Federal Ministry
for Economic Cooperation
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Potsdam Institute for
Climate Impact Research

Deutsche Gesellschaft
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Zusammenarbeit (GIZ) GmbH

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Authors' contributions:

Christoph Gornott, Felicitas Röhrig, Nele Gloy and Sophie von Loeben coordinated and edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Christoph Gornott, Lisa Murken and Felicitas Röhrig designed the study approach with steering input from stakeholders. Felicitas Röhrig, Oblé Neya and Boubacar Ibrahim coordinated the stakeholder engagement process. Paula Aschenbrenner performed the climate analysis in Chapter 1. Hagen Koch, Stefan Liersch and Michael Wortmann conducted the hydrological analysis for Chapter 2. Ponraj Arumugam analysed climate impacts on crop yields and suitability for Chapter 3 and the biophysical risk assessments in Chapter 8-10, under the guidance of Abel Chemura, Bernhard Schauberger, Felicitas Röhrig and Christoph Gornott; Bernhard Schauberger analyzed climate impacts on crop yields with statistical methods; Abel Chemura conducted a crop suability analysis. Sebastian Ostberg and Roopam Shukla conducted the impact assessment on livestock production in Chapter 4 and Stefanie Wesch contributed the Info Box on climate change as a driver of conflicts in Niger. Sophia Lüttringhaus, Juliane Kaufmann, Steffen Noleppa and Matti Cartsburg conducted the farm level cost-benefit analyses in Chapters 8-10. Julia Tomalka contributed Chapters 6-8. Sophia Lüttringhaus contributed Chapter 10. Sophie von Loeben contributed Chapter 9. All authors contributed to Chapter 5 on methods and Chapter 11 on uncertainties. Felicitas Röhrig, Nele Gloy, Sophie von Loeben, Lisa Murken, Julia Tomalka provided overall research support. The summary for policy makers was compiled by Hye-Rin Léa Baek together with Nele Gloy, Sophie von Loeben and Christoph Gornott. Oblé Neya and Boubacar Ibrahim reviewed the summary for policy makers to ensure alignment with key national policies.

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Abstract

Niger has a high socio-economic dependency on agriculture which is strongly influenced by weather-related factors and highly vulnerable to climate change. Currently, only limited information on climate risks and its impacts is available for the agricultural sector in the country. Therefore, this study aims to provide a comprehensive climate risk analysis including a thorough evaluation of four potential adaptation strategies that can guide local decision makers on adaptation planning and implementation in Niger: (1) agroforestry and farmer managed natural regeneration (FMNR) of trees, (2) integrated soil fertility management (ISFM), (3) irrigation and (4) improved fodder management for livestock. The impact assessment includes climate projections based on two future emissions scenarios (SSP3-RCP7.0 and SSP1-RCP2.6), hydrological modelling on water availability, modelling and comparison of future yields of four dominant crops (sorghum, millet, maize and cowpeas) and an assessment of livestock production under future climate conditions. Based on the projected climate change impacts on agricultural production, the four adaptation strategies suggested by different national stakeholders were analysed regarding their potential to risk mitigation, cost-effectiveness and suitability for local conditions. The analyses have been complemented by expert- and literature-based assessments, semi-structured interviews and two stakeholder workshops. The results show that the mean daily temperature is projected to increase further in Niger, up to +1.3 °C (SSP1-RCP2.6) and +4.2 °C (SSP3-RCP7.0) by 2090, in reference to 2004. The mean annual precipitation sum is also projected to increase until 2050 under both emissions scenarios, with a slight decrease in the interannual variability. In the second half of the century, this trend in precipitation is likely to continue (SSP3-RCP7.0) or decrease slightly (SSP1-RCP2.6), while the year-to-year variability would increase. Greater annual rates of groundwater recharge due to increasing precipitation amounts and higher annual mean river discharge are expected until mid-century. Sorghum yields would decline in general, by 20-50% (SSP1-RCP2.6) or 40-75% (SSP3-RCP7.0) by 2090, compared to 2005. Crop models hinted at an increase in the suitability of sorghum and millet, and no significant change for maize and cowpeas in Niger under both emissions scenarios. In addition, the potential for multiple cropping would decrease from mid-century, limiting farmers' diversification options. Regarding the livestock sector, the grazing potential is likely to decrease in the south and increase in the central regions of Niger, under SSP1-RCP2.6, while it is expected to increase in the whole country under SSP3-RCP7.0. All four adaptation strategies were found to be economically beneficial, risk-independent, with a medium to high risk mitigation potential, and can bring about various co-benefits. FMNR practice can be highly recommended, as the upscaling potential is high and the climate resilience of local livelihoods will be strengthened. ISFM can help to improve water use efficiency and benefit from positive environmental and social outcomes. Irrigation has a medium potential to improve livelihoods of smallholder farmers but is also a support-intensive adaptation strategy that needs to be carefully implemented in order to avoid overexploitation of local water resources. Lastly, improved fodder management, especially alfalfa production, contributes to building up resilience of livestock farming systems and affects women and youth employment positively. Generally, a combination of different adaptation strategies can yield additional benefits and active stakeholder engagement as well as participatory approaches are needed to ensure the feasibility and sustainability of adaptation strategies. The findings of this study can help to inform national and local adaptation as well as development planning and investments in order to strengthen the climate resilience of the Nigerien agricultural sector and especially of smallholder farmers.

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

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List of abbreviations

AEZ	Agro-Ecological Zone
AGRA	Alliance for the Green Revolution in Africa
AGSDS	Accelerated Growth and Sustainable Development Strategy
AIC	Akaike Information Criterion
ALR	Agrarian Land Re-organization
AMGP	African Market Garden Project
AMPLIFY	Agricultural Model for Production Loss Identification and Failures of Yields
ANAM	National Meteorological Agency
AUC	Area Under the receiver operating Curve
BCR	Benefit-Cost Ratio
BMZ	German Federal Ministry for Economic Cooperation and Development
C3S	Copernicus Climate Change Service
CBA	Cost-Benefit Analysis
CFA	Communauté Financière Africaine (African Financial Community)
CGIAR	Consultative Group on International Agricultural Research
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CILSS	Permanent Interstates Committee for Drought Control in the Sahel
CIS	Climate Information Services
CMIP	Coupled Model Intercomparison Project
CWR	Crop Water Requirement
DSSAT	Decision Support System for Agrotechnology Transfer
ECS	Equilibrium Climate Sensitivity
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
FAO	Food and Agriculture Organization of the United Nations
FEWS NET	Famine Early Warning Systems Network
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GLC	Global Land Cover
GrCO2	Global CO2 emissions
GRDC	Global Runoff Data Centre
HWSD	Harmonised World Soil Database
IAM	Integrated Assessment Models
ICT	Information and Communication Technologies
ICV	Improved Crop Varieties
IITA	International Institute of Tropical Agriculture
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISFM	Integrated Soil Fertility Management
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ITCZ	Intertropical Convergence Zone
LPJmL	Lund-Potsdam-Jena with managed Land
MAG/EL	Ministère de l'Agriculture et de l'Élevage
MDA	Ministère du Développement Agricole
MMEM	Multi-Model Median

NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organisation
NPV	Net Present Value
OOS	Out-Of-Sample
PAGIRE	Action Plan for the Integrated Management of Water Resources
PIK	Potsdam Institute for Climate Impact Research
PSDB9	Programme Sahel Burkina
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SDGs	Sustainable Development Goals
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
SWIM	Soil and Water Integrated Model
TLU	Tropical Livestock Unit
USAID	United States Agency for Internal Development
USD	United States Dollar
WAM	West African Monsoon
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WMO	World Meteorological Organization
XGBoost	eXtreme Gradient Boosting

PART I – CLIMATE CHANGE IMPACTS

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

Introduction

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

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

The study area

The Republic of Niger is a landlocked Sahelian country in Western Africa, with a population of over 23 million and an annual demographic growth rate of 3.8%, the highest in Africa (World Bank, 2020).

As other countries in sub-Saharan Africa, Niger is highly vulnerable to climate change due to a combination of naturally high levels of climate variability, high reliance on rainfed agriculture, and limited economic and institutional capacity to cope with and adapt to climate variability and change (Challinor et al., 2007; Müller et al., 2010; Roudier et al., 2011). Climate change adaptation in Niger is especially important for the agricultural and livestock sector, given that this sector (together with its components in forestry and fisheries) generates around 39.2% of the national GDP (World Bank, 2018). Most of Niger's agricultural production is based on smallholder subsistence farming systems and livelihoods depend to a large extent on rainfed crop and pastoralist livestock production (Global Yield Gap Atlas, n.d.). Land degradation and desertification constitute major challenges to agricultural production and increasing temperatures and precipitation variability add to existing stressors. Major cultivated crops are staples, with a clear predominance of pearl millet (46% of total acreage), sorghum (18%), and cowpea (32%), while key livestock types include cattle, goat, sheep and camel (Global Yield Gap Atlas, n.d.).

Figure 1: Map of Niger with administrative regions.

All countries in West Africa are net importers of cereals, indicating that their current production is insufficient to meet domestic demands (FAO, 2014).

Given that Niger's population is one of the fastest growing int he world, a massive increase in food demand is expected and will become increasingly difficult to meet, especially under climate change (Schmidhuber & Tubiello, 2007). The existing trends in African agriculture indicate that shortages are expected already without the adverse effects of climate change (Gerland et al., 2014; Ray et al., 2013), underlining the need to invest in agricultural technologies that can stimulate agricultural productivity both today and under future climate conditions.

The study approach

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

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

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

In order to ensure alignment of the study focus with national goals and priorities, a wide range of local experts and stakeholders have been involved throughout the study process via stakeholder workshops, farmer surveys and expert discussions. Close collaboration with the local partner institute, the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) allowed us to get continuous validation of our focus and results.

The study is organized as follows: Chapters 1-4 cover the impact dimension of climate change in Niger, whereas Chapters 5-10 focus on the action (or adaptation) dimension:

- **Chapter 1** provides an overview of past and projected future climatic changes in Niger focusing on changing temperature and precipitation regimes in the country. All future projected climate impacts are based on outputs of ten Global Climate Models under two future climate scenarios, a low-emissions scenario (SSP1-RCP2.6) and a high emissions scenario (SSP3-RCP7.0).
- **Chapter 2** analyses changing water availability for crop production, looking at both river discharge and groundwater level availability for irrigation.
- **Chapter 3** presents a comprehensive overview of climate impacts on crop production, ranging from weather influence on crop yields, changes in crop suitability under climate change and projected impacts of climate change on crop production.
- **Chapter 4** assesses climate impacts on livestock production by analysing both a trend in livestock numbers and projected grazing potential and associated fodder availability in the country under climate change.
- **Chapter 5** introduces the action component of the study and presents the methods and approaches used for the evaluation of the adaptation strategies, starting with the multi-criteria assessment, then the biophysical evaluation and the cost-benefit analysis.
- **Chapter 6** provides an overview of adaptive capacity in Niger and presents the assessment framework for selecting and evaluating adaptation recommendations for the agricultural sector, including biophysical, economic and soft-assessment indicators.
- **Chapters 7–10** assess selected adaptation strategies. Chapter 7 looks at agroforestry and farmer managed natural regeneration of trees, Chapter 8 at use of integrated soil fertility management, Chapter 9 at irrigation and Chapter 10 at improved fodder management.
- **Chapter 11** discusses sources of uncertainty and limitations of the study to facilitate the interpretation of its results.
- Finally, **Chapter 12** draws a conclusion of the study results and derives policy recommendations. The results are meant to inform and support local and national government authorities, non-profit, and private sector stakeholders in prioritizing and designing their adaptation investments to increase the resilience of small-holder farmers and herders under climate change.

Chapter 1 – Changing climatic condition

To identify changes in future climatic conditions in Niger, this chapter analyses several indicators concerning temperature and precipitation under two global emissions scenarios, scenario RCP2.6 and scenario RCP7.0, which are low and high GHG concentration pathway scenarios, used in the reports of the Intergovernmental Panel on Climate Change (IPCC) (details in box 1). RCP2.6 represents a scenario with global temperature increases of less than 2 °C compared to pre-industrial times (Van Vuuren et al., 2011b) and is thereby in line with the goals of the Paris Agreement. RCP7.0 is a high emissions scenario and refers to the "without climate policy" scenario. Projected climate data were analysed to show the full range of possible future climatic conditions by 2030, 2050 and 2090 and thus inform political decision makers and implementers in the medium and long term.

