ethiopia alone (FAO, 2017; World Bank, 2018). Rising consumer demand, both national and international, is expected to induce a further increase in the Ethiopian livestock population (Tiruneh & Tegene, 2018).

In case of a shock, for instance a drought, selling livestock is a frequently used coping mechanism amongst pastoral and agro-pastoral households.

In the last five years, on average, the livestock sector contributed 21.4% of agricultural GDP, 8.1% of total GDP, and 12% of total merchandise export earnings (NBE, 2017). Besides, the livestock sector contributes to the livelihoods of nearly 70% of the households in Ethiopia (Gebremariam et al., 2010). The livestock sector provides many economic services (e.g. draught power and transport) whose monetary values are usually difficult to estimate. Depending on region of residence, 4-16% of rural households report loss/death of livestock as a major shock affecting their economic wellbeing (CSA, 2012). It is also worth mentioning that selling livestock is a common coping mechanism against many shocks (e.g. droughts, illness or death of the main 'bread' earner of the household) among rural households (CSA, 2012; Dercon, 2004). By implication, climate change impacts on the livestock sector may impair the resilience of rural households to other environmental and economic shocks. The aforementioned socio-economic problems are expected to be more severe in the agro-pastoral areas, where livestock is the single main source of employment, income and food, and has further implications for spatial inequalities and propensity to migrate.

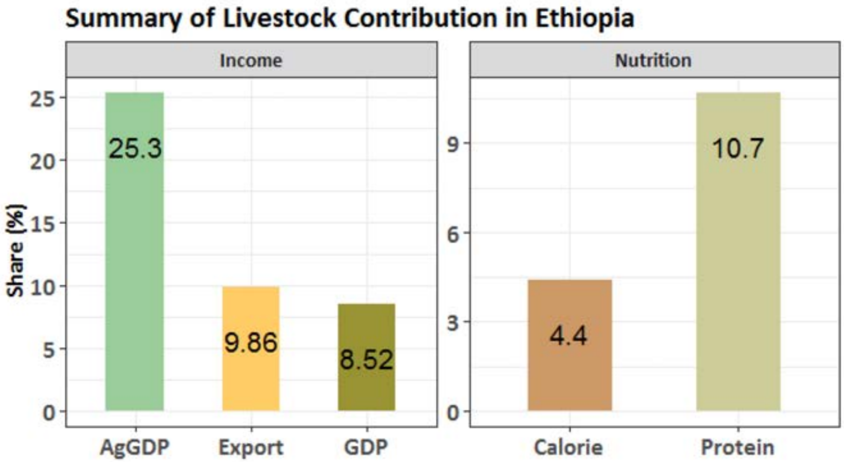


Figure 36: Shares in total nutrition intakes which refer to the year 2005 are extracted from FAO (2009). Total calories refers to kcal/person/day and total protein refers to g/person/day. Whereas the shares in total Agricultural GDP (AgGDP), total GDP and merchandise export earnings are retrieved from NBE (2017).

The potential impacts of climate change on Ethiopia's livestock sector

Climate change affects the livestock sector both directly and indirectly (Adams et al. 1998; Nardone et al., 2010; Thornton et al., 2009; FAO, 2009). The effects range from direct effects on productivity (due to physiological stress) to effects through changes in water availability, quality and quantity of animal feed as well as changes in pest and disease incidence. The magnitude and the main channel of these effects vary across regions and production systems, e.g. grazing versus non-grazing and temperate versus tropical climate (Seo and Mendelsohn, 2008; FAO, 2009; Nardone et al., 2010).

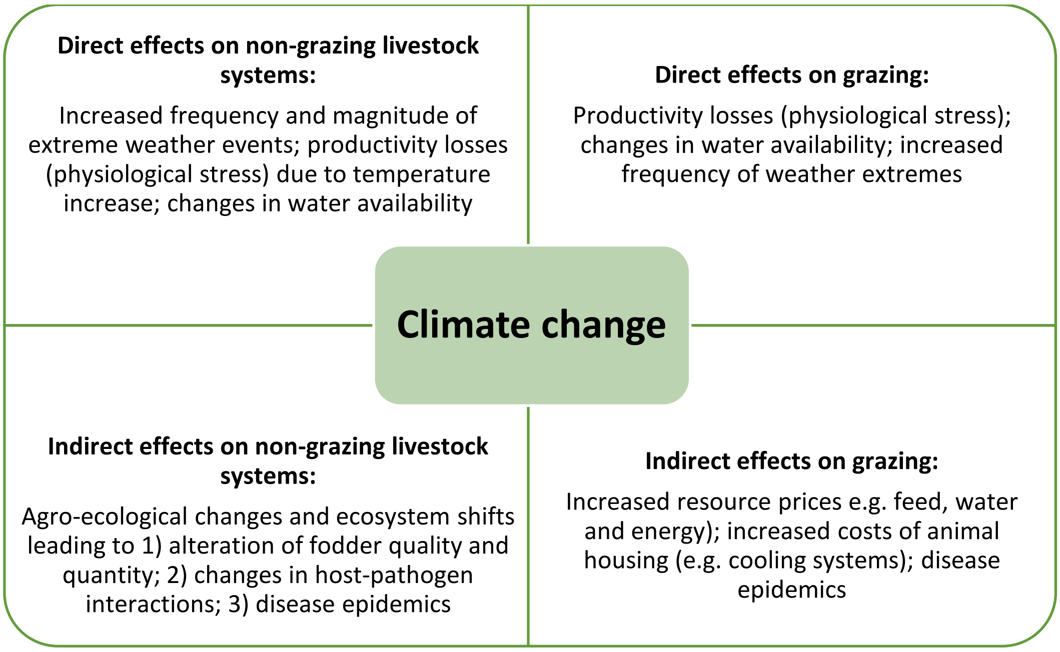


Figure 37: Summary of climate change impacts on the livestock sector. Direct (upper) and indirect (lower) effects of climate change on grazing (right) and non-grazing (left) livestock systems. Source: adapted from FAO (2009).

Already today, availability and quality of animal feed are major concerns in Ethiopia, and could further aggravate with climate change. Most animal feed comes from grazing land and crop residues.

The livestock sector in Ethiopia is a case in point: The country's livestock sector mostly consists of smallholder mixed rainfed production systems, where both crops are grown and livestock is raised (Gebremariam et al., 2010; CSA, 2015; ILRI, 2015). More than 85% of animal feed in the country comes from grazing land and crop residue (CSA, 2015). Yet, lack of feed availability and inadequate quality mean that in Ethiopia, "animals' performance measured by birth weight, growth rate, milk yield, mortality rate, and reproductive performance are below the expected range and different animals in the country are not able to produce at their genetic potential" (Birhanu, Girma, & Puskur, 2017a, p. 2). In fact, over recent years, meat production per animal (in kg) has either declined (cattle) or remained stagnant (sheep and goat) (Shapiro et al., 2017). Feed resources and feeding regimes in Ethiopia vary according to livestock production systems and AEZs. In the arid lowland grazing systems, grazing of natural pastures and browsing of shrub lands and trees supply the bulk of livestock feed, while in the highland mixed farming systems, natural grazing is supplemented with hay, crop residues and by-products, such as oilseed cakes or cereal bran (Birhan & Adugna, 2014). Current feed balances calculated for the Ethiopia Livestock Masterplan indicate that feed resources are sufficient only in the lowland grazing agro-pastoral systems during good years with above-average precipitation, whereas all other zones experience constant shortages independent of the precipitation situation (Shapiro et al., 2015). Looking into the near future, the report raises further concerns: "Assuming a 'business as usual' scenario for feed resources (without major feed development interventions), with the growth of animal numbers at the same rate as in the past, (...) [the] feed requirements [in 2030] will not be met under any climatic condition." (Shapiro et al., 2015 p. 70). With climate change, rising temperatures and shifting precipitation regimes resulting in shorter growing periods and a higher frequency of droughts, the national feed resources will be put under further pressure (Lamesegn, 2018; Thornton, Steeg, & Notenbaert, 2009; Tiruneh & Tegene, 2018). Changes in precipitation and temperature regimes alter plant physiological processes and species composition and thus affect feed quantity and nutritive quality, grazing ranges as well as incidence of weeds, pests and diseases (Tubiello, Soussana, & Howden, 2007). Furthermore, declining primary productivity of rangelands due to erratic precipitation and increased frequency of drought may lead to overgrazing and degradation, which eventually can lead to food insecurity and conflicts over scarce resources (FAO, 2009).

Increasing temperatures and changes in precipitation quantity and timing affect plants and grazing areas.

In addition, there is little attention paid to animal health and nutrition, breeding and sectoral development in general (MoARD, 2010; ILRI, 2015). Only 2% of the total Ethiopian cattle and poultry are crossbred (ILRI, 2015). Limited healthcare and low availability of feed weaken livestock and make them less resilient to cope with climate extremes, such as heat or hot-humid weather conditions. Higher temperatures (which are projected to increase under climate change in Ethiopia, see Chapter 1) tend to reduce animal feed intake and lower feed conversion rates (FAO, 2009 citing Rowlinson, 2008). With higher temperatures and more variable precipitation, new diseases may emerge or existing diseases may occur in formerly unaffected locations. New transmission mechanisms and new host species could also arise with climate change (FAO, 2009).

Climate change could influence the choice of livestock species in different areas of Ethiopia. Sheep and goats may better withstand climatic changes and be chosen over larger ruminants like cattle.

Climate change impacts could also influence the type of animal species being raised in a given location. For example, with increasing temperature, farmers might choose small ruminants (e.g. sheep and goats) over big ruminants like cattle (Seo and Mendelsohn, 2008). This argument is corroborated by the observed spatial distribution of livestock species in Ethiopia (CSA, 2015), in particular in regions where mean annual temperature is also higher than the national average. This will be further aggravated by declining per capita grazing land (due to high population growth and competition for cropland). These biophysical impacts of climate change can eventually bear consequences on the employment, income, and nutritional status of farmers who primarily depend on the livestock subsector. The consequences are both economic and environmental. First, it will impact the total income of livestock herders. Second, it may reduce cattle manure, which, however, is an important soil fertiliser for crops (FAO, 2009). In fact, previous studies have shown that not using animal dung as organic fertiliser is estimated to reduce Ethiopia's agricultural GDP by 7% (Zenebe, 2007 cited in Zelleke et al., 2010). Third, changes in livestock mix will influence the animal feed composition and the source of feed accordingly. Small ruminants mainly graze, rather than being fed by crop residues. As such, wood and bushlands may further be encroached and thus lead to degradation in rangeland biodiversity. This will eventually affect the carrying capacity of rangelands in the long-term. Put differently, "sheep and goats can severely reduce land cover and the potential for forest regrowth. Under overstocked conditions, they are particularly damaging to the environment through degradation of vegetative cover and soil" FAO (2009, pp. 60-61). As such, "climate change represents a special feedback loop, in which livestock production both contributes to the problem and suffers from the consequences" FAO (2009, p.53).

The need for improved livestock management and design and implementation of adaptation strategies to changing climatic conditions thus becomes evident. One example of a promising adaptation strategy for the livestock sector, improved fodder and feed management, will be discussed in more detail in Chapter 9.

Chapter 3 Summary

Key climate change impacts on crop production in Ethiopia

- Climate has a substantial impact on crop production in Ethiopia. On national average, weather explains 55-89% of the year-to-year yield variability.
- The results show that there will be a maize yield increase of 5% under RCP2.6 and 1% under RCP8.5 in Ethiopia by 2050.
- However, six zones are projected to experience maize yield losses under climate change: Western Tigray, South Omo, North Shewa (Amhara), Metekel, Guraghe and Gamo-Gofa.
- Crop suitability modelling results show that the suitability of areas to produce maize, teff, sorghum and wheat in Ethiopia is variable across the different AEZs and will change with future climate change.
- At national level, a net loss in maize suitability of 5% under RCP2.6 and 7% under RCP8.5 is projected, although some areas will see increased suitability and others will experience lower suitability.
- For teff, a net suitability loss in Ethiopia of 4% under RCP2.6 and 7% under RCP8.5 is projected.
- Under climate change, a net increase in the areas suitable for sorghum of 5% under RCP2.6 and by 2% under RCP8.5 at national level by 2050 is projected.
- For wheat, the suitability will decrease by 9% under RCP2.6 and by 12% under RCP8.5 at national level, representing the largest losses in suitability for the four crops.
- As regards the suitability to produce multiple crops, under projected climatic change, the area suitable for sustaining four or two crops will reduce, while the area that is suitable for three, one and none of the crops will increase.
- The suitability to produce coffee in Ethiopia will be reduced by 3% under RCP2.6 and by 8% under RCP8.5 by 2050.
- Climate change can impact crop production in two ways: through changes in area suitability and/or directly through changes in yield.
- Regarding maize yield changes, the economic impacts will be higher in zones in the Oromia and SNNP regions, compared to zones in Tigray and Amhara.
- Area suitability changes of the four main cereal crops in Ethiopia may result in a sum of 168 and 281 million USD gross value losses under RCP2.6 and RCP8.5, respectively. The biggest share comes from projected losses in suitable areas for wheat and teff.
- At national level, gains are expected from growing sorghum, following net area suitability gains for sorghum. Yet, the gain will significantly decline to 26 million USD under RCP8.5, from 48 million USD under RCP2.6.

Chapter 4 – Assessing spatial vulnerability in Ethiopia

Smallholder farmers and pastoralists are particularly vulnerable to climate change impacts.

The impacts of climate change and climate variability are rising in Ethiopia over time. The projected impacts imply further increases in frequency and intensity of climate extremes, such as droughts and higher temperature (McSweeney et al., 2007). These changes are expected to impinge on the productivity and suitability of Ethiopian crops (Deressa, Hassan & Ringler, 2015; Evangelista et al., 2013). Observed trends of climatic conditions in Ethiopia translate into a disproportionate effect on the livelihoods and food security of smallholder subsistence farmers and pastoralists. Yet, vulnerability to such impacts differs spatially within Ethiopia (Gebreyes and Theodory, 2018), due to the variations in the country's agro-ecological conditions, characterised by differences in soil type, climate, water availability and topography. The variation in the socio-economic development and the use of modern agricultural inputs in different administrative units is another source of differences in agricultural production within the country. Therefore, the distinct administrative regions across Ethiopia presently face differential magnitude and extent of climatic stress and differ in the capacity to respond to these stresses (Simane et al., 2016).

Given this background, this chapter aims to assess the vulnerability of different zones in Ethiopia to observed climate change in order to gain insight into factors that may shape vulnerability in the future. The chapter recognises vulnerability as a function of exposure, sensitivity and adaptive capacity (IPCC, 2007) and captures the spatial dynamics at subnational level using geo-referenced data from different sources. This provides a detailed spatially disaggregated analysis of vulnerability and its three components. The chapter pursues an index-based approach, which is suitable for assessing vulnerability, as it includes both biophysical and socio-economic dimensions. This allows for covering a broad range of factors shaping vulnerability (Eakin & Luers, 2006; Füssel & Klein, 2006; Bruno Soares et al., 2012).

In this chapter, we follow an index-based approach, which combines biophysical and socio-economic information, to assess spatial vulnerability.

4.1 Conceptual Framework

The concept of vulnerability has emerged to be an important area of research in climate and environmental change studies (Janssen et al., 2006). As a relative concept, vulnerability forms a component of risk and has a negative connotation attached to it (Adger, 2006; Ionescu et al., 2009). There are several ways to conceptualise and operationalise vulnerability. In this study, we adopt the IPCC recommended definition of vulnerability which defines vulnerability as the degree to which a system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes (McCarthy et al., 2001). Vulnerability to climate change is defined to be a function of exposure, sensitivity and adaptive capacity of a system (McCarthy et al., 2001). Exposure reflects the magnitude and degree to which a system is stressed by climatic variation. Sensitivity refers to the inherent susceptibility of a system to be affected by climate-related exposure, and the capacity of the system to adapt to these shocks is termed as its adaptive capacity. Adaptive capacity is shaped by socio-economic, technological and institutional factors (Brooks et al., 2005). Figure 38 provides the analytical framework for our vulnerability assessment.

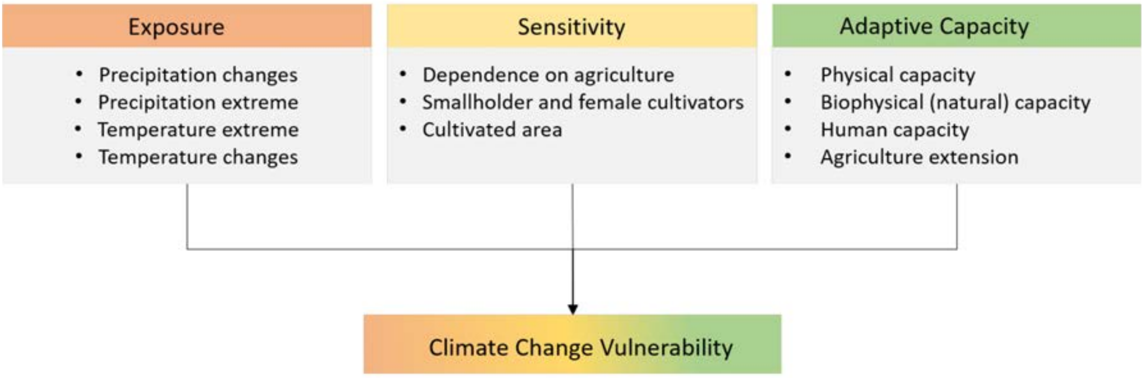


Figure 38: Conceptual framework for the vulnerability assessment.

Exposure is mainly characterised by changes in precipitation and temperature, and extreme dry (consecutive dry days) and hot spells (temperature above 35°C). Precipitation is critical for agriculture in Ethiopia, as barely 3% of harvested area is irrigated (FAO, 2018). Indicators for sensitivity characterise the cropland area, and socio-economic aspects of dependence on agriculture, smallholder (less than 1 hectare) and female cultivators. In addition, the main dimensions of adaptive capacity are based on the level of physical capacity (irrigated area, fertilised area), biophysical capacity (water and soil moisture availability), human capacity (literacy), and external agricultural support (credit availability and agricultural extension) for each administrative zones.

4.2 Assessment of Vulnerability

Scale of assessment

Immense diversity exists in the social, economic and ecological landscape of Ethiopia, with high inter-regional variation reported in the literature (Husmann, 2016). Favourable agro-ecological conditions for crop production are mainly concentrated in the highlands, where the population density is also highest. The agricultural area in the highlands covers mostly four regions, namely Amhara, Oromia, SNNP and Tigray. In contrast, the peripheral Arid and Semi-Arid Lowlands (ASAL) are the areas that are located below 1 500 m, where the main source of livelihood is pastoralism. Ethiopia has two main cropping seasons, namely, *Meher* and *Belg*. Of the two, *Meher* is the main cropping season in the highlands. The *Meher* production is affected by the rain in the *Kiremt* months (summer: from June until September), which is the main growing season. Given such variations in topography, climate, livelihood and development within the country, spatially disaggregated assessments of vulnerability of the agricultural system in Ethiopia are needed – as opposed to remaining masked in coarse scale assessments (Frazier et al., 2014). Therefore, we conducted a subnational zone-level analysis for Ethiopia. Zones in Ethiopia represent Level-2 administrative units according to the global administrative areas classification[11]. Zones are intermediate administrative levels formed by a group of *woredas* (Level-3). Accordingly, Ethiopia currently has more than 75 administrative zones. The number of the zones are increasing and the boundaries of these zones have been modified over time. The present study, however, focuses on 64 administrative units, where *Meher* crop production is important and where data is available from the Annual Agricultural Sample Survey by the Central Statistical Agency of Ethiopia (CSA).

[11] See https://gadm.org/ for further information.

Indicators for the vulnerability assessment

It is difficult to quantify vulnerability, because it changes over time and combines many dimensions.

Quantifying vulnerability is difficult, owing to the concept's dynamic, multi-dimensional, cross-scalar and site-specific nature (Ciurean and Schröter 2013). Despite these constraints, however, various quantitative and semi-quantitative methods for assessing vulnerability to climate change have been proposed. The most common of them is using composites of proxy indicators (Luers et al., 2003; O'Brien et al., 2004). According to Gallopin (2006), indicators are the proxies for attributes that characterise a system. Generally, indicators representing exposure, sensitivity and adaptive capacity of a system are chosen and combined to obtain a composite index. Table 4 lists the selected indicators in this study under each component of vulnerability and defines the functional relationship with the overall vulnerability, which determines whether an indicator positively or negatively affects vulnerability (i.e. augments or decreases the vulnerability level). For instance, a high share of cropped area in a zone means a large area would be affected by any changes in climate, thereby increasing vulnerability, which is thus defined to have a positive relationship with vulnerability.

This approach combines environmental and socio-economic data from different sources (agricultural surveys, climate and remote sensing data) to capture the multi-dimensional attributes of vulnerability. Climate data to estimate the exposure to climate change was collected from the WATCH-ERAinterim (WFDEI) dataset, which is ERAinterim reanalysis data. The WFDEI dataset is also bias-adjusted with observational data with a 0.5° resolution (~50km) (Weedon et al., 2014). As the majority of the crop farmers practice rainfed agriculture, changes in precipitation patterns have a direct effect on crop production. Further, extreme temperature would also have a negative effect on crop yields. In the study, we took the annual count of the days above 35°C to capture the temperature extremes. Socio-economic data on agriculture was extracted from the Annual Agricultural Sample Survey for 2015/16 Meher Season (CSA, 2016). Data for Normalized Difference Vegetation Indices (NDVI) was downloaded using MODIS (Moderate Resolution Imaging Spectroradiometer) 250 m resolution data. Average NDVI values were calculated for 2015. Surface soil moisture data was downloaded using the NASA-USDA SMAP Global soil moisture dataset at 0.25°x0.25° spatial resolution.

Table 4: List of indicators for vulnerability assessment.

Component	Indicator *(Codes)*	Functional relationship with Vulnerability	Data Source (Time period)
Exposure	Annual mean of Consecutive Dry Days (CDD) with daily precipitation amount below 1 mm *(CDD_Annual)*	Positive	WATCH-ERAinterim [WFDEI] (2006-2015)
	Annual mean of number of days where maximum of temperature is above 35 degree Celsius *(Temp_35)*	Positive	
	Coefficient of Variation (CV) of annual mean precipitation *(CV_MeanPr)*	Positive	
	Coefficient of Variation (CV) of annual mean temperature *(CV_MeanTemp)*	Positive	
Sensitivity	Percentage of the four main cereal crops (teff, wheat, maize, sorghum) in total crop area *(Crop_Area)*	Positive	Agricultural Sample Survey (2015)
	Percentage of crop only holders in total agricultural holders *(Crop_Holder)*	Positive	
	Percentage of holders with land holding less than 1 ha (Holder_1ha)	Positive	
	Percentage of female crop holder *(F_Crop_holder)*	Positive	
Adaptive capacity	Annual average Normalised Difference Vegetation Index (NDVI) *(Mean_NDVI)*	Negative	MODIS (2015)
	Annual average surface soil moisture *(Mean_SM)*	Negative	NASA-USDA SMAP (2015)
	Percentage of crop area applied chemical fertilisers *(Fertiliser_Area)*	Negative	Agricultural Sample Survey (2015)
	Percentage of crop area applied irrigation *(Irrigation_Area)*	Negative	
	Percentage of literate (only formal education) holders in total holders *(Literate)*	Negative	
	Percentage of crop area received agricultural extension services *(Extension_Area)*	Negative	
	Percentage of holders using agricultural credit services *(Credit_holder)*	Negative	

Calculation and mapping of the vulnerability index

The indicators for the analysis were selected based on a literature review of vulnerability mapping studies.

Constructing a vulnerability index involves several steps. It includes indicator selection, normalisation and aggregation. The selection of the indicators presented in Table 4 was based on a review of the related literature on vulnerability mapping studies in sub-Saharan Africa. Peer-reviewed articles on vulnerability of farmers, agricultural systems, crops, poverty and marginality due to climate change were downloaded from the Scopus database, a database for scientific abstracts and citations, using a comprehensive list of indicators. The final selection of the 19 indicators used in this study was based on the relevance to agricultural systems in Ethiopia and availability of data. Normalisation of indicators was done using the linear (minimum-maximum) scaling, which scales the data in the range of 0 to 1 (Tate, 2012). Based on the relationship an indictor has with vulnerability, the following formulas were used for normalisation. All the indicators with a positive and negative functional relationship were normalised using equation 1 and equation 2, respectively.

$$\text{Normalised Value (NV)} = \frac{\text{Actual value - Minimum value}}{\textit{Maximum value} - \textit{Minimum value}} \qquad (1)$$

$$\text{Normalised Value (NV)} = \frac{\text{Maximum value - Actual value}}{\textit{Maximum value} - \textit{Minimum value}} \qquad (2)$$

Normalised values of all the indicators were aggregated to obtain the final vulnerability index. The results of each vulnerability component (Exposure, Sensitivity and Adaptive Capacity) are presented using geographic visual representations. This facilitates easy communication of complex multidimensional behaviour of vulnerability (Preston et al. 2011) and exploration of its spatial variability. Assessments of vulnerability to climate change using a composite index provide comparative results rather than absolute values, which range between 0 (least vulnerable) and 1 (most vulnerable). Finally, indices for each component and vulnerability were divided into five categories: very low, low, moderate, high and very high using the quantile classification.

4.3 Statistical description of the variables

We performed correlation analysis among these indicators before the start of the indexing analysis to ensure that none of the variables is over-represented. Among the exposure variable, we dropped indicators on wet days which were highly correlated with mean precipitation (r = 0. 879). For sensitivity, we dropped EVI (Enhanced Vegetation Index) which was found to be highly correlated with NDVI (r = 0.982). With regard to adaptive capacity, high correlation values were found between literate crop holder and literate female crop holder (r = 0.9), and between credit holder and advisory holder farmer (0.8860). Therefore, after the correlation analysis we selected a total of 15 indicators.

Figure 39 shows the distribution of the 15 indicators selected for the vulnerability assessment at overall country level. Out of the 15 indicators, four indicators captured exposure, four indicators captured sensitivity, and the remaining seven were selected for determining adaptive capacity. Among the exposure indicators, consecutive dry days (CDD) shows the largest mean value. With respect to sensitivity indicators, the maximum values are noted for cropped area and the contribution of smallholder farmers (less than 1 ha). Evidently, irrigated area (Irrigated_Area) observed the most skewed distribution with minimum values followed by fertilised area, and crop holders with access to credits (Credit_holder).

15 indicators were included in the final assessment: four indicators for exposure, four indicators for sensitivity and seven indicators for capturing adaptive capacity.

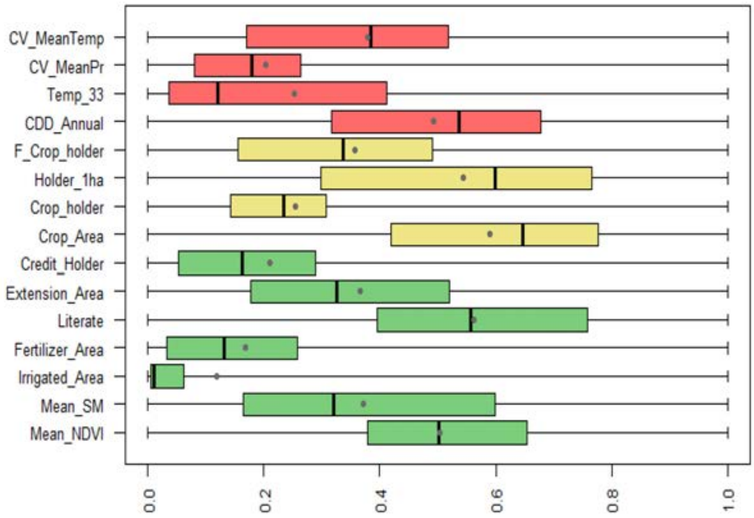


Figure 39: Distribution of normalised score: 15 indicators of climate vulnerability. The bold middle line represents the median, the grey dot is the mean, and the vertical lines represent the minimum (0) and the maximum value (1). For codes please refer to Table 4.

4.4 Spatial patterns of vulnerability to climate impacts

Exposure index

Figure 40 shows the spatial distribution of the exposure index. Overall, out of the 64 zones, approximately 40% of the zones show a very high and high exposure to changes in climatic variables. Most of these zones are located in the Afar, Somali, Tigray (Western, Northwestern) and Benishangul-Gumuz regions[12]. The farmers in these zones rely on agro-pastoralist livelihood strategies. Higher exposure here is measured by greater occurrence of consecutive dry days and a higher coefficient of variation (CV) in temperature. In contrast, a low exposure is observed in zones in the SNNP region, and parts of Somali region. The precipitation coefficient of variation records lower values over the period of 2006-2015 in these regions. As pointed out by Funk et al. (2015), the moist conditions in these regions could offset precipitation decline in other regions in the country.

[12] Data was not available for all zones in the Somali and Afar regions, as indicated by the grey shading. This is why statements pertaining to zones in those two regions should be viewed with particular caution and not be confused with the regions as a whole.

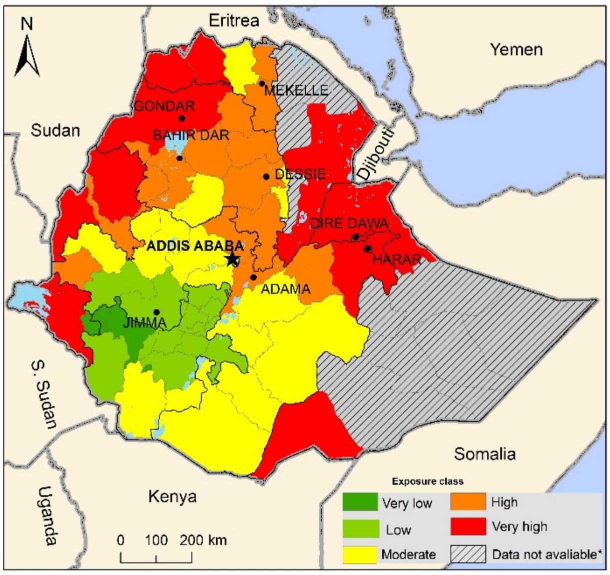


Figure 40: Spatial distribution of the exposure index showing the five classes at zone-level.

Sensitivity index

The spatial distribution of the sensitivity index is shown in Figure 41. We calculated the sensitivity dimension based on the dependence on agriculture as cropped area, percentage of smallholder farmers, female farmers and total number of cultivators. Accordingly, Figure 41 shows that zones in Tigray region were the most sensitive regions to changes in climate parameters, followed by zones in Amhara region, Gambela and one of the zones in Somali region. In the highly sensitive zones, there is a higher number of smallholder farmers and female crop holders. Female crop holders are particularly vulnerable to climate change impacts, as women typically have lower educational levels as well as more limited access, ownership and control over agricultural productive resources. In addition they have weaker bargaining power, as compared to male farmers. Similar findings have been shown by Abebe and Bekele, 2017.

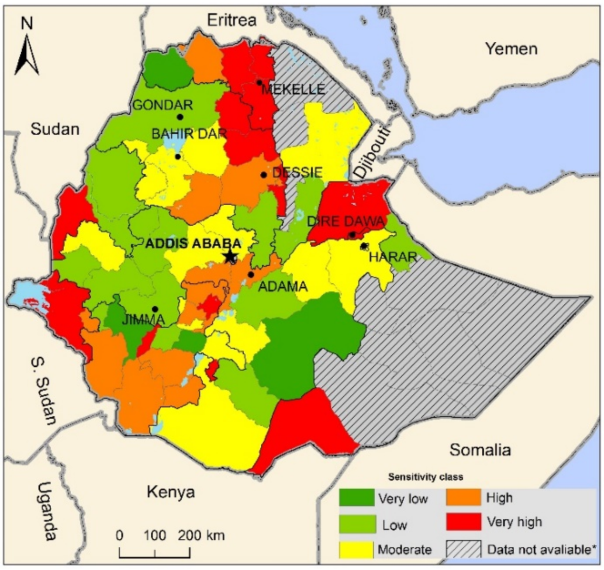


Figure 41: Spatial distribution of the sensitivity index showing the five classes at zone level.

Lack of adaptive capacity index

Adaptive capacity refers to the capacity of a system to adapt to changes in climate and related stressors (Adger, 2006). Adaptive capacity indicators were assumed to have a negative relationship with vulnerability, i.e. the lower the values of adaptive capacity indicators, the higher is the vulnerability of the system in a given area. Figure 42 depicts the lack of adaptive capacity for different zones. Zones with the lowest scores of adaptive capacity were found in Dire Dawa, Oromia, Amhara and Afar regions. The percentage share of crop area where chemical fertilisers were applied and agricultural extension services were received are lowest in the zones with higher lack of adaptive capacity. Lack of irrigation facilities and of access to improved seeds limit farmers' capacities to manage challenges to agricultural production, thereby restricting the economic gains and straining the resilience of smallholder farmers in these zones.

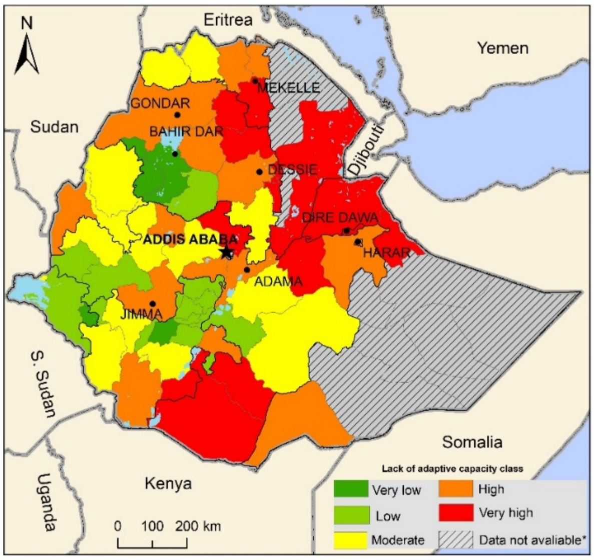


Figure 42: Spatial distribution of the lack of adaptive capacity index showing the five classes at zone-level.

Vulnerability index

Most of the zones with the highest vulnerability values lie in the Dire Dawa, Gambela, Somali, Oromia and SNNP regions.

The vulnerability index was calculated by aggregating the exposure, sensitivity and lack of adaptive capacity index. Figure 43 (a) shows the spatial distribution of vulnerability based on the final vulnerability score. Most of the zones with the highest quantile values that are represented in the very high vulnerability class are located in the regions of Dire Dawa, Gambela, Somali, Oromia and SNNP. It can be seen that the high vulnerable areas are located along the periphery of the country surrounding the least vulnerable areas. Generally, the low vulnerable areas correspond to the urban areas and areas with higher agricultural potential, which are less affected by changes in climate. This corroborates the reports on food aid demand by the National Disaster Risk Management Commission of Ethiopia (NDRMC).