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

1.1 What drives Niger's climate?

Geographically, Niger is located at the southern edge of the Sahara with almost two-thirds of its territory being covered by desert. The country can be divided into five agro-ecological zones (AEZ) (Figure 3). The Sahara zone covers 74% of the country and forms the northern territory. It is characterized by arid climates of grassy steppe, covered with thorny plants and Acacia tree species, and has typically less than 200 mm precipitation per year. The population density in this area is generally very low (<10 inh./km^2) and inhabitants are devoted to livestock production (goats and camels) and non-agricultural activities except for in a few irrigated oases (RECA, 2004). The Sahara-Sahelian zone builds the transition to the Sahelian zone, both of which are successively adjoining the Saharan zone to the south and experience a gradual increase in annual precipitation amounts at 200-300 mm (Sahara-Sahelian) and 300-400 mm (Sahelian zone). Farming is increasingly practised in these zones that occupy together 18% of the land, with the traditional pastoral zone of the Sahara-Sahelian zone becoming rapidly colonised by crop fields as the demographic pressure shifts the crop front northwards. The Sahelian zone is a densely populated light savannah with traditional cereal and legume production systems, occasionally interspersed with market gardening and agroforestry activities. Animal husbandry is also common in extensive transhumant or agropastoral systems.

Towards the southern border of the country follows the Sahelo-Soudanian zone (7% of territory) with precipitation amounts between 400 – 600 mm per year and a comparably high crop production potential, while at the southern tip of the country (1% of territory), the Soudanian zone with >600 mm precipitation per year holds even higher yet vastly unexploited cropping potential, especially in terms of irrigated production systems (RECA, 2004).

Most of Niger is dominated by hot and dry climate. Precipitation decreases from south to north (see Figure 4) and is linked to the migration of the Intertropical Convergence Zone (ITCZ) and thus the formation of the West African Monsoon (WAM). The atmospheric and oceanic processes influencing the WAM are complex and sensitive to external forcing. Following the migration of the sun's zenith, the WAM develops around March at the Atlantic coast and brings precipitation northwards to Niger, reaching maximum precipitation sums in July and August (Drobinski et al., 2009). The WAM is mainly driven by the temperature gradient between the ocean and the land surface. The high temperatures over the Sahara in boreal summer create a heat low which drives the moist air from the Atlantic Ocean inland towards the Sahel and thus brings precipitation inland (Herzschuh et al., 2014; Minka & Ayo, 2014).

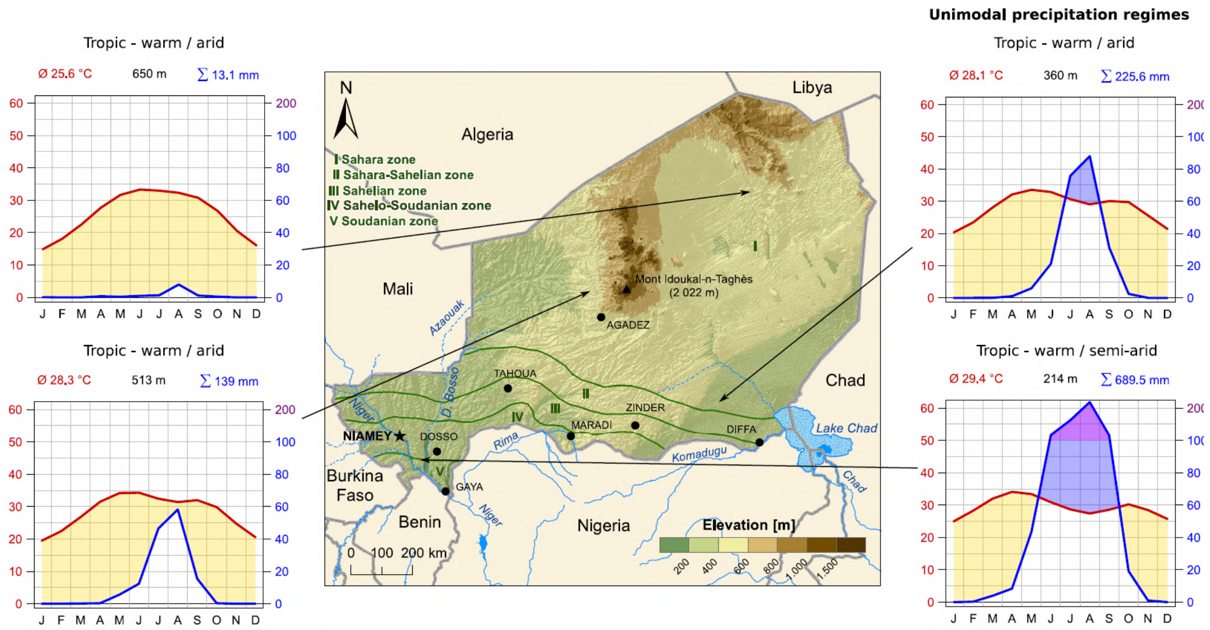


Figure 3: Topographic map of Niger with agro-ecological zones.

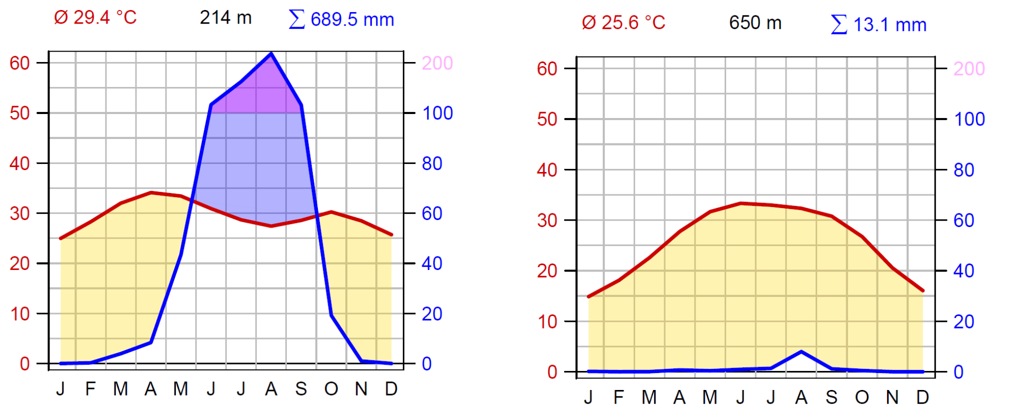


Figure 4: Two climate diagrams displaying the annual distribution of precipitation and temperature in the south [12.75;2.75] (left) and in the north [21.25;12.25] (right).

Precipitation amounts in Niger and the whole Sahel region have shown high variability in recent decades. This includes a severe drying of the Sahel in the 1970s and 1980s. Studies have shown that this dry period can be indirectly attributed to the unique combination of aerosols and greenhouse gases that characterised the post-World War II period (Giannini & Kaplan, 2019).

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

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

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

The future emissions scenarios used in this report are a new set of emissions and land-use scenarios that are based on the standard set of future scenarios used in the 6th Assessment Report of the IPCC to be released in 2021/22 (as compared to the four Representative Concentration Pathways (RCPs) used in the 5th Assessment Report): pathways of societal development, the shared socioeconomic pathways (O'Neill et al., 2017), linked with forcing levels of the representative concentration pathways (Eyring et al., 2016; O'Neill et al., 2016).

The SSPs comprise five alternative narratives that describe socioeconomic trends which shape future society (Figure 5). They include quantitative descriptions for key elements like population, economic growth and urbanisation (O'Neill et al., 2016). SSP1 envisions an optimistic trend for human development with substantial investments in health, education, well-functioning institutions, and economic growth and, at the same time, a shift towards sustainable practices. SSP3, on the contrary, shows a pessimistic development trend with increasing inequalities and prioritisation of regional security (O'Neill et al., 2016). To translate the socioeconomic conditions of the SSPs into possible greenhouse gas emissions trajectories, different integrated assessment models (IAMs) were employed (Hausfather, 2018). The IAMs project different emissions pathways for individual SSPs.

These different emissions pathways are grouped and represented by the seven representative concentration pathways (RCPs), which define a radiative forcing[1] achieved in 2100. The RCPs are labelled after the additional radiative forcing level reached in the year 2100 relative to pre-industrial times (+1.9, +2.6, +3.4, +4.5, +6.0, +7.0 and +8.5 W/m^2, respectively) (van Vuuren et al., 2011a; Wayne, 2013).

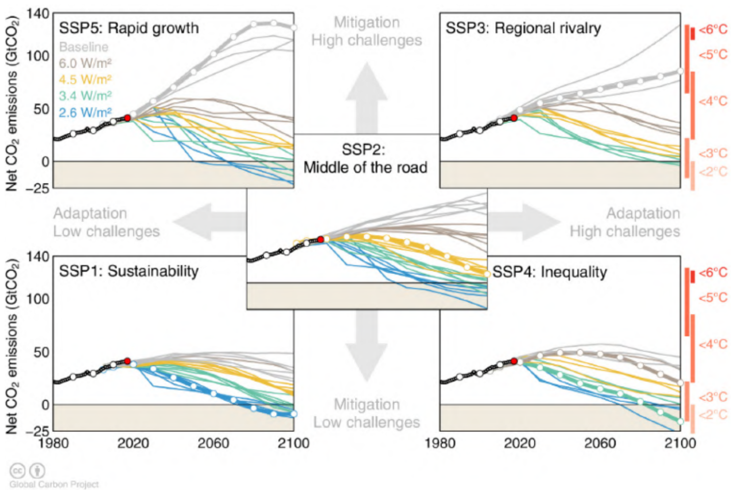


Figure 6: Global CO_2 emissions ($GrCO_2$) for all IAM runs in the SSP database. Chart produced by Global Carbon Project.

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

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

1.2 Data and method

The basis for the evaluation of the current and near-past climate in this study is the climate observational dataset W5E5 (Cucchi et al., 2020; Lange et al., 2021), a dataset based on a combination of simulations from global weather models, satellite data and in-situ observations. The dataset covers the time period 1979-2016 at daily temporal resolution and the entire globe at 0.5° x 0.5° grid spacing (corresponding to approximately 55 km x 55 km in Niger). W5E5 was compiled to support the bias adjustment of climate data, which drive the impact assessments carried out in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; (Lange, 2019a, Lange & Büchner, 2021)), of which this report also makes extensive use.

Future climate projection data simulated by Global Climate Models (GCMs) was obtained from ISIMIP3b. Historical simulations cover the years 1850-2014 and future projections (under both greenhouse gas emissions scenarios) cover the years 2015-2100. W5E5 is the observational reference dataset used for bias adjustment and statistical downscaling of ISIMIP3b. The GCMs[2] included in ISIMIP3b are: CanESM5 (short: Can), CNRM-ESM2-1 (short: CNES), CNRM-CM6-1 (short: CNCM), EC-Earth3 (short: EC), GFDL-ESM4 (short: GFDL), IPSL-CM6A-LR (short: IPSL), MIROC6 (short: MIROC), MPI-ESM1-2-HR (short: MPI), MRI-ESM2-0 (short: MRI) and UKESM1-0-LL (short: UKE) (Lange, 2019a, Lange & Büchner, 2021).

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

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

Rainy season onset was obtained using a definition adapted from Laux et al. (2008) and Stern et al. (1981), which was designed for West Africa and suitable for the southern parts of Niger, while in the north precipitation amounts are too small to detect a rainy season. Rainy season onset is thus considered to be the first day of the year on which the following conditions are simultaneously met:

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

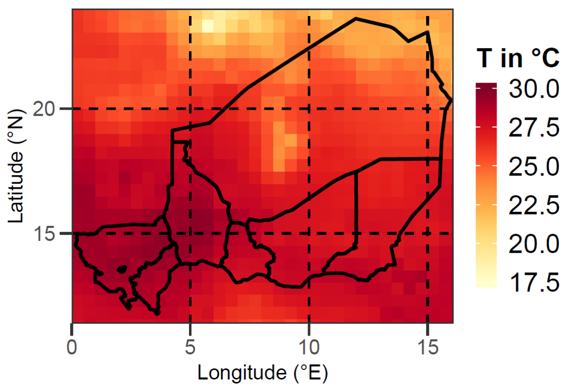
GCMs cannot perfectly represent the current and future climate. They naturally show slightly different projections in modelling the climate, even if they are driven with the same emissions scenario. A detailed validation of all ten GCMs showed that the multi-model ensemble medians (MMEM) is closest to the observations in West Africa. Different projections of all individual models give an indication of the range of uncertainty and the MMEM provides a conservative estimate of possible climatic changes. Thus, the MMEM is shown additionally to the individual model results. Within the report, climate change projections are based on 20-year averages[3], meaning that the mean annual temperature in e.g. 2030 is calculated as an average over the mean temperature between 2021 and 2040. The reference climate, used as the baseline in this study, refers to the climate in 2004 (1995-2014) as the period is included in the historical simulations of ISIMIP3b. The projected climate data is evaluated for the periods 2030 (2021-2040), 2050 (2041-2060) and 2090 (2081-2099). When referring to the changes in the future, the computations have been done for each of these three periods in differentiation to the baseline 2004 (1995-2014) for each model and scenario. For the analysis of the observational data sets, the present climate was obtained by averaging over the most recent available years 1997-2016.

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

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

1.3 Present climatic conditions

Niger currently experiences a mean annual temperature between 23 and 30 °C, with higher values in the south of the country and substantially cooler values in the mountainous regions (Figure 7). While the southern parts of Niger experience only weak inter-seasonal temperature differences, mean monthly temperatures in the north vary between 15 and 35 °C. The number of tropical nights per year ranges from 0 to 180 days with higher values in the west. The number of very hot days is high with around 200 days per year in almost all parts of the country except the high elevated regions and the far north.