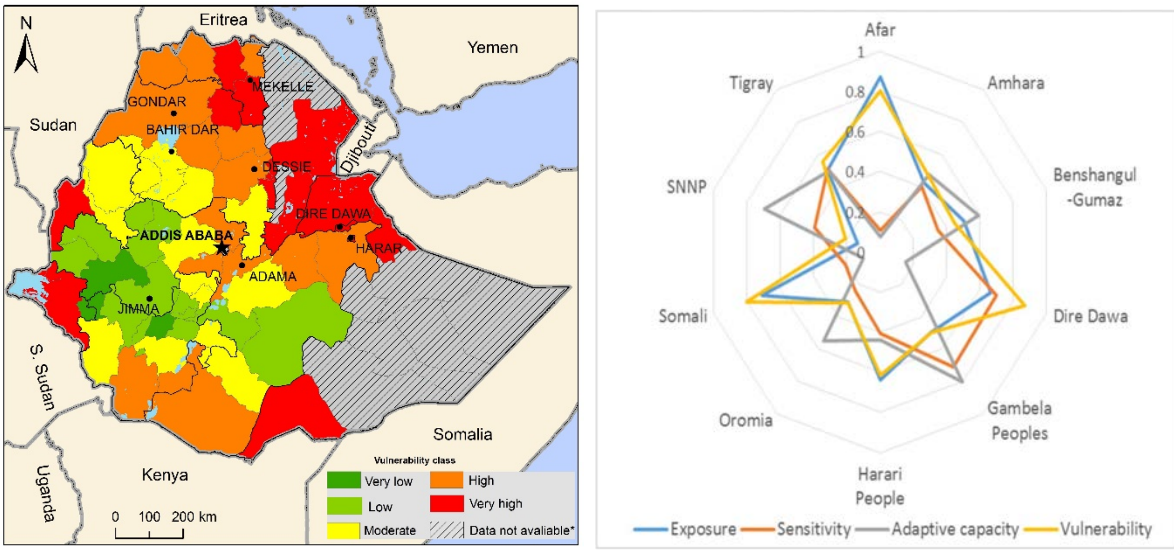


Figure 43: (a) Map of vulnerability classes of zones of Ethiopia to climate change; (b) average score of normalized vulnerability index (0-1) and its component for regions of Ethiopia[13].

Figure 43(b) shows a spider diagram with the average values of vulnerability and its components. At a regionally aggregated level, the value of vulnerability is highest for Dire Dawa and Gambela peoples regions, compared with the other regions. In Dire Dawa region, although the exposure is low, the high lack of adaptive capacity marks the region as highly vulnerable, whereas the high sensitivity score of Gambela region is due to high sensitivity.

Adaptation planning is necessary to respond to the growing challenges that the agricultural communities in Ethiopia are facing. To identify target areas for adaptation and prioritise regions with greatest need for building adaptive capacity, vulnerability assessments can be useful (Eakin & Patt, 2011). This chapter contributes to evidence-based adaptation planning in Ethiopia by identifying areas and patterns of high vulnerability and its components.

Chapter 4 Summary

Spatial vulnerability in Ethiopia
• Highest exposure was found in the Afar, Somali, Tigray (Western, Northwestern) and Benishangul-Gumuz regions. • The Gambela region was observed to be most sensitive to changes in climate parameters, followed by zones in the Dire Dawa region. • Zones with the lowest scores of adaptive capacity were found in the Dire Dawa, Amhara, and Harari region. • Overall, most of the zones in the very high vulnerability class are located in the regions of Dire Dawa, Gambela, Somali, Oromia and SNNP.

[13] Figure 43 (b) shows the normalized index score of Adaptive Capacity (AC). Values of adaptive capacity were calculated using the formula: AC = 1- lack of adaptive capacity. The higher the values of adaptive capacity, the better is the ability of a region to adapt to climate-induced changes.

PART II - ADAPTATION

While the first part of the climate risk study analysed climate impacts on Ethiopia's agricultural sector, the second part presents an assessment of five selected adaptation strategies suitable for dealing with these climate impacts.

Based on the impact analysis of the first four chapters, the second part of this study now assesses the potential for selected adaptation strategies in the context of Ethiopian agriculture. Informed by the projected climate risk and thus adaptation needs for Ethiopian farmers, five concrete adaptation strategies are analysed with regard to their suitability and effectiveness to adapt farmers' livelihoods to climate change. The five adaptation strategies were selected based on Ethiopia's Agriculture and Forestry Climate Resilient Green Economy Strategy (CRGE) (FDRE, 2016) and Ethiopia's National Adaptation Plan (NAP) (FDRE, 2019) as well as input from a range of Ethiopian stakeholders consulted. As findings on climate impacts should inform adaptation action, a key aim of this study is to incentivise evidence-based adaptation. While a range of criteria is employed for assessment of the adaptation strategies' suitability, a specific focus lies on their economic potential as well as on their performance with regard to addressing climate risk.

Adaptive capacity in Ethiopian agriculture

Before assessing the individual adaptation strategies selected for analysis, a brief summary on adaptation challenges and proposed design requirements is given, as a necessary first step for adaptation planning. This also informs about the general feasibility of adaptation in Ethiopia. Linking with the spatial vulnerability analysis conducted as part of this study (Chapter 4), interviews with different local key informants allowed for a closer qualitative analysis of social adaptive capacity in Ethiopia's agricultural sector as one component of vulnerability, focusing on institutional barriers and enablers for adaptation.

Methods

We conducted 27 in-depth interviews with key stakeholders working on climate adaptation and agriculture as well as with farmers in Tigray.

For this study, 27 in-depth interviews were conducted, interviewing a total of 33 individuals (for full list please refer to the supplementary material). Purposeful sampling was employed to identify experts on climate change adaptation in agriculture in Ethiopia, from academia as well as the public, private and non-profit sector. In addition, six farmers from a village in the Tigray region were interviewed in order to cover the full chain of agricultural expertise. The interviews were semi-structured and questions were adapted to each interview situation (see topic guide in the supplementary material). Three main themes were covered: 1) perception of climate change impacts on agriculture, 2) adaptive capacity of Ethiopia's agricultural sector, with a specific focus on farmers' needs and institutional barriers to adaptation and 3) assessment of existing and potential future adaptation strategies for agriculture, based on a preselection of ten adaptation strategies (see Chapter 5). All interviews were conducted in person in Ethiopia, 20 interviews took place in Addis Ababa, with seven additional interviews close to the town of Wukro, in the Tigray region in northern Ethiopia.

Adaptive capacity as defined by the IPCC refers to "the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2014b). Social adaptive capacity forms a subset of adaptive capacity and is concerned with the ability of humans and communities to react to changing conditions, while retaining the person or system's original state over time, as opposed to ecological adaptive capacity referring to ecosystems or species (Whitney et al., 2017). The study of social adaptive capacity can offer valuable insights to better understand and tailor adaptation. A wide range of methods can be used to analyse adaptive capacity (Siders, 2019), due to the complex and often fragmented nature of social interactions, perceptions and institutions, quantitative data can only capture a part of the picture. Semi-structured interviews allow for open answers and high flexibility, with qualitative analyses uncovering the salient themes and nuances of adaptive capacity.

We coded the interview material collected in Ethiopia according to four central pillars of social adaptive capacity, as identified by Whitney et al. (2017): 1) access to assets, 2) diversity and flexibility, 3) learning and knowledge and 4) governance and institutions. Of interest was the social adaptive capacity of the subsistence agricultural sector in Ethiopia, embodied by smallholder farmers, pastoralists and agro-pastoralists. Naturally, the limited sample size (N=27/33) does not allow for generalisation. Yet, key informants and experts with highly aggregate knowledge were interviewed and this information was triangulated with a small case study interviewing selected farmers. The interview data generated rich information, of which only a part is presented here.

Results and discussion

Access to assets

For agricultural livelihoods in Ethiopia, interviewees listed land and water as key assets, which are increasingly affected by climate change. With regard to water, shortages in water availability were brought forward as a frequent challenge, which most interviewees connected to increasing pressures from climate change. Even though Ethiopia has ample water resources at its disposal, precipitation is becoming more and more erratic, diverging from previously known patterns, with extremes in both directions. Especially early cessation or late onset of precipitation was mentioned as a severe barrier to farming in Ethiopia. With rainfed agriculture predominating in Ethiopia, water harvesting is a key mechanism offering scope for irrigation expansion, however, interviewees judged water harvesting to be challenging in the current context. As regards land, shortage of land and land degradation were brought forward as major challenges for farmers, agro-pastoralists and pastoralists alike. Interviewees identified population growth as a main pressure leading to farmland fragmentation and smaller landholding sizes. Scattered land plots pose a particular challenge for some farmers, leading to long travel times between land parcels.

Every generation, I mean during my childhood, the percentage of population engaged in the agricultural sector used to be like 85%, now it is around 80%, even by that time the Ethiopian population was 25 million, and now more than 100 million, ok. And the land is the same. So, the individual holding is reducing, ok, the farming plot size of every household is getting smaller and smaller from generation to generation. (Interview 4, a practitioner)

Across the interviews, poverty levels in Ethiopia were mentioned as a major obstacle to adaptation, impeding adaptation action in many cases. Connected to this, the interviewees expressed that lack of access to inputs poses challenges for smallholder farmers and pastoralists, diminishing their ability to adapt. This is further aggravated by difficulties to access credit, at least for some farmers. Such access also varies from year to year, as reported by farmers, and is sensitive to wider macro-economic developments. For access to inputs, this can be constrained by both poor infrastructure (e.g. large distance to markets, low quality roads) and high prices of inputs. Some farmers may rely on remittances to improve their financial situation, with young family members migrating to cities or abroad to work in other sectors outside agriculture. Other key themes were the loss of production assets due to climate change impacts, such as livestock in pastoralist and agro-pastoralist systems as well as crop failure and even loss of life as a result of natural hazards. For pastoralists in particular, lack of access to feed or shortage of feed are key constraints.

Lack of access to inputs and credit was reported as a major constraint to climate change adaptation among Ethiopian farmers.

Diversity and flexibility

Farmers employ a wide range of strategies to diversify their livelihoods and to respond to climatic shocks. Yet, negative coping mechanisms are also common, such as selling important assets or migrating to urban areas due to lack of alternative income opportunities.

Another important component of social adaptive capacity is the ability to diversify livelihoods and to adjust to changing situations. Such ability is difficult to capture or even measure quantitatively, qualitative information can offer some insights based on experiences and behaviour of farmers. While many farmers and pastoralists appear constrained in their livelihoods given their limited asset base and low access to inputs, some diversifying strategies were nonetheless reported. Farmers as well as pastoralists appear to adapt to changes in climatic conditions using different techniques. On a positive side, they range from changing planting dates, switching to other crops to livelihoods diversification in the form of engaging in off-farm activities and higher investment in education. However, negative coping mechanisms also show the difficulty especially for pastoralists to adjust their income generation: Selling of livestock at reduced prices and the frequently evoked phenomenon of pastoralist drop-outs are cases in point for the limited flexibility of some marginalised and economically restricted communities in Ethiopia. Moving into agro-pastoralism and cultivating crops in addition to livestock rearing is often mentioned as a positive development, but this requires (access to) arable land, which is scarce. In addition, existing farming communities have stronger claims to land in many areas, as opposed to pastoralists who newly venture into crop agriculture. While farmers can request land for cultivation from the government under the current land tenure regime, pastoralists are often not recognised as legitimate claimants, with traditionally mobile lifestyles complicating inclusive land policies. Some communities have established their own social safety nets like saving communities to cope with disasters and reallocate assets in the face of shocks. Others reported to reduce consumption and switch to less water intensive crops and livestock breeds to limit their resource dependency. Finally, some interviewees mentioned migration as another resort, with especially young people migrating to cities in the search for opportunities outside farming. While many appear to migrate voluntarily, others described migration as a process driven by family pressure, lack of alternatives in rural areas and lack of perspective in agriculture due to the non-availability of farmland.

So in my study area, what I identified is that, during the last thirty years, particularly during the last two decades, twenty years, up to 40% of the pastoral communities are already drop out of pastoralism because for a person to be a pastoralist, he has to have some livestock at least, otherwise you cannot call him pastoralist because pastoralist, more than 50% of their income of that household has to come from animal production. So, if it doesn't have any animal then he is not anymore pastoralist. (Interview 1, a researcher)

Learning and knowledge

The ability to adapt to changes effectively is also significantly influenced by knowledge and the ability to learn. Again this is difficult to measure, especially when it comes to the perception and understanding of a problem as complex as climate change and its consequences. The interviews showed that generally, farmers appear to have good knowledge about the environment and climatic conditions, with a number of researchers and practitioners confirming this. However, climate change presents an effectively changed situation, notably increased variability to and changes of historical weather patterns, which challenges farmers' and pastoralists' understanding of the latter. While they used to be highly skilful in navigating the climatic landscape and were well prepared for recurring, but expected extreme situations, such as droughts, they yet need to adapt to the new situation. Erratic weather events defy the former logic of cyclic,

(...) they understand very well because formerly, the farmers forecast properly when the rain comes and when the rains go. But today it is difficult to forecast when it comes and when it stops. So to grow crops it is difficult (...) (Interview 7, a practitioner)

somewhat predictable patterns, requiring a change in farmers' and pastoralists' anticipation and response to weather and climate. Regarding the basis for learning and knowledge amongst farmers and pastoralists in Ethiopia, experts interviewed frequently evoked low educational levels as a challenge to tackle. Ethiopia's large extension system is supporting farmers in this undertaking, but interviewees provided mixed assessments on the effectiveness of the current system, citing lack of inputs for distribution and a bias with regard to the distribution of training and support in favour of established families and clans.

Governance and institutions

Land tenure rules were reported to significantly influence adaptive capacity of Ethiopian farmers. While rights to use and control land are relatively secure in most areas, land markets are poorly developed and land fragmentation poses challenges particularly to the youth.

A final key component of social adaptive capacity is the strength of governance and institutions. With regard to the agricultural sector in Ethiopia, a variety of governance levels are important. At the local level, land tenure rules structure livelihoods and determine access to land and the resources tied to it. Almost all interviewees confirmed land tenure to be an important topic in Ethiopia, with about one third of interviewees also pointing to the particular sensitivity of the issue. The current Ethiopian land tenure system is a relict from the communist period, all land is owned by the state and only certain rights are given to farmers, such as the right to use and also rent out the land, and in some cases also to pass it on to the children. Rights can vary according to region, which in Ethiopia enjoy considerable power. Authority over many regulatory issues is decentralised. As farmers do not actually own land, they also cannot sell it. While this is often seen as an indicator for tenure insecurity and as a barrier to investment into land and adaptation strategies, some interviewees also view the current system as offering at least perceived ownership, which may grant sufficient security over land. Farmers in Ethiopia normally have the rights to use, manage and even bequeath it to descendants. The main legal restriction on land rights is thus with regard to land transfers. This stems from the government's perspective on land, which holds that privatising land (i.e. allowing full private ownership and unrestricted land markets) may lead to massive land sales, landless smallholder farmers, unemployment and big investments in farmland, which would reduce the land availability for smallholder agriculture. Due to this controversial debate, which recently became less restricted with the new government promoting civil rights, most practitioners interviewed were reluctant to sketch their opinion on the topic, repeating that the government is the only actor who can take decisions on the tenure system. In some areas, interviewees report communal systems with flexible land allocation and common grazing areas to function well, while for other regions, practitioners interviewed expressed a wish to move towards more privately owned land. Overall, there seems to be a need for tenure reform, as the current system provokes discontent and occasional conflict, especially when marginalised groups, such as women, young people and pastoralists are involved.

Last year, we have been involved by the government in the food for work practice. We call it safety net. They constructed some terraces or other activities and then they will get some grains, per person. So last year, we have been involved by the government in food for work, but at this time we are free from such activities and the support is a little bit shorter comparing with the last year's season. (Interview 19, a farmer)

On a wider level, the government appears to have a strong influence on and interest in agricultural livelihoods and their adaptation to climate change, but not necessarily sufficient capacity. Interviewees voiced concern regarding lack of coordination across actors and a strained agricultural extension system. The fact that many regulatory competences lie with the powerful Ethiopian regional governments is mostly seen as impeding coherent policy development and strong governance, although it allows for more context-specific adaptation action. Nonetheless, the Productive Safety Net Programme (PSNP) was repeatedly mentioned as a key pillar of social policy supporting many of the most vulnerable farmers in Ethiopia[14]. In addition, Ethiopia's Agriculture and Forestry Climate Resilient Green Economy (CRGE) strategy has started an important process of mainstreaming climate change into all development fields, although more remains to be done.

Adaptation design

From the interviews and the above analysis, a number of favourable features emerge that should be considered for designing suitable adaptation strategies in Ethiopian agriculture (Figure 44). The design elements can be clustered along four themes, namely adaptation effectiveness, institutional design, integrated adaptation and inclusiveness. Keeping those aspects in mind when designing adaptation programmes and projects can improve uptake, effectiveness, ownership and overall sustainability of adaptation strategies in Ethiopia.

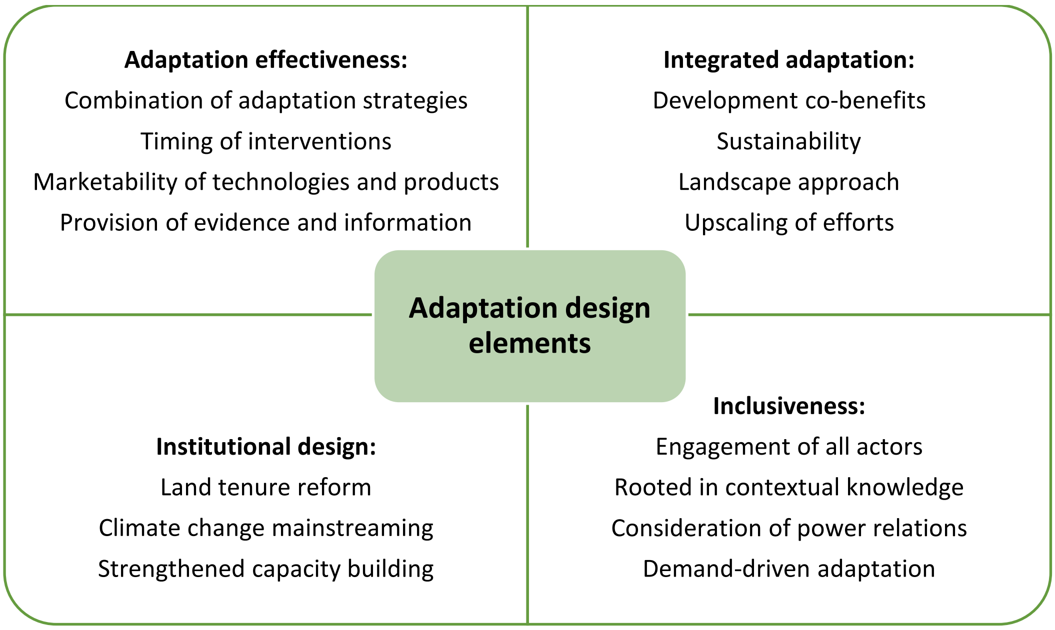


Figure 44: Adaptation design elements identified from key informant interviews.

[14] The Productive Safety Net Programme (PSNP) is a programme which aims to offer support to poor and chronically food-insecure households. It is one of the largest social protection programmes in sub-Saharan Africa and works via cash or food transfers as well as cash for work activities.

Timing is important for successful climate change adaptation, for instance for providing inputs or trainings to farmers at the right moment.

Many concrete examples were given during the interviews, which highlight the importance of the design elements. For instance, the right timing of interventions was mentioned as crucial: Where inputs are, for example, provided in the wrong season, it may be difficult to store them adequately (Interview 2). Timely capacity building is also important, if training is given too late, farmers may not be able to capture its benefits fully; likewise, repeated trainings may be necessary for knowledge to sink in (Interview 23). Generally, the need for capacity building on adaptation and good agricultural practices was the key theme emerging from the interviews, being highlighted, in 21 out of 27 interviews. More than one third of interviewees also said that demonstrating adaptation benefits would be important, as farmers respond to evidence on the performance of adaptation strategies.

Another important theme identified during the interviews was the importance of marketability of adaptation technologies and products. Interviewees stated that adaptation interventions needed to consider and promote the market value of products and enable farmers to commercialise their agricultural activities (Interview 3, 4, 6, 14, 15, 18, 19, 20, 21, 22, 25). In terms of inclusive adaptation design, interviewees stressed that engagement of all actors implicated by adaptation is important, for instance through community conversation sessions (Interview 9). The concept of sustainability also frequently came up during the interviews, both with regard to long-term benefits of adaptation and for wider socio-economic or development co-benefits. Here, gender equality and climate change mitigation co-benefits were mentioned most often.

Chapter 5 – Methods and data for adaptation assessment

Having established the climate change risks and the institutional environment around adaptation in Ethiopia, selected adaptation strategies are now assessed within a multi-criteria framework in order to facilitate policy design and adaptation decision-making.

5.1 Selection of adaptation strategies

The selection of five adaptation strategies for this study was conducted in several steps, including advice from Ethiopian stakeholders via workshops, interviews and an expert survey.

The selection of adaptation strategies to be analysed formed the first step of the assessment. In order to enhance the policy relevance of this study and to tailor the analysis to local needs and preferences in Ethiopia, the selection of adaptation strategies for assessment was conducted considering a landscape approach, i.e. through engagement of a wide range of stakeholders from different sectors of government, and based on a review of key adaptation and climate change policy documents from Ethiopia. As the results of this study are meant to inform adaptation policy, to incentivise adaptation action and to be useful also for implementation of adaptation strategies, special emphasis was placed on engaging relevant stakeholders in a process of continuous learning and collaborative adjustment. This was achieved through several engagement steps, namely stakeholder workshops, building of government partnerships, validation of decisions and feedback rounds with stakeholders, expert interviews and surveys as well as final presentation and validation of results.

In the first phase of the process, a stake-holder workshop was held in Addis Ababa in March 2019, with participants from government, academia, civil society and development organisations, in the fields of climate change, agriculture, forestry, water management and development. The main objective was to introduce the study approach to the participants and to jointly debate crucial design elements as well as to foster a common understanding of the study's relevance. A second important aim of the workshop was to collect experiences with adaptation in the agricultural sector from stakeholders present and to compile opinions on which specific adaptation strategies should be analysed within the study. To this end, a list of ten preselected adaptation strategies was discussed and critically evaluated.

Ethiopia's CRGE Climate Resilience Strategy for Agriculture and Forestry served as a starting point. Within the CRGE, 41 adaptation strategies were assessed, for our study we preselected ten strategies from this list, according to the focus of the study on the agricultural (crop) sector and the capacity of our models and expertise. They are also in line with 18 priority adaptation strategies that were identified within Ethiopia's NAP process, being included in and offering specification to some of the 18 strategies. As the adaptation strategies are defined on a more general level to be all inclusive, we used the definitions from the CRGE, but then further specified the adaptation strategies using concrete interventions subsumed under the general adaptation strategies to enable model-based analysis.

The starting point for the selection of adaptation strategies was Ethiopia's CRGE Climate Resilience Strategy for Agriculture and Forestry, which already identified crucial adaptation strategies for the agricultural sector.

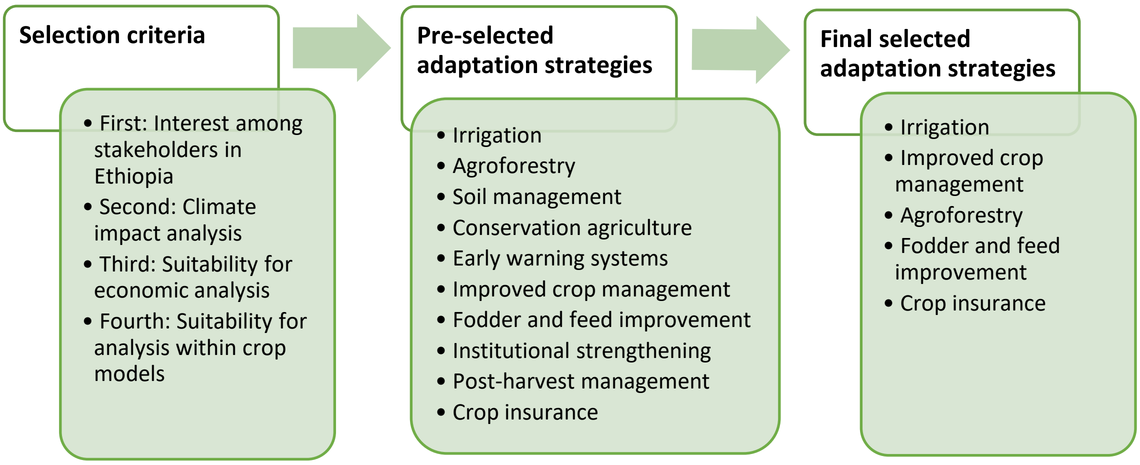


Figure 45: Selection process for the adaptation strategies analysed.

Five adaptation strategies are assessed in this study: irrigation, crop switching and improved crop management, agroforestry, fodder and feed improvement and crop insurance.

Figure 45 shows the selection process for the adaptation strategies with the ten pre-selected measures at the centre and the five measures selected for final analysis to the right. We used four criteria for taking the decision on inclusion in the study: While criteria 2-4 were assessed and ranked based on assessments from the authors of this study, the interest among stakeholders for the adaptation strategies (criterion 1) was determined from the stakeholder workshop, the expert survey and the in-depth interviews. This assemblage of data resulted in the following list of priority adaptation strategies for assessment in this study: **irrigation, crop switching and improved crop management, agroforestry, fodder and feed improvement and crop insurance.**

After selection of the five adaptation strategies for analysis, the selection was validated with government partners and stakeholders. In order to discuss the final study findings and identify channels for uptake in policy and planning, a validation workshop was conducted in October 2019, reuniting the stakeholders engaged in the study. Feedback from the stakeholders was then taken up in a further review round.

During workshop, survey replies and interviews many more interesting adaptation strategies were discussed and put forward, a list of which can be found in the supplementary material. While all of those adaptation strategies are highly relevant and may bring important benefits, a pragmatic decision was taken only to analyse adaptation strategies according to the study focus on crop production and where our models can deliver meaningful analyses to further advance the understanding of those strategies. Many soft adaptation strategies or changes in livelihood sources were mentioned as important adaptation strategies, which are difficult to assess using quantitative indicators, both bio-physically and economically. Nonetheless, the adaptation strategies selected for this study are in high agreement with the priorities identified from Ethiopian policy documents, for instance stemming from regional prioritisation exercises for Ethiopia's NAP process. Here, the four major agricultural regions Amhara, Oromia, Tigray and SNNP all put a focus on "Enhancing food security by improving agricultural productivity in a climate-smart manner", which amongst others includes shifting planting dates, crop switching, application of organic fertiliser (Chapter 7) and improved livestock feed systems (Chapter 9). Amhara and Tigray also prioritised sustainable forest management, which is addressed with agroforestry interventions assessed in this study (Chapter 8). Finally, a need for improved soil management, water harvesting and water retention mechanisms was voiced, which includes a focus on irrigation (Chapter 6). This strategy is also addressed in the study, with regard to soil management we considered the effects of enhanced soil organic carbon (Chapter 7).

The five adaptation strategies analysed in this study are aligned with the priorities defined in Ethiopia's National Adaptation Plan (NAP), thereby supporting its implementation.

5.2 Multi-criteria framework

The five adaptation strategies were then assessed using the following framework, depicted in Figure 46:

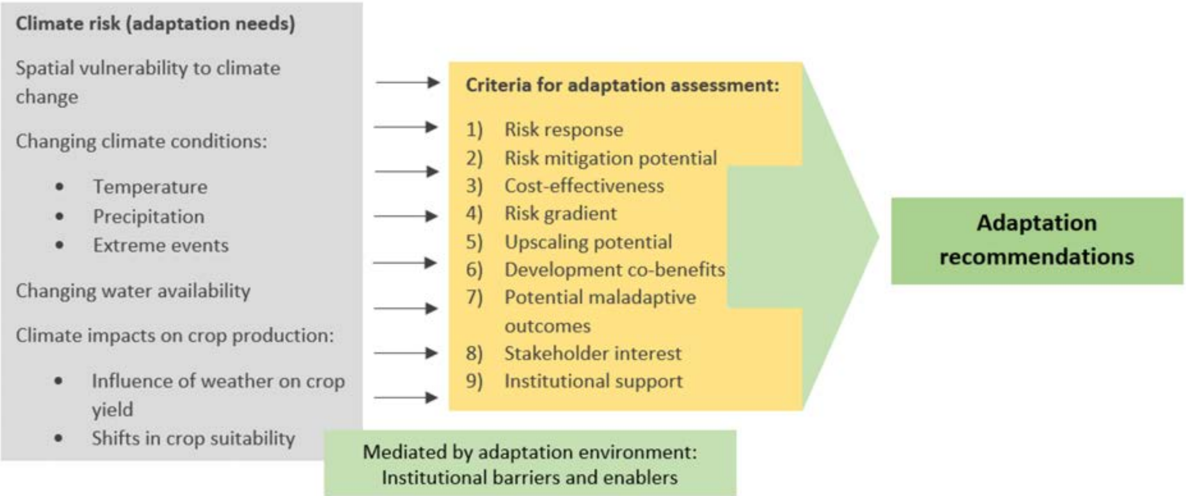


Figure 46: Adaptation assessment framework.

A multi-criteria framework with nine assessment indicators was used to evaluate the five adaptation strategies on the basis of biophysical, economic and soft assessment indicators.

The framework builds on the impact analysis and integrates the findings into the wider context, using biophysical, economic, social and institutional indicators to derive a comprehensive picture of adaptation suitability. The assessment is informed by economic and biophysical modelling, academic literature, case studies and expert judgement, which also served as a starting point to select appropriate adaptation strategies. Based on the climate risk findings and country-specific adaptation information, adaptation recommendations are formulated. A focus is placed on performance assessment based on impact models, both biophysically and economically. We chose this framework in order to integrate different perspectives and indicators, as a focus on only one performance measurement could lead to overly simplistic recommendations (Mechler, 2016). Generally, assessments of adaptation effectiveness and suitability are challenging and should ideally include different metrics and assessment approaches (Dilling et al., 2019).

The following five adaptation strategies were assessed based on multiple criteria to determine their overall suitability and feasibility for the Ethiopian context. The criteria are as follows:

1. **Risk response (risk mitigation vs. risk sharing or transfer):** Adaptation strategies can either reduce climate risk and increase resilience (for instance better water management) or share/transfer risk amongst groups to lessen the burden on individuals (e.g. insurances).
2. **Risk mitigation potential:** An important assessment criterion for adaptation strategies is their potential to mitigate risk, i.e. to reduce yield losses due to climate change. Where possible, this was assessed based on adaptation evaluation within the impact models (see Chapter 3).
3. **Cost effectiveness:** Although absolute costs depend on the size of the intervention, information on the costs and cost effectiveness of different adaptation strategies on scenarios are included in the assessment.
4. **Risk gradient (risk-independent vs. risk-specific):** Adaptation strategies can be useful even in the absence of climate change or in case of uncertainty regarding future climate change impacts (= risk-independent) or they can be risk-specific, where their implementation is only sensible when a risk is actually present (e.g. insurances).
5. **Upscaling potential:** In this category, it is considered how much further potential there is for different adaptation strategies to be exploited in Ethiopia, i.e. how to increase usage of a strategy amongst smallholder farmers. We

define this as a product of the current level of usage, the area suitable for implementation of a strategy and the demand by smallholder farmers for adoption, as assessed by experts and validated with data, where available.

6. **Co-benefits for sustainable development goals (SDGs):** Many adaptation strategies do not only adjust systems to cope with climate risk, but have the potential to contribute to other development benefits as well. Here, this is indicated by referring to relevant Sustainable Development Goals (SDGs), which can also be addressed by specific strategies.
7. **Potential maladaptive outcomes:** However, adaptation interventions may also produce undesired effects or maladaptive outcomes (e.g. biodiversity losses, increased energy demand), which need to be considered for a comprehensive assessment and which are discussed under this indicator for each adaptation strategy.
8. **Stakeholder interest:** Another indicator for assessing adaptation strategies is the interest that stakeholders show in a strategy, as this crucially determines future uptake and implementation.
9. **Institutional support requirements (institution-led vs. autonomous):** While most adaptation strategies can be initiated and implemented by different actors, depending on their concrete design, a distinction can be made between strategies which generally require high institutional support and those that can be initiated by farmers themselves. Barriers to adoption are also important to consider for assessing this indicator.

The subsequent chapters present an assessment of the five adaptation strategies according to those indicators.

5.3 Crop model-based evaluation

Crop models were used to evaluate the effectiveness of different adaptation strategies.

The second indicator on the risk mitigation potential of adaptation strategies was assessed using the crop models employed in Chapter 3, where possible. We used the suitability models for the different crops (sorghum, wheat, maize, teff) to evaluate the effect of selected adaptation strategies on crop suitability, in order to determine which practices will reduce the loss in crop suitability under climate change. The process-based crop model APSIM was also used to identify the effect of different adaptation strategies on maize. For both models, key parameters were changed as compared to the baseline settings to model the effect of adaptation. As this is not possible for all adaptation strategies, for some adaptation strategies we complemented this information with findings from the literature.

5.4 Economic analysis

For economically assessing the different adaptation strategies selected, we employed two different approaches to cover both macro-economic and micro-economic perspectives on adaptation.

The first approach looking at the macro-level is based on the economic modelling approach presented in Chapter 3.5. This economic analysis of adaptation strategies uses different scenarios to assess the cost effectiveness of specific adaptation strategies. The baseline and climate change scenarios used for the economic impact analysis remain the same as in Chapter 3.5 and are now complemented with a further adaptation scenario, namely for irrigation (IR). We conducted a comparative static analysis (i.e. with and without scenario) using gross value of production (GVP) and net value of production (NVP) as indicators. For the adaptation scenario (IR), the climate change impact scenario (CC) is the reference scenario. This is because the rationale for adaptation is to reduce the economic consequences of climate change. Irrigation as an adaptation option is supposed to dampen the adverse consequences of climate change impacts on crop yields by compensating yield losses.

We applied both a macro-economic and a micro-economic cost-benefit approach to assess the economic potential of adaptation.

A second approach follows the rationale of a micro-level cost-benefit analysis, which uses a dynamic approach and considers the costs and benefits of adaptation strategies over time, from 2020 until 2050. Like the first approach, it is based on different scenarios in order to calculate the economic efficiency of implementing different adaptation strategies. The action scenario is compared with two baseline scenarios: one with climate change impacts, but no adaptation, and the other without climate change impacts and no adaptation, all other things being equal. In addition to net values of production, for the micro-level analysis other indicators for cost-efficiency, such as benefit-cost ratios (BCR), internal rates of return (IRR) and payback periods for farmers are also calculated. Since the time dimension in this approach requires comparing impacts at different periods of time, future values need to be discounted to present values to allow for comparison. For the purpose of our analysis, this was done using the current inflation rate, which is 6%, according to World Bank data. Not all costs and benefits can be monetised and included in quantitative cost-benefit analyses, for instance factors related to wellbeing, equity and the environment are often difficult to quantify. Here, the costs included in the calculations are: 1) Establishment costs of the initial investment, including foregone revenues from production option before action/adoption of the adaptation strategy; 2) Maintenance costs (labour costs for management, fertiliser etc.); 3) "Re-establishment" costs, where the adaptation infrastructure or inputs need to be renewed. The benefits are increases in agricultural production due to the adaptation strategy implemented.

More information on both approaches and methodologies can be found in the supplementary material.

5.5 Expert assessment and literature review

Additional indicators were assessed based on inputs from experts and the literature, which we systematically reviewed.

A variety of different data sources informed this part of the study on adaptation. In addition to data assembled from various existing sources, some data was also collected in person in Ethiopia. During the expert interviews, which were already introduced, a part of the conversations centred on assessing the selected adaptation strategies, using expert elicitation as a tool to collect expert judgment on the performance and usefulness of the adaptation strategies. A list with the ten preselected adaptation strategies was presented to the experts for their evaluation and assessment based on the nine assessment indicators. In addition, 27 interviewees (except for the six farmers inter-viewed) and a network of key stakeholders was invited to participate in an expert survey via email. With 17 responses only a part of the experts replied, but the answers nonetheless provide interesting expert judgement on a range of questions. Furthermore, a systematic literature review was conducted for each of the five adaptation strategies, using mainly the databases Scopus and Web of Science. Empirical and modelling studies related to the five adaptation strategies were screened for information regarding the nine assessment indicators.

In the following five chapters, the selected adaptation strategies are assessed according to the nine criteria. A joint assessment is then given as part of the conclusion.

Chapter 6 – Irrigation

The FAO distinguishes between three types of irrigation: surface irrigation, where water flows over the land; sprinkler irrigation, where water is sprayed under pressure over the land; and drip irrigation, where water is directly brought to the plant (FAO, 2016).

Although use of irrigation remains limited in Ethiopia, scientific interest in irrigation is high, particularly in small-scale irrigation systems.

Even though irrigation is not widely implemented yet in Ethiopia, scientific interest in irrigation in Ethiopia is high: A literature search with the database Scopus returned 539 results on the terms "irrigation" and "Ethiopia", many of which were published since 2009 with another sharp increase in 2017. Publications from the last ten years show a clear focus on small-scale irrigation as linked to climate change, exploring irrigation in the context of climate adaptation and in comparison to other adaptation strategies (Kassie et al., 2015; Teshager, Adgo, & Tilahun, 2014; Tessema, Aweke, & Endris, 2013). A significant portion of studies has also explored the linkages between irrigation and its effects on food security and welfare (Amare & Simane, 2018; Bacha et al., 2011; Hagos et al., 2017; Sani & Kemaw, 2019).

Climate change impacts the availability of water, causing temporal water shortages, dry spells and droughts where people rely on water for agriculture. Erratic and insufficient precipitation have created uncertainty and led to frequent crop failures in agricultural production, which in Ethiopia is primarily subsistence-based and rainfed (Seleshi & Camberlin, 2006). Especially smallholder farmers suffer from the impact of climate variability, which can reduce their food supply and increase the risk of food insecurity and poverty. Irrigation can help smallholder farmers to compensate for the negative impacts of erratic and insufficient precipitation and significantly stabilise agricultural production (Woldemariam & Gecho, 2017). More specifically, it can raise agricultural production, allow for greater cropping intensity and crop diversity (i.e. higher-value crops), and lengthen agricultural seasons (Awulachew, 2010; Woldemariam & Gecho, 2017). Irrigation thus serves three main adaptive purposes: 1) Increasing yields by supplying water needed, 2) reducing risk due to a more constant water supply and 3) enabling multiple harvests and cultivation of high-value cash crops, as irrigation supplies water in the dry season.

The main crops grown under irrigation across Ethiopia are maize and high-value vegetable crops.

Current irrigation schemes in Ethiopia vary in terms of size and structure, ranging from small-scale to large-scale irrigation schemes which cover several thousands of hectares (Awulachew, 2010). The most common type of irrigation is surface irrigation with around 98% (FAO, 2015b). Sprinkler irrigation accounted for around 2% and localised irrigation was marginal (ibid). Surface irrigation uses gravity forces and does not depend on mechanised equipment (Haile & Kasa, 2015). Usually, entire fields are flooded or water is directed through small canals. On the one hand, such traditional irrigation schemes are relatively simple and inexpensive and farmers can build them on their own initiative using local materials. On the other hand, diversion structures are not built on a permanent basis and have to be rebuilt after every growing season, requiring intensive maintenance (MoA, 2011). Another issue regarding surface irrigation is inefficient use of water, as large amounts of water are lost to runoff, infiltration and evaporation. The main crops grown under irrigation vary from region to region, however, in general major irrigated crops include cereals, such as maize, followed by vegetables, pulses, root crops, fruit and fibre (FAO, 2005; MoA, 2011).

Rainwater harvesting (RWH) is the practice of collecting and storing precipitation that can serve as additional source of water not only for irrigation, but also for livestock and domestic use. The RWH techniques most commonly practiced in Ethiopia are run-off, flood, in-situ and roof water harvesting (Binyam & Desale, 2015). RWH is also an effective strategy to manage floods and, thereby, prevent erosion and damage to crops and livestock. However, some of the major challenges for developing RWH in Ethiopia are the lack of storage facilities for some RWH techniques, high labour demand as well as significant water losses through seepage and evaporation (ibid).

6.1 Risk mitigation potential

Irrigation can help to mitigate climate risks. Various studies have found a positive link between irrigation, agricultural production and welfare levels:

Summary of evidence on irrigation performance in Ethiopian agriculture

Region	Reference	Time frame	Key message	Yield/Income/Expenditure change
Ambo district	Bacha et al., 2011	2006	Incidence, depth, and severity of poverty were significantly lower among farm households with access to irrigation due to higher yields.	Yield per hectare of irrigating households was 58% higher than that of non-irrigating households.
Gorogutu district	Eshetu et al., 2010	May – June 2009	Introduction of irrigation led to an increase in average reported income resulting from the ability to grow additional higher-value horticultural crops for sale at the market, and to harvest more than once a year.	20% mean income increase (23% income increase from horticultural crops, 19% income increase from cereal crops). Some farmers reported gains of up to 400%.
Amhara, Oromia, SNNPR, Tigray	Garbero and Song-sermsawas, 2018	March – May 2015	Beneficiaries of the PASIDP project (a modern irrigation scheme) gained higher crop yields and a greater crop diversity compared to households using traditional irrigation schemes or relying on rainfed agriculture.	Yield of PASIDP beneficiaries was almost 5 times the yield of households pursuing rainfed agriculture.
Tigray, Oromia	Hagos et al., 2017	2013	Users of spate irrigation were better off than non-users in terms of food expenditure, non-food expenditure and completion of primary education.	Monthly food expenditures of users of spate irrigation were 31% higher than those of non-users.
Wondo Genet (SNNPR)	Adela, Auerbacher & Abebe, 2019	2019	Access to irrigation has a positive impact on farm income and consumption expenditures, however, small-scale irrigation schemes need to be accompanied by proper governance, management, infrastructure and access to information.	Participation in small-scale irrigation schemes improved farm income by 42% and consumption by 35% as compared to farms without access to irrigation.

6.2 Economic analysis: Irrigation as adaptation to maize yield changes

Irrigation can be considered as an adaptation strategy for several reasons: It can supplement water, when there is no precipitation, or allow for multiple harvests even in the dry season.

Irrigation can help to adapt to climate change either through allowing farmers to grow several times within a year, diversifying the type of crops grown in a field and/or supplementing water at the time of water deficiency in the main crop-growing season. In this study, we simulated the impacts of climate change based on the main crop-growing season in Ethiopia, i.e. *meher*. Therefore, irrigation here is considered only for supplementing the water deficiency during the growing period, which is assumed to be approximately four months, according to FAO's crop calendar. We adjusted the costs of irrigation on the basis of these respective growing periods from the total annual costs of irrigation per ha obtained from the literature (e.g. Gebreegziabher et al., 2013). The economic analysis of both impacts and adaptation in this study are conducted with the implicit assumption of what is commonly known as monocropping.

Other things remaining the same, the purpose of irrigation is to provide higher yield per ha compared to the rainfed production system. In that regard, we conservatively assume that irrigated yields are higher than rainfed yields by 20%. Using the methods described in the methodology section (in the supplementary material), we derived the

The analysis is conducted for the same four zones which were already considered in the economic impact analysis. We assume a policy target that wants to offset 75% of the projected climate-induced yield losses for those zones.

demand for irrigation, which we express as irrigated area as percentage of total cultivated area required to reverse the yield loss induced by climate change. In principle, such offsetting targets shall be specified by adaptation policies. In absence of such adaptation policy targets, we merely assumed the policy aims to offset a specified portion of yield losses due to climate change. The analysis in this section presumes that the adaptation policy target is to offset about 75% of climate change-induced maize yield losses. To model the costs of full adaptation (for maize), we also provide the case with reversing the losses by 100% (i.e. to maintain the average yields from falling by increasing the share of irrigated land) in the supplementary material. As for the economic analysis of climate change impacts on maize yields (see Chapter 3.5), we again focus on the four exemplary zones, selected for the analysis: Western Tigray, Gamo-Gofa, Illubabor and North-Shewa.

The starting point for economic analysis of adaptation strategies is the scenario under climate change. Because the incremental demand for irrigation bears additional costs, we will focus on the net value of production (NVP) for our analysis. We analyse the demand for irrigation as represented by the percentage of irrigated area in the total harvested crop area.

For a given adaptation target, the demand for irrigation depends on the projected yield declines. Thus, the demand, for example, is higher under RCP8.5 than under RCP2.6 in the Gamo-Gofa zone because maize yields are projected to be higher under RCP2.6 than under RCP8.5 (see Chapter 3.2). Likewise, the share of irrigated land remains the same in the current and RCP2.6 climate change scenarios for a given zone, if no yield changes are expected under climate change.

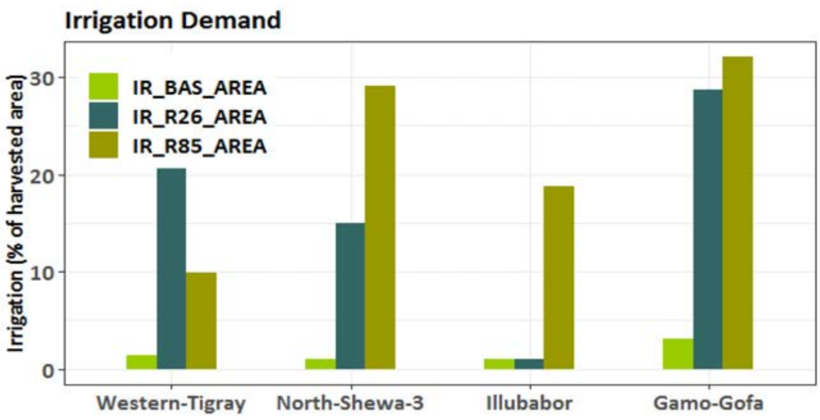


Figure 47: Demand for irrigation area in the baseline (IR_BAS_AREA), and under RCP2.6 (IR_R26_AREA) and RCP8.5 (IR_R85_AREA). Note that the demand for irrigation area is inversely related to projected yield impacts as exhibited in the case of Western Tigray (RCP2.6 vs RCP8.5) and Illubabor (baseline and RCP2.6).

The next step is to calculate the costs of irrigation as adaptation to climate change. For the highest unit costs of irrigation, the highest costs of irrigation are expected in Illubabor (6.3 million USD) and Gamo-Gofa (5.8 million USD) for adapting to the RCP8.5 scenario up from 330 thousands USD (in Illubabor) and 570 thousands USD (in Gamo-Gofa) incurred due the current irrigation practices. Note that the unit costs of irrigation are very important factors. With the lowest unit cost of irrigation, the irrigation costs for adapting to yield changes under RCP8.5 in Illubabor and Gamo-Gofa are 1.85 and 1.75 million USD, respectively. The total costs of irrigation in Western-Tigray and North-Shewa zones are not comparable to those in Illubaor and Gamo-Gofa, simply because of the difference in total harvested areas in the baseline scenario or the importance of the crop in the zones. Therefore, the costs and marginal benefits of irrigation can be interpreted only relative to the respective baseline net value of production in a given zone, not in relation to other administrative units.

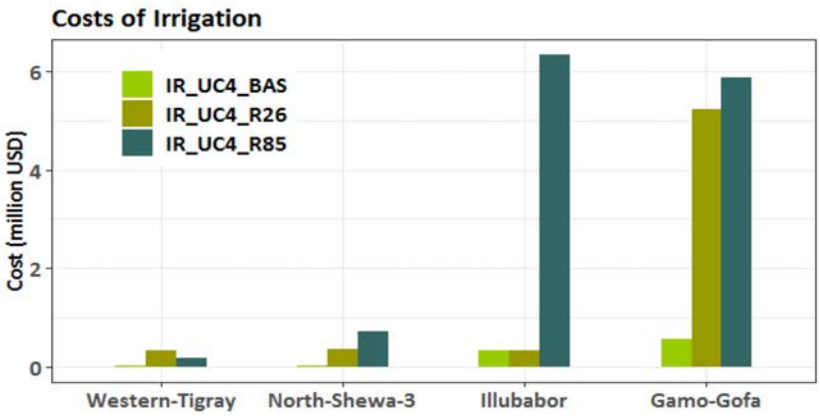


Figure 48: Costs of irrigation (IR) associated with high unit costs (UC4 = 298 USD/ha/meher) in the baseline (BAS), under RCP2.6 (R26), and under RCP8.5 (R85).

To allow for a comparison between zones and scenarios, we calculate the ratios of the net value of production under climate change with irrigation and without, as absolute values depend on the size of area cultivated.

Thus, we perform a comparative analysis of the net value of production (NVP) under different scenarios per zone. For simplicity, we calculated the ratio of NVP under climate change with irrigation and without. The differences between the two scenarios stem from the differences in the total costs of irrigation (the cost aspect of irrigation) and the marginal gross value added due to irrigation (the benefit aspect of irrigation). The net gain is influenced by the unit costs of irrigation and the projected impacts of climate change.

Table 5 summarises these ratios. The table shows the ratios are greater than one for many of the scenarios. This demonstrates the effectiveness of irrigation as adaptation to climate change. Besides, for a given unit cost of irrigation and a given zone, the ratios are slightly higher when the anticipated yield changes are high. This can be seen by comparing the ratios under RCP2.6 and RCP8.5 for a specific zone. However, as shown in Table 5, the attractiveness of irrigation as adaptation to climate change would decline, as unit costs of irrigation increase. The ratios eventually become less than one under the highest irrigation cost scenario (298 USD/ha). This implies that the NVPs with irrigation (because of high irrigation costs) are lower than the NVPs without irrigation (sustaining the climate change-induced gross value lost).

Table 5: Ratio of NVP of maize under climate change with irrigation to NVP without irrigation.

Region	Zone	Ratio			
		IR_UC1	IR_UC2	IR_UC3	IR_UC4
RCP2.6					
Tigray	Western-Tigray	1.06	1.04	1.02	0.99
Amhara	North-Shewa-3	1.04	1.02	1.00	0.97
Oromia	Illubabor	1.00	1.00	1.00	1.00
SNNP	Gamo-Gofa	1.18	1.14	1.07	0.97
Average over the four zones		**1.07**	**1.05**	**1.02**	**0.98**
RCP8.5					
Tigray	Western-Tigray	1.02	1.01	1.00	0.99
Amhara	North-Shewa-3	1.13	1.10	1.05	0.98
Oromia	Illubabor	1.38	1.27	1.10	0.85
SNNP	Gamo-Gofa	1.25	1.20	1.11	0.99
Average over the four zones		**1.20**	**1.14**	**1.07**	**0.95**

Notes: IR stands for costs of irrigation associated with different unit costs per meher season (UC1 = USD 87/ha, UC2= 133 USD/ha, UC3 =USD 200/ha, and UC4= USD 298/ha). The unit costs are obtained from the literature and assumed to be equal for all zones.

To sum up, irrigation has the potential to dampen parts of the economic loss due to climate change. However, its net return highly hinges on the unit cost of irrigation, anticipated impacts of climate change and the extent to which adaptation policies aim to offset climatic impacts.

6.3 Cost-benefit analysis: Switching from rainfed to irrigated maize production

In addition to the macro-level economic analysis, we also carried out a micro-economic case study of a maize farmer who starts using irrigation.

In addition to the macro-level approach for assessing the economic potential of irrigation at different spatial scales in Ethiopia, we also conducted a micro-economic cost-benefit analysis at farm level. This adaptation strategy describes a farmer who switches from growing maize (*Zea mays*) in a purely rainfed system to an additionally irrigated system that allows to produce during the dry season, too. In fact, Ethiopia is largely dependent on rainfed agriculture and the agricultural area equipped for irrigation is one of the lowest in Africa (FAO, 2015a). However, Ethiopia's surface water systems would suffice for an intensification of irrigation activities (FAO, 2015a).

For each adaptation strategy, we will evaluate four scenarios: baseline, adaptation, no adaptation and improvement. These four scenarios are composed of a distinction between action vs. no action under climate change or no climate change impacts. The natural comparison for evaluating adaptation is to compare the cost effectiveness of implementing an adaptation strategy under climate change (action) vs. the case of inaction under climate change. In addition, we also compare the action vs. inaction case with the assumption that no climate change impacts on agricultural yields are felt. This is done in order to account for potential uncertainties in climate impact projections and to assess the usefulness of adaptation strategies in the face of those uncertainties. Where action is cost-effective even with no climate impacts taken into account and more cost-effective than the inaction case, the adaptation strategy can be classified as a "no-regret" strategy, since it will be profitable and sensible to implement either way. Table 6 shows the comparisons taken between the different scenario building blocks.

We compared an action with an inaction scenario in order to evaluate the adaptation strategy. To account for uncertainties in climate impact projections, we also compared action and inaction without taking into account climate change impacts.

Table 6: Scenario comparisons for the cost-benefit analyses.

	Action	Inaction
Climate change impacts on agriculture are felt	If action is more cost-effective than inaction: it is a suitable adaptation strategy	
No climate change impacts are felt (= baseline)	If action is more cost-effective than inaction: it is a no-regret strategy	

The action component describes the situation when the farmer adopts the adaptation strategy, while inaction means that the farmer does not adopt the adaptation strategy. The baseline scenario with no climate change impacts being felt means the current climatic conditions are constant over the analysed time period (to 2050).

In order to analyse the economic feasibility of this switch in irrigation, we hereafter work with the following specific scenarios:

Baseline (no action, no climate impacts): Rainfed maize production under current climatic conditions – We consider an Ethiopian farmer who produces maize in a rainfed system within the catchment area of the two rivers Blue Nile and Awash. Due to water constraints during the dry period, one harvest is possible per year. Yield changes due to future climate change are not incorporated.

Adaptation (action, climate change impacts): Switch from purely rainfed to an additionally irrigated maize production under climate change impacts – As the farmer experiences negative climate change impacts on the production, the farmer adopts the adaptation strategy irrigation and hence produces maize in an irrigated system (all other things being equal). Ideally, this stabilises water supply, therefore also the maize production over all seasons and it furthermore allows for harvest twice a year.

No adaptation (no action, climate change impacts): Rainfed maize production under climate change impacts – In the no adaptation scenario, the maize farmer also experiences negative climate change impacts on the maize yields, but the farmer does not adopt the adaptation strategy irrigation and thus yield quantity and quality is susceptible to future climate change. Due to water constraints, the farmer can harvest only once a year.

Improvement (action, no climate change impacts): Switch from rainfed to irrigated maize production under current climatic conditions – In this scenario, there are no negative future climate change impacts felt by the farmer. Nevertheless, the farmer switches from rainfed to irrigated maize production.

Data, assumptions and initial monetarisation

Our case study was situated in the catchment area of the two rivers Blue Nile and Awash. Since water availability is projected to increase with future climate change, establishing an irrigation system for maize seems feasible.

Hereafter, we use the following data and assumptions for the CBA calculations. They refer to the adaptation scenario and also to the other scenarios, if applicable. This case study is situated in the zone North-Shewa in the catchment area of the two rivers Blue Nile and Awash. When adopting the switch, the size of the crop area remains the same, i.e. the area cultivated with rainfed maize is the same size as the area planted with irrigated maize. Here, we analyse the costs and benefits which can be associated to one hectare, irrespective of the actual field size originally allocated to maize. The irrigation type is surface irrigation by river diversion. This is the most common type in Ethiopia and does not require much installation equipment, as it is established by digging canals within the field. Furthermore, the annual river discharge of the two Ethiopian rivers is projected to increase in the future and hence this irrigation type is likely to be feasible due to increased water availability for irrigation (see Chapter 2). Assuming this irrigation type in accordance with National Irrigation Board (2018), one third of the field will be covered with the irrigation trenches or canals in between the rows sowed with maize. This means that in comparison to the unirrigated baseline scenario, in an irrigated system, the overall harvest decreases (ceteris paribus), as only two thirds of the field are covered with maize. The subsequent yield penalty can be (over-) compensated, as the farmer harvests twice a year due to a more constant water supply and further considering a yield benefit induced by irrigation. In our analysis, this irrigation-related benefit is 20%. This is a rather conservative approach compared to other sources, e.g. Bacha et al. (2011) and Garbero and Songsermsawas (2018) project yield increases of 50% and more.

As a basis for the yield projections, we firstly take Ethiopian yield data from FAO (2019b) and calculate a three-year average for the most recent data points which is then extrapolated to the start year of our analysis, i.e. 2020. Hence, we use a yield of 3.95 tons per hectare as a starting point for our analysis. In terms of technological change, we assume that the farmer's land productivity increases due to "autonomous technological progress". For maize, we thus use a growth rate of 1.4% per annum reflecting global growth rates (FAO, 2019b) and a "catching up" effect. For the climate change impact, we rely on maize yield projections from ISIMIP for all of Ethiopia. The ISIMIP was created to offer a framework for the comparison of climate impact projections in different sectors, combining the power of a suite of impact models in different sectors. It thus provides sound aggregate results on projected climate impacts (see Frieler et al. 2017 for further information). In connection with the technological progress assumption, this leads to annual maize yield increases at national level of between 1.0-1.5% under RCP8.5.

Altogether, the farmer spends about 450 hours per hectare to dig and stabilise irrigation trenches that connect to the catchment area's surface water supply. We assume that 15 meters of trenches can be formed per working hour. In total, 67 trenches are needed (given a square of 100 meters). This time is valued in accordance to ILOSTAT (2019) with almost 20 Ethiopian Birr (ETB) (= 0.7 USD)[15]. To include costs for some material, such as shovels, we add 10% to the labour costs. These two elements – labour and material – can be defined as the establishment costs of this adaptation strategy. Annual variable costs for irrigation originate from the labour input for maintenance to check, stabilise and re-dig canals, if necessary. We assume that these costs are 10% of the above establishment costs. Finally, the maize production will be valued at domestic market prices. We take domestic market prices from FAO (2019a), where the producer price for maize is 4,323 ETB (= 142 USD) per ton. These data points are additionally substantiated using gross margin calculations as provided by (Sellasie, 2016) and cross-checked by using information from Alemu et al. (2014) as well as Elias et al. (2017).

We collected information from literature and international databases in order to better inform our assumptions.

Specific costs and benefits

Using this basic data and qualified assumptions, it is now possible to allocate specific costs and benefits to the switch from maize production to sorghum production. Allocating these benefits and costs over time allows for a proper Cost-Benefit-Analysis (CBA)[16].

- Per hectare of maize, the farmer – prior to the switch – has earned an economic margin of 2,565 ETB (= 84 USD) per hectare. Due to the higher yield and an additional harvest, this income indicator increases by 1,974 ETB (= 65 USD), i.e. although less maize plants per hectare are planted, an extra income is generated right from the beginning.
- However, the establishment costs are larger and account for 9,518 ETB (= 313 USD) per hectare in 2020. Hence, the farmer loses a total of more than 7,500 ETB (= 247 USD) per hectare in the first year of switching from rainfed to irrigated maize.
- In the second year, the situation already improves. The establishment costs disappear and are substituted by the much lower maintenance costs. Also, the economic margin increases (due to higher yields and the additional harvest). Hence, in total, more than 1,000 ETB (= 33 USD) per hectare are net gained.
- Over time, the economic margin potentially to be earned from irrigated maize will further increase (due to the embedded "autonomous technological progress"). This will lead to a situation in the year 2030, when the additionally earned income from irrigated maize will be around 2,000 ETB (= 66 USD) per hectare. In the year 2050, a net cash flow of almost 4,200 ETB (= 138 USD) per hectare is possible.

Major findings

The key outcome of this analysis is that switching from rainfed to irrigated maize production would be highly beneficial for a farmer under future climate change.

Based on the CBA, we can draw the conclusion that in 2030 and even more in 2050, the adaptation strategy of switching from rainfed to irrigated maize (adaptation scenario) would be (very) beneficial in comparison to the no adaptation scenario. Over time, irrigation has a positive return on investment (see Figure 49).

[15] Calculations were done in ETB. All conversions into USD were completed based on the exchange rate from 25 November 2019.

[16] The basic methodological and mathematical foundation of the CBA as it is applied hereafter are already described in Chapter 5 as well as the supplementary material. Therefore, a detailed description of the methodology as well as some other methodology-related data requirements (such as the use of inflation rates) shall not be repeated here.

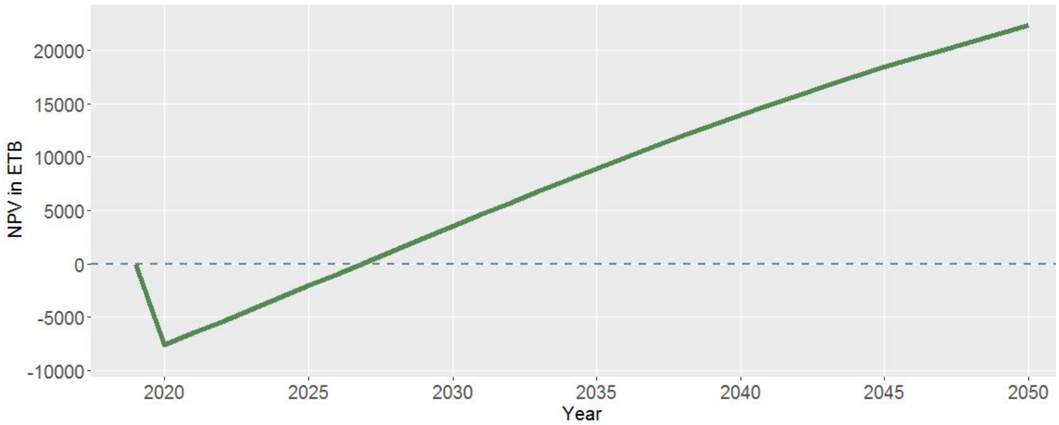


Figure 49: Development of the net present value from 2020 to 2050 when switching from rainfed to irrigated maize under future climate change impacts (in ETB).

The NPV difference between the adaptation and the no adaptation scenario, as can be seen, is negative for a couple of years. However, only in the first year, the net cash flow is negative, i.e. the NPV decreases. This already changes after 2020, when the minimum NPV is –7,544 ETB (= -248 USD). From then on, the net cash flow is positive, and consequently the NPV starts to increase and becomes positive in the year 2027. In the following time, the NPV further increases and in 2050, it is 22,319 ETB (= 735 USD).

The benefit-cost ratio (BCR) is one indicator for the economic effectiveness of an intervention. In this irrigation scenario, the BCR is 1.21 in 2030 and 1.99 in 2050.

The corresponding internal rate of return (IRR) is thus only 14% for 2030, but amounts to almost 21% in 2050. This indicator must be greater than the local interest rate or in the absence of comprehensive data, the growth rate of Ethiopia's gross domestic product (GDP) per capita, in order to indicate a "good" investment. According to the World Bank (2019b), the GDP per capita growth rate is currently around 6% in the country. As the IRR (of 21%) is higher than this growth rate, the adaptation strategy to switch from rainfed to irrigated maize is very profitable from a farmer's point of view. This is also reflected in the benefit cost ratio (BCR): In 2030, it is 1.21 and in 2050, it is 1.99. For further details, we provide a screenshot of the annual benefit and costs streams in the supplementary material.

The results show that the farmer's investment into irrigation pays off after 8 years. The break-even point between accumulated net costs and net benefits is in 2027. However, this time span must be bridged. Policy makers and/or other decision-makers should ensure that the associated temporary income loss is met with transitional funding (subsidies in kind). Otherwise, the adaptation strategy might not be affordable for many maize growing farmers in Ethiopia. In addition to the adaptation scenario (see also supplementary material), the improvement scenario (see supplementary material) is also economically beneficial for the farmer as our CBA results suggest (see Table 7).

Table 7: Adaptation and Improvement scenario results by 2050.

Adaptation	Improvement
• IRR: 20.89% • NPV: 22,319 ETB (= 735 USD) • BCR: 1.99	• IRR: 21.05% • NPV: 23,123 ETB (= 761 USD) • BCR: 2.02

The comparison shows that there is very little difference between the adaptation and the improvement scenario, with irrigation as set out above bringing high benefits even in the case of climate change uncertainty and with no climate change impacts included in the analysis. This can be explained with the relatively small climate change effects on maize yields at national level in Ethiopia: Other factors, such as the costs for irrigation and the benefits from irrigation to receive additional harvests and yield raises of 20% influence the results much more. Irrigation is thus highly profitable in areas where enough water is available and in the case of low installation and maintenance costs, even if no negative climate change impacts on yields are projected.

All in all, we conclude that additionally installing irrigation is more profitable than purely rainfed agriculture. Due to the intensive land use when double cropping maize, special attention should be given to uphold soil quality and other agronomic factors. When looking at the CBA results, we must bear in mind that here, we look at the CBA indicators (IRR, NPV and BCR) of only one option. For policy makers, the question is rather how to most efficiently and sustainably spend a constraint budget for adaptation or poverty alleviation. Other non-monetary benefits from irrigation are discussed in the next section.

6.4 Soft assessment indicators

Upscaling potential for irrigation in Ethiopia is high: Only 5% of the potential is currently seized, even though Ethiopia has ample water resources and land suitable for irrigation.

The potential for irrigation in Ethiopia is enormous, as it has ample surface water and groundwater resources on the one hand and land suitable for irrigation on the other hand (Woldemariam & Gecho, 2017). Twelve major river basins lie in Ethiopia, which form four main drainage systems. However, there is high spatial and temporal variability (FAO, 2005; Worqlul et al., 2015). According to various studies, there is sufficient water in Ethiopia to develop around 4.5 million hectares of agricultural land that could be irrigated through pump, gravity, pressure, underground water, water harvesting and other mechanisms (Makombe et al., 2011; Woldemariam & Gecho, 2017; Worqlul et al., 2017). The hydrological analysis in Chapter 2 also confirms this and projects ample water available for irrigation in the future. Yet, overall uptake rates remain low with only 0.16 million hectares, i.e. 5% of the potential, being currently irrigated (Woldemariam & Gecho, 2017). Consequently, experts consulted for this study concluded that the potential to upscale irrigation is high, as irrigation penetration could be increased considerably.

Some challenges to upscaling, however, need to be overcome: While the emphasis accorded to small-scale irrigation is strong and abundant water resources and suitable land exist, development of modern small-scale irrigation schemes is facing various constraints in policy, institutions, technologies, capacity, infrastructure and markets. Some of the largest constraints include weak institutional capacity and lack of physical infrastructures, such as pumps, conveyance structures and storage facilities, but also access to electricity in rural areas (Awulachew, 2010; FAO, 2015b; Worqlul et al., 2017). Further bottlenecks include lack of qualified staff, low levels of user participation in the development and management of irrigation technologies, not enough and untrained extension services and lack of access to reliable technical and market information (MoA, 2011). Especially smallholder farmers, the majority of whom are among the poorest in Ethiopia, face relative high costs when entering the irrigation market and when seeking to invest in modern irrigation technologies (Awulachew, 2010; Eshetu et al., 2010). In addition, many smallholder farmers keep from investing due to unclear land tenure conditions (FAO, 2015b).

The Ethiopian government aims to increase irrigation implementation in order to adapt agriculture to climate change.

Stakeholder consultations, interviews, the expert survey conducted and document analysis made clear that irrigation is a top adaptation priority in Ethiopia. The Ethiopian government is aiming to transform its agricultural sector from a subsistence mode to a market-oriented one: The Agricultural Development Led Industrialization (ADLI) strategy aimed at fostering overall economic growth through agriculture with a focus on enhancing irrigation (Woldemariam & Gecho, 2017). In its Climate Change National Adaptation Programme of Action (NAPA), the Ethiopian government has listed the development of small-scale irrigation and water harvesting schemes as a top priority for adaptation in Ethiopia (MoWR, 2007). As a result of the NAPA, IFAD along with the MoA launched the Participatory Small-Scale Irrigation Development Programme (PASIDP), which is now in its second phase. The programme aims to improve the food security, nutrition and incomes of poor rural households by developing small-scale irrigation schemes (Garbero & Songsermsawas, 2018). Its goal is also to reduce the impact of slow onset climate change and enhance farmers' resilience against weather and climate-related shocks.

Table 8 gives an overview of potential development co-benefits as well as maladaptive outcomes from irrigation in Ethiopia. In terms of development co-benefits, irrigation has the potential to improve levels of food security and quality of nutrition and to contribute to rural poverty alleviation and welfare improvements. Eshetu et al. (2010) conducted a study in the Oromia region and found that improved irrigation had a positive impact on income and nutrition security: Increased expenditures on food and the availability of a greater variety of crops led to a more diversified and healthier diet including vegetables and fruit, which in turn reduced household expenditures on healthcare (Eshetu et al., 2010). Irrigation enables rural households to produce larger amounts for sale at the market and hence to generate more income to be used for larger-scale production and investments in education and healthcare (Bacha et al., 2011; Woldemariam & Gecho, 2017). According to a study by Awulachew et al. (2010), investments in irrigation could help to ensure food security for up to six million Ethiopian households.

Table 8: Potential for co-benefits and maladaptive outcomes from irrigation.

Potential development co-benefits	Potential maladaptive outcomes
• Higher income generation and welfare improvements • Increased expenditure on food can improve the nutritional diversity of households' diets • Higher agricultural output (yield per hectare) improves land use efficiency • Can reduce soil erosion	• A deterioration of river water quality and an over-use by farmers • Use conflicts between upstream and downstream water users • Trade-offs between different usage types: e.g. water for energy, household consumption or agriculture • Increased GHG emissions from agriculture due to higher energy needs for irrigation and higher fertiliser application • Shift from traditional locally adapted intercropping systems to monoculture cultivation of riskier and more demanding crops • In the absence of a well integrated market system, irrigation may result in over supply of products to the local market and consequently to low prices of products

Even though irrigation has a high potential to improve resilience of crop agriculture to climate change, potential maladaptive outcomes need to be considered.

However, since overall access to water is limited, water usage needs to be analysed and irrigation development needs to be regulated in order to avoid potential maladaptive outcomes. Otherwise, irrigation development could result in conflicts between neighbouring communities, where more powerful or wealthy users - or simply those located upstream - appropriate water resources for irrigation (Awulachew, 2010). It can also cause intra-household conflicts, where water is needed for drinking, cooking and sanitation. Furthermore, alterations in agricultural management as a result of irrigation usage and increased energy needs (see e.g. Zou et al., 2013) could lead to higher GHG emissions from agriculture (conflicting with SDG13 on climate action) or to the cultivation of riskier and more demanding crops, lowering agricultural resilience levels. Yet, if developed in a planned and equitable manner, irrigation has the potential to tackle a variety of challenges and contribute directly or indirectly to a majority of SDGs including SDG 1 for poverty alleviation, SDG 2 for food security and SDG 13 for climate action. To address some of the potential pitfalls and thinking in a longer-term perspective, irrigation types, such as sprinkler or (solar powered) drip irrigation would be more beneficial than conventional irrigation schemes due to less water use and reduced space occupied by irrigation equipment or trenches. The latter could be further combined with fertiliser supply.

Table 9: Summary assessment of irrigation strategies as adaptation in Ethiopia.

Risk response	Risk mitigation potential	Cost effectiveness	Risk gradient	Upscaling potential	Development co-benefits	Potential maladaptive outcomes	Stakeholder interest	Institutional support requirements
Risk mitigation	High	Medium	Risk-independent	High	High	High	High	Medium

Colour legend: blue = neutral, red = negative, yellow = medium, green = positive

Chapter 7 – Improved crop management: Crop switching

Improved crop management can support adaptation of agriculture to climate change. This includes for instance cultivating different crops, changing the planting dates and applying more inputs, such as fertilizer.