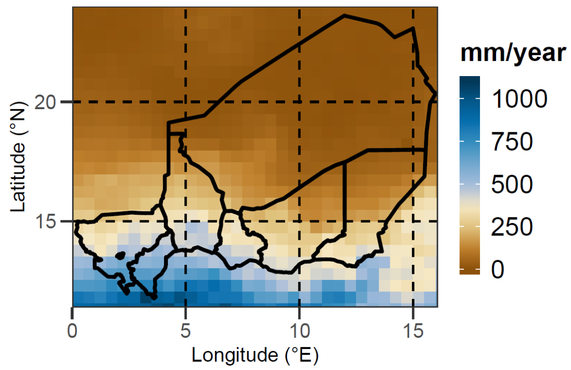


Figure 7: Mean annual temperature in °C (left) and mean annual precipitation in mm (right) over Niger 1997-2016.

The mean annual precipitation sum is between 10 and 800 mm per year, with very scarce precipitation north of 15 °N. The rainy season is between May and October with a substantially shorter period in the north and a general peak in August. Rainy season onset starts mid of June in the south-west and beginning of August in central Niger (Figure 8). Further north, precipitation is too scarce to detect a rainy season.

The rainy season onset and length as well as the precipitation amounts show high year-to-year variability in all parts of Niger with increasing variability towards the north.

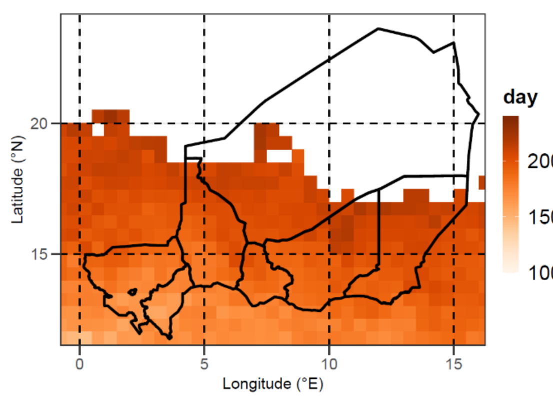


Figure 8: The day of the year marking rainy season onset averaged over the years 1997-2016. White areas indicate very scarce precipitation.

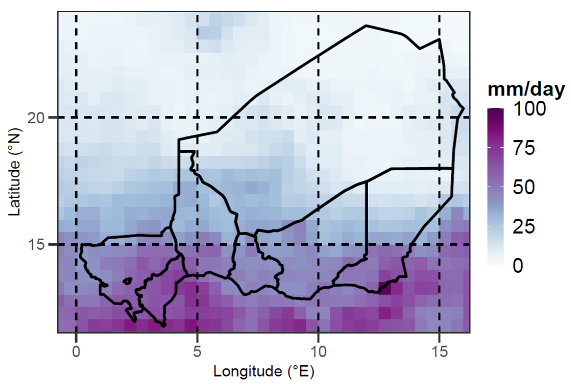


Figure 9: Annual maximum daily precipitation averaged over the years 1997-2016.

While farmers in Niger express large concerns associated with low precipitation amounts, dry spells or late rainy season onset, floods due to increased heavy precipitation events also occasionally lead to crop failure and increased soil erosion.

The maximum daily precipitation amounts averaged over 1997-2016 are between 22 mm and 75 mm (Figure 9) thus showing smaller extreme precipitation values than in other West African countries. Nevertheless, the long dry period and subsequent hardened soils can lead to high damages in case of extreme precipitation events.

1.4 Climate change and variability in the past and near future

Temperature

During the recent past, mean annual temperature showed a robust rise over Niger (Figure 10). Consistently, the number of very hot days and tropical nights increased as well.

Climate models project a robust trend towards increasing temperatures in Niger over the 21st century. This is evident in both analysed scenarios, albeit to different degrees. The multi-model ensemble median (MMEM) indicates an average increase of the mean annual temperature over Niger of 0.9 °C (2030), 1.3 °C (2050) to 1.3 °C (2090) under SSP1-RCP2.6 (low emissions scenario) and of 0.9 °C (2030), 1.9 °C (2050) to 4.2 °C (2090) under SSP3-RCP7.0 (high emissions scenario) in reference to 2004 (compare Figure 11). Under the low emissions scenario, temperatures do not increase strongly after 2050, following the stabilisation of GHG emissions before mid-century. Taking the temperature rise before 2004 into account (IPCC, 2014), temperature rise would be well above the 1.5 °C target by 2050 for most models, even under the low emissions scenario.

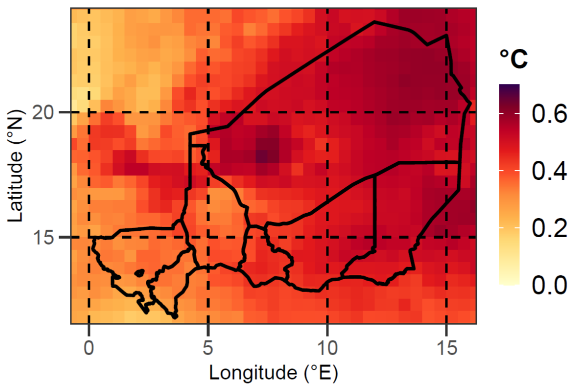


Figure 10: Difference in mean annual temperature in °C over Niger from 1988 to 2006.