As the analysis in Chapter 3 showed, the suitability of areas in Ethiopia to grow certain crops is projected to change substantially in the future (Chapter 3.3). In addition, although weather explains a considerable share of yield output, there is still scope to improve crop management in Ethiopia (Chapter 3.1). This chapter thus considers a range of adaptation strategies pertaining to improved crop management: In reaction to the shifts in crop suitability, switching to other crop types can be useful. Cultural reasons and dietary preferences can impede such switching of crops, yet, it can bring important increases in agricultural production. Further, the planting date for crops can be modified in order to adjust to changing agricultural seasons. Usually, this means a later sowing date, when rains are delayed and farmers need to wait for improved sowing conditions, but early sowing can also be useful where rain fails at the end of the season. This is already practiced in many African rainfed systems, but it requires good forecasting systems for farmers to know when the rains will begin, which is especially challenging with increasing climate variability (Fisher et al., 2015). Finally, we test in how far increased fertiliser application and enhancement of soil organic carbon can improve yields in order to evaluate different ways of improved crop management.

We conducted a literature review and found 378 results in the database Scopus: For the search terms “shifting planting dates” OR “late sowing” OR “delayed planting” AND “Ethiopia”, we only found 18 results, some of which investigate cases where late sowing can protect from insect infestations. Only very few studies thus analyse the effect of shifting the sowing date per se (without changing crop varieties) on agricultural yields. The results of the few studies vary: For barley, a study found yields to improve with either normal/late sowing based on farmers’ judgment or early/normal sowing as predicted by Aquacrop model simulations (Araya et al., 2012). Regarding teff, Tsegay et al. (2015) based their conclusion on the Aquacrop model as well, saying that early sowing by two to three weeks could reduce the risk of yield failure by 72-100% in the northern Tigray region.

Switching cropping patterns and adjustments in planting dates can be designed to specifically address climatic risks, as they allow for coping with increasing climatic variability, notably lack of precipitation during critical stages of the growing cycle. Other important adaptation strategies related to improved crop management are use of improved seeds and of improved post-harvest management technologies. Both adaptation strategies are briefly presented in the boxes below, but are not the focus of this chapter.

Improved seeds as adaptation strategy

In the global South, most smallholder farmers use open pollinated, local crop varieties, which can be vulnerable to changing climatic conditions and climate extremes, such as droughts and floods, but also diseases. Improved crop varieties bred from traditional varieties can increase the resilience of crops to climatic shocks or slow onset climatic change and can raise yields. Even under low input conditions, improved varieties perform better than the traditional varieties (Voss-Fels et al., 2019). Generally, there is a wide range of traditional and improved crop varieties in Ethiopia, which are adapted to local climatic and agro-ecological conditions, with great variation between highlands and lowlands. According to the Ethiopian Institute for Agricultural Research (EIAR) (Interview 3), good varieties exist for maize, sorghum, beans, chickpea and teff. For wheat, however, further efforts are needed to increase its production in the lowlands. Most of the breeding efforts in Ethiopia are carried out by EIAR and the International Maize and Wheat Improvement Center (CIMMYT). They released more than 40 improved maize varieties for Ethiopia in the last decades (Zeng et al., 2017). In addition to early-maturing maize (Zea mays L.), especially improved varieties for haricot beans (Phaseolus vulgaris L.) are in use (Sime & Aune, 2018), with other improved varieties being more marginal in usage, for instance Irish potato (Interview 4). One of the key challenges for promotion and use of improved crop varieties is the lengthy and costly breeding process, but once better varieties are released, used and accessible, they can substantially improve agricultural yields and resilience, depending on their specific characteristics. So far, uptake of improved crop varieties in Ethiopia was ranked medium by experts who participated in our survey. Some improved crops or more resistant varieties like haricot beans (Phaseolus vulgaris L.) and early-maturing maize (Zea mays L.) have seen good adoption rates in Ethiopia (Sime & Aune, 2018), but generally, adoption of improved crop technologies appears low (Abate et al., 2016; Bingxin et al., 2011). This low uptake is due to a range of factors, of which lack of access to credit appears an important one (Abate et al., 2016). For improved maize, one expert estimated uptake at 30-40% (Interview 11), but cautioned that for other crops, such as teff and sorghum the adoption rate is much lower, which can be explained by lack of options and ineffective supply channels. The estimate for improved maize seed usage is consistent with a CIMMYT estimate from 2016, which states that about 70% of maize planted is still from traditional varieties (CIMMYT Ethiopia, 2016). Consequently, experts see high potential to upscale the adoption of improved seeds in Ethiopia. A main constraint for upscaling may be the sub-national approach to breeding needed for catering to specific needs of different agro-ecologies and local environments, which is especially important in a highly diverse landscape, such as Ethiopia's, where improved seeds are mostly only suitable for a low share of the total agricultural land area. Yet, smallholder farmers appear to value improved seeds and are generally ready to adopt improved varieties that are available (MoA & ATA, 2013). A key challenge is that many farmers do not replace seeds frequently, but recycle them for several years (Interview 11), a behaviour which is induced by high prices of improved seeds. Other institutional bottlenecks to better availability of improved seeds include low involvement of the private sector as of yet and lengthy registration processes (Interview 11). Ethiopia's Agricultural Transformation Agency (ATA) is planning a reform of the registration process to tackle the latter challenge, aiming to enable fast-track registration of varieties that have already been approved in neighbouring countries, such as Kenya (MoA & ATA, 2013). As regards the involvement of the private sector and alternative seed supply systems, they are increasingly available for maize and to a lesser extent teff, but need to be strengthened for other crops to improve quality, affordability and accessibility (Bogale et al., 2018). The ATA plans to better coordinate the development and diffusion of improved seed varieties between the public and the private sector in order to concentrate on gaps that are not filled by the private sector due to lower profitability, such as improved varieties for teff and wheat (MoA & ATA, 2013). Introducing improved crop varieties can bring significant development co-benefits, particularly with regard to increased agricultural production (linking to SDG2 – zero hunger) and income (contributing to SDG1 – no poverty). Yet, they are often expensive to develop and prices are high, which needs to be tackled for further benefitting improved agricultural output and income generation. Empirical evidence for improved production using improved seeds in Ethiopia was for instance found for maize (Ahmed et al., 2017) wheat (in a packaged initiative by ATA) (Abate et al., 2018) and chickpea (Verkaart et al., 2017). Where the nutritious value of crops is enhanced or additional crops are cultivated, such as legumes, improved crop technologies also have the potential to support SDG3 on good health and wellbeing, as was for instance found for improved groundnut seed in Ethiopia (Ahmed et al., 2016). With regard to improved maize varieties, Zeng et al. (2017) found positive effects on nutritional outcomes for children via the increased consumption of self-produced maize, particularly for those that suffer from severe malnutrition. Despite this transformational potential of improved seeds, potential maladaptive outcomes also need to be considered, such as biodiversity losses or negative nutritional outcomes, where improved crop varieties lead to higher yields, but lower nutritional value.

Improved post-harvest management as adaptation strategy

A similar climate risk study for the agricultural sector in Ghana conducted by the same PIK study team (Murken et al., 2019) found improved post-harvest management to be a very cost-effective and efficient adaptation strategy. Some results from this study and relevant literature are presented here: Reducing post-harvest losses significantly increases agricultural production, bringing important economic benefits to farmers. Promising examples of climate smart post-harvest management technologies include the utilisation of moisture meters, solar dryers or small affordable plastic or metal silos (Opit et al., 2014). A particularly interesting technology are so called PICS bags (Purdue Improved Crop Storage): simple and affordable yet effective hermetic storage bags originally developed for storing cowpea. So far, PICS bags have been piloted in many African countries, including Ethiopia, with different crops. For maize and tested in 12 sites across Ghana, Burkina Faso and Benin, they have proven to reduce insect and rodent infestation of stored grains by 95-100%, while maintaining quality and germination potential of the seeds (Baoua et al., 2014; Opit et al., 2014). In addition, weight of grain remained constant in PICS bags over a 6.5 month storage period, compared to a 21% reduction in standard woven bags, while insect damage remained the same as in the beginning, compared to a 60% increase in standard woven bags (Baoua et al., 2014). However, PICS bags alone are not enough. Farmers should also be trained and supported in conducting baseline assessments of insect pest populations and aflatoxin levels in maize and learn effective methods of ecological and integrated pest management even before harvest.

7.1 Risk mitigation potential

We used crop suitability models to assess how different crop management strategies can affect crop suitability under climate change: delaying the planting date, increasing soil organic carbon and a combination of both approaches.

We used the suitability models to evaluate the effect of different crop management practices on crop suitability to determine their potential to reduce the loss in crop suitability under climate change. In this regard, two adaptation strategies and their combinations were tested which are (a) delaying planting by four weeks (4Weeks) and (b) increasing soil organic carbon by 20% (20%OC) and (c) a combination of delaying the planting date by 4 weeks and 20% soil organic carbon (4Wks20%OC). The basic assumption underlying the four weeks shift is that climate change is reported to be causing a forward shift in the agricultural season and, therefore, delaying the planting season can work as an adaptation strategy. Adding soil organic carbon, the basis for soil fertility, works via increasing water holding capacity and increasing the productive capacity of soils, as it enhances soil biological, physical and chemical functioning. This can cushion projected losses in crop suitability. Several methods can be implemented to increase soil organic carbon, which include mulching, addition of manure, agroforestry, composts, leaving residues and green manures.

The evaluation of the adaptation strategies with the suitability models shows that shifting the growing season forward by four weeks will result in detrimental effects on suitability of the four crops also under current climatic conditions. The greatest effects of shifting the growing season will be for sorghum and wheat (Figure 50). Increasing soil organic carbon in Ethiopia by 20%, however, has positive effects on crop suitability for all crops, especially for maize and wheat. Enhancing organic carbon produces the greatest suitability increases under RCP8.5 for maize, teff and sorghum. The changes in suitability for maize and sorghum are far greater than the current gain from soil organic carbon, indicating that this could be a good strategy for increasing crop suitability. The greatest impact of adding 20% soil organic carbon in the soil occurs in the Humid lowland moisture reliable agro-ecological zone for maize, teff and sorghum under both scenarios (see table with results, according to AEZ in the supplementary material). However, results show that combining the four weeks shift in the season and the 20% soil organic carbon will be detrimental

Delaying the planting date by four weeks leads to negative model results, while increasing soil organic carbon is projected to have positive effects under both emissions scenarios and for all four crops analysed in this study.

for crop suitability, except for sorghum under RCP8.5 (Figure 50). The greatest gains in suitability from adding soil organic carbon will be for maize and teff in Tigray region under both RCP2.6 and RCP8.5, with maize responding more positively than other crops across all areas. This indicates that the suitability gains from addition of soil organic matter are eroded by shifting of the seasons, and that weather is more important than soil organic carbon in influencing crop suitability in Ethiopia.

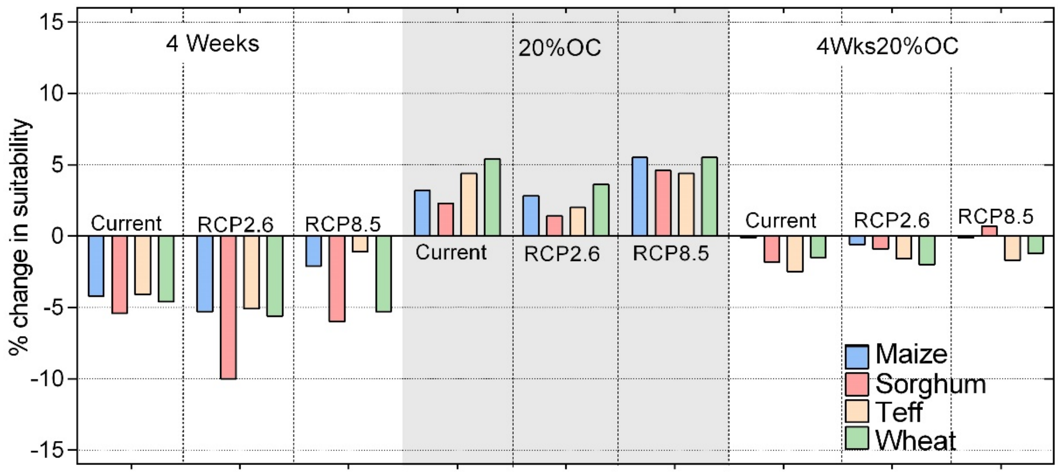


Figure 50: Evaluation of crop management adaptation strategies in reducing crop suitability.

Applying fertilizer can significantly increase maize yields in Ethiopia, but sustainability of inorganic fertilizer application needs to be considered before adopting this strategy.

Using the process-based crop model APSIM, we also evaluated the effect of increasing first basal and then top dressing NPK (Nitrogen, Phosphosous, Potassium) fertiliser on maize yield in Ethiopia for all zones (All) and for zones projected to experience yield losses (Loss). The total fertiliser use for each zone was available from 2006 to 2016. Fertiliser application among smallholders in Ethiopia is estimated to be of rather low intensity, some 30-40% of smallholder farmers apply fertiliser (Spielman, Mekonnen & Alemu, 2015). Applying fertiliser is one means for improving lower and more variable yields due to climate change impacts and can thus also be regarded as an adaptation strategy. Yet, increasing synthetic nitrogen fertiliser application will also lead to higher CO_2 emissions, a thorough assessment of its usefulness for each specific case is thus needed. The results show that increasing basal fertiliser by 50% will increase yields by between 10 and 200% depending on the zone. At national level, an average increase of 56% for all modelled zones under current climatic conditions is projected (Figure 51). For zones projected to experience yield losses, the yield will increase by 53% under current conditions from this measure. Under projected climatic conditions, increasing basal fertiliser by 50% will increase maize yields by 45% under RCP2.6 and 43% under RCP8.5 for all zones. For zones with projected yield decreases, yield increases from basal fertilisers will be 38% (RCP2.6) and 34% (RCP8.5).

When only zones with yield losses are considered, there is a strong decrease in the effect of increasing basal fertiliser on yield to 38% under RCP2.6 and 34% under RCP8.5. Increasing basal fertiliser produces a higher yield effect than increasing top dressing for all zones (Figure 51). Increasing current top dressing levels by 50% will increase maize yield by 11% from current levels and by 18 and 21% as compared to current levels under RCP2.6 and RCP8.5 respectively. When only zones with yield losses are considered, increasing top dressing will increase yields by 15.7% and by 19% under RCP2.6 and RCP8.5 scenarios respectively.

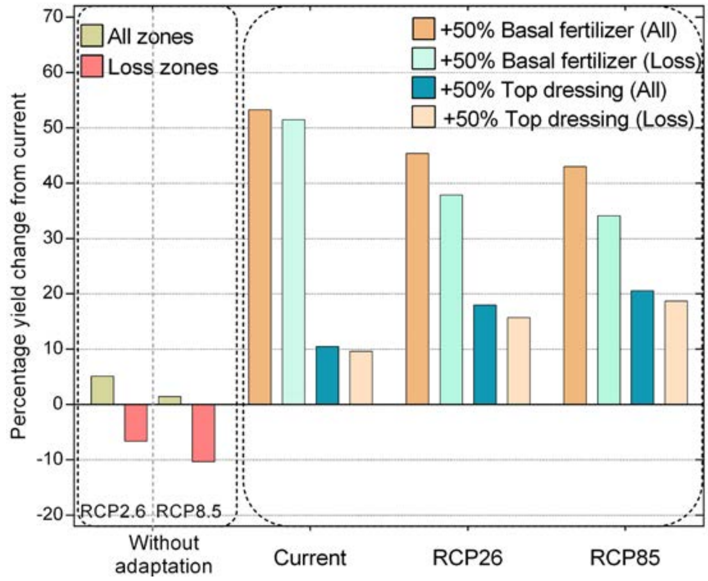


Figure 51: Evaluation of the effect of increasing basal and top dressing fertiliser on maize yields in Ethiopia for all zones and for zones with projected yield losses.

7.2 Cost-benefit analysis: Switching from maize production to sorghum production

Here we analysed the cost effectiveness of a switch from maize to sorghum cultivation for a farmer, given that climate change is projected to improve conditions for sorghum, but to negatively affect maize suitability.

The crop suitability analysis (see Chapter 3.3) showed that in some regions in Ethiopia, suitability of areas to produce sorghum will increase, whereas other crops will be more difficult to produce in the future. To analyse the potential benefits of shifting cropping patterns based on this projection, this adaptation strategy describes a farmer who has been planting maize (*Zea mays*) on his/her arable land, but then switches from the production of maize to the production of sorghum (*Sorghum bicolor*). Sorghum can better withstand dry and erratic conditions and plays a significant role in Ethiopian agriculture – especially for smallholder and subsistence farmers (Embaye et al., 2017). Due to its robustness – sorghum is particularly important in drought prone areas (FAO, 2015b) – the crop should be considered a valuable option that can help to ensure food security under climate change conditions.

In order to analyse the economic feasibility of this crop switch, we hereafter work with the following scenarios:

Baseline (no action, no climate impacts): Rain-fed maize production under current climatic conditions – a farmer cultivates rainfed maize on a field. Yield changes due to future climate change are not incorporated.

Adaptation (action, climate change impacts): Crop switch from maize to sorghum under climate change impacts - As the farmer experiences negative climate change impacts on the maize production, the farmer switches from maize to sorghum cropping and, hence, cultivates sorghum on the area formerly dedicated to maize (ceteris paribus). According to the suitability analysis (see Chapter 3.3), this scenario is likely to happen in the zones Benishangul-Gumuz or Gambela. There, the suitability for maize declines, while the suitability for sorghum increases. Indeed, it is important to note that crop suitability is very site-specific and thus such a crop switch does not have to be agronomically or economically beneficial in other regions. We will calculate this CBA for Gambela.

No adaptation (no action, climate change impacts): Rainfed maize production under climate change impacts - As in the action scenario, the maize farmer experiences negative climate change impacts because the maize suitability decreases in Gambela. But in the inaction scenario the farmer does not adopt the adaptation strategy of switching crops and thus yield penalties occur.

Improvement (action, no climate change impacts): Crop switch from maize to sorghum under current climatic conditions - In this scenario, there are no further negative climate change impacts felt by the farmer, as we assume the current climate to persist. Nevertheless, the farmer switches from maize production to sorghum production.

The analysis is undertaken analogous to the CBA for adopting irrigation in Chapter 6.3.

Data, assumptions and initial monetarisation

The following main data and assumptions are the basis for the CBA calculations. They refer to the action scenarios and also to the other scenarios, if applicable.

Increased cultivation of sorghum would also lead to more research and technological innovation in the field of sorghum production.

When adopting the crop switch, the size of the crop area remains the same, i.e. the area cultivated with maize has the same size as the area planted with sorghum. Here, we analyse the costs and benefits which can be associated to one hectare, irrespective of the actual field size originally allocated to maize. The analysed farmer uses maize and sorghum seeds of regular quality and does not irrigate the land. Due to an almost similar crop establishment and management, the input costs of both crops are assumed to be comparable. This particularly refers to the allocated labour and seed costs. In terms of technological change over time, we assume that the farmer's productivity increases each year due to "autonomous technological progress". This factor measures input and management improvements, such as improved varieties or mechanisation. We use the global average growth rate of maize yields, which is 1.4% per annum (FAO, 2019b). In the case of sorghum, we add 1% to the growth rate of maize. Using data from FAO (2019b) for sorghum in East Africa, it can be shown that the growth rate accelerates, including a "catching-up" effect of sorghum production: Prior to the switch defined here, sorghum was of lesser sectoral importance which also affected sorghum breeding, crop management skills etc. Now, sorghum becomes more popular in Gambela, and this also promotes agricultural research and development, as well as knowledge transfer accumulating to comparably high growth rates.

However, at the beginning of the switch, many farmers have still limited experience and knowledge on sorghum cultivation. Although some farmers may already practice sorghum cultivation, the majority will benefit from a knowledge transfer. So, in the first two years of the crop switch, time for knowledge transfer and costs of self-learning are allocated. These costs for knowledge acquisition are two-fold: First, we include service costs (e.g. for extension services). We assume that 48 hours of advice are used in the first year and 24 hours in the second year. We calculate opportunity costs of almost 20 Ethiopian Birr (ETB) (= 0.7 USD) per hour of advice (ILOSTAT, 2019). Second, we assume that due to the poor expertise of the farmer in cultivating sorghum, the first two years are associated with some yield losses (20% in the first and 10% in the second year) in comparison to the achievable yield with proper knowledge (after the learning by doing phase). These two elements of knowledge acquisition can be termed as the establishment costs of this adaptation strategy.

Moreover, we use the following specific data to properly display maize production in Gambela: As a basis we take yield data for Ethiopia from FAO (2019b) and calculate a three-year average for the most recent data points which is then extrapolated to the start year of our analysis, i.e. 2020. Hence, we use a yield of 3.95 tons per hectare as starting point of analysis. In addition to the "autonomous technological progress" (see above), we also apply a climate change impact rate on maize yields in Gambela which we take from the ISIMIP model ensemble considering RCP8.5.

The resulting production is valued at domestic market prices. Monthly domestic market prices are taken from FAO (2019a). Accordingly, the producer price for maize is 4,323 ETB (= 142 USD) per ton. These data points are additionally substantiated using gross margin calculations as provided by Sellasie (2016) and cross-checked by using information from Alemu et al. (2014), as well as Elias et al. (2017). Production costs for sorghum production are derived in a similar manner. The yield of the starting year 2020 is again taken and extrapolated from FAO (2019b), it is 2.71 tons per hectare. Climate change induced yield developments are also derived from ISIMIP projections for the area of Gambela and under RCP8.5. In this respect, however, we use millet project-tions as a proxy for sorghum projections due to data constraints. Both crops belong to the same plant family *Poaceae*. The producer price for sorghum is 5,767 ETB (= 190 USD) per ton (FAO, 2019a).

Specific costs and benefits

Using these data and qualified assumptions, it is now possible to allocate specific costs and benefits to certain times along the analysed time frame from 2020 to 2050 and for this adaptation strategy, switching from maize to sorghum production[17].

- Per hectare of maize the farmer could earn an economic margin of 2,565 ETB (= 84 USD) per hectare. Due to the switch to sorghum, this amount will be lost in the first year. In addition, the farmer has establishment costs accumulating to 917 ETB (= 30 USD). Altogether, this sums up to costs (and income foregone) of 3,482 ETB (= 115 USD) per hectare in the initial year of crop switching.
- Concurrently, the farmer earns income from sorghum. Normally, this would be around 1,125 ETB (= 37 USD) per hectare. However, due to the embedded learning effect, it is only 900 ETB (= 30 USD) per hectare in the first year.
- In the second year, the situation slightly improves. The establishment costs become lower and the economic margin of cultivating sorghum will increase.
- Over time, the potential economic margin to be earned from sorghum will further increase. However, the foregone income from maize production will also slightly increase (due to the embedded "autonomous technological progress"). This will lead to a situation in the year 2030, when the additionally earned income from sorghum (5,178 ETB (= 170 USD) per hectare) – for the first time – becomes higher than the loss of income from growing maize (5,037 ETB (= 166 USD) per hectare).
- From then on, the positive gap between the additional income from sorghum and the lost income from maize becomes larger and larger. In the year 2050, the additional income from sorghum is approximately 60% higher than the lost economic margin from maize.

Major findings

The results of the analysis show that switching from maize to sorghum production under climate change in Gambela region could be economically beneficial from the year 2041 onwards.

The CBA arrives at the major conclusion that in comparison to the no adaptation scenario, the crop switch (adaptation scenario) will be economically beneficial from the year 2041 on. From then on, the crop switch has a positive return on investment. The following figure shows this development of the net present value (NPV) from 2020 to 2050.

[17] The basic methodological and mathematical foundation of the CBA as it will be applied hereafter are already described in Chapter 5. Therefore, a detailed description of the methodology as well as some other methodology-related data requirements (such as the use of inflation rates) shall not be repeated here.

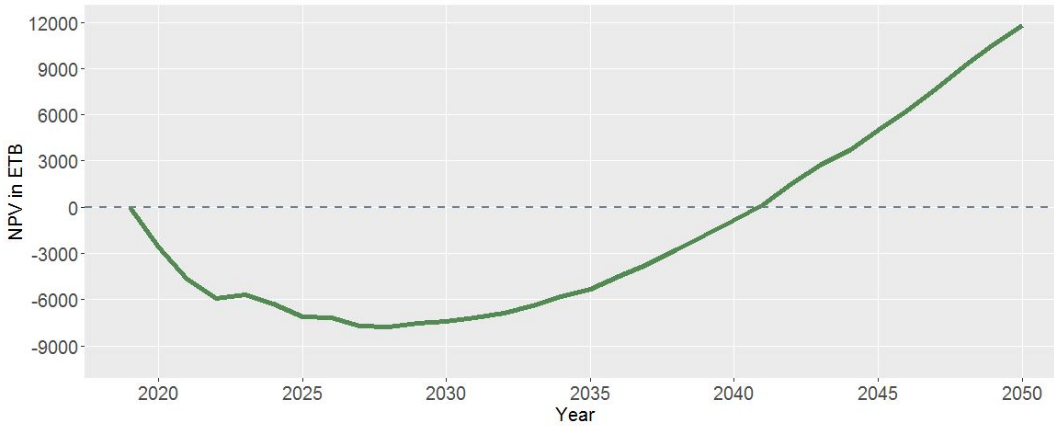


Figure 52: Development of the net present value of switching from maize to sorghum cultivation in Gambela under future climate change and over time (in ETB).

During the first ten years, the net cash flow is negative, i.e. the NPV of adopting the switch decreases. This changes after 2029, when the NPV is –875 ETB (= -29 USD). From now on, the net cash flow is positive. Hence, the NPV starts to increase. Finally, the NPV becomes positive in the year 2041 and further increases to until 2050. The corresponding NPV in 2050 consequently is 11,771 ETB (= 387 USD).

The corresponding internal rate of return (IRR) is thus not definable for 2030, but amounts to 11% in 2050. Again, as for the case of irrigation, this indicates that the investment to switch from maize to sorghum is profitable from a farmer's point of view in the long run because the IRR is higher than the local interest rate. This can also be expressed with another algebraic term, the BCR: Here, the BCR is 0.79 after ten years (in 2030) and 1.16 after 30 years (in 2050). This points to the fact that the farmer's investment in the crop switch will pay off after over 20 years, when the break-even point between accumulated net costs and net benefits is reached. Table 10 shows the comparison also with the improvement scenario (action, no climate impacts felt). Here, the indicators show lower values than in the adaptation scenario, reflecting the fact that switching crops is a risk-dependent strategy. The late break-even point suggests that switching from maize to sorghum cannot be recommended in the near future, but rather in the medium term, once climate change impacts on the crop sector in Ethiopia further materialise. For this analysis, we carefully selected an area where maize suitability is projected to decline and sorghum suitability is projected to increase under future climate change. Such information from Chapter 3.3 needs to be taken into account before giving recommendations regarding crop switching in order to avoid maladaptive outcomes.

> Switching crops is a risk-dependent strategy: If climate change does not influence crop suitability, modifying cropping patterns may not be useful or less useful.

Table 10: Adaptation and improvement scenario results by 2050 for switching crops from maize to sorghum.

Adaptation	Improvement
• IRR: 11.06%	• IRR: 9.31%
• NPV: 11,771 ETB (= 387 USD)	• NPV: 6,908 ETB (= 227 USD)
• BCR: 1.16	• BCR: 1.09

Yet all in all, we conclude that looking at this specific adaptation strategy, action is more profitable than inaction in the long run.

7.3 Soft assessment indicators

Following from the biophysical and economic analysis, we see that the upscaling potential for switching crops and for adjusting planting dates is not yet high (at least for shifting planting dates by four weeks), as demand by farmers is rather low and the climatic risks to which those strategies respond manifest only slowly in the near term. In the medium to long term, this assessment will change considerably, with both strategies likely to be quite effective and useful towards 2040-2050. For other crop management improvements, such as applying fertiliser or using improved seeds, the upscaling potential is already high. With regard to fertiliser, this especially means to increase the intensity of usage.

Reliable weather forecasts and information on expected long-term changes in crop suitability are an important foundation for farmers' crop management decisions.

Changing planting dates, switching crops and applying (more) fertiliser is dependent on reliable information regarding climatic changes and shifts in weather patterns as well as crop suitability. Although farmers can implement such strategies autonomously, they are thus dependent on weather services, research institutes and information distribution channels for deciding whether and when to implement them.

Improved crop management is seen as key to a climate-resilient agriculture in Ethiopia, as evidenced by stakeholder prioritisation and the interviews conducted. Stakeholder interest, including in improved crop varieties, can be ranked as high. Interviewees in particular mentioned early maturing varieties as important (e.g. Interviews 1, 4, 10, 16) to adjust to changing agricultural seasons in Ethiopia and for coping with less reliable precipitation. Other desired traits include moisture tolerance (Interview 26) and disease resistance (Interview 3). Stakeholders also showed high interest in improved soil management and soil rehabilitation as key to sustain yields.

Switching crops and changing planting dates can be highly beneficial in case climatic risks start manifesting. Yet, those practices do not offer considerable co-benefits besides their intended objective, when compared to the other adaptation strategies analysed in this study. Potential maladaptive outcomes can equally be qualified as medium. When deciding on switching crops, farmers might end up growing less nutritious crops than before or crops that do not correspond to their dietary preferences. However, this effect can also work in the other direction. Furthermore, an adjustment in planting dates could mean a prolongation of the period between harvests, which would need to be bridged by farmers with other food sources.

Table 11: Potential co-benefits and maladaptive outcomes from improved crop management: switching crops and changing sowing dates.

Development co-benefits	Potential maladaptive outcomes
• Improved food security and income generation through higher production • Higher agricultural output (yield per hectare) improves land use efficiency • Where more nutritious crops are planted, health and nutrition can improve	• Biodiversity losses possible • Food production may no longer correspond to dietary preferences, hence reducing wellbeing • Food may be less nutritious, where crops lower in nutrient content are adopted • For shifts in the growing season: The time in between harvests may be longer and needs to be bridged by households, food security might thus decline

Table 12 summarises the assessment on using switching of crops as adaptation strategy.

Table 12: Summary assessment of switching crops and improved crop management as adaptation strategies in Ethiopia.

Risk response	Risk mitigation potential	Cost effective-ness	Risk gradient	Upscaling potential	Develop-ment co-benefits	Potential maladaptive outcomes	Stake-holder interest	Institutional support requirements
Risk mitigation	High	Medium	Risk-specific	Medium	Medium	Medium	High	Medium

Colour legend: blue = neutral, red = negative, yellow = medium, green = positive

Chapter 8 – Agroforestry

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

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

ICRAF thus distinguishes between different types of agroforestry strategies; for this study, we will mainly consider the integration of trees in farming systems and tree-crop production.

A literature search using Scopus returned 170 publications for the search terms "agroforestry" and "Ethiopia", with a clear increase in publications since 2009. This shows the high interest in agroforestry measures for Ethiopia, which accompanies a rapid deforestation trend in the country. Out of the 170 publications screened, 34 passed a test for inclusion based on relevance and empirical or modelling contribution to assessing the performance of agroforestry measures in Ethiopia with regard to climate change adaptation, food security and attainment of other sustainable development goals more widely. Studies focusing on the mitigation aspects of agroforestry, although interesting, were not assessed for this study. Many studies concentrate on biomass production and the associated carbon sequestration potential of Ethiopian agroforestry systems (e.g. Negash & Starr, 2015), which was equally not a focus of this analysis.

In Ethiopia, different types of agroforestry practices are in use, with different objectives and benefits. Jemal, Callo-Concha, & van Noordwijk (2018) find for southwestern Ethiopia that home garden agroforestry (HG), multi-storey-coffee-systems (MCS) and multi-purpose-trees-on-farmlands (MTF) are the main agroforestry practices used. Oftentimes, households use all of those systems in combination, with each of them serving different purposes: MCS is used for income generation, MTF for food production and HG complements both. Another way of distinguishing agroforestry systems in Ethiopia is between high value agroforestry combined, for food, fibre (mainly timber for construction), fuel (fuelwood) or fodder production, and farmer managed natural regeneration of trees (Iiyama et al., 2017; Amare et al., 2019).

Many different tree species are used in Ethiopian agroforestry systems. The species composition of an agroforestry system in Ethiopia depends on characteristics of the respective household, e.g. gender, market access and local social capital, as different agroforestry systems require different amounts of labour and market access may determine whether high value crops, such as coffee are grown (Jemal et al., 2018). Depending on the tree species, agroforestry systems also offer value for preserving biodiversity and offering ecosystem services, e.g. hosting birds that are key for seed dispersal and pest control (Amare et al., 2019), although some species, such as Eucalyptus trees can also lead to negative outcomes, for instance regarding water availability and soils.

Agroforestry practices can support adaptation to climate change in several ways: They can save water, improve the microclimate and enhance soil fertility.

Agroforestry practices are considered as climate change adaptation for several reasons: Trees integrated in farming systems provide shade and thus lower temperature and enhance soil moisture, regulating the microclimate (Lasco, Delfino, & Espaldon, 2014). They generally save water, as they reduce evapotranspiration and improve soil fertility, for instance with falling leaves acting as mulch. Further, agroforestry systems can reduce pests and diseases. In terms of risk response, agroforestry systems are thus able to reduce risk from changing climatic conditions, such as rising temperatures and erratic precipitation. In addition, soil erosion can be lowered with targeted forestation, particularly on steep slopes.

Sustainable land management (SLM) in Ethiopia

Fertile soils play a crucial role for food security, climate change adaptation and agricultural development. Soil erosion and decline in soil fertility, however, are increasingly becoming major environmental problems in Ethiopia, which are exacerbated by farmers' use of slash and burn practices as well as population growth. Farmers have traditionally used practices, such as fallowing, crop rotation, application of crop residues, manuring, incorporation of weeds and terraces to maintain and enhance soil fertility (Corbeels, Shiferaw & Haile, 2000). However, while those practices are certainly useful, land constraints, limited land rights and the use of manure for fuel and of crop residues for fodder and building are reducing the effectiveness of those traditional practices (Assefa & Bork, 2016). As a consequence, the Ethiopian government has integrated sustainable land management (SLM) as a key priority into various development plans. The Plan for Accelerated and Sustainable Development to End Poverty (PASDEP) outlines detailed interventions for water and soil conservation including use of fertilisers, land closures for rehabilitation of land and the development of land for irrigation (Ministry of Finance and Economic Development of Ethiopia, 2006). Similarly, the Growth and Transformation Plan (GTP) addresses land rehabilitation through water and soil conservation measures (Ministry of Finance and Economic Development of Ethiopia, 2010). Under the first GTP (GTPI, 2010/11-2014/15), 15.5 million ha of multi-purpose trees were planted, which help to lower temperature, while enhancing moisture and fertility where soils suffer from degradation and the effects of climate change (Ministry of Finance and Economic Development of Ethiopia, 2010). In 2009, the MoA along with GIZ and KfW launched the Sustainable Land Management Program (SLMP) which introduced SLM practices in the regions of Amhara, Tigray, Oromia, SNNPR, Benishangul-Gumuz and Gambella, and is now in its second phase (World Bank, 2013). The SLMP follows a watershed development approach, which links the use of land, water and forests at upper and lower levels of watersheds. Under the SLMP, treatment of hillsides through the construction of terraces and trenches has helped to minimise the risk of flooding and erosion on the one hand, while helping to divert and retain water for irrigation on the other hand (GIZ, 2015). SLMP experience from Tigray shows that especially deep trenching has proven to be successful for water and soil retention. Hence, implementation of one adaptation strategy can help address impacts caused by a variety of weather extremes including torrential rainfalls and droughts. In the context of the SLMP, the Ethiopia Strategic Investment Framework for Sustainable Land Management (ESIF) was drafted in order to promote SLM practices for poverty alleviation among smallholder farmers (World Bank, 2013). In 2015, the MoA launched the Ethiopian Soil Campaign which involved a series of educational and networking events targeting decision-makers, experts and other relevant stakeholders to discuss the status of Ethiopian soils and good practices for SLM (FAO, 2015c). Lessons from these programmes are valuable and should be integrated with improved crop management to ensure beneficial outcomes also for soils.