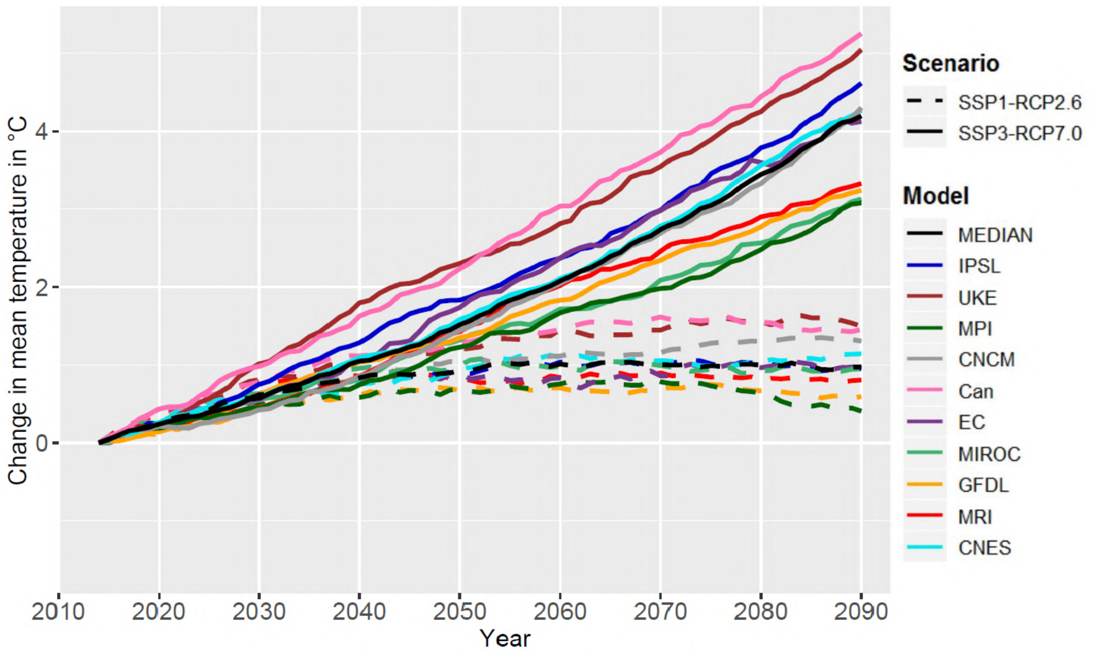


Figure 11: The 21-year moving average of projected change in mean temperature in °C compared to 2014. Values are averages over Niger. Each variegated line indicates a projection of one of the ten individual models. The black line displays the MMEM.

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

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

In the future, the number of very hot days and tropical nights increases in all parts of the country and under both emissions scenarios. Due to the more seasonal climate in the north, the south experiences even stronger increases. On average, models project 276 very hot days per year (Figure 12) and 212 tropical nights (Figure 13) in Niger by the end of the century under the high emissions scenario. The southern parts of the country are currently and will in the future experience more very hot days and tropical nights. Due to an increasing temperature seasonality towards the north, the northern part experiences the extremes mainly in boreal summer.

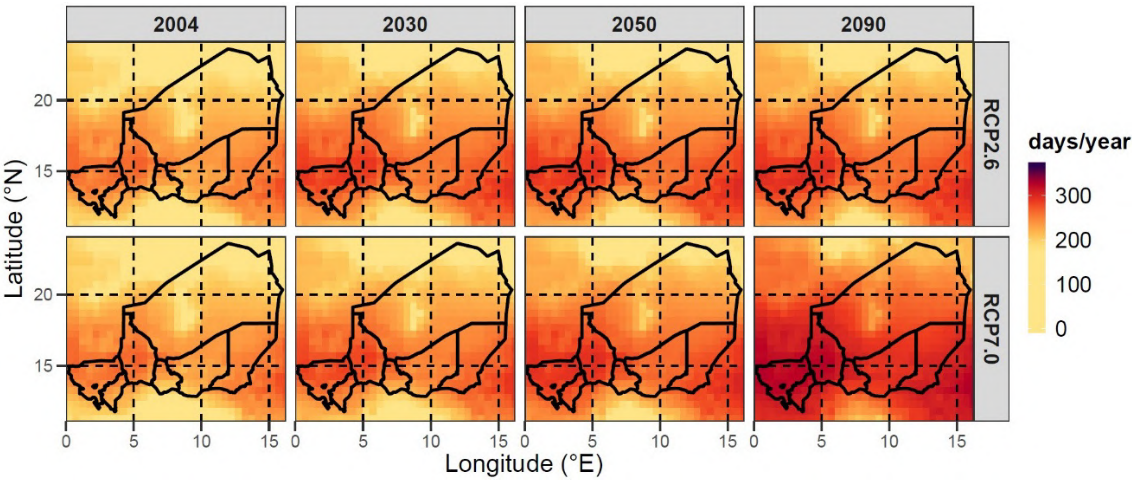


Figure 12: Projected and simulated number of very hot days per year, for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

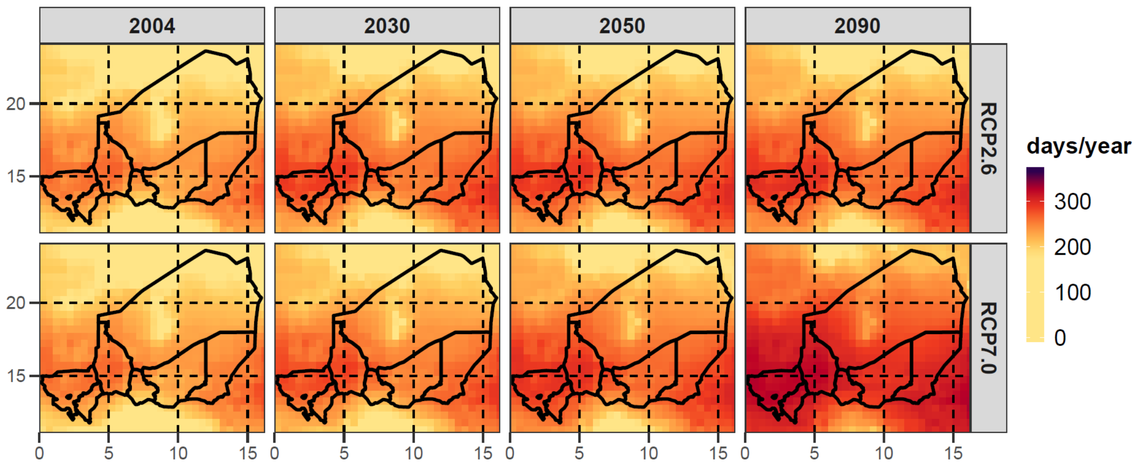


Figure 13: Projected and simulated number of tropical nights per year, for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

Precipitation

Niger experienced decades of drought in the 1970s and 1980s. The mean annual precipitation sum has partially recovered since then but has not yet returned to its pre-1970s values. Annual precipitation increased in the recent past in all parts of Niger (Figure 14). In the southern part of Niger, precipitation has increased even by several dozen percent.

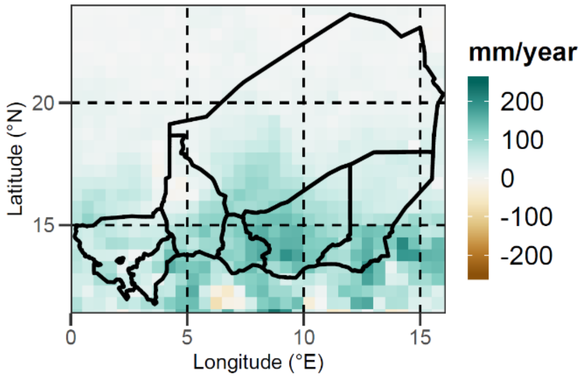


Figure 14: Difference in and mean annual precipitation sum in mm over Niger from 1988 to 2006.