8.1 Risk mitigation potential

The effect of agroforestry on maize production in Ethiopia was simulated by reducing the solar radiation in meteorological files, with respective effects of this radiation reduction on temperature modelled through fitting a random forest model between radiation and temperature. Within APSIM, it is possible to perform virtual experiments to predict and understand options, with enough confidence to guide the development of agricultural policies and the promotion or upscaling of agroforestry practices. The most important of the tree-crop interactions under agroforestry is shade and its impact on crop growth and yield (Dilla et al., 2018). This is so because the level of shade is directly related to the structure of the agroforestry tree and its ability to influence other processes, such as improving soil fertility, influencing moisture availability and regulating the crop microclimate (Beedy et al., 2010; Jonsson, Ong, & Odongo, 1999). Microclimate amelioration with the help of trees can increase growth and production of understory crops, especially during periods of adverse weather, such as droughts. However, excessive shading can also have negative effects on plant photosynthetic potential, adversely affect growth and yield for C4 crops, such as maize and sorghum[18]. Based on the ability of APSIM to simulate experimental shading trials in Ethiopia

[18] C_4 crops are crops which have a more elaborate carbon fixation path than the more common C_3 path, which makes them more efficient in conditions of high temperatures, lack of nitrogen or CO_2, and drought. Under normal conditions, C_3 crops have an energy advantage.

With the help of the crop model APSIM, we evaluated the ways in which 10% or 20% shade from agroforestry systems would affect Ethiopian maize yields under climate change.

(Dilla et al., 2018), we evaluated agroforestry effects on maize yield by simulating 10% and 20% shade. These values were used because Jonsson et al. (1999) identified 25% shading as the threshold at which adverse effects of shading on crop productivity start. We simulated the effect of shade on the microclimate by use of machine learning to predict the effect of the 10% and 20% shade on temperature from long term weather data. Agroforestry can also lead to higher soil organic carbon content, which is why the results presented in Chapter 7 are also of interest for evaluating agroforestry's risk mitigation potential and the effect of enhanced soil organic carbon on crop yields. Further, as stated above, agroforestry practices can reduce soil erosion by stabilising the soil, especially on slopes and after heavy precipitation events.

The results show that 10% shade does not necessarily increase the yield of maize under climate change conditions, but can have an adverse effect on those zones that have higher maize yields. However, both 10% and 20% shade are able to stabilise the maize yield under both RCP2.6 and RCP8.5 in Ethiopia, with the greatest adaptation effect occurring under RCP8.5 (Figure 53). For zones that are projected to experience yield losses under climate change, 10% shade will reduce the national yield loss from a loss of 10% to a loss of 4% (RCP2.6) or to 1% (RCP8.5). When the shade is increased to 20%, at national level, maize yields will be increased by 1% under current climatic conditions for all zones (Figure 53). For zones projected to see yield losses under future climate change, those losses will be reduced from 10% to 4% (RCP2.6) and yield increases of 1% are projected under RCP8.5. This indicates that the shading effect works better in specific zones, which are projected to experience warming, but it may have detrimental effects in zones of Ethiopia that are less affected by climate change and experience no yield losses under climate change. In addition, changing the crop microclimate alone may not provide yield increases, but can reduce the yield losses by ensuring that yields remain stable.

The modelling results show that shading may only work in those areas of Ethiopia which are projected to experience maize yield losses. In other areas, shading could even lead to lower yields. This is however a conservative result, since not all factors were taken into account, such as improved soil fertility.

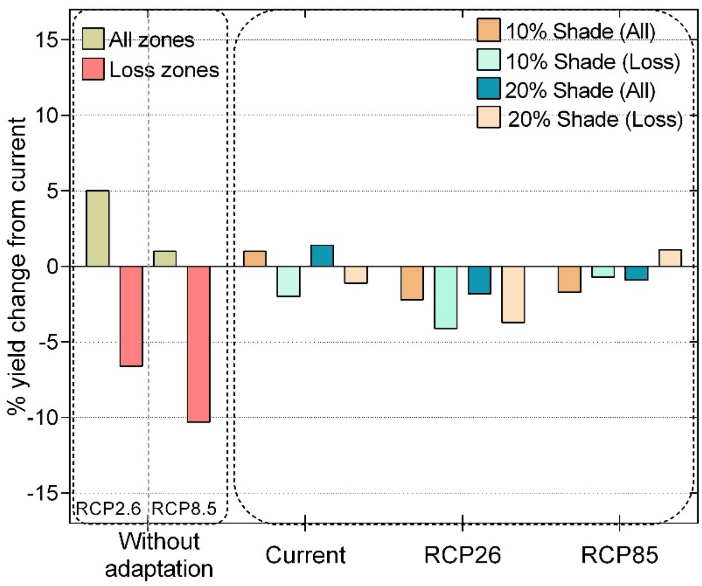


Figure 53: Effect of agroforestry shading on maize yield changes in Ethiopia.

8.2 Cost-benefit analysis: Maize production within an agroforestry system

In this micro-economic cost-benefit analysis, we evaluate the application of agroforestry to maize production.

Taking up the results regarding the bio-physical potential of introducing agro-forestry into maize production systems, we now analyse the economic potential of such an adaptation strategy. This specific adaptation strategy describes a farmer who has been planting maize as a single field crop and who, in 2020, introduces an agroforestry system to combine it with maize production. The direct effect of a combination of forestry and agriculture (agro-forestry) is assumed to be the provision of shading for the maize plants and thus an improved micro-climate. Hence, it can stabilise and potentially also increase maize yields under climate change, while also providing income diversification through extra (non-agricultural) income (for further discussion on co-benefits, see the subsequent section 8.3).

In order to analyse the economic feasibility of this adaptation strategy, we hereafter work with the following scenarios:

Baseline (no action, no climate impacts): Rain-fed maize monoculture - A farmer in Ethiopia plants maize (*Zea mays*) on a field and uses regular inputs (such as farmer saved indigenous seeds) and management practices.

Adaptation (action, climate change impacts): Maize production within an agroforestry system under future climate change impacts - The farmer adopts the adaptation strategy agroforestry and, therefore, plants mango trees (*Mangifera indica)* in between the maize on the field which was formerly occupied by maize monoculture. Mango production is a common perennial crop in the broader region (see, e.g., Anshiso et al., 2017; Chay et al., 2019). We consider these changes ceteris paribus, i.e. all other things being equal and not considering other changes.

No adaptation (no action, climate change impacts): Rainfed maize monoculture under future climate change impacts - In this scenario, the farmer does not adopt agroforestry and keeps the maize monoculture, while future climate change impacts on maize production are felt.

Improvement (action, no climate change impacts): Maize production within an agroforestry system under current climatic conditions - In this scenario, there are no further negative climate change impacts felt by the farmer. Nevertheless, the farmer adopts the adaptation strategy agro-forestry and, hence, plants mango trees along with maize.

Data, assumptions and initial monetarisation

The specific approach used hereafter will be based upon the following main data and assumptions (referring to the action scenarios and then also applied to the other scenarios, if applicable):

When adopting the agroforestry system, the size of the crop area remains the same, i.e. the area cultivated in monoculture with maize has the same size as the maize and mango tree combination. Here, we analyse the costs and benefits which can be associated to one hectare, irrespective of the actual field size originally allocated to maize. For the base year of our analysis, 2020, we used extrapolated yield data from FAO (2019b). In terms of technological change, we furthermore assume that the farmer's land productivity increases due to "autonomous technological progress". In the case of maize, we use a growth rate of 1.4% per annum reflecting global growth rates (see FAO, 2019b). Being a perennial used for decades, the (technology-driven) yield from mango trees is kept constant over time.

Moreover, we use the following specific data to display maize production: As a basis for the climate change impact on maize production, we firstly take yield data from FAO (2019b) and calculate a three-year average for the most recent data points which is then extrapolated to the start year of our analysis, i.e. 2020. Hence, we use a yield of 3.95 tons per hectare as starting point of analysis. In addition to the "autonomous technological progress" (see above), we also apply a climate change impact on maize yield which we have taken from ISIMIP projections for overall Ethiopia. The agroforestry production will be valued at domestic market prices. Domestic market prices are taken from FAO and GIEWS (2019a) where the producer price for maize is 4,323 ETB (= 142 USD) per ton. These data points are additionally substantiated using gross margin calculations as provided by Sellasie (2016) and cross-checked using information from Alemu et al. (2014) as well as Elias et al. (2017).

Now, the farmer adopts the adaptation strategy and thus shade-providing mango trees are integrated into the maize farming system. The benefits and potential co-benefits of agroforestry systems in Ethiopia as well as the associated costs are based upon regional data provided by Anshiso et al. (2017), Bekele-Tesemma (2007), Berhe et al. (2009), Bezu et al. (2014), Chay et al. (2019), Honja et al. (2016), Kunhamu and Santhoshkumar (2012), Recha (2017), as well as Recha et al. (2016) cross-checked with Jemal (2018), Jemal and Callo-Concha (2017), Kassie (2016), and Amare & Simane (2018). According to Recha (2017) as well as Kunhamu and Santhoshkumar (2012), one can assume a "10 meters x 10 meters" grid for planting one mango tree within an agroforestry system. This means that 81 (young) trees are planted per hectare which do not allow the cultivation of maize in the surrounding grid of 2.5 meters x 2.5 meters. Consequently, more than 5% of the field size are taken away from maize cultivation and are now solely used for mango production.

The establishment of mango trees comes at a cost. A seedling costs 80 ETB (= 2.6 USD) (see Berhe et al., 2009; adjusted for inflation in accordance to Statista, 2019). In this respect, it is assumed that six seedlings can be set per hour. This working time is valued at 20 ETB (= 0.7 USD) per hour (ILOSTAT, 2019). Expenses for minor material are included by adding 10% to the labour costs. These three elements – seedlings, labour and material – are the establishment costs of this adaptation strategy. Annual variable costs mainly originate from the labour input for checking and pruning mango trees if necessary and are assumed to be 25% of the establishment costs (also taking into consideration that the first mango trees may need re-establishment after 25 years (see Anshiso et al., 2017; Bezu et al., 2014)).

The mango trees' shading effect on yields needs to be taken into consideration. Here, we assume a positive yield impact of 20% once the trees are matured. In this respect, it is assumed that the full shading and also entire harvest potential of the mango trees is reached after seven years (see Bekele-Tesemma, 2007; Recha, 2017). The years before the seventh year show a lesser shading degree and harvest potential. Over time, a gradual linear approach is chosen to add shading from year one to seven and incorporate mango yield from year three – the first year when mango can be harvested (Recha et al., 2016) – to seven.

Planting mango trees would lead to increasing shade levels over the years and enable harvest of mangos starting from the third year after planting the trees.

In addition, the following economic data on mango production will be used: Costs and revenues (gross margin calculations) are taken from Honja et al. (2016), cross-checked by looking at Chay et al. (2019). Domestic market prices were obtained from FAO (2019b). Mango yield data are also taken from FAO (2019b), but adjusted in order to analyse an agroforestry system (consisting of just 81 trees) instead of a typical Ethiopian mango orchard (consisting of an average of 300 trees (see, e.g., Menzel and Le Lagadec, 2017)).

Specific costs and benefits

Using this basic data and qualified assumptions, it is now possible to allocate specific costs and benefits to the instalment of an agroforestry system within a maize production system. Allocating these benefits and costs over time allows for a proper Cost-Benefit-Analysis (CBA).

- Per hectare of maize, the farmer – prior to the adaptation – has earned an economic margin of 2,565 ETB (= 84 USD) per hectare. Due to a partly removal of maize plants (on 5% of the area), this income indicator slightly decreases to 2,335 ETB (= 77 USD), i.e. the net benefit is minus 130 ETB (= 4.3 USD) per hectare.
- This comes along with establishment costs which account for 6,764 ETB (= 223 USD) per hectare in 2020. Hence, the farmer loses a total of almost 6,900 ETB (= 227 USD) per hectare in the first year of adjustment.
- In the next year, however, the situation starts to improve. The establishment costs disappear and are substituted by the much lower maintenance costs. Also, the economic margin increases (due to increasingly higher yields). Nevertheless, a minus of 1,469 ETB (= 48 USD) still occurs in the second year; in the third year a net gain of 678 ETB (= 22 USD) per hectare is realised.

- Over time, the potential economic margin to be earned from agroforestry will further increase (due to the embedded "autonomous technological progress" and increased shading). This will lead to a situation in the year 2030, when the additional income from agroforestry will already be more than 10,000 ETB (= 329 USD) per hectare. In the year 2050, a net cash flow of more than 17,000 ETB (= 559 USD) per hectare is possible.

Major findings

Adapting maize production with agroforestry is highly beneficial in comparison to the no adaptation scenario. Over time, it has a very positive return on investment (see Figure 54).

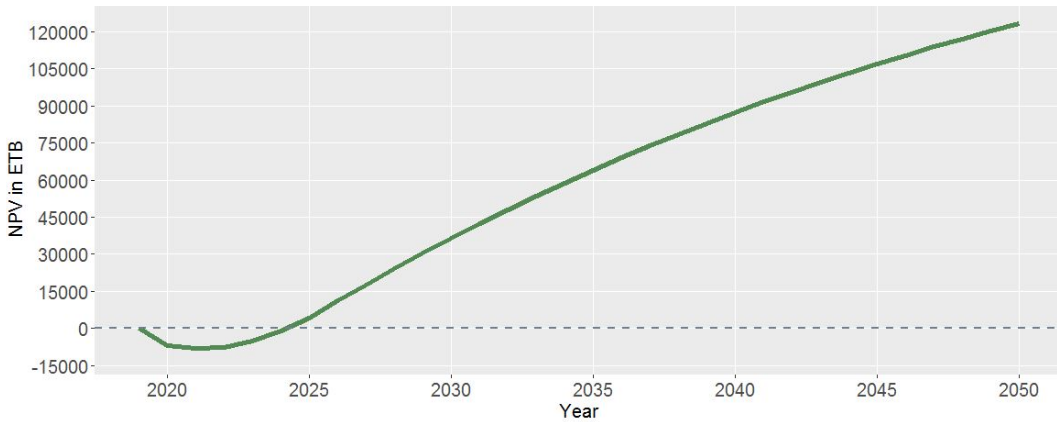


Figure 54: Development of the net present value from 2020 to 2050 when switching from maize monoculture to maize production within an agroforestry system under future climate change impacts (in ETB).

Establishing an agroforestry system with maize production is very cost-effective, leading to high economic gains under future climate change, as model results show.

The NPV from switching to agroforestry (i.e. the difference to maize monoculture), as can be seen, is negative for a couple of years. During the first two years, the net cash flow is negative, i.e. the NPV decreases. This changes after 2021, when the NPV is –8,279 ETB (= -272 USD). From now on, the net cash flow is positive, and the NPV is starting to increase. It becomes positive in the year 2025 and further increases until 2050 when the value reaches 123,273 ETB (= 4,057 USD).

The corresponding internal rate of return (IRR) is already large in 2030 with more than 39% and amounts to almost 43% in 2050. As the IRR is greater than the local interest rate, agroforestry is a beneficial investment. The BCR also indicates this: It is 2.90 after ten years (in 2030) and 5.10 after 30 years (in 2050). This, once again, points to the fact that the farmer's investment in the agroforestry system will pay off after just a few years (see supplementary material for the detailed timeline of costs and benefits). The results under the improvement scenario with no climate impacts felt (climate change uncertainty) are equally positive and differ only marginally, the figures are thus given in the supplementary material.

Table 13: Adaptation scenario results for installing an agroforestry system.

Adaptation
• IRR: 42.65%
• NPV: 123,273 ETB (= 4,057 USD)
• BCR: 5.10

All in all, we conclude that combining maize with mango production is more profitable than inaction. The return to investments is highly positive, when assuming constant climatic conditions and also under future climate change impacts. Further, agroforestry practices offer scope for many development co-benefits, which are described in the next section.

8.3 Soft assessment indicators

An important question regards the upscaling potential of agroforestry practices in Ethiopia and the approaches to do so. According to the expert survey and consultations, so far, agroforestry strategies have low to medium uptake across Ethiopia. As a key area where agroforestry is already widely practiced appears southwestern Ethiopia (Jemal, 2018). Survey participants indicated that there is a medium to high potential for upscaling and interviews as well as the literature review confirmed the high value of widely implementing agroforestry practices. Farmer to farmer replication can be useful for agroforestry practices, but national legislation for incentivising agroforestry expansion is also needed (Reij & Garrity, 2016). An institutional challenge for upscaling of agroforestry systems often lies in the cross-cutting nature of agroforestry (Reij & Garrity, 2016): In Ethiopia, agroforestry falls into the competence sphere of the Ministry of Agriculture (MoA) and the Environment, Forest, Climate Change Commission (EFCCC). The two governmental entities may prioritise different approaches and objectives with regard to agroforestry. It is thus crucial for them to jointly work on upscaling plans for agroforestry, with both sides equally represented. Other bottlenecks for agroforestry uptake include land shortage, lack of knowledge and planning, financial constraints and high prices for seedlings as well as labour scarcity (e.g. Duguma, 2013, for Ethiopia's central highlands). The private sector can support agroforestry expansion with the development of tree-crop value chains, for instance for mango and coffee (Reij & Garrity, 2016).

The degree of institutional support needed for implementing agroforestry practices naturally depends on the concrete type of agroforestry practice. Generally, training for correct implementation of agroforestry techniques may be useful, but many indigenous practices exist which can be implemented autonomously by farmers. For large-scale restoration projects, such as under the PSNP, government coordination and support is needed. Otherwise, it is mainly information on good tree species and suitability for integration with different crops, which is required.

Stakeholders confirmed that there is very high interest in upscaling agroforestry practices in Ethiopia, which can have multiple co-benefits for soil fertility and climate change mitigation, amongst others.

Stakeholder interest in agroforestry practices for Ethiopian agriculture is very high, as evidenced by the survey results, the workshop consultation and the interviews conducted with key informants, where agroforestry practices and landscape restoration were repeatedly mentioned.

Finally, agroforestry practices can offer important development co-benefits. With regard to the potential for agroforestry practices to contribute to the SDGs, ICRAF states (ICRAF, 2019):

"Agroforestry, as evidenced by the activities of ICRAF and our partners, contributes directly to Sustainable Development Goals 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 7 (affordable and clean energy), 8 (decent work and economic growth), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action), and 15 (life on land) and indirectly through implementation approaches to Goals 4 (quality education), 5 (gender equality), 9 (industry, innovation and infrastructure), 10 (reduced inequalities), 14 (life below water), 16 (peace, justice and strong institutions) and 17 (partnerships for the goals)".

Application of agroforestry could help to achieve multiple development co-benefits, likely outnumbering potential maladaptive outcomes.

While the indirect links are more difficult to assess and likely hold for most adaptation strategies, particularly the potential contribution of agroforestry to SDGs 13, 15 and 2 is interesting.Agroforestry practices offer considerable benefits to climate change mitigation (SDG13), as they bind carbon in both woody biomass and soil as well as indirectly lead to lower fossil fuel consumption by providing alternative biomass fuel sources (Lasco et al., 2014). With regard to SDG15 for life on land, agroforestry can contribute to many of the sub-targets: It can enhance soil fertility and lower soil salinity, protect biodiversity, advance reclamation of degraded lands and expand tree cover. For improving soil fertility and biodiversity in southwestern Ethiopia for instance, Kassa et al. (2018) find that mixed crop-tree agroforestry systems positively affect forest biodiversity, conservation and topsoil fertility. Comparing three different tree species in Ethiopia, Seid et al. (2016) recommend the *B. aegyptiaca* species to counter salinity in arid and semi-arid areas.

SDG2 (zero hunger) is evidently addressed by agroforestry systems, especially where trees serve as fruit trees or where crop yields improve due to better climatic conditions brought about by tree-crop integration. However, yields can also be negatively impacted, if trees create unfavourable conditions for crops (Lasco et al., 2014). Thus, careful consideration of optimal tree and crop species is crucial. Through fodder from trees, improved livestock rearing can also enhance food security. In addition and closely linked to food security benefits, agroforestry systems can diversify food and offer enhanced nutritional values, especially in HG agroforestry with different fruit trees. This would contribute to SDG3 on good health and wellbeing. Furthermore, the water-saving aspect of agroforestry practices links them to SDG6 and trees for fuelwood production can offer co-benefits for SDG7.

An important link can be the one with SDG8 for decent work and economic growth: Agroforestry offers opportunities to diversify livelihoods and increase incomes, which for Ethiopia was for instance found with regard to HG agroforestry (Kumar and Nair, 2006; Nigussie et al., 2018). Value chain approaches appear especially promising, where high-value tree products can be marketed to gain additional income and lower farmers' dependence on subsistence agriculture. Finally, agroforestry systems provide shade and can thus increase labour productivity of agricultural workers, who are less exposed to heat and sunshine when working outside.

Table 14: Potential co-benefits and maladaptive outcomes from agroforestry.

Potential development co-benefits	Potential maladaptive outcomes
• Soil improvement, for instance increased soil fertility due to tree leaves that act as mulch and enhance soil organic carbon • Agroforestry systems can create incentives for further intercropping with other crops (e.g. legumes), for cultivating new crops and for crop rotation, which can benefit soils • Increased carbon sequestration and thus GHG mitigation • Biodiversity improvements • Protection against soil erosion • Higher agricultural output (yield per hectare) improves land use efficiency • Can offer alternative income sources, such as timber and high-value tree crops • More nutritious food, where fruit trees are grown and/or where fodder trees for enhanced livestock production are cultivated • Shade can improve productivity of farm workers, who are shielded from the sun in agroforestry systems	• Agroforestry systems take up space and thus require land area, which may conflict with other more profitable agricultural uses • Agroforestry systems become profitable only after a couple of years, farmers may thus loose income from the land dedicated to agroforestry in the meantime • Risk of decreasing yield and lower income generation, if maltargeted • Higher labour requirements, which especially in the case of homegarden agroforestry could increase the burden on women

Yet, such benefits of course depend on the overall performance of the agroforestry system. In case of decreasing yield or lower overall economic benefits as compared to monocropping, agroforestry practices may conflict with income generation objectives. Nischalke et al. (2017) caution that integration of vegetable crops to diversify lively-hoods and income in Ethiopia is beneficial, but only possible at limited scales. They also call for attention to women's participation in forest livelihoods and unequal labour distribution, which may occur to the detriment of women, as they found for southwestern Ethiopia. Still, concerns regarding maladaptive outcome of agroforestry interventions appear limited. Challenges regarding land availability and land usages can be minimised by seizing the potential of agroforestry for multiple usage and benefits, for instance via integrating agroforestry into cropping systems or using forage trees. Distributional questions can be addressed by designing inclusive and equitable agroforestry interventions. Table 15 synthesises the assessment for agroforestry strategies as adaptation in Ethiopian agriculture.

Table 15: Summary assessment of agroforestry strategies as adaptation in Ethiopia.

Risk response	Risk mitigation potential	Cost effective-ness	Risk gradient	Upscaling potential	Develop-ment co-benefits	Potential maladaptive outcomes	Stake-holder interest	Institutional support requirements
Risk mitigation	High[19]	High	Risk-specific	Medium-high	High	Low	High	Medium

Colour legend: blue = neutral, red = negative, yellow = medium, green = positive

[19] The risk mitigation potential is high up until a threshold of shade and only in specific environments, where yields are projected to decline under climate change. Careful targeting of agroforestry interventions is thus crucial.

Chapter 9 – Fodder and feed improvement

In order to adapt Ethiopia's livestock sector to climate change, a range of adaptation strategies exists. Proactive measures in terms of breeding, water and fodder management, animal health, and risk transfer mechanisms need to be assessed in both country-wide and regional development plans. Specific adaptation strategies should be tailored to the agro-climatic conditions and types of livestock production systems. Fodder and feed improvement is regarded as a promising adaptation strategy that, according to interviewed experts, has high potential for upscaling in Ethiopia. Fodder and feed improvement is an umbrella term subsuming different strategies and technologies to improve nutritional quality, digestibility, quantity and availability of fodder and feed resources for livestock production. These include, for example, integration of pasture and forages into farm production, establishing fodder banks with improved forages and fodder trees, treatment of crop residues (e.g. with urea), silage and hay production, irrigation for production of off-season pasture and feed crops, improved grazing land resources management, increase of administering high-quality feed concentrate (Birhan & Adugna, 2014; Birhanu, Girma, & Puskur, 2017b).

Fodder and feed improvement is an umbrella term combining different adaptation strategies related to nutritional quality, digestibility, quantity and availability of fodder and feed for livestock.

Adaptation strategies for the livestock sector in Ethiopia

Adjustments in Production

- Diversification, intensification, integration of pasture management, livestock & crop production
- Changing land use and irrigation, altering the timing of operations, conservation of nature and ecosystems
- Introduction of mixed livestock farming systems, i.e. stall feeding and grazing

Breeding Strategies

- Strengthening breeds, which are adapted to local climate stress & feed sources
- Improving breeds through cross-breeding with heat- and disease-tolerant breeds

Market Responses

- Promoting interregional trade, credit schemes, market access, insurance

Institutional & Policy Changes

- Introduction of livestock early-warning systems
- Forecasting & crisis preparedness systems

Science & Technology Research

- Understanding of the causes of climate change & its impact on livestock
- Facilitate development of new breeds & genetic types
- Improve animal health
- Improve water & soil management

Livestock Managment System

- Shade & water to reduce heat stress
- Improve livestock productivity (to limit number of livestock)
- Adjust the livestock numbers & herd composition to optimise use of feed resources

Figure 55: Adaptation strategies for the livestock sector, source: Sidahmed (2008, cited in FAO, 2009).

9.1 Risk mitigation potential

To address the issues around feed scarcity and to improve livestock production and productivity in Ethiopia, a plethora of research and development efforts have been implemented by national and international research institutes (Amede, Mengistu, & Roothaert, 2005; Assefa et al., 2016; Birhan & Adugna, 2014; Dawson et al., 2014; Shapiro et al., 2015; Shapiro et al., 2017; Tegegne et al., 2013). These efforts brought forward a multitude of strategies for feed improvement. For example, the Ethiopian Institute of Agricultural Research (EIAR) has registered and released about 33 improved and high-yielding forage varieties for the different AEZs in the country, selected due to desirable characteristics including adaptation to the prevailing climatic and soil conditions, ease of establishment, resistance to pests and diseases, forage quality, multi-purpose uses and suitability for integration into the farming system (Assefa et al., 2016). Other strategies include, for example, introducing high-quality forage species, such as Napier, Desho, oats or Rhodes grass into grazing pastures; intercropping grasses and cereals with legumes, such as native Desmodium, alfalfa, cowpea or vetch; cultivation of irrigated fodder banks; natural pasture improvement through removing of invasive weeds (such as *Hygrophilla auriculata*); temporal zero-grazing and cut-and-carry feeding regimes on degraded pastures to restore and increase carrying capacity; urea treatment of crop residues to improve digestibility and feeding value of low quality feeds; feed conservation practices, such as standing hay, silage making and crop residue stacking to conserve feed for the dry seasons; or establishing high-quality fodder trees, such as *Sesbania sesban* in agroforestry systems for contour forage banks, or under-sowing of fodder trees. Where applied correctly, many of these strategies have proven successful to boost livestock production, resilience and farmer income. For example, recent trial projects with small-scale irrigated Napier grass in the Amhara region resulted in a doubling of milk yields from a previous 2.3lt/day to 4.6lt/day for local cows, and up to 7-10 lt/day for crossbred dairy cows. At a farm gate price of 0.45 USD (13.3 ETB) per lt milk, participating farmers can thus achieve a monthly income of 62 USD per local cow and between 94.5 - 135 USD per crossbred cow (Adie & Blummel, 2019).

9.2 Cost-benefit analysis: Irrigated Napier grass fodder bank on a mixed farm

In this cost-benefit analysis, we consider a farmer who starts growing irrigated Napier grass, a fodder grass which can be used to feed cows.

Following the second approach for a cost-benefit analysis as outlined in Chapter 5.4, we analysed the introduction of Napier grass (*Pennisetum purpureum*) as a fodder grass for smallholder dairy production in a cut-and-carry production system (Heuzé et al., 2016; SNV and DTC, 2017). The aim of the introduction of Napier grass is to increase feed quantity and quality especially during the dry season to subsequently improve animal health and stabilise and increase milk yields under climate change.

The four scenarios for evaluating the introduction of irrigated Napier grass fodder banks on a mixed farm are as follows:

Baseline (no action, no climate impacts): milk and khat production - a farmer who produces milk with a small herd of dairy cows and additionally produces khat (*Catha edulis*) as a cash crop, without growing his or her own fodder.

Adaptation (action, climate change impacts): action under future climate change impacts - The farmer adopts the adaptation strategy, which in this case means a shift from no specific fodder production to irrigated Napier grass. We consider these changes ceteris paribus, i.e. all other things being equal and not considering other changes.

No adaptation (no action, climate change impacts): future climate change impacts - In this scenario, the farmer does not adopt irrigated Napier grass fodder banks and his or her original production system is impacted by climate change.

Improvement (action, no climate change impacts): irrigated Napier grass fodder banks under current climatic conditions - In this scenario, there are no further negative climate change impacts felt by the farmer. Nevertheless, the farmer adopts the adaptation strategy.

Data, assumptions and initial monetarisation

The specific approach used hereafter is based upon a research project conducted by the International Livestock Research Institute (ILRI) (see Karaimu, 2019) which focuses on irrigated Napier grass fodder banks to improve overall feed quality, animal health and climate change adaptation. Various data have been obtained from this source, but also from other scientific literature and expert opinions. In particular, the following basic data and qualified assumptions have been used to define the relevant (monetary) information necessary for a full, i.e. a meaningful, cost-benefit analysis (CBA):

Based on Karaimu (2019), the basic consideration is that of a farmer who produces milk with a small herd of dairy cows and additionally produces khat (*Catha edulis*) as a cash crop. The khat and milk producing farmer is now assumed to stop producing khat and instead focuses on the adaptation of his milk production (and overall farm production) under climate change. This is done by growing Napier grass on the area formerly devoted to the production of khat. The herd size of the defined farm is four dairy cows, two of them are local breeds and the other two crossbreeds. According to Ndambi et al. (2017), the average daily milk yield for a local-bred cow is 2.3 litres (also supported by the information gained from Karaimu (2019)), whereas the daily milk yield for the cross-bred cows lies around 8.4 litres. Hence, the average milk yield of the farm is 5.35 litres per day and cow. According to Ndambi et al. (2017), the milk price at farm gate can be set at 13.3 ETB (= 0.4 USD) per litre. Again, this finding is supported by data obtained from Karaimu (2019).

Having the above-mentioned information and further taking into consideration production costs in accordance with Ndambi et al. (2017), the daily gross benefit of a cross-bred cow amounts to 40.5 ETB (= 1.3 USD), while the gross benefit of a local bred cow amounts to 15.2 ETB (= 0.5 USD) – averaging at 27.9 ETB (= 0.9 USD) per cow and day. The lactation period is assumed to be 150 days per year (Tegegne, 2018). The acreage for khat and then Napier grass production is 1,000 m² (Karaimu, 2019). Switching from khat to Napier grass production and its subsequent use as fodder grass is assumed to double the daily milk yield and with this the gross benefit from dairy production (Karaimu, 2019).

> Switching from khat to irrigated Napier grass and using Napier grass as fodder could help to double the daily milk yield from cows.

When it comes to khat, it is important to note that this plant is classified as an illegal drug in most parts of Europe, Asia and North America (Cochrane and O'Regan, 2016). In Ethiopia, the production of khat is not explicitly prohibited and has been steadily growing in the past years (Cochrane and O'Regan, 2016). Today, Ethiopia is the largest global producer of khat with an average khat yield of 8 tons per hectare (Dessie, 2015; Cochrane and O'Regan, 2016). While khat is considered a very profitable cash crop for Ethiopian farmers, attaining information on the income generated by the cultivation of khat is quite challenging (Dessie, 2013; Dessie, 2015). With the information from Yibeltal (2016), who states that khat has a net return of up to four times that of coffee and Tamru et al. (2015), who locate the annual profit per hectare for coffee in Ethiopia at 8,030 ETB (= 264 USD), it was possible to estimate the net return from khat production as 32,120 ETB (= 1,057 USD) per ha and year.

Specific costs and benefits

Using this data and qualified assumptions, it is now possible to allocate specific costs and benefits to the switch from khat to Napier grass production under climate change:

- The acreage available to the farmer for khat production is, as described above, 1,000 m² (Karaimu, 2019). This means, the current annual net return from khat production amounts to 3,212 ETB (= 106 USD).
- With a herd size of four cows, a daily milk yield of – on average – 5.35 litres per day and a lactation period of 150 days, the farmer produces 3,210 litres of milk per year. Relying on information provided by Karaimu (2019), this doubles thanks to the introduction of Napier grass. At an average gross benefit of 27.9 ETB (= 0.9 USD) per cow and day, the farmer has additional returns of 16,710 ETB (= 550 USD) per year due to the increase in milk production and if the farmer sells the entire additional milk yield (or uses it directly for own consumption or at farm at opportunity costs).
- It becomes clear: The switch from khat production to Napier grass cultivation does not come without costs. In fact, there are two different kinds of costs that the farmer must deal with. First, by stopping to produce khat, the farmer loses the net returns of 3,212 ETB (= 106 USD) each year. Additionally, deciding to switch to Napier grass comes with some establishment cost in the first year (i.e. for ploughing soil, planting Napier grass, application of fertiliser). These establishment costs can be considered to amount to 10,943 ETB (= 360 USD) (Lukuyu et al., 2013; NAFIS, 2019). Adding these two cost impacts amounts to 14,155 ETB (= 466 USD) costs in the first year. This value is the initial investment necessary to switch from khat to Napier grass production.
- In addition to this singular investment cost, annual maintenance costs of 3,419 ETB (= 113 USD) for maintaining Napier grass production (i.e. for weeding, fertilising, harvesting, re-establishing after ten years, etc.) occur (Rashid et al., 2013; Lukuyu et al., 2013; NAFIS, 2019).
- To complete the cost considerations, it is furthermore assumed that the complete Napier grass harvest will be used as additional fodder for the herd of dairy cows. As the farmer could also sell the Napier grass at market prices instead of using it as fodder, opportunity costs arise. In the underlying case, these opportunity costs amount to 2,824 ETB (= 94 USD) (Lukuyu et al., 2013; NAFIS, 2019).

To assess the cost effectiveness of the planned intervention, different costs and benefits need to be weighed against each other.

The information discussed above marks the starting point for the CBA – both costs and benefits can now be quantified in monetary value over time. On the cost side:

- Initial establishment costs of 14,155 ETB (= 466 USD) occur in the first year, and
- Every subsequent year adds 3,419 ETB (= 113 USD) (valued at current prices) for maintenance.

On the benefit side, additional returns (i.e. a positive benefit) of 16,710 ETB (= 550 USD) occur due to the increased milk production. However, the lost income (i.e. a negative benefit) from khat production (3,212 ETB) and the opportunity costs of selling the Napier grass to the market instead of using it as fodder (2,824 ETB) must additionally be taken into consideration and subtracted from these additional returns. This leads to an annual benefit (again, valued at current prices) of 10,674 ETB (= 351 USD).

At this point it is very important to factor the impact of time into the calculations. Two aspects are important: Climate change will impact the farmer. Both milk (based on Napier grass) as well as khat production are impacted. In the underlying case, the impact of climate change on milk production is – due to the lack of reliable region-specific data, but condensed “scientific wisdom” (see, e.g., Summer et al., 2019) – conservatively assumed to be a reduction in milk yield of 0.5% per year; and in khat production a reduction of 1% per year is assumed with climate change. In addition, a proper discount rate has to be established in order to value costs and benefits over time and not only at current prices. We apply a discount rate of 6%. It symbolises the growth in Ethiopian gross domestic product (GDP) per capita in most recent years (see World Bank, 2019b).

Major findings

The CBA conducted by using all this information arrives at the major conclusion that in 2030 and in 2050 the adaptation strategy Napier grass (adaptation scenario) is highly beneficial in comparison to the no adaptation scenario. It has a high and fast return to investment, as the following figure visualises.

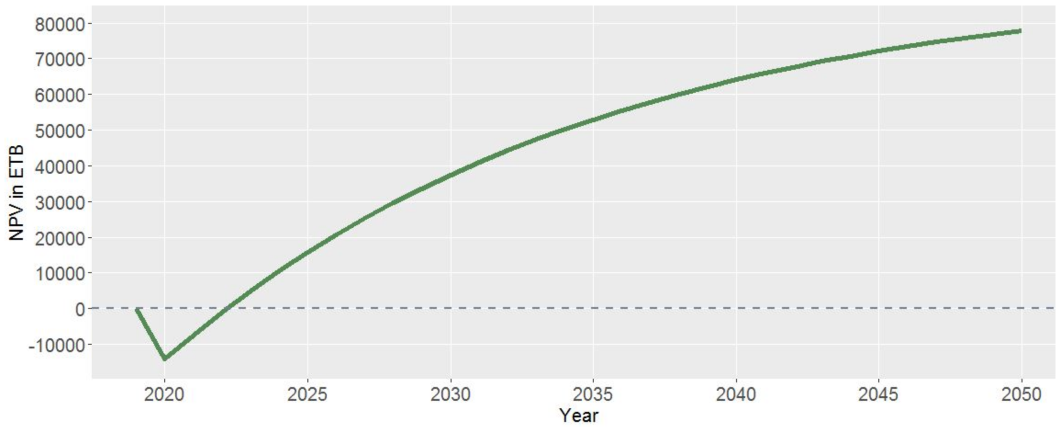


Figure 56: Net present value over time of switching from khat to Napier grass production in Ethiopia under climate change (in ETB).

Here, we consider 2020 as the base year and analysed the CBA flow for the time span from 2020 to 2030 and from 2020 to 2050. After ten (30) years, i.e. in 2030 (2050), a net present value (NPV) of 37,413 ETB (= 1,231 USD) (77,911 ETB = 2,564 USD) is generated. This NPV has to be positive for a beneficial investment. It describes the present value of the investment in Napier grass adaptation in the future, here 2030 and 2050. As such, it describes the future return discounted to the present. The corresponding internal rate of return (IRR) is 49% in 2030 and 50% in 2050. As the IRR is again much higher than the local interest rate, it becomes clear that the strategy is highly profitable. This can also be expressed with an additional algebra term, the benefit cost ratio (BCR): Here, the BCR is 1.95 after ten years (in 2030) and 2.27 after 30 years (in 2050). For the improvement scenario in light of climate change uncertainty, the results are very similar to the adaptation scenario and are not given here, but can be found in the supplementary material.

The results show that introduction of irrigated Napier grass as fodder would be highly beneficial in economic terms. The intervention would pay off after only three years, when the break-even point between net costs and net benefits would be reached.

Table 16: Adaptation scenario results for implementing irrigated Napier grass fodder banks.

Adaptation
• IRR: 50.0%
• NPV: 77,911 ETB (= 2,564 USD)
• BCR: 2.27

Importantly, the farmer's investment in Napier grass will pay off after three years when the break-even point between net costs and net benefits is reached. So, a crucial point for policy makers is to ensure that the associated income loss is met with transitional funding. Otherwise, the adaptation strategy might not be affordable for farmers in Ethiopia at large scale. All in all, we conclude that looking at this specific adaptation strategy, action is much more profitable than inaction, although other improved fodder and feed strategies or factors, such as prices would change the results.

9.3 Soft assessment indicators

While the examples above demonstrate the potential to increase livestock production even under a changing climate, the adoption of improved feed and fodder management strategies across the country so far remains rather low (Birhanu et al., 2017a), which was also confirmed by experts interviewed for this study. Yet, stakeholders and experts consistently expressed high interest in this measure throughout interviews, the survey and the workshop. In fact, due to the high importance and increasing policy awareness of this topic, experts interviewed see high upscaling potential for adoption of improved feed technologies in the country. Not all concrete strategies can be applied everywhere, irrigated Napier grass for instance may be difficult to implement in the lowland pastoralist and agro-pastoralist regions, but suitable strategies and improvements over the current practices can be found for all regions.

However, several issues need to be addressed to achieve this goal. Insufficient financial means, lack of market access and infrastructure and limited capacity among extension agents to provide adequate information and training are common constraints to technology adoption in smallholder farming that also apply to livestock production (Gebremedhin, Ahmed, & Ehui, 2003). In addition, the introduction of improved fodder species is constrained by a general lack of seeds and planting material of fodder crops and forage species in rural areas, indicating the need for investments in seed production and distribution channels (Shapiro et al., 2015). This should be complemented with training of lead farmers and the establishment of local forage seedbanks at community level, allowing to quickly reach large numbers of farmers, while building capacity at local level to produce their own seedlings or planting materials (Mengistu et al., 2016). The importance of access to credit and extension services for improved livestock feed adoption is underlined by a study that identifies factors for adoption and intensity of use of improved forages in northern Ethiopia (Beshir, 2014). Another study further finds that the adoption rate of feed technology in Ethiopia is positively and significantly affected by education levels of the household head, livestock herd size and membership in cooperatives, among others (Birhanu et al., 2017a). Therefore, significant institutional support is needed to strengthen efforts towards education and training around feed technologies, distribution of seeds and planting material in rural areas, improved market integration and support for self-organisation of farmers into community farmer groups and cooperatives. For implementing improved fodder and feed practices, again the government, development actors, researchers and practitioners were mentioned as central actors, with special emphasis on including pastoralists in the process, as communities that are often marginalised.

Significant institutional support is needed to produce seeds of forage species and to train farmers on their use.

Table 17: Potential co-benefits and maladaptive outcomes from fodder and feed improvement.

Potential development co-benefits	Potential maladaptive outcomes
• Increase in nutritional diversity, thus also health and wellbeing • Income diversification • More or higher-value livestock assets to sell in cases of climatic emergencies • Higher livestock productivity improves land use efficiency and relative GHG emissions	• Need for land, could decrease land available for other agricultural uses • Higher GHG emissions from more livestock contribute to climate change

Growing fodder requires land, which could lead to trade-offs with crop production. This needs to be considered when designing fodder and feed interventions.

With regard to potential development co-benefits, improving fodder and feed has the potential to increase livestock production, thus contributing to SDG1 and SDG2 on no poverty and zero hunger. Beyond this direct link, nutritional values could also be improved, potentially contributing to SDG3 on improved health and wellbeing. Further, farmers implementing improved fodder and feed practices will benefit from more or higher-value livestock assets to sell in cases of climatic emergencies. The case study on Napier grass presented in section 9.2 specifically revealed benefits for income diversification and regarding improved health outcomes, as Napier grass cultivation and increased livestock production replaced harmful khat production and consumption. However, improved fodder and feed practices can also lead to unintended negative consequences: Generally, growing fodder needs land, which may compete with other usages and could lower crop production. This competition can be reduced by integrating fodder trees into farming systems, but the general need for land allocation remains, which smallholders do not always consider the most important use for land, as confirmed by the interviews conducted for this study. In addition, increased livestock production as a result of improved fodder and feed practices can lead to higher GHG emissions from agriculture, which conflicts with SDG13 on climate action. Here, the measurement approach is crucial for determining the effect: GHG emissions can either be measured per production unit or as a whole. Improved fodder and feed will likely lead to higher overall GHG emissions, but to lower emissions per production unit, leaving the assessment ambiguous.

Table 18: Summary assessment of fodder and feed improvement strategies as adaptation in Ethiopia.

Risk response	Risk mitigation potential	Cost effective-ness	Risk gradient	Upscaling potential	Develop-ment co-benefits	Potential maladaptive outcomes	Stake-holder interest	Institutional support requirements
Risk mitigation	High	High	Risk-inde-pendent	High	High	Medium	High	Medium

Colour legend: blue = neutral, red = negative, yellow = medium, green = positive

Chapter 10 – Crop insurance

Crop insurance is a risk transfer strategy, which allows farmers to insure their crop yields against weather-induced losses.

While most adaptation strategies seek to minimise risks stemming from climate change, not all risks can be eliminated. Weather perils, such as droughts, storms or erratic precipitation represent so-called systemic risks that go beyond the farmers' or communities' coping ability. Thus, mechanisms are needed that distribute risk to avoid that certain groups or individuals are particularly affected and lose their livelihoods. One of such risk transfer solutions is crop insurance, which allows farmers to insure their crop yields against weather-induced losses. It is also a risk-specific adaptation strategy, which becomes irrelevant in the absence of weather and climate risks. While insurance usually is based on indemnity-assessment, with smallholder farmers this model is problematic due to the high transaction costs such an insurance scheme entails, e.g. for claim disbursements. Thus, a more suitable approach for smallholder farmers are weather index-based insurances (WII), a scheme that uses a weather index, such as temperature or precipitation to determine a payout. Alternative index-based insurance schemes can also be useful, such as area-yield index insurance.

Index insurance schemes for crops and livestock have been developed and tested in several pilot schemes in Ethiopia, and a number of studies have been conducted around their feasibility and potential for scale (Bageant & Barrett, 2017; Bishu et al., 2018; Bogale, 2015; Brans, Tadesse, & Takama, 2010; Dercon et al., 2014; Gebrekidan et al., 2019; Hazell & Hess, 2010; Hill, Hoddinott, & Kumar, 2013; Madajewicz, Tsegay, & Norton, 2013; Mcintosh, Sarris, & Papadopoulos, 2013; Ntukamazina et al., 2017). Yet, available literature is largely grey literature, only few peer-reviewed studies on insurance in Ethiopia exist, as literature search with the database SCOPUS revealed (which yielded only 23 results despite using a range of search terms).

In experimental set ups, a number of studies have tested interest and demand for crop insurance among smallholder farmers under different packages and premium rates. Results unveil a complex array of factors increasing or decreasing (potential) demand for insurance. Hill et al. (2013) for example, find that insurance markets are most likely to be entered by educated, rich and pro-active individuals, at least initially. In a study from 2015 among three villages in the central rift valley of Ethiopia, Bogale, on the other hand, finds that those households "that are better educated, that are worried about risk associated with weather and with better credit access are more likely to pay for weather-indexed insurance, whereas households that have better non-farm income and remittance are less likely to pay for the rainfall-based index insurance" (Bogale, 2015, p. 9).

10.1 Risk mitigation potential

Crop insurance is often combined with agricultural inputs, such as seeds or fertilizer, or credit to improve uptake and crop production.

As already mentioned, insurance as such does not overall mitigate climate risk, but transfers it to other sectors to reduce the risk in the agricultural sector for individual farmers. Among the existing index-based crop insurance schemes in Ethiopia, most rely on donor funding and come with subsidised premiums. Insurance products are often bundled with other measures for risk reduction and production enhancement, such as agricultural inputs or credits. The first private insurance company in Ethiopia to pilot weather-index insurance (WII) schemes for smallholder farmers is the Nyala Insurance Company (NISCO) (McIntosh, Sarris, & Papadopoulos, 2013). Since 2009, NISCO has been offering its Weather Index Crop Insurance (WICI) product, which is subsidised by donors, covering haricot beans, teff, and other cereals against drought. According to a study from 2017, NISCO has an estimated client base of around 22 200 farmers (Ntukamazina et al., 2017).

Another promising insurance programme in Ethiopia is the Horn of Africa Risk Transfer for Adaptation (HARITA) project, which was initiated by Oxfam America in 2009 and is now led under the R4 Rural Resilience Initiative in partnership with the World Food Programme (WFP). The programme offers precipitation index-based crop insurance as part of a wider risk management package and extends insurance and disaster risk reduction measures in exchange for labour. The R4 programme has grown from some 13,000 farmers reached in 2009-2011 to over 24,000 in 2014 in Ethiopia alone (Greatrex et al., 2015; Ntukamazina et al., 2017). By 2018, the programme reached over 57,000 farm households (over 300,000 people) in Ethiopia, Senegal, Malawi, Zambia and Kenya (WFP, 2018). An early evaluation has shown its positive impact among policyholders in terms of poverty reduction and maintaining individual farmers' livelihoods in case of droughts, amongst others. Yet, the overall client base remains too low for the programme to have a significant impact at a larger scale (Madajewicz et al., 2013). Nevertheless, the R4 Initiative stands out as one of the largest index insurance programmes in the region where farmers voluntarily purchased unsubsidised premium insurance products that are not linked to a loan, where, however, additional risk management components were also included (Vasilaky et al., 2019).

There is continued interest and engagement from within the country to further promote insurance solutions for the agricultural sector. For example, the Japan International Agency for Cooperation (JICA) recently launched a new "Index-based Crop Insurance Promotion (ICIP) project" in 2019 together with the Ministry of Agriculture and the Oromia Bureau of Agriculture and Natural Resources (OBoANR) (JICA, 2019). The programme is expected to cover 20,000 farmers in the Oromia region over the next five years.

10.2 Soft assessment indicators

So far, uptake of crop insurance in Ethiopia is very low. More research on agricultural insurance and demonstration of the benefits of crop insurance can thus be useful.

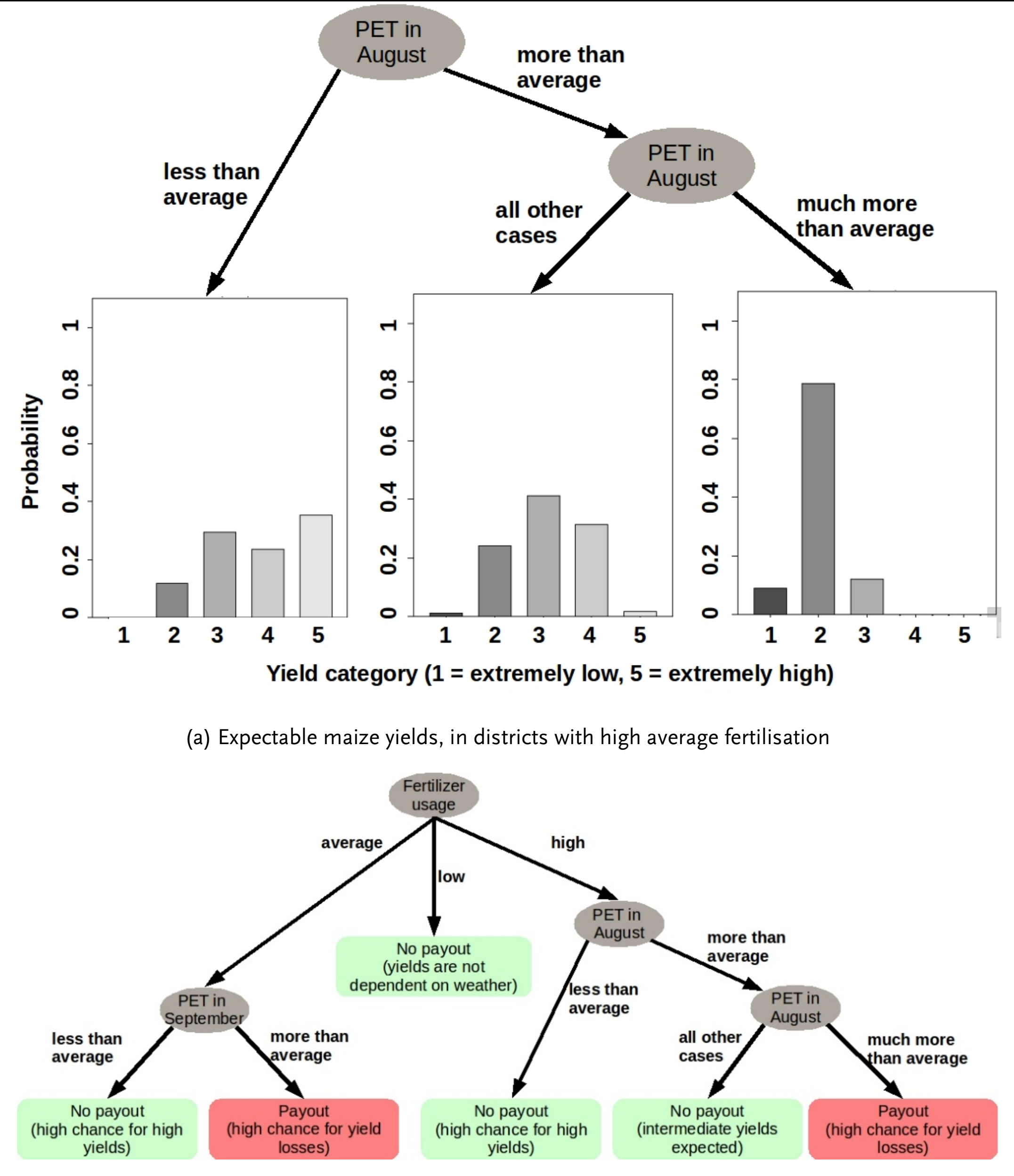
During expert and stakeholder interviews conducted for this study, there was wide consensus that crop and livestock insurance has a low uptake in Ethiopia as of yet, and is regarded as having only limited upscaling potential in the country. Accordingly, interest in insurance among interviewees, survey and workshop participants was low, which may, however, be rather an expression of difficult implementation of insurance schemes than of general lack of interest, as the in-depth interviews revealed. Thus, there appears to be a need for further research on how to effectively operationalise insurance in Ethiopia and how to ensure better uptake and sustainability.

Evidently, such insurance schemes continue to rely on international donor or governmental subsidies. In order to reach wider scale, a more profound institutional transformation and government engagement is needed in Ethiopia. Insurance solutions are necessarily institution-led adaptation strategies, since they cannot be set up autonomously by individual farmers or beneficiaries. For implementation of insurance schemes in Ethiopia, survey participants see a particular role for private insurance companies and financial institutions, in addition to government partners, such as the Ministry of Agriculture.

Crop insurance can benefit any parts of the population, depending on the design of the insurance scheme. Although it may be easier for larger farms to afford insurance and coverage of larger units is also more convenient for insurers to handle, government support and the setting up of WII schemes can help to make insurance affordable. It is then more accessible also for the most vulnerable parts of the population, namely smallholder farmers. However, it is difficult to offer self-sustaining insurance schemes for smallholder farmers, the need for affordability may require continued subsidies by the government or third parties, which can hamper the development of insurance products for the most vulnerable. Here, new solutions are needed to address the trade-off between affordability for smallholder farmers and high transaction costs as part of the insurance premium (the insurance premium contains the average claim costs, transaction costs and insurance industry's profits). Generally, insurance schemes are rather costly adaptation strategies, at least when considering the overall costs and the increasing overall risks that a continuing climate change presents to the agricultural sector. Insurance schemes can be rather easily scaled up, in fact they depend on large coverage for becoming operational and they provide potential opportunities for the private sector to be engaged, with private insurers holding large expertise in this sector. For the assessment of the upscaling potential, there is thus a contrast between stakeholder interest and technical potential in Ethiopia. From the user perspective, insurance is currently not highly demanded. Yet, crop insurance could cover a large area and many farmers in Ethiopia, offering them the option to reduce their income risk, where climate change may induce harvest failures.

Potential design of an index-insurance scheme for Ethiopia based on weather and fertilisation regime

Crop insurance is one possible option to improve farmers' resilience against the vagaries of climate with ensuing losses in crop production. Such insurance requires a robust assessment of expected losses ideally immediately after the occurrence of a yield loss. Here, we present a pathway to model such yield losses categorically for maize. Depending on the values of different climate variables (like precipitation, temperature or evapotranspiration) during the growing season, evaluated against their long-term means, the probability for observing yield losses at the end of the season can be gauged. The method applied here is a decision tree, where expected categories of yield values (1 = very low via 3 = intermediate up to 5 = very high) are hierarchically dependent on climate variables (Figure 57). The results from decision tree analyses are intuitively understandable and have the advantage of being based on observable quantities (e.g. the potential evapotranspiration, which can easily be calculated from weather observations) during the season. Clear distinctions can be drawn between climatic conditions that very likely lead to losses or gains, respectively. An example of an insurance design for maize, depending on climate and average historical fertiliser use per region is provided in Figure 57. The decision variables and their thresholds are derived from a machine-learning approach that results in an optimal split of the data set into "loss", "gain" or "average" yield conditions based on weather determinants. The efficiency of the design is currently biased, with 93% of all cases where no yield loss occurred also triggering no payout, but only 41% of all cases where a yield loss occurred triggering a payout. This efficiency will have to be improved, but is currently limited by the size of the data base (yield data only start in 2006). Insurance providers in Ethiopia could make use of such a design by monitoring the relevant climate variables and fertiliser usage for taking decisions on payouts based on the calculated yield probabilities.



(a) Expectable maize yields, in districts with high average fertilisation

(b) Insurance design for maize, based on average fertiliser usage and weather

Figure 57: Decision trees for (a) expected yield losses for highly fertilised maize as an example and (b) a possible insurance design for maize, based on fertiliser usage and climate, including the example from (a) on the rightmost branches. In (a), depending on the different climatic variables, probabilities for observing relative categories of yield (in comparison to the long-term mean, with 1 = very low to 5 = very high) can be derived. For maize in Ethiopia, Potential Evapotranspiration (PET) during the growing season is decisive for yield formation, with values higher than average raising the chance for observing yield losses. In (b), the decision for or against a payout of insurance can be derived by traversing the path from the root node (on top) along the observations. Payouts are ungraded here (i.e. they consist of a simple yes/no decision), but such a grading could be included into the decision tree straightforward.

Crop insurance is important for the management of risks that are too high to adapt to. Yet, potential maladaptive outcomes need to be taken into consideration.

Generally, crop insurance can be considered an important adaptation strategy because it can address residual risk, which cannot be mitigated in an economically sensible way with physical adaptation strategies. However, if poorly designed, crop insurance schemes can produce maladaptive outcomes. This can happen for instance with regard to agricultural biodiversity, when cash crops are cultivated instead of resilient subsistence crops and with lower adoption of intercropping, or with regard to existing social support structures, which may be undermined by commercial insurance (Müller et al., 2017).

Table 19: Potential co-benefits and maladaptive outcomes from crop insurance.

Potential development co-benefits	Potential maladaptive outcomes
• Insurance smooths income • It can incentivise uptake of improved technologies, such as improved seeds and (organic) fertiliser • It can allow farmers to get access to agricultural credit for investments • Higher agricultural output (yield per hectare) through improved land use efficiency	• Agricultural biodiversity can be negatively affected if farmers use insurance to switch to riskier, but potentially more profitable mono-culture high-value crop cultivation • Traditional social support systems acting as quasi-insurances can be eroded by formal insurance markets • Insurance uptake could induce risky behaviour (moral hazard) • Costly insurance can reduce expenditure in other important areas, such as health and education

Nonetheless, insurance has an important role to play in a sensible adaptation portfolio. As a safety net for farmers in times of extreme weather events, which prevents them from losing their whole income, it can contribute considerably to the achievement of the SDGs.

Table 20: Summary assessment of insurance as adaptation in Ethiopia.

Risk response	Risk mitigation potential	Cost effectiveness	Risk gradient	Upscaling potential	Development co-benefits	Potential maladaptive outcomes	Stakeholder interest	Institutional support requirements
Risk transfer	No risk mitigation	Risk transfer	(Weather) risk specific	Medium	Medium	Medium	Low	High

Colour legend: blue = neutral, red = negative, yellow = medium, green = positive

Case study crop: Potential adaptation strategies for coffee systems in Ethiopia

As shown in the impact part of this study (Chapter 1-4), climate change impacts on crops are highly differential. It is thus important to consider how best to address the climatic impacts on different crops. While the above analysis focuses mostly on maize production, Table 21 below gives an overview on how the coffee sector in Ethiopia could adapt to climate change. In order to maintain or increase coffee production in Ethiopia under climate change, the following adaptation strategies can be considered, together with their strengths and weaknesses for the Ethiopian context.

Table 21: Potential climate change adaptation strategies for the Ethiopian coffee sector.

Adaptation strategy	Description of method	Strengths	Weaknesses
Coffee production intensification	Increasing coffee production per unit area through increased external inputs, high intensity planting and increased crop attention.	Does not require new land to achieve production targets. Current coffee intensification systems already exist for implementation.	Could be costly for smallholder farmers and may result in reduction of forest coffee systems which have co-benefits. In addition, it could affect the quality of coffee and the international market demand.
Agroforestry	Increasing shading to regulate temperature and soil moisture.	Some form of shade is already being practiced in Ethiopia so this will be scaling up. It can also provide co-benefits, for instance on coffee quality, although the direction and size of the effect depend on the climatic and edaphic conditions.	Can reduce yield levels and incomes for farmers, thus requires premiums to compensate for losses. Takes considerable time from establishment to provide benefits.
Irrigation	Providing supplementary or deficit irrigation to coffee plants during periods of need.	It provides water for the plant and also cooling of the fields, meaning it could be very effective.	Could be costly to install and maintain. Could also result in salinisation depending on water sources and quality.
Breeding coffee varieties for resilience	Development of new coffee varieties that are drought, heat and flood tolerant. This includes developing disease and pest tolerant varieties.	Very effective and low cost to the farmer. Easy to implement through current structures, with local research institutes like Jimma Agricultural Research Institute advancing breeding activities in this field.	Takes time to breed and produce varieties and can compromise on quality and productivity to achieve drought and flood tolerance. It will take time for new varieties to start producing coffee.
Diversification into other crops or off-farm income	Coffee farmers in areas projected to be adversely affected consider switching to other crops or enterprises that are not adversely affected.	This is relatively easy to implement and can increase resilience, as investments are not wasted in deteriorating crop conditions.	Years of experiential learning in coffee production are lost. Alternative crops could be less profitable or requiring more labour or other production means than coffee. In addition, coffee is Ethiopia's main export crop and switching to other crops could lead to important losses in foreign currency earnings.
Coffee crop insurance	Coffee farmers can insure their crops against yield and quality losses related to climate change.	Easy to arrange through current coffee marketing channels and since coffee is a cash crop.	Could be costly for smallholder farmers, as margins may already be low.

Chapter 11 – Uncertainties

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

11.1 Climate model data

Global climate models have become much better over the past decades, but some biases still need to be addressed with the help of statistical, so-called bias-adjustment approaches.

The development of climate models has made vast improvements in recent decades, but climate models still display substantial biases (systematic differences between observed and simulated climate). To remove these biases, climate data is usually statistically processed (bias-adjustment) before applied for impact modelling. This approach has critical limitations (Ehret et al., 2012; Maraun, 2016), but it is necessary for the realistic simulation of climate impacts (Teutschbein & Seibert, 2012; Chen et al., 2013). The analysis of future climate in this report is based on the suite of bias-adjusted global climate models produced within the ISIMIP2b project. ISIMIP2b provides data from four models (GFDL-ESM2M, IPSL-CM5-LR, HadGEM2-ES and MIROC5). To address model uncertainties and avoid results to be dominated by individual models, it is generally recommended to include as many models as possible. However, the IPSL-CM5-LR data showed to be unfeasible for an assessment of Ethiopia's future climate. The raw model data displays a very strong dry bias (more than factor 10, which is the upper bound of the correction factor of the bias-adjustment method) in some regions of Ethiopia in the historical simulations, in comparison to the other three models (Lange, 2017). This strong bias leads to the maximum correction factor (factor 10). In combination with a strong positive future trend (regionally up to 35 mm/year), this large correction factor leads to very amplified and unrealistic extreme events in the climate projections, which is a known limitation of this bias-adjustment method (Lange, 2018) as well as a very high annual precipitation rate (regionally beyond 5,000 mm per year by the end of the 21st century under RCP8.5). As unrealistically high projected precipitation for Ethiopia within IPSL-CM5-LR also strongly affected the results of the hydrological and agricultural assessments and generally dominates all precipitation-related analysis, it was decided to not include the IPSL-CM5-LR results in our analyses.

The impact models used for this study were thus forced by the three remaining climate models. While this weakens the forcing input, climate model agreement on precipitation trends in Ethiopia is generally high. Looking at the most recent climate scenario data as delivered by the Coupled (climate) Model Intercomparison Project (CMIP5, Taylor et al. 2012) for RCP8.5 (van Vuuren et al. 2011), the results show a general pattern of precipitation increases over Ethiopia, with more than 80% agreement in trend direction (see right-hand map in Figure 58).

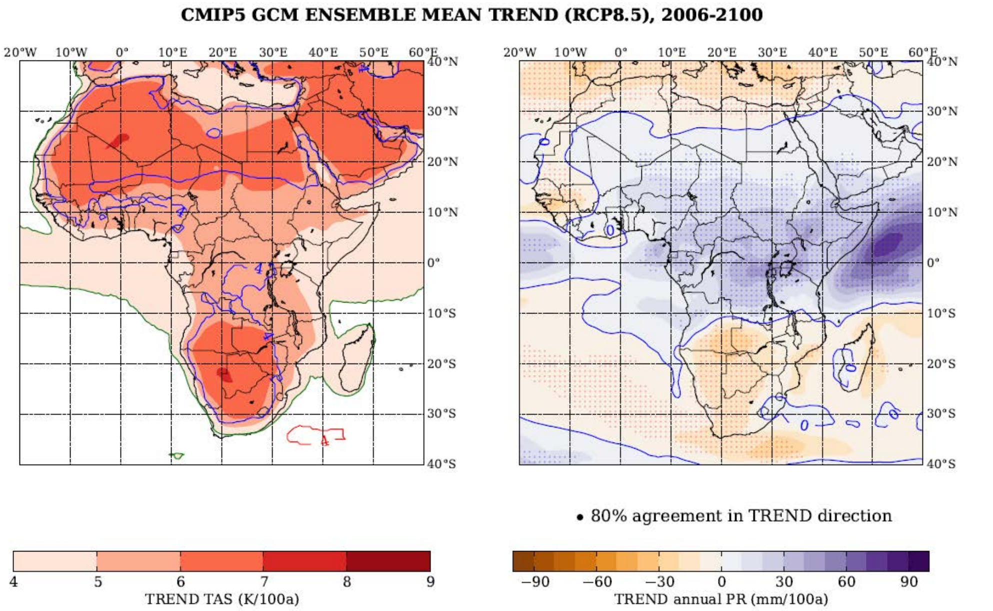


Figure 58: Mean trend in annual precipitation until end of this century under RCP8.5 climate scenario conditions (2010-2099), using linear regression of the annual sums of 18 CMIP5 global climate model results. Shaded areas indicate where at least 80% of the model ensemble agrees in the direction of the trend. Data processed at PIK.

11.2 Hydrological model

Uncertainty in hydrological models mainly stems from the climate model results that are used and the quality of other data inputs.

The largest source of uncertainty in hydrological modelling and impact assessment comes from climate model outputs (see e.g. Vetter et al., 2015; Vetter et al., 2017). As explained in section 11.1, for Ethiopia we observed a high deviation of some climate models, which lead to extreme changes in the river discharge and water balance towards the end of the century. One of the examples is the IPSL model where annual precipitation increases much stronger compared to other models and can double in comparison to the historical period. On the other hand, during the historical period in some areas IPSL shows a large underestimation of annual precipitation, one of the examples is an area near Lake Tana presented in the supplementary material. Based on what was mentioned above and the analysis of data for the historical and future periods, it was decided to exclude the IPSL model from the assessment of climate change impacts on the hydrological cycle in the Blue Nile basin.

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

- Data availability of observed river discharge data in terms of the number of stations, available periods and the many gaps in the time series are limiting hydrological model calibration and validation.
- Climate data for the Blue Nile and Awash River basins are needed for the parametrisation of SWIM. Therefore, (gridded) global climate data sets (WATCH and WFDEI, depending on the availability of observed discharge data) were used in the calibration of SWIM. Where precipitation (spatial and temporal) distribution is uncertain, verification of these data using observed data would be necessary.
- Lack of information on water resources management (irrigation and reservoir management and parameterisation). All data for this study was collected from scientific papers and reports.
- Furthermore, it would be good to employ more advanced quality checks for the input data (soil parameterisation including, for instance, an adaptation of soil depth, land use/cover parameterisation combined with a validation on vegetation cycles etc.).

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

11.3 Crop models

Crop models are used to determine the share of weather-related variation in yields and to project impacts of changing climatic conditions on crop yields. Such analyses can support farmers in taking decisions related to yield stabilisation and crop yield improvement to cope with uncertain climatic conditions in the future. Crop models are widely used to project these impacts – beyond the observed range of yield and weather variability – of climate change on future yields (Ewert et al., 2015; Folberth et al., 2012; Rosenzweig et al., 2014). However, when employing crop models some limitations needs to be considered. For instance, limited data availability may restrict model fitting, such as a lack of information on growing season dates, land use allocation, intercropping or information on fertiliser applications (Müller et al., 2016). Also, the quality of soil data contributes to uncertain yield assessments (Folberth et al., 2016). Fragmented and imprecise weather data from regions with few weather stations further increase uncertainty (Van Wart et al., 2013). Finally, specific to this case study, the rather short time series of only eleven years of crop data makes it difficult to estimate climatic impacts on crop yields. In order to address such limitations, we carefully evaluated the data used to minimise uncertainty as far as possible: As regards weather, we used the data judged most reliable in this region (based on re-analysis models and satellite observations) where few measurement stations on the ground are available. Regarding the yield database, we applied pre-processing filters to ensure that only zones without any obviously unorthodox time series were studied (e.g. zones with constant yield time series were removed). Flaws in the model formulation may also exist, which would lead to a sub-optimal simulation of yield responses. Yet, we applied two established crop models with different approaches which showed good fit and prediction skill, producing consistent results.

Quality and availability of data are major constraints for crop modelling. We carefully evaluated the data to be used and triangulated data sources where possible in order to minimise uncertainty.

Some challenges also need to be considered with regard to crop suitability models. First, long-term crop production trends are considered without potential non-linear effects of extreme years, the models are unable to adequately capture variability. Second, a positive change in suitability does not necessarily translate into good production levels, as the change may still be below the threshold required to meet a certain production target. Third, the limitation with regard to data quality and availability also holds for suitability models. The suitability models depend on the ISIMIP data used for projection, which can introduce further uncertainties due to the rather large spatial resolution of ~50 km. Modelled weather data with its shortcomings adds another source of potential uncertainty. Furthermore, the suitability models are driven by climate data, which in itself have its uncertainties (see section 11.1). Lastly, the suitability models rely on pseudo-absences because there can be no “true” absence for crops, as they are introduced and produced by people. Thus said, a model with both presence and absence data as for naturally occurring species has a better fit than that using presence-only data, as for crops.

11.4 Spatial vulnerability assessment

Although our study provides a comprehensive assessment of vulnerability for Ethiopia at zone level, it also shares the general caveats of an indicator-based assessment. Indicator selection and indicator weighing have been highlighted as the two main methodological challenges when using indicator-based assessments (Preston, Yuen, & Westaway, 2011; Wiréhn, Opach, & Neset, 2016). In the present study, we aimed at overcoming these challenges by making use of long-term remote sensing data. Further, we used equal weights for all the indicators, thereby removing any subjective biases. In order to weigh the indicators, expert and stakeholders' opinion could be used to assign weights through usage of multi-criteria weigh methods, such as Analytical Hierarchical Process (AHP). Finally, we also acknowledge that the present study is based on a one-time outcome based approach and does not capture the dynamic nature of vulnerability.