In continuation of this existing trend, the MMEM projects increases of annual precipitation sums in the whole country under both emissions scenarios until 2050. Under the low emissions scenario, only slight increases are projected for the next decades and after 2050 precipitation is projected to decrease slightly. Continuous increases of the precipitation amounts are projected under the high emissions scenario (Figure 15 & Figure 16). Year to year variability of annual precipitation shows slight decreasing trends in the first half of the century, whereby the results are highly uncertain. At the end of the century, the variability is projected to increase clearly with high model agreement.

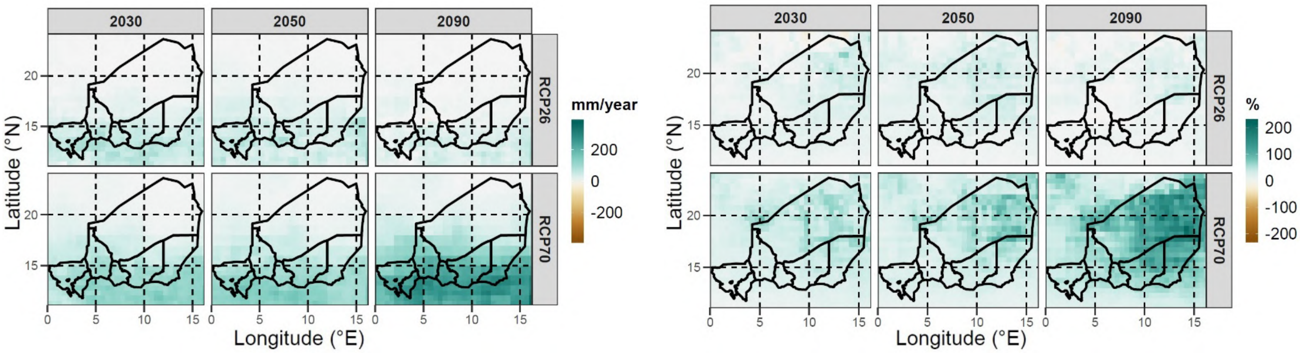


Figure 15: Projected change in mean annual precipitation in mm/year (left) and percent (right) for the 20-year period averages 2030, 2050 and 2090 in relation to 2004 (1995-2014) under SSP1-RCP2.6 and SSP3-RCP7.0.

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

Recent studies have indicated a future strengthening of the WAM and a westwards shift of current precipitation patterns under global warming[4] (Aschenbrenner, 2018; Roehrig et al., 2013; Schewe & Levermann, 2017). However, even though most models analysed also point to a wetter climate in Niger, it cannot be ruled out that the country could experience a drier future climate, as some models under both scenarios suggest. Defrance et al. (2017) conclude that the continuation of the rapid melting of the Greenland ice sheet could lead to a sudden weakening of the WAM[5] and thus a decrease in annual precipitation amounts in the Sahel.

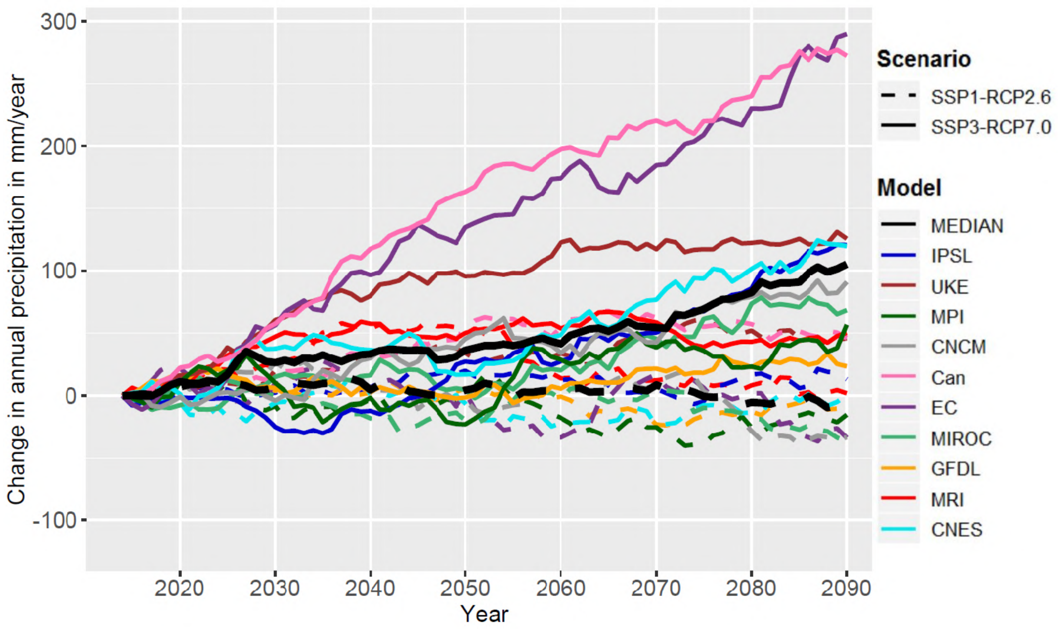


Figure 16: The 21-year moving average of projected change in annual precipitation in mm compared to 2014. Values are averages over Niger. Each variegated line indicates a projection of an individual model. The black line displays the MMEM.

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

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

Heavy Precipitation Events

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

Furthermore, heavy precipitation intensity as well as frequency are also projected to increase in all parts of the country with similar patterns to the projected increase of the mean annual precipitation amount (Figure 18). Under the high emissions scenario, all models agree on an increasing trend in heavy precipitation intensity. This also holds for those models that project only slight changes in mean annual precipitation sums. Under the low emissions scenario, the models project no or small changes in heavy precipitation intensity until the end of this century.

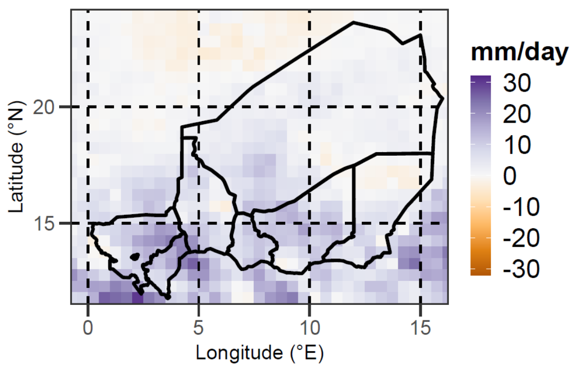


Figure 17: Change in annual maximum daily precipitation from 1988 to 2006.