For indicator-based approaches, the main challenges are the selection of indicators to be included as well as the weights that are assigned to them.

11.5 Expert-based assessment of adaptation strategies

For future studies, more experts could be interviewed and more geographic regions of Ethiopia could be covered in order to expand the analysis and enhance reliability of the findings.

The expert-based assessment complementing the adaptation evaluation suffers from a number of limitations: First, only a subset of experts was consulted or actually participated in the assessment exercise, as naturally not all people with expertise on adaptation in Ethiopian agriculture could be involved in this study. Some information or perspectives may thus be lacking, although there was high agreement across responses and the different expert groups (i.e. researcher or practitioner). Second, further consultations and expert elicitation in Ethiopia's key agricultural regions could prove useful, given the large differences between regions. Third, the expert elicitation itself was challenging, as questions had to be sufficiently open to include all relevant aspects, but thus remained at a more general level. Evaluation of specific measures from the onset could have led to more targeted and practical information from experts, however, such an approach was difficult to pursue considering regional differences and the macro-level departure of this study. Fourth, the assessment categories with "low", "medium" and "high" for many questions did not allow for nuanced responses, although more detailed responses were captured during the qualitative interviews conducted. For future research, it would be useful to also engage with local communities, for instance via focus groups or household surveys to gather experiences and assessments from the ultimate beneficiaries of the interventions planned, smallholder farmers. This was done to some extent, but could be improved considerably.

11.6 Economic analysis and cost-benefit analysis

Uncertainty is a very important challenge in the assessment of adaptation to climate change impacts. The explicit consideration of uncertainty of climate change in adaptation assessments is unavoidable (see, e.g., World Bank, 2010; Dittrich et al., 2016) and there are many reasons for uncertainty in economic assessments of climate change adaptation. Limitations notably refer to the assumptions taken and limited data availability as well as uncertainty already inherent in input data from biophysical impact models. We consulted the literature to fill data gaps, which, however, does not produce results to full satisfaction. Uncertainties were not accounted for – for example of climate change impacts, adaptive effects and unit costs of adaptation strategies – to the fullest range. Further, the analysis does not consider inter-annual variability as projected to increase under climate change, but is restricted to the effects produced by mean climatic changes. A particular uncertainty

We tried to reduce uncertainties for the economic analysis as far as possible, but input data and assumptions influence the results and can lead to biases.

relates to the timing of climate change. Even if an outcome of climate change might be projectable in greater detail, the question is when a risk will occur. A current risk might be different from future risks and this implies, at least, uncertainty about the probability and extent of that risk. Because of the uncertainty with respect to both the magnitude and the timing of impacts of climate change, the question 'What are the expected losses?' is often not easy to answer. Many assessment studies thus try to avoid the inclusion of too many impacts and use a narrow scope of climate change impacts instead. Another aspect of uncertainty regards the development of socio-economic indicators in the long run. Against this background, it must be stated that most assessment studies try to avoid the inclusion of such developments, as was also done in our analysis. Finally, uncertainty may also exist regarding adaptive capacities of a region and respectively the people acting in a specific region. While uncertainty might be low with respect to available resources for adaptation in the short run, uncertainties might be high concerning (long-term) resources to adapt. In addition, there might be incomplete knowledge about the extent, frequency and, hence, speed with which knowledge to adapt can be transferred. Taking all those limitations into account, the results from the economic analyses shall be interpreted only as indicative, although every effort was made to address limitations and to enhance validity of the findings.

Taken altogether, the range of uncertainties and limitations discussed in this chapter calls for cautious interpretations of the results in this study and explains the context in which the specific results should be seen. Limited availability and quality of data was the main constraint for the analysis conducted in this study, which is a common challenge for research. Yet, the methods applied reflect the current state of research and the data that were used are the best available. We are thus confident that our analysis reflects the overall trends in future climate impacts on Ethiopian agriculture well and provides a sound base for decision-making.

Despite some challenges regarding quality and availability of data, we applied state-of-the-art research methods, making sure to use the best data available. Hence, we are confident about the overall quality of the results presented in this study.

A macro-level approach was taken in this study, with the key aim to address decision-makers for adaptation policy and programming at national, regional and zonal level and to provide supporting scientific analyses. Beyond that, the results of this study can also be useful for agricultural extension officers and farmer advisory services, which can sensitise farmers on expected climatic risks to their farming systems and possible adaptation strategies. The study approach as such is scalable and replicable, it could thus be used also at more local scales for more fine-grained analysis and spatially explicit results on local climate risk and performance of adaptation strategies.

Conclusion

The climate risk analysis for Ethiopia's agricultural sector provides a mixed account of Ethiopia's future exposure and vulnerability to climate change. A spatial vulnerability assessment evaluating indicators of exposure, sensitivity and adaptive capacity to climate change revealed that Somali, Dire Dawa and Tigray region are the most vulnerable across the ten Ethiopian regions. In terms of future changes in climatic conditions, while mean annual temperature is projected to increase by between 1.8°C and 4.6°C by 2090, depending on the emissions scenario and compared to pre-industrial levels, mean annual precipitation may increase in the future under the high emissions scenario and shows no clear trend under the low emissions scenario. Yet, extreme weather events like very hot days, tropical nights and heavy precipitation events are projected to increase. Not all regions in Ethiopia will be equally affected by climate change: The lowlands will experience much greater temperature increases and more frequent heat extremes. With regard to precipitation, the picture is less clear: While mean annual precipitation trends vary according to scenario, region and time period, precipitation extremes are especially projected to increase for the Oromia and SNNP regions. We also analysed future water availability under climate change in the Blue Nile and Awash River basins. Here, the model projections show an increase in river discharge for the Blue Nile under all scenarios and in all future periods, while the Awash River will see a considerable increase in discharge only under RCP8.5 and by the end of the century. Generally, an increase of the river discharge in the Blue Nile basin means a higher water availability for agriculture in the future under both RCPs.

As regards climate change impacts on crop production in Ethiopia, our analyses found climate to substantially impact on crop production. On national average, climate explains 55-89% of the year-to-year variability in crop yields. An analysis of future maize yield changes projects an increase of 5% under RCP2.6 and 1% under RCP8.5 in Ethiopia by 2050. However, six zones are projected to experience maize yield losses under climate change: Western Tigray, South Omo, North Shewa (Amhara), Metekel, Guraghe and Gamo-Gofa. We also evaluated how the suitability of areas in Ethiopia to grow certain crops may change under future climate change. The findings indicate that climate change will alter the suitability patterns for wheat, teff, maize and sorghum. At the national level, net suitability losses are projected for maize, teff and wheat, whereas for sorghum a net increase is expected. Such expected yield changes and suitability losses will also translate into economic impacts on the agricultural sector: Regarding maize yield changes, the economic impacts will be higher in zones in the Oromia and SNNP regions, compared to zones in Tigray and Amhara.

Overall, Ethiopia's agricultural sector may benefit from increasing yields under climate change, while the areas where staple crops can be grown may shrink. Climate change impacts for agriculture are thus ambiguous in Ethiopia and need to be carefully considered for agricultural policy and planning. Uncertainty from precipitation projections is high and other results would substantially influence the agricultural outlook. Yet, CO_2 fertilisation effects and technological improvements over time are not considered in this analysis, leading to optimism regarding future yield increases even when considering uncertainty in precipitation projections.

Based on these projected climate change impacts, we analysed five adaptation strategies: irrigation, improved crop management, agroforestry, fodder and feed improvement, and crop insurance. The assessment was conducted within a multi-criteria framework, combining assessment indicators from a biophysical model, economic analysis and soft assessment indicators. The results can be seen in the table below.

Overall adaptation assessment

Table 22: Multi-criteria assessment of the five selected adaptation strategies.

Adaptation strategy	Irrigation	Switching crops	Agroforestry	Fodder and feed improvement	Insurance
Risk response	Risk mitigation	Risk mitigation	Risk mitigation	Risk mitigation	Risk transfer
Risk mitigation potential	High	High	High[20]	High	No risk mitigation
Cost effectiveness	Medium	Medium	High	High	Risk transfer
Risk gradient	Risk-independent	Risk-specific	Risk-specific	Risk-independent	(Weather) risk specific
Upscaling potential	High	Medium	Medium-high	High	Medium
Development co-benefits	High	Medium	High	High	Medium
Potential maladaptive outcomes	High	Medium	Low	Medium	Medium
Stakeholder interest	High	High	High	High	Low
Institutional support requirements	Medium	Medium	Medium	Medium	High

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

Generally, the assessment confirms that there is no single adaptation strategy, which is best suited across Ethiopia, but rather many useful adaptation strategies exist. In most cases, a combination of multiple adaptation strategies can be recommended to tackle different challenges and risks introduced by climate change and to seize synergies between strategies for enhancing overall resilience of agricultural livelihoods. Examples explored in this study include an assessment of irrigated Napier grass as well as the combination of shifting planting dates and enhancing soil organic carbon. Overall, especially agroforestry interventions, but also improved fodder and feed appear to have high potential for agricultural adaptation in Ethiopia. Irrigation, improved crop management and crop insurance are also important for a diversified adaptation portfolio. Insurances can play a particularly important role with respect to transferring the risk to other sectors. For all adaptation strategies, the concrete design is key, as this determines the strategies' ultimate effectiveness and positive co-benefits.

[20] The risk mitigation potential is high up until a threshold of shade and only in specific environments, where yields are projected to decline under climate change. Careful targeting of agroforestry interventions is thus crucial.

Policy recommendations

Based on the analyses conducted within this climate risk study and stakeholder as well as expert input, the following recommendations regarding adaptation in Ethiopia's agricultural sector can be given.

Irrigation

Stakeholder consultations, interviews, the expert survey conducted and document analysis made clear that irrigation is a top adaptation priority in Ethiopia. Irrigation can help smallholder farmers to compensate for the negative impacts of erratic and insufficient precipitation and significantly stabilise agricultural production. It has high potential to reduce climate risks to crop production and increase resilience. Currently, irrigation is not wide-spread in Ethiopia (estimates range between 2-3% of agricultural land and 5% of irrigable land), with considerable potential to upscale its usage. Water does not appear a limiting factor to irrigation in Ethiopia, as ample water resources exist and more available water is projected for the future, although this does not hold for all areas in Ethiopia. Further, irrigation requires a significant investment and only becomes profitable after some years, depending on the type of irrigation system and the farm location. Institutional support is usually required and care has to be taken to avoid potential maladaptive outcomes from irrigation. Specific recommendations regarding irrigation in Ethiopia are:

- Low-cost irrigation options with low maintenance requirements can be promoted across Ethiopia, where water resources are available.
- Ideally, the implementation of solar-powered drip irrigation systems could be promoted, as they offer important benefits with regard to energy needs and sustainability over conventional irrigation systems. However, their establishment and maintenance costs should be weighed against the expected benefits.
- Since irrigation may not be profitable in the first years, institutional support is needed to help farmers bridge the transition period. This could for instance mean subsidising water pumps, tax-free imports of pumps or offering loans for buying pumps.
- For upscaling irrigation, all user interests in water and energy should be considered and dispute settlement mechanisms be implemented, also to address potential conflicts between upstream and downstream users.

Improved crop management: crop switching

Improved crop management, such as switching crops, applying fertiliser and shifting the planting dates, has high potential for increasing yields, where climate change alters seasonal weather patterns. Increasing soil organic carbon in Ethiopia by 20% for instance has positive effects on crop suitability for all crops, especially for maize and wheat. Enhancing organic carbon produces the greatest suitability increases under RCP8.5 for maize, teff and sorghum. However, shifting the growing season forward by four weeks will result in detrimental effects on suitability of the four crops and can thus not be recommended as an adaptation strategy. Depending on the type of strategy employed, cost effectiveness is medium to high. Some investments, such as shifting cropping patterns according to projected future suitability, only become profitable after a considerable time period, e.g. shifting from maize to sorghum production. The following recommendations can thus be given:

- Careful consideration of projected climate change impacts and changes in climatic conditions and seasons is needed before deciding on crop switching or shifts in planting dates.
- Where climate projections suggest a shift in planting patterns and dates, the correct timing should be chosen: Many such interventions can be recommended rather in the medium term from 2030 onwards, where climate impacts manifest further, for instance changes in crop suitability patterns.
- Capacity building should be made a priority to enable local stakeholders to conduct the analyses needed themselves. This includes strengthening institutions, such as the Ethiopian Meteorological Agency to produce timely, location-specific and reliable weather forecast information for the major growing periods. The agricultural extension service system could

work together with farmers to make good use of the weather forecast information to identify optimum planting dates.

- Where farmers are reluctant to cultivate more resilient crops, such as sorghum, trainings and campaigns to show the benefits of sorghum adoption may be useful.
- When shifting and especially shortening growing seasons, farmers may require support in bridging periods of low food availability.
- Organic fertiliser application can be recommended across Ethiopia, albeit context-dependent. Sufficient levels of fertiliser application should be reached, for which fertiliser needs to be made more affordable and available at a given time.

Agroforestry

Agroforestry systems can achieve both climate change adaptation and mitigation objectives, making it a key adaptation strategy in the agricultural sector. In addition, they offer many important co-benefits for biodiversity, income diversification and healthy soils. In Ethiopia, agroforestry has the potential to stabilise maize yields in zones which are projected to experience yield losses under climate change. 10% or 20% shade levels can reduce the losses projected, but would negatively affect yields in zones which are projected to benefit from climate change. Those results are rather conservative, as they do not take into account the potential yield increases and other benefits of enhanced soil organic carbon due to agroforestry strategies, for instance. The economic analysis showed that adapting maize production with agroforestry is very beneficial in comparison to the inaction scenario. Over time, it has a highly positive return on investment. The following recommendations can thus be given:

- Implementing agroforestry systems can be recommended across Ethiopia, in zones where negative crop yields are projected (e.g. Gamo-Gofa, Western Tigray, Metekel and Guraghe).
- Where future yield increases are projected, careful evaluation of agroforestry co-benefits is needed to decide on its implementation.
- Numerous co-benefits and conservative modelling suggest that introducing some carefully designed agroforestry system with species suitable for the local context may be beneficial across Ethiopia, even where crop yield increases are projected.
- The type of tree species and intercropping should be decided based on local suitability, preferences and opportunities for dual benefits, e.g. when cultivating high-value trees, such as mango or coffee, or fodder trees for improved livestock production.
- Restoring of degraded land and preservation of existing forests should also be considered.
- A concrete policy intervention could be the provision of tree seedlings to farmers of carefully selected tree and fruit species according to the local environment.
- Further, trainings on establishment and management of agroforestry systems could be provided to farmers.

Improved fodder and feed

To improve fodder and feed, a number of adaptation strategies have proven successful in Ethiopia, e.g. improved and high-yielding forage varieties, intercropping grasses and cereals with legumes, cultivation of irrigated fodder banks, natural pasture improvement through removing of invasive weeds, temporal zero-grazing and cut-and-carry feeding regimes on degraded pastures to restore and increase carrying capacity. Such strategies can boost livestock production, resilience and farmer income. A cost-benefit analysis of irrigated Napier grass as a particularly promising adaptation strategy showed that it is highly cost-effective. Importantly, the farmer's investment in Napier grass will pay off after three years already, when the break-even point between net costs and net benefits is reached.

- Allocating space for growing fodder can be recommended across Ethiopia, where farmers wish to improve their livestock production and to increase their nutritional intake.
- Yet, such decisions need to be balanced carefully with other potential usages of the land, also with regard to agricultural activities that are less GHG emissions intensive.
- Among the many options available, irrigated Napier grass is a very interesting strategy showing high economic returns for farmers.
- Growing fodder and feed can also be a business model: Targeted production of high quality feed resources can benefit livestock production in the whole of Ethiopia.

Crop insurance

Crop insurance is considered an important adaptation strategy because it can address residual risk, which cannot be mitigated in an economically sensible way with physical adaptation strategies and acts as a safety net for farmers in times of extreme weather events. However, if poorly designed, crop insurance schemes can produce maladaptive outcomes. Index insurance schemes for crops and livestock have been developed and tested in several pilot schemes in Ethiopia, but are not widely implemented yet. The following recommendations can thus be given:

- Since more frequent extreme weather events are projected for the future in Ethiopia, upscaling of crop insurance coverage as an important risk-transfer strategy can be recommended across Ethiopia.
- As many smallholder farmers may not be able to afford high premiums, technological and societal solutions for low-cost insurance need to be found.
- Government or donor subsidies can lower the cost of insurance for smallholder farmers.
- Index-based insurance designs can substantially lower costs for crop insurance; here, the decision tree approach presented in Chapter 10 can provide a starting point for future insurance designs.
- To increase acceptance and uptake of insurance among farmers, insurance products can be bundled with other inputs, such as improved seeds or fertiliser. In addition, awareness campaigns and trainings on the usefulness of insurance could be conducted by extension officers.
- Alternative premium payment arrangements, for instance with non-monetary premiums, could be an option to increase uptake and acceptance of insurance by smallholder farmers in Ethiopia. For instance, premiums paid in the form of labour services to communal land restoration activities can act as effective form of premium payment, which has been successfully piloted in Ethiopia.

General recommendations

In addition to recommendations for the specific five adaptation strategies, some general recommendations regarding adaptation in Ethiopia can be given:

- Planning for adaptation should be **regionally specific**, as different areas in Ethiopia will be impacted by climate change differently.
- The response of crops to adaptation strategies also differs according to crop and region, which requires **crop-specific adaptation response**.
- **Improved soil and water management** should be mainstreamed in all adaptation activities and be considered wherever possible.
- Regardless of the specific climate risk addressed, **combinations of adaptation strategies** are often more effective than single approaches.
- Rich and diverse **indigenous and traditional knowledge** exists on adaptation in Ethiopia's regions, which should be seized for successful adaptation. However, more research into this is needed as well as re-activation of formerly practiced indigenous adaptation strategies, which have partly lost traction in the past decades.
- **Smart adaptation incentives** are key to induce uptake of suitable adaptation strategies. Such incentive structures are for instance built around land tenure systems, credit accessibility and market access.
- Farmers need support in **bridging the financing gap** between investment and the break-even point, where the adaptation strategy becomes profitable. This is usually only after a couple of years, transitional financial support is thus needed.
- **Trainings and extension services** should be provided to farmers to support them in setting up and maintaining the adaptation strategies.
- **The right timing of input provision and capacity building** is key, as otherwise, farmers may be unable to store the inputs adequately or to retain knowledge and use it when needed. Late training provision can also negatively affect adaptation strategies, where farmers may not be able to fully implement what they have learned. Oftentimes, repeated trainings may be needed to ensure that information provided turns into long-term knowledge.

- **Marketability of adaptation technologies and products** is important. Value chains and access to markets should be considered in adaptation strategies for smallholder farmers to enable them to commercialise their agricultural activities.
- In terms of **sustainable co-benefits**, adaptation strategies should especially be designed to ensure gender equality, climate change mitigation and to protect soils, as prioritised by stakeholders interviewed for this study.
- **Adaptation design should be inclusive**, when interventions from outside actors are planned communities should be engaged at all planning stages, for instance through community conversation sessions.

Policy context

The study was designed in alignment with important policy documents and processes in Ethiopia, in particular the CRGE Climate Resilience Strategy for Agriculture and Forestry as well as Ethiopia's National Adaptation Plan (NAP). Results from this climate risk analysis can thus feed into further development and implementation of both the CRGE and the NAP, as also confirmed by stakeholders during the validation workshop in Addis Ababa. Workshop participants identified EFCCC and the Ethiopian Ministry of Finance as the most important governmental partners for adopting and implementing the study and its findings. Local pilot projects based on the study were recommended by participants of the validation workshop to test and implement the study findings.

Bibliography

Abate, G. T., Bernard, T., de Brauw, A., & Minot, N. (2018). The impact of the use of new technologies on farmers' wheat yield in Ethiopia: evidence from a randomized control trial. *Agricultural Economics (United Kingdom)*, *49*(4), 409–421. https://doi.org/10.1111/agec.12425

Abate, G. T., Rashid, S., Borzaga, C., & Getnet, K. (2016). Rural Finance and Agricultural Technology Adoption in Ethiopia: Does the Institutional Design of Lending Organizations Matter? *World Development*. https://doi.org/10.1016/j.worlddev.2016.03.003

Abate, T., Shiferaw, B., Menkir, A., Wegary, D., Kebede, Y., Tesfaye, K., … Keno, T. (2015). Factors that transformed maize productivity in Ethiopia. *Food Security*. https://doi.org/10.1007/s12571-015-0488-z.

Abebe, Y., & Bekele A. (2017). Vulnerability of smallholder farmers to climate change in the central rift valley of Ethiopia: a gender disaggregated approach. *Ethiopian Journal of Agricultural Sciences, 27(2).*

Adams, R. M., Hurd, B. H., Lenhart, S., and Leary, N. (1998). Effects of global climate change on agriculture: An interpretative review. *Climate Research*, 11, 19–30.

Adela, F. A., Aurbacher, J., & Abebe, G. K. (2019). Small-scale irrigation scheme governance - poverty nexus : evidence from Ethiopia. *Food Security*. Springer Netherlands. https://doi.org/10.1007/s12571-019-00953-8.

Adger, W. N. (2006). Vulnerability. *Global Environmental Change*, *16*(3), 268–281.

Adie, A., & Blummel, M. (2019). Irrigated forages improve livestock productivity and livelihoods in Ethiopia. Retrieved June 6, 2019, from https://feeding-innovation.ilri.org/2019/03/14/irrigated-forages-improve-livestock-productivity-and-livelihoods-in-ethiopia/.

African Development Bank (AfDB), (2019). Analysis of Adaptation Components of Africa's Nationally Determined Contributions (NDCs). https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Analysis_of_Adaptation_Components_in_African_NDCs_2019.pdf.

Agena, M.A.; Emana, B.; Haji, J. (2017). Impact of small scale irrigation on farmers' cropping system choice, productivity and food security in Meskan district of southern Ethiopia. Haramaya: Haramaya University.

Ahmed, M. H., Mesfin, H. M., Abady, S., Mesfin, W., & Kebede, A. (2016). Adoption of improved groundnut seed and its impact on rural households' welfare in eastern Ethiopia. *Cogent Economics and Finance*, *4*(1), 1–13.

Ahmed, M. H., Geleta, K. M., Tazeze, A., & Andualem, E. (2017). The impact of improved maize varieties on farm productivity and wellbeing: Evidence from the east hararghe zone of Ethiopia. *Development Studies Research*, *4*(1), 9–21.

Alemu, D., Yirga, C., Bekele, A., Tesfaye, A. (2014). Situation and outlook of maize in Ethiopia. Addis Ababa: Ethiopian Institute of Agricultural Research.

Amamo, A. A. (2014). Coffee Production and Marketing in Ethiopia. *European Journal of Business and Management* Www.Iiste.Org ISSN, 6(37), 109–122.

Amare, A., & Simane, B. (2018). Does adaptation to climate change and variability provide household food security? Evidence from Muger sub-basin of the upper Blue-Nile, Ethiopia. *Ecological Processes*, *7*(1).

Amare, D., Wondie, M., Mekuria, W., & Darr, D. (2019). Agroforestry of Smallholder Farmers in Ethiopia: Practices and Benefits. *Small-Scale Forestry*, *18*(1), 39–56.

Amede, T., Mengistu, S., & Roothaert, R. (2005). Intensification of livestock feed production in Ethiopian highlands: Potential and experiences of the African Highlands Initiative. Retrieved from https://cgspace.cgiar.org/handle/10568/76954

Anshiso, A.; Woldeamanuel, T.; Asfaw, Z. (2017). Financial analysis of fruit tree based agro-forestry practice in Hadero Tunto Zuria Woreda, Kembata Tembaro Zone, South Ethiopia. *Research Journal of Finance and Accounting* (8): No.3.

Araya, A., Stroosnijder, L., Habtu, S., Keesstra, S. D., Berhe, M., & Hadgu, K. M. (2012). Risk assessment by sowing date for barley (Hordeum vulgare) in northern Ethiopia. *Agricultural and Forest Meteorology*, 30, 154–155.

Araya, N. S. (2011). Weather Insurance for Farmers: Experience from Ethiopia. Paper presented at the IFAD Conference on New Directions for Smallholder Agriculture 24-25 January, 2011, Rome.

Asfaw, A., Almekinders, C. J. M., Blair, M. W., & Struik, P. C. (2012). Participatory approach in common bean (Phaseolus vulgaris L.) breeding for drought tolerance for southern Ethiopia. *Plant Breeding*, *131*(1), 125–134.

Assefa, G., Mengistu, S., Feyissa, F., & Bediye, S. (2016). Animal feed resources research in Ethiopia: Achievements, challenges and future directions. *Ethiopian Journal of Agricultural Sciences*, (50th Year Special Issue), 139–153.

Awulachew, S. B. (2010). Irrigation potential in Ethiopia Constraints and opportunities for enhancing Irrigation potential in Ethiopia Constraints and opportunities for enhancing the system International Water Management Institute Teklu Erkossa and Regassa E . Namara. *IWMI Research Report*.

Bacha, D., Namara, R., Bogale, A., & Tesfaye, A. (2011). Impact on Small-Scale Irrigation on Household Poverty: Empirical Evidence from the Ambo District in Ethiopia. *Agricultural Water Management*, *56*(1), 161–177.

Bageant, E. R., & Barrett, C. B. (2017). Are There Gender Differences in Demand for Index-Based Livestock Insurance? *Journal of Development Studies*, *53*(6), 932–952.

Beedy, T. L., Snapp, S. S., Akinnifesi, F. K., & Sileshi, G. W. (2010). Impact of Gliricidia sepium intercropping on soil organic matter fractions in a maize-based cropping system. *Agriculture, Ecosystems and Environment*. https://doi.org/10.1016/j.agee.2010.04.008

Bekele-Tesemma, A. (2007). Profitable agroforestry innovations for Eastern Africa: experience from 10 agroclimatic zones of Ethiopia, India, Kenya, Tanzania and Uganda. Nairobi: Agroforestry Centre.

Berhe, K.; Dessalegn, Y.; Baredo, Y.; Teka, W.; Hoekstra, D.; Tegegne, A. (2009). Smallholder-based fruit seedling supply system for sustainable fruit production in Ethiopia: lessons from the IPMS experience. Addis Ababa: ILRI.

Beshir, H. (2014). Factors affecting the adoption and intensity of use of improved forages in North East Highlands of Ethiopia. *American Journal of Experimental Agriculture*, *4*(1), 12–27.

Bezu, T.; Woldetsadik, K; Tana, T. (2014). Production scenarios of mango (Mangifera indica L.) in Harari Regional State, Eastern Ethiopia. *Science, Technology and Arts Research Journal,* (4), 59–63.

Bingxin, Y., Alejandro, N.-P., Jose, F., & Sinafikesh, A. G. (2011). Cereal Production and Technology adoption in Ethiopia. *Journal of Development and Agricultural Economics*. https://doi.org/10.5897/JDAE2013.0508.

Binyam, A. Y., & Desale, K. A. (2015). Rainwater harvesting: An option for dry land agriculture in arid and semi-arid Ethiopia. *International Journal of Water Resources and Environmental Engineering*, 7(2), 17–28.

Birhan, M., & Adugna, T. (2014). Livestock feed resources assessment, constraints and improvement strategies in Ethiopia. *Middle-East Journal For Scientific Research*, *21*(4), 616–622.

Birhanu, M. Y., Girma, A., & Puskur, R. (2017a). Determinants of success and intensity of livestock feed technologies use in Ethiopia: Evidence from a positive deviance perspective. *Technological Forecasting and Social Change*, *115*, 15–25.

Birhanu, M. Y., Girma, A., & Puskur, R. (2017b). Determinants of success and intensity of livestock feed technologies use in Ethiopia: Evidence from a positive deviance perspective. *Technological Forecasting and Social Change*, *115*, 15–25.

Bishu, K. G., Lahiff, E., O'Reilly, S., & Gebregziabher, M. (2018). Drivers of farmers' cattle insurance decisions: evidence from smallholders in northern Ethiopia. *Agrekon*, *57*(1), 40–48.

Boansi, D., Crentsil, C., Boansi, D., & Crentsil, C. (2013). Competitiveness and Determinants of Coffee Exports Producer Price and Production for Ethiopia. *Journal of Advanced Research in Economics and International Business*, 1(1), 31–45.

Bogale, A. (2015). Weather-indexed insurance: an elusive or achievable adaptation strategy to climate variability and change for smallholder farmers in Ethiopia. *Climate and Development*, *7*(3), 246–256.

Bogale, S. A., Verhees, F. J. H. M., & Trijp, H. C. M. va. (2018). Customer Evaluation of Supply Systems: The Case of Ethiopian Seed Supply Systems. *Journal of African Business*, *19*(4), 550–570.

Brans, M., Tadesse, M., & Takama, T. (2010). Community-based solutions to the climate crisis in Ethiopia. In R. Fujikura & M. Kawanishi (Eds.), *Climate Change Adaptation and International Development. Making Development Cooperation More Effective.* UK: Earthscan.

Brooks, N., Adger, W. N., & Kelly, P. M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation, *15*, 151–163.

Bruno Soares, M., Gagnon, A. S., & Doherty, R. M. (2012). Conceptual elements of climate change vulnerability assessments: A review. *International Journal of Climate Change Strategies and Management*. https://doi.org/10.1108/17568691211200191

Calton, B., Schellekens, J., & Martinez-De La Torre, A. (2016, July 13). Water Resource Reanalysis v1: Data Access and Model Verification Results. Zenodo.

Chemura, A., Kutywayo, D., Chidoko, P., & Mahoya, C. (2016). Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe. *Regional Environmental Change*, 16(2).

Central Statistical Agency of Ethiopia (CSA). (2012). Welfare Monitoring Survey 2011. Addis Ababa.

Central Statistical Agency of Ethiopia (CSA) (2018): Ethiopia – socioeconomic survey 2015-2016, wave 3. Washington D.C.: The World Bank.

Central Statistical Agency of Ethiopia (CSA) (2016): Ethiopia - socioeconomic survey 2014-2015. Washington D.C.: The World Bank.

Central Statistical Agency of Ethiopia (CSA) (2015): Ethiopia - socioeconomic survey 2013-2014. Washington D.C.: The World Bank.

Central Statistical Agency of Ethiopia (CSA) (2014): Ethiopia - rural socioeconomic survey 2011-2012. Washington D.C.: The World Bank.

CGIAR-CSI. (2017). CGIAR-CSI SRTM 90m DEM Digital Elevation Database.

Chamberlin, J., & Schmidt, E. (2014). Ethiopian Agriculture: A Dynamic Geographic Perspective. *Food and Agriculture in Ethiopia*. https://doi.org/10.9783/9780812208610.21

Chay, K.G.; Workeneh, A.; Shifera, B. (2019). A review on production and marketing of mango fruit. *World Journal of Agriculture and Soil Science*. https://doi.org/10.33552/WJASS.2019.02. 000533.

Chen, J., Brissette, F. P., Chaumont, D., and Braun, M. (2013). Finding appropriate bias correction methods in downscaling precipitation for hydrologic impact studies over North America, *Water Resour. Res.*, 49, 4187– 4205.

Ciurean, R. L., & Schröter, D. (2013). Conceptual Frameworks of Vulnerability Assessments for Natural Disasters Reduction, 3–32. https://doi.org/10.5772/55538.

Cochrane, L. and O'Regan, D. (2016): Legal harvest and illegal trade: trends, challenges and options in khat production in Ethiopia. *International Journal of Drug Policy*, 30, 27–34.

Conway, D., & Schipper, E. L. F. (2011). Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2010.07.013.

Davis, A. P., Gole, T. W., Baena, S., & Moat, J. (2012). The Impact of Climate Change on Indigenous Arabica Coffee (Coffea arabica): Predicting Future Trends and Identifying Priorities. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0047981.

Dawson, I., Carsan, S., Franzel, S., Kindt, R., van Breugel, P., Graudal, L., … Ramni, J. (2014). *Agroforestry, livestock, fodder production and climate change adaptation and mitigation in East Africa: issues and options*. *ICRAF Working Paper No. 178*. Nairobi, Kenya. https://doi.org/http://dx.doi.org/10.5716/WP14050.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*. https://doi.org/10.1002/qj.828.

Degefu, D. M., He, W., & Zhao, J. H. (2015). Hydropower for sustainable water and energy development in Ethiopia. *Sustainable Water Resources Management*, *1*(4), 305–314.

Dercon, S. (2004). Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics*, 74, 309–329.

Dercon, S., Hill, R. V., Clarke, D., Outes-Leon, I., & Seyoum Taffesse, A. (2014). Offering rainfall insurance to informal insurance groups: Evidence from a field experiment in Ethiopia. *Journal of Development Economics*, *106*, 132–143.

Deressa, T., Hassan, R., & Ringler, C. (2015). The Case Of Farmers In The Nile Basin Of Ethiopia, AGRIS FAO, Retrieved from: http://agris.fao.org/agris-search/search.do?recordID=QB2015105716.

Dessie, G. (2013). Favouring a Demonised Plant: Khat and Ethiopian smallholder-enterprises. https://www.researchgate.net/publication/261436272_Favouring_a_Demonised_Plant_Khat_and_Ethiopian_smallholder-enterprises (Last access: July 12th, 2019)

Dessie, G. (2015). Land and Water for Drugs, Cash for Food: Khat Production and Food Security in Ethiopia. In: A History of Water, Edition: Vol. 3: Water and Food, Chapter 20, 482–501.

Dilla, A., Smethurst, P. J., Barry, K., Parsons, D., & Denboba, M. (2018). Potential of the APSIM model to simulate impacts of shading on maize productivity. *Agroforestry Systems*. https://doi.org/10.1007/s10457-017-0119-0.

Dilling, L., Prakash, A., Zommers, Z., Ahmad, F., Singh, N., de Wit, S., … Bowman, K. (2019). Is adaptation success a flawed concept? *Nature Climate Change*. https://doi.org/10.1038/s41558-019-0539-0.

Dinku, T., Connor, S.J., Ceccato, P. & Ropelewski C.F. (2008). Comparison of global gridded precipitation products over a mountainous region of Africa. *International Journal of Climatology*, 28, 1627–1638.

Dittrich, Ruth, Anita Wreford, and Dominic Moran (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics,* 122, 79–89.

Duguma, L. A. (2013). Financial analysis of agroforestry land uses and its implications for smallholder farmers livelihood improvement in Ethiopia. *Agroforestry Systems*, *87*(1), 217–231.

Eakin, H., & Luers, A. L. (2006). Assessing the Vulnerability of Social-Environmental Systems. *Annual Review of Environment and Resources*, *31*(1), 365–394.

Eakin, H. C., & Patt, A. (2011). Are adaptation studies effective, and what can enhance their practical impact? *Wiley Interdisciplinary Reviews: Climate Change*, *2*(2), 141–153.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J. (2012). HESS Opinions “Should we apply bias correction to global and regional climate model data?”, *Hydrol. Earth Syst. Sci.*, 16, 3391-3404.

Elias, A., Nohmi, M., Yasunobu, K. (2017). Cost-benefit analysis of cultivating three major crops and its implication to agricultural extension services: a case study in North-West Ethiopia. *Japanese Journal of Agricultural Economics* (19): 31–36.

Embaye, W.; Hendricks, N.; Lilja, N. (2017). Sorghum research and poverty reduction in the presence of trade distortions in Ethiopia. *African Journal of Agricultural and Resource Economics* (12): 174–187.

Endris, Hussen Seid & Lennard, Chris & Hewitson, Bruce & Dosio, Alessandro & Nikulin, Grigory & Panitz, Hans-Jürgen. (2015). Teleconnection responses in multi-GCM driven CORDEX RCMs over Eastern Africa. *Climate Dynamics*. https://doi.org/10.1007/s00382-015-2734-7.

Eshetu, S., Belete, B., Goshu, D., Kassa, B., Tamiru, D., Worku, E., … Abebe, Z. (2010). Income diversification through improved irrigation in Ethiopia : impacts, constraints and prospects for poverty reduction. Technical Report, Retrieved from https://www.researchgate.net/publication/274256433_Income_diversification_through_improved_irrigation_in_Ethiopia_impacts_constraints_and_prospects_for_poverty_reduction_Evidence_from_East_Hararghe_Zone_Oromia_Region_Ethiopia

Evangelista, P., Young, N., & Burnett, J. (2013). How will climate change spatially affect agriculture production in Ethiopia? Case studies of important cereal crops. *Climatic Change*, *119*(3–4), 855–873.

Ewert, F., Rötter, R. P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K. C., … Asseng, S. (2015). Crop modelling for integrated assessment of risk to food production from climate change. *Environmental Modelling & Software*, *72*, 287–303.

FAO (2009). The State of Food and Agriculture. Rome.

FAO/IIASA/ISRIC/ISSCAS/JRC. (2012). Harmonized World Soil Database.

FAO (UN Food and Agriculture Organization), (2005). Irrigation in Africa in figures – AQUASTAT Survey 2005, 1–14.

FAO, (2011). Ecocrop database.

FAO, (2015a). Ethiopia Irrigation Market Brief. Rome, FAO.

FAO, (2015b): Analysis of price incentives for red sorghum in Ethiopia for the time period 2005-2012. Rome: FAO.

FAO, (2015c). Ethiopia Soil Campaign underway. Retrieved from http://www.fao.org/soils-2015/news/news-detail/en/c/344319/.

FAO, (2016). AQUASTAT – FAO’s Information System on Water and Agriculture, 4–8.

FAO, (2017). Africa Sustainable Livestock 2050: Ethiopia Country Brief.

FAO, (2018). Ethiopia: small family farms country factsheet, 1–2. Retrieved from www.fao.org/family-farming/data-sources/dataportrait/farm-size/en.

FAO: Global Information and Early Warning System (GIEWS), (2019a): Country briefs – Ethiopia. Rome: FAO.

FAO, (2019b): FAOSTAT. Rome: FAO.

FDRE, (2016). Ethiopia's climate resilient green economy - Climate resilience strategy agriculture and forestry.

FDRE, (2019). Ethiopia's National Adaptation Plan.

Fisher, M., Abate, T., Lunduka, R. W., Asnake, W., Alemayehu, Y., & Madulu, R. B. (2015). Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change*, *133*(2), 283–299.

Folberth, C., Gaiser, T., Abbaspour, K. C., Schulin, R., & Yang, H. (2012). Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields. *Agriculture, Ecosystems & Environment*, *151*, 21–33.

Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L. B., Obersteiner, M., & van der Velde, M. (2016). Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. *Nature Communications*, *7*(May), 11872. https://doi.org/10.1038/ncomms11872.

Frazier, T. G., Thompson, C. M., & Dezzani, R. J. (2014). A framework for the development of the SERV model: A Spatially Explicit Resilience-Vulnerability model. *Applied Geography*, *51*, 158–172.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., … Yamagata, Y. (2017). Assessing the impacts of 1.5°C global warming - Simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geoscientific Model Development*. https://doi.org/10.5194/gmd-10-4321-2017.

Füssel, H.-M., & Klein, R. J. T. (2006). Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. *Climatic Change*, *75*(3), 301–329.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., … Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, *2*, 150066.

Gallopín, G. C. (2006). Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, *16*(3), 293–303.

Garbero, A.; Songsermsawas, T. (2018). Impact of modern irrigation on household production and welfare outcomes: evidence from the participatory small-scale irrigation development programme (PASIDP) project in Ethiopia. IFAD Research Series 31. Rome: IFAD.

Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2019). Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. *International Journal of Climatology*, *39*(1), 18–30.

Gebreegziabher, G.; Villholth, K.; Hanjra, M.A.; Yirga, M. (2013). Cost-benefit analysis and ideas for cost sharing of groundwater irrigation: Evidence from north-east Ethiopia. *Water International* (38): 852–863.

Gebrekidan, T., Guo, Y., Bi, S., Wang, J., Zhang, C., Wang, J., & Lyu, K. (2019). Effect of index-based livestock insurance on herd offtake: Evidence from the Borena zone of southern Ethiopia. *Climate Risk Management*, *23*, 67–77.

Gebremariam, S., Amare, S., Baker, D., and Solomon, A. (2010). Diagnostic Study of Live Cattle and Beef Production and Marketing: Constraints and Opportunities for Enhancing the System. International Livestock Research Institute.

Gebremedhin, B., Ahmed, M., & Ehui, S. (2003). Determinants of adoption of improved forage technologies in crop-livestock mixed systems: Evidence from the highlands of Ethiopia. Retrieved from https://cgspace.cgiar.org/handle/10568/27820.

Gebreyes, M., & Theodory, T. (2018). Understanding social vulnerability to climate change using a 'riskscapes' lens: case studies from Ethiopia and Tanzania. *Erdkunde*, *72*(2), 135–150.

Gleixner, S., Keenlyside, N.,Viste, E. & Korecha, D. (2017). The El Niño effect on Ethiopian summer rainfall, *Climate Dynamics*, 49: 1865

Gornott, C., & Wechsung, F. (2016). Statistical regression models for assessing climate impacts on crop yields: A validation study for winter wheat and silage maize in Germany. *Agricultural and Forest Meteorology*, *217*, 89–100.

GRDC, 56068 Koblenz, G. (2017). The Global Runoff Data Centre.

Greatrex, H., Hansen, J., Garvin, S., Diro, R., & Guen, M. Le. (2015). *Scaling up index insurance for smallholder farmers: Recent evidence and insights*. *CCAFS Report Nr. 14*. Copenhagen. Retrieved from https://cgspace.cgiar.org/handle/10568/53101.

Griffiths, J.F. (1972). Ethiopian Highlands. In *World survey of climatology*. Amsterdam: Elsevier Publishing Company.

Hagos, F., Mulugeta, A., Erkossa, T., Langan, S., Lefore, N., & Abebe, Y. (2017). Poverty Profiles and Nutritional Outcomes of Using Spate Irrigation in Ethiopia. *Irrigation and Drainage*, *66*(4), 577–588.

Haile, G. G., & Kasa, A. K. (2015). *Review Paper Irrigation in Ethiopia : A review. Academia Journal of Agricultural Research 3(10),* 264-269.

Haileselassie, H., Araya, A., Habtu, S., Meles, K. G., Gebru, G., Kisekka, I., … Foster, A. J. (2016). Exploring optimal farm resources management strategy for Quncho-teff (Eragrostis tef (Zucc.) Trotter) using AquaCrop model. *Agricultural Water Management*. https://doi.org/10.1016/j.agwat.2016.09.002.

Hazell, P. B. R., & Hess, U. (2010). Drought insurance for agricultural development and food security in dryland areas. *Food Security*, *2*(4), 395–405.

Heuzé, V., Tran, G., Reverdin-Giger, S. and Lebas, F. (2016): Elephant grass (Pennisetum purpureum). Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. https://www.feedipedia.org/node/395 (Last access: July 12th, 2019)

Hill, R. V., Hoddinott, J., & Kumar, N. (2013). Adoption of weather-index insurance: learning from willingness to pay among a panel of households in rural Ethiopia. *Agricultural Economics*, *44*(4–5), 385–398.

Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., … Keating, B. A. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, *62*, 327–350.

Honja, T.; Geta, E.; Mitiku, A. (2016). Mango value chain analysis: the case of Boloso Bombe Woreda, Wolaita Zone, Southern Ethiopia. *Developing Country Studies* (6)1.

Husmann, C. (2016). Marginality as a Root Cause of Poverty: Identifying Marginality Hotspots in Ethiopia. *World Development*, *78*, 420–435.

ICRAF, (2019). What is Agroforestry? Website, http://new.worldagroforestry.org/about/agroforestry (Last access: 06.06.2019.

IFDC (2012): Ethiopia fertilizer assessment. Alabama: IFDC.

Iiyama, M., Derero, A., Kelemu, K., Muthuri, C., Kinuthia, R., Ayenkulu, E., … Sinclair, F. L. (2017). Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agroforestry Systems*, *91*(2), 271–293.

ILO (2017). ILOSTAT database: www.ilo.org/ilostat.

ILOSTAT (2019): Statutory nominal gross monthly minimum wage (Local currency). Geneva: ILO.

International Livestock Research Institute (ILRI). (2015). Animal breeding and genetics in the Ethiopia livestock master plan. Ethiopian Livestock Masterplan Brief, No.4. Addis Ababa.

Ionescu, C., Klein, R. J. T., Hinkel, J., Kavi Kumar, K. S., & Klein, R. (2009). Towards a Formal Framework of Vulnerability to Climate Change. *Environmental Modeling & Assessment*, *14*(1), 1–16.

IPCC (2007). Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC, (2014a). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp., https://doi.org/10.1256/004316502320517344.

IPCC (2014b). Glossary. *Climate Change 2013: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1757–1776. https://doi.org/10.1016/S0959-3780(06)00031-8.

Janssen, M. A., Schoon, M. L., Ke, W., & Börner, K. (2006). Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. *Global Environmental Change*, *16*(3), 240–252. https://doi.org/10.1016/j.gloenvcha.2006.04.001.

Japan International Cooperation Agency (JICA). (2019). Index-based Insurance to benefit Smallholder Farmers through JICA Project. Retrieved June 13, 2019, from https://www.jica.go.jp/ethiopia/english/office/topics/190419.html.

Jemal, O.M. (2018). The role of local agroforestry practices for enhancing food and nutrition security of smallholding farming households: The case of Yayu area, south-western Ethiopia. Bonn: Zentrum für Entwicklungsforschung.

Jemal, O.M.; Callo-Concha, D. (2017). Potential of agroforestry for food and nutrition security of small-scale farming households. *ZEF Working Paper 161*. Bonn: Zentrum für Entwicklungsforschung.

Jemal, O., Callo-Concha, D., & van Noordwijk, M. (2018). Local agroforestry practices for food and nutrition security of smallholder farm households in southwestern Ethiopia. *Sustainability (Switzerland)*, *10*(8).

Jonsson, K., Ong, C. K., & Odongo, J. C. W. (1999). Influence of scattered nere and karite trees on microclimate, soil fertility and millet yield in burkina faso. *Experimental Agriculture*. https://doi.org/10.1017/S0014479799001039.

Karaimu, P. (2019). Irrigated forages improve livestock productivity and livelihood in Ethiopia. https://feeding-innovation.ilri.org/2019/03/14/irrigated-forages-improve-livestock-productivity-and-livelihoods-in-ethiopia/ (Last access: July 12th, 2019).

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A., & Nyssen, J. (2018). Agro-ecological implications of forest and agroforestry systems conversion to cereal-based farming systems in the White Nile Basin, Ethiopia. *Agroecology and Sustainable Food Systems*, *42*(2), 149–168.

Kassie, B. T., Asseng, S., Rotter, R. P., Hengsdijk, H., Ruane, A. C., & Van Ittersum, M. K. (2015). Exploring climate change impacts and adaptation options for maize production in the Central Rift Valley of Ethiopia using different climate change scenarios and crop models. *Climatic Change*, *129*(1–2), 145–158.

Kassie, G.W. (2016). Agroforestry and land productivity: Evidence from rural Ethiopia. *Cogent Food and Agriculture*, (2): 1–17.

Krysanova, V., Wechsung, F., Arnold, J., Ragavan, S., & Williams, J. (2000). *SWIM—Soil and Water Integrated Model User Manual. PIK Report No. 69*. Potsdam, Germany.

Kumar and Nair. (2006). Tropical Home Gardens: A Time-Tested Example of Sustainable Agroforestry. Environmental Experts, India Mcneely, 1–9.

Kunhamu, T.K.; Santhoshkumar, A.V. (2012). Mango in agroforestry. Kerala: College of Forestry, Kerala Agricultural University.

Lamesegn, D. (2018). Review on Effects of Climate Change on Livestock. *Online Journal of Animal and Feed Research*, *8*(16).

Lange, S. (2017). ISIMIP2b bias-correction fact sheet, Supplementary figures for IPSL-CM5A-LR, https://cloud.pik-potsdam.de/index.php/s/8l1ZVYJbp7Mkgbv#pdfviewer.

Lange, S. (2018). ISIMIP2b bias-correction fact sheet, https://www.isimip.org/documents/284/ISIMIP2b_biascorrection_factsheet_24May2018.pdf.

Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), *Geoscientific Model Development*, https://doi.org/10.5194/gmd-12-3055-2019.

Lasco, R. D., Delfino, R. J. P., & Espaldon, M. L. O. (2014). Agroforestry systems: Helping smallholders adapt to climate risks while mitigating climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(6), 825–833.

Liersch, S., Tecklenburg, J., Rust, H., Dobler, A., Fischer, M., Kruschke, T., … Hattermann, F. F. (2018). Are we using the right fuel to drive hydrological models? A climate impact study in the Upper Blue Nile. *Hydrology and Earth System Sciences*. https://doi.org/10.5194/hess-22-2163-2018b.

Luers, A. L., Lobell, D. B., Sklar, L. S., Addams, C. L., & Matson, P. a. (2003). A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Global Environmental Change*, *13*(4), 255–267.

Lukuyu, B., Sikumba, G., Baltenweck, I. and Njehu, A. (2013). Costs and benefit analysis of feed technologies promoted by the East Africa Dairy Development Project (EADD). https://de.slideshare.net/ILRI/eadd-cost-benefitsoct2013-79798475 (Last access: July 12th, 2019).

Madajewicz, M., Tsegay, A. H., & Norton, M. (2013). *Managing Risks To Agricultural Livelihoods: Impact Evaluation of the Harita Program in Tigray, Ethiopia, 2009–2012*. Retrieved from http://www.climate-insurance.org/news-events/news/harita-r4-impact-evaluation-shows-the-impact-of-insurance-on-poverty-reduction/.

Makombe, G.; Kelemework, D.; Aredo, D. (2007). A comparative analysis of rain-fed and irrigated agricultural production in Ethiopia. *Irrigation and Drainage Systems* (21): 35–44.

Makombe, G., Namara, R., Hagos, F., Awulachew, S. B., Ayana, M., & Bossio, D. (2011). *A comparative analysis of the technical efficiency of rain-fed and smallholder irrigation in Ethiopia. IWMI Working Papers* (Vol. 143). https://doi.org/10.5337/2011.202.

Maraun, D. Curr (2016). Bias Correcting Climate Change Simulations - a Critical Review, *Clim Change* Rep, 2: 211. https://doi.org/10.1007/s40641-016-0050-x.

McCarthy JJ, Canziani OF, Leary NA et al (2001). Climate change 2001: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge.

McIntosh, C., Sarris, A., & Papadopoulos, F. (2013). Productivity, credit, risk, and the demand for weather index insurance in smallholder agriculture in Ethiopia. *Agricultural Economics*, *44*(4–5), 399–417.

McSweeney C, New M, Lizcano G (2007). Ethiopia: UNDP climate change country profiles.

MDA BaseVue 2013 Global Land Cover available on ArcGIS Online. (2019). Retrieved August 9, 2019, from https://www.esri.com/arcgis-blog/products/defense/defense/mdas-basevue-2013-global-land-cover-available-on-arcgis-online/.

Mechler, R. (2016). Reviewing estimates of the economic efficiency of disaster risk management: opportunities and limitations of using risk-based cost–benefit analysis. *Natural Hazards*, *81*(3), 2121–2147.

Melke, A., & Fetene, M. (2014). Eco-physiological basis of drought stress in coffee (Coffea arabica, L.) in Ethiopia. *Theoretical and Experimental Plant Physiology*. https://doi.org/10.1007/s40626-014-0022-2.

Mengistu, A., Kebede, G., Assefa, G., & Feyissa, F. (2016). Improved forage crops production strategies in Ethiopia: A review. *Acad. Res. J. Agri. Sci. Res*, *4*(6), 285–296.

Menzel, C.M.; Le Lagadec, M.D. (2017). Can the productivity of mango orchards be increased by using high-density plantings? *Scientia Horticulturae* 218 (2017) 222–263.

Ministry of Finance and Economic Development of Ethiopia. (2006). A Plan for Accelerated and Sustained Development to End Poverty (PASDEP).

Ministry of Finance and Economic Development of Ethiopia. (2010). Growth and Transformation Plan 2010/11-2014/2015. https://doi.org/10.1002/ejoc.201200111.

MoA. (2011). Ministry of Agriculture Natural Resources Small-Scale Irrigation Situation Analysis, (October).

MoA (Ministry of Agriculture) and ATA (Ethiopian Agricultural Transformation Agency) (2013), A Roadmap towards the Transformation of the Ethiopian Seed System, MoA and ATA. http://extwprlegs1.fao.org/docs/pdf/eth172079.pdf.

Ministry of Agriculture and Rural Development (MoARD). (2010). Ethiopia's Agricultural Sector Policy and Investment Framework: 2010-2020. Addis Ababa.

Moat, J., Williams, J., Baena, S., Wilkinson, T., Gole, T. W., Challa, Z. K., … Davis, A. P. (2017). Resilience potential of the Ethiopian coffee sector under climate change. *Nature Plants*. https://doi.org/10.1038/nplants.2017.81.

MoWR. (2007). The Federal Democratic Republic of Ethiopia Climate Change National Adaptation Programme of Action (NAPA), (June).

Müller, B., Johnson, L., & Kreuer, D. (2017). Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, 46, 23–33.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., … Yang, H. (2016). Global Gridded Crop Model evaluation: benchmarking, skills, deficiencies and implications. *Geoscientific Model Development Discussions*, 1–39. https://doi.org/10.5194/gmd-2016-207.

Murken, L., Aschenbrenner, P., Chemura, A., Hattermann, F., Koch, H., Lehmann, J., Liersch, S., Roehrig, F., Schauberger, B., Yalew, A. & Gornott, C. (2019). *Climate risk analysis for identifying and weighing adaptation strategies in Ghana's agricultural sector*. A report prepared by the Potsdam Institute for Climate Impact Research for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the German Federal Ministry for Economic Cooperation and Development (BMZ), 94 pp.

NAFIS (National Farmers Information Service of Kenya) (2019): Economic Analysis of Napier Grass: http://www.nafis.go.ke/fodders/napier-grass/economic-analysis/ (Last access: July 12th, 2019).

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., and Bernabucci, U. (2010). Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, 130, 57-69.

National Bank of Ethiopia (NBE). (2017). National Bank Annual Report: 2017-2018. Addis Ababa.

National Irrigation Board (2018). Bura irrigation scheme. Nairobi: National Irrigation Board.

Ndambi, A., van der Lee, J., Endalemaw, T., Yigrem, S., Tefera, T. and Andeweg, K. (2017): Four Important facts on opportunities in the Ethiopian dairy sector. Practice Brief DairyBISS project. Wageningen University. https://www.researchgate.net/publication/319007549_Four_important_facts_on_opportunities_in_the_Ethiopian_dairy_sector (Last access: July 12th, 2019).

Negash, M., & Starr, M. (2015). Biomass and soil carbon stocks of indigenous agroforestry systems on the south-eastern Rift Valley escarpment, Ethiopia. *Plant and Soil*, *393*(1–2), 95–107.

Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, (2014): Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working GroupII to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field,D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma,E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press,Cambridge, United Kingdom and New York, NY, USA, 1199–1265.

Nicholson, S. (2016). The Turkana low-level jet: mean climatology and association with regional aridity. *International Journal of Climatology*, 36, 2598-2614.

Nigussie, Z., Fisseha, G., Alemayehu, G., & Abele, S. (2018). Smallholders' apple-based agroforestry systems in the north-western highlands of Ethiopia. *Agroforestry Systems*, *93*(3), 1–12.

Nischalke, S. M., Abebe, M., Wondimagegnhu, B. A., Kriesemer, S. K., & Beuchelt, T. (2017). Forgotten Forests? Food Potential of Ancient Coffee Forests and Agroforestry Systems in the Southwestern Ethiopian Mountains, Seen Through a Gender Lens. *Mountain Research and Development*, *37*(3), 254–262.

Ntukamazina, N., Onwonga, R., Sommer, R., Rubyogo, J., Muankusi, C., Mburu, J., & Kariuki, R. (2017). Index-based agricultural insurance products: challenges, opportunities and prospects for uptake in sub-Sahara Africa. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *118*(2).

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., ... West, J. (2004). Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, *14*(4), 303–313.

Ortiz, R., Sayre, K. D., Govaerts, B., Gupta, R., Subbarao, G. V., Ban, T., ... Reynolds, M. (2008). Climate change: Can wheat beat the heat? *Agriculture, Ecosystems and Environment,* 126(1–2), 46–58.

Petit, N. (2007). Ethiopia's coffee sector: A bitter or better future? *Journal of Agrarian Change*. https://doi.org/10.1111/j.1471-0366.2007.00145.x.

Philip, S., S.F. Kew, G. Jan van Oldenborgh, F. Otto, S. O'Keefe, K. Haustein, A. King, A. Zegeye, Z. Eshetu, K. Hailemariam, R. Singh, E. Jjemba, C. Funk, and H. Cullen, (2018). Attribution Analysis of the Ethiopian Drought of 2015. *J. Climate*, 31, 2465–2486.

Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. *Sustainability Science*, *6*(2), 177–202.

Rashid, S.; Tefera, N.; Minot, N.; Ayele, G. (2013). Fertilizer in Ethiopia. An assessment of policies, value chain, and profitability. *IFPRI Discussion Paper 01304*. Washington D.C.: IFPRI.

Recha, J. (2017). Intercropping mango trees benefits farmers in the Albertine Rift. Research Program on Climate Change, Agriculture and Food Security. In: https://ccafs.cgiar. org/blog/intercropping-mango-trees-benefits-farmers-albertine-rift#.XYhTXmZCSUI. (Lass access on: October 19th, 2019).

Recha, J.; Radeny, M.; Kimeli, P.; Hafashimana, D.; Masanyu, J.; Ssekiwoko, F.; Odongo, W. (2016). Progress in achieving household food security in climate-smart villages in the Albertine Rift, western Uganda: preliminary results from climate change adaptation and mitigation initiatives in Hoima climate-smart villages. CCAFS Info Note. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security.

Reed, J., Deakin, L., & Sunderland, T. (2015). What are "Integrated Landscape Approaches" and how effectively have they been implemented in the tropics: A systematic map protocol. *Environmental Evidence*, 4(1), 1–7.

Reij, C., & Garrity, D. (2016). Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. *Biotropica*, *48*(6), 834–843.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., ... Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, *111*(9), 3268–3273.

Sani, S., & Kemaw, B. (2019). Analysis of Rural Households Food Security in Western Ethiopia. *Food and Nutrition Sciences*, *10*(03), 249–265.

Sayer, J., Sunderland, T., Ghazoul, J., Pfund, J.-L., Sheil, D., Meijaard, E., ... Buck, L. E. (2013). Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proceedings of the National Academy of Sciences of the United States of America*, 110(21), 8349–8356.

Schauberger, B., Gornott, C., & Wechsung, F. (2017). Global evaluation of a semiempirical model for yield anomalies and application to within-season yield forecasting. *Global Change Biology*, *23*(11), 4750–4764.

Segele, Z.T., et al. (2009). Large-scale atmospheric circulation and global sea surface temperature associations with Horn of Africa June–September rainfall. *International Journal of Climatology*, 29, 1075-1100.

Seid, H., Birhane, E., Kebede, F., Hadgu, K. M., Negussie, A., & Norgrove, L. (2016). Response of selected indigenous dryland agroforestry tree species to salinity and implications for soil fertility management. *Agroforestry Systems*, *90*(6), 1133–1142.

Selassie, Y.G. (2016). Response and economic feasibility of maize (Zea mays L.) to P fertilization in acidic Alfisols of North-western Ethiopia. *Environmental System Research* (5): doi 10.1186/s40068-016-0056-3.

Seleshi, Y., & Camberlin, P. (2006). Recent changes in dry spell and extreme rainfall events in Ethiopia. *Theoretical and Applied Climatology*, *83*(1–4), 181–191.

Seo, S.N., and Mendelsohn, R. (2008). Measuring impacts and adaptations to climate change: a structural Ricardian Model of African Livestock Management. *Agricultural Economics*, 38, 151–165.

Seyoum Taffesse, A., Dorosh, P., & Gemessa, S. A. (2013). Crop production in Ethiopia: Regional patterns and trends. In Food and Agriculture in Ethiopia: Progress and Policy Challenges. https://doi.org/10.9783/9780812208610.53.

Shapiro, B.I., Gebru, G., Desta, S., Negassa, A., Nigussie, K., Aboset, G. and Mechal, H. (2015). *Ethiopia livestock master plan. ILRI Project Report.* Nairobi, Kenya.

Shapiro, B. I., Gebru, G., Desta, S., Negassa, A., Nigussie, K., Gezahegn, A., & Henok, M. (2017). Ethiopia livestock sector analysis. *ILRI Project Report*. Retrieved from http://hdl.handle.net/10568/92057.

Siders, A. R. (2019). Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(3), e573.

Simane, B., Zaitchik, B. F., & Foltz, J. D. (2016). Agroecosystem specific climate vulnerability analysis: application of the livelihood vulnerability index to a tropical highland region. *Mitigation and Adaptation Strategies for Global Change*, *21*(1), 39–65.

Sime, G., & Aune, J. (2018). Sustainability of Improved Crop Varieties and Agricultural Practices: A Case Study in the Central Rift Valley of Ethiopia. *Agriculture*, *8*(11), 177.

SNV and DTC (2017): Forage production and management – training package for extension workers, SNV Ethiopia: Addis Abeba.

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H. C. J., Gollin, D., … Scarborough, P. (2016). Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, *387*(10031), 1937–1946.

Stackhouse Jr., P. W., Gupta, S. K., Cox, S. J., Mikovitz, C., Zhang, T., & Hinkelman, L. M. (2011). The NASA/GEWEX surface radiation budget release 3.0: 24.5-year dataset. *GEWEX News*, 21(1), 10–12.

Statista (2019): Ethiopia: inflation rate from 1984 to 2024 (compared to the previous year). Hamburg: Statista.

Summer, A., Lora, I., Formaggioni, P., & Gottardo, F. (2019). Impact of heat stress on milk and meat production. *Animal Frontiers*, 9(1), 39-46.

Taddese, G., Sonder, K., & Peden, D. (2003). The water of the Awash river basin a future challenge to Ethiopia. Addis Ababa.

Taffesse, A. S., Dorosh, P., & Gemessa, S. A. (2014). 3 Crop Production in Ethiopia: Regional Patterns and Trends. *Food and Agriculture in Ethiopia*. https://doi.org/10.9783/9780812208610.53

Tamru, S., Engida, E., Hiluf, M., Dereje, M. and Minten, B. (2015). Structure, pricing and margins in Ethiopia's coffee value chain. IFPRI. https://de.slideshare.net/essp2/structure-pricing-and-margins-in-ethiopias-coffee-value-chain (Last access: July 12th, 2019).

Tate, E. (2012). Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis. *Natural Hazards*, *63*(2), 325–347.

Taye, M. T., & Willems, P. (2012). Temporal variability of hydroclimatic extremes in the Blue Nile basin. *Water Resources Research*, *48*(3). https://doi.org/10.1029/2011WR011466.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-11-00094.1.

Tegegne, A., Gebremedhin, B., Hoekstra, D., & Belay, B. (2013). Smallholder dairy production and marketing systems in Ethiopia: IPMS experiences and opportunities for market-oriented development. Retrieved from https://cgspace.cgiar.org/bitstream/handle/10568/27914/ipmsWP31.pdf.

Tegegne, A. (2018). Why Ethiopia's dairy industry can't meet growing demand for milk. https://theconversation.com/why-ethiopias-dairy-industry-cant-meet-growing-demand-for-milk-100067 (Last access: July 12th, 2019).

Teklesadik, A. D., Alemayehu, T., van Griensven, A., Kumar, R., Liersch, S., Eisner, S., … Wang, X. (2017). Inter-model comparison of hydrological impacts of climate change on the Upper Blue Nile basin using ensemble of hydrological models and global climate models. *Climatic Change*. https://doi.org/10.1007/s10584-017-1913-4.

Teshager, M., Adgo, E., & Tilahun, T. (2014). Investigating the Determinants of Adaptation Strategies to Climate Change: A Case of Batti District, Amhara Region, Ethiopia. *International Journal of Agricultural Research*, *9*(4), 169–186.

Tessema, Y. A., Aweke, C. S., & Endris, G. S. (2013). Understanding the process of adaptation to climate change by small-holder farmers: the case of east Hararghe Zone, Ethiopia. *Agricultural and Food Economics*, *1*(1), 1–17.

Teutschbein, C. and Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods, *J. Hydrol.*, 16, 12–29.

Thornton, P., Steeg, J. van de, & Notenbaert, A. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, *101*, 113–127.

Tiruneh, S., & Tegene, F. (2018). Impacts of climate change on Livestock production and productivity and different adaptation strategies in Ethiopia. *Journal of Applied and Advanced Research*, *3*(3), 52.

Tsegay, A., Vanuytrecht, E., Abrha, B., Deckers, J., Gebrehiwot, K., & Raes, D. (2015). Sowing and irrigation strategies for improving rainfed tef (Eragrostis tef (Zucc.) Trotter) production in the water scarce Tigray region, Ethiopia. *Agricultural Water Management*, *150*(1), 81–91.

Tubiello, F. N., Soussana, J.-F., & Howden, S. M. (2007). Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19686–19690.

Turner 2nd, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., ... Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proc Natl Acad Sci U S A*, *100*(14), 8074–8079.

van Oosten, C. (2015). The landscape puzzle: An introduction to the landscape approach. Netherlands: Wageningen Center for Development Innovation. Retrieved from https://www.youtube.com/watch?v=fB5BiKCerFo.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*. https://doi.org/10.1007/s10584-011-0148-z.

Van Wart, J., Kersebaum, K. C., Peng, S., Milner, M., & Cassman, K. G. (2013). Estimating crop yield potential at regional to national scales. *Field Crops Research*, *143*, 34–43.

Vasilaky, K., Diro, R., Norton, M., McCarney, G., & Osgood, D. (2019). Can Education Unlock Scale? The Demand Impact of Educational Games on a Large-Scale Unsubsidised Index Insurance Programme in Ethiopia. *The Journal of Development Studies*, 1–23.

Verkaart, S., Munyua, B. G., Mausch, K., & Michler, J. D. (2017). Welfare impacts of improved chickpea adoption: A pathway for rural development in Ethiopia? *Food Policy*, *66*, 50–61.

Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X., Krysanova, V., & Hattermann, F. (2015). Multimodel climate impact assessment and intercomparison for three large-scale river basins on three continents. *Earth System Dynamics*. https://doi.org/10.5194/esd-6-17-2015.

Vetter, Tobias, Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., ... Krysanova, V. (2017). Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. *Climatic Change*. https://doi.org/10.1007/s10584-016-1794-y.

Voss-Fels, K. P., Stahl, A., Wittkop, B., Lichthardt, C., Nagler, S., Rose, T., ... Snowdon, R. J. (2019). Breeding improves wheat productivity under contrasting agrochemical input levels. *Nature Plants*, *5*(7), 706–714.

Wayne, G. P. (2013). The Beginner's Guide to Representative Concentration Pathways. *Skeptical Sciece*. https://doi.org/10.1063/1.1370531.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., & Viterbo, P. (2014). The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. *Water Resources Research*, 50(9), 7505–7514.

White, J.W., D.G. Tanner, and J.D. Corbett. (2001). An Agro-Climatological Characterization of Bread Wheat Production Areas in Ethiopia. NRG-GIS Series 01-01. Mexico, D.F.: CIMMYT.

Whitney, C. K., Bennett, N. J., Ban, N. C., Allison, E. H., Armitage, D., Blythe, J. L., ... Yumagulova, L. (2017). Adaptive capacity: From assessment to action in coastal social-ecological systems. *Ecology and Society*, *22*(2).

Wiréhn, L., Opach, T., & Neset, T.-S. (2016). Assessing agricultural vulnerability to climate change in the Nordic countries – an interactive geovisualization approach. *Journal of Environmental Planning and Management*, *0568*(July). https://doi.org/10.1080/09640568.2016.1143351.

Woldemariam, P., & Gecho, Y. (2017). Determinants of Small-Scale Irrigation Use: The Case of Boloso Sore District, Wolaita Zone, Southern Ethiopia. *American Journal of Agriculture and Forestry*, *5*(3), 49.

World Bank (2010). Economic evaluation of climate change adaptation projects: approaches for the agricultural sector and beyond. Washington, DC: The World Bank.

World Bank. (2013). Sustainable Land Management Project (SLMP-2). Washington, D.C.

World Bank. (2018). Population, Ethiopia. Retrieved July 12, 2019, from https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ET.

World Bank. (2019a). Ethiopia Overview. Retrieved July 23, 2019, from https://www.worldbank.org/en/country/ethiopia/overview.

World Bank (2019b). 3 year average, GDP per capita nominal. Washington, DC: World Bank.

World Bank (2019c). World Bank national accounts data, and OECD National Accounts data files. (Last access: 21.11.2019).

World Food Programm (WFP). (2018). The R4 Rural Resilience Initiative. Retrieved June 13, 2019, from https://www1.wfp.org/r4-rural-resilience-initiative.

Worqlul, A. W., Collick, A. S., Rossiter, D. G., Langan, S., & Steenhuis, T. S. (2015). Assessment of surface water irrigation potential in the Ethiopian highlands: The Lake Tana Basin. *Catena*, *129*, 76–85. https://doi.org/10.1016/j.catena.2015.02.020.

Worqlul, A. W., Jeong, J., Dile, Y. T., Osorio, J., Schmitter, P., Gerik, T., … Clark, N. (2017). Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. *Applied Geography*, *85*, 1–13.

Yang, W., et al. (2015). The Annual Cycle of East African Precipitation. *Journal of Climate*, 28, 2385-2404.

Yibeltal, K. (2016). Khat – the perils and promises. In: Addis Standard: http://addisstandard.com/khat-the-perils-and-promises/ (Last access: July 12th, 2019).

Zelleke, G., Agegnehu, G., Abera, D., and Rashid, S. (2010). Fertilizer and Soil Fertility Potential in Ethiopia: Constraints and opportunities for enhancing the system. International Food Policy Research Institute (IFPRI). http://www.ifpri.org/publication/fertilizer-and-soil-fertility-potential-ethiopia.

Zeng, D., Alwang, J., Norton, G., Jaleta, M., Shiferaw, B., & Yirga, C. (2018). Land ownership and technology adoption revisited: Improved maize varieties in Ethiopia. *Land Use Policy*, *72*(March 2016), 270–279.

Zeng, D., Alwang, J., Norton, G. W., Shiferaw, B., Jaleta, M., & Yirga, C. (2017). Agricultural technology adoption and child nutrition enhancement: improved maize varieties in rural Ethiopia. *Agricultural Economics (United Kingdom)*, *48*(5), 573–586.

Zou, X., Li, Y., Li, K., Cremades, R., Gao, Q., Wan, Y., & Qin, X. (2013). Greenhouse gas emissions from agricultural irrigation in China. *Mitigation and Adaptation Strategies for Global Change*, *20*(2), 295–315.