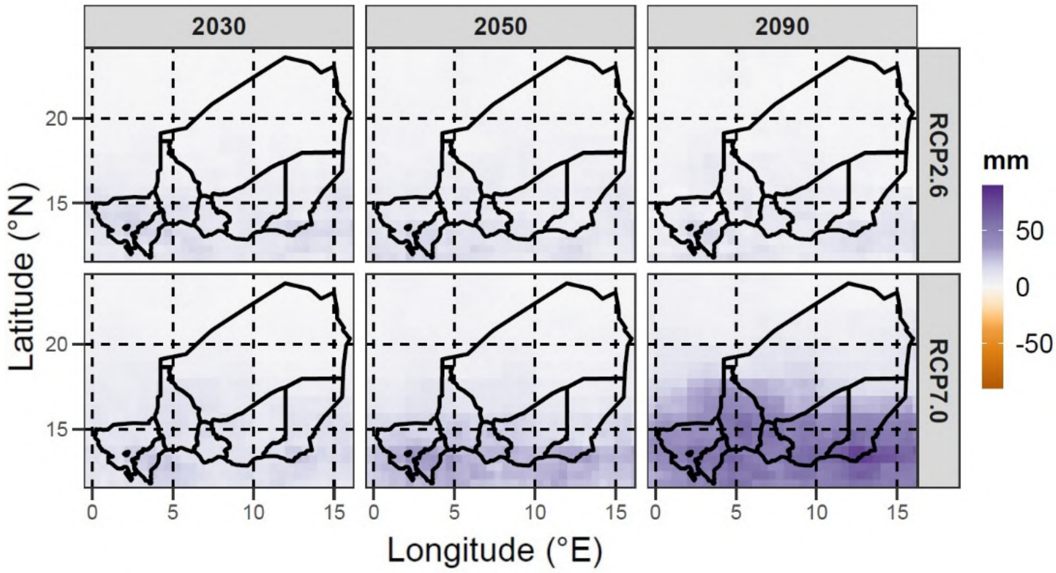


Figure 18: Projected change in annual maximum daily precipitation in 2030, 2050 and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row).

Rainy season onset

Rainy season onset and length showed high variability, but no clear trend in any direction in recent decades. For the future, the climate models tend to project an earlier start of the rainy season under both emissions scenarios until 2030. Afterwards, the trends are diverging with a projection of a later onset under SSP1-RCP2.6 and an earlier onset under SSP3-RCP7.0 including regional differences (Figure 19). These results are characterized by high uncertainties due to the differences between the individual model projections, especially under SSP3-RCP7.0 (Figure 20).

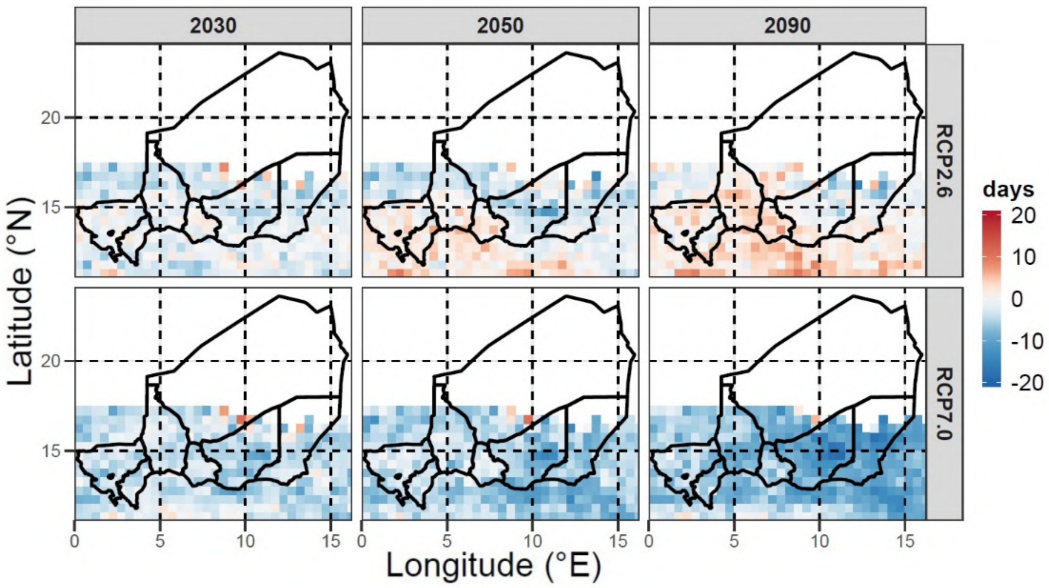


Figure 19: Projected change in rainy season onset in days in 2030, 2050 and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row). Red colour indicates later rain while blue colour indicates earlier rain. White areas indicate areas with too little precipitation to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

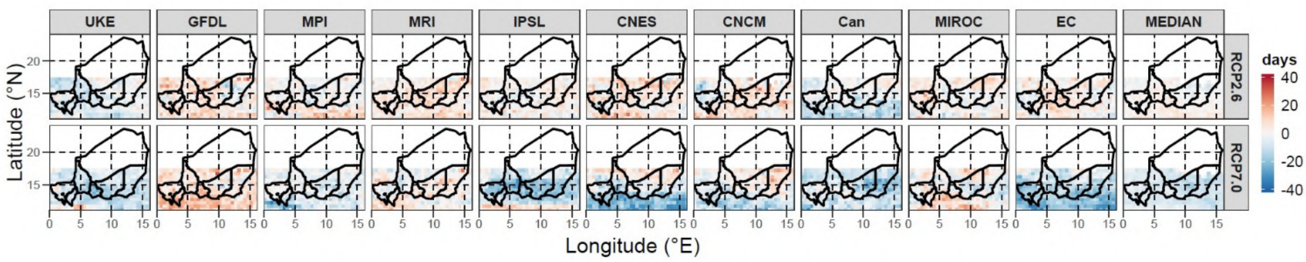


Figure 20: Projected change in rainy season onset in days in 2090 (2081-2100) compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row) for all ten individual models and the MMEM. Red colour indicates later rain while blue colour indicates earlier rain. White areas indicate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

Chapter 1 Summary

In addition to natural variability, the climate in Niger showed a clear changing trend. Future projections mainly show a continuation of the existing trends. For higher future GHG-emissions, the projections show stronger climatic changes and higher ranges of possible future climate conditions. Mean temperature and temperature extremes are clearly projected to rise continuously. Even though projections related to precipitation are subject to some uncertainties, the models agree well on projecting an increase in annual precipitation sums and precipitation extremes in Niger. Under the low emissions scenario the climate is projected to stabilize after 2050 while the changing trends are projected to continue under the high emissions scenario during the second half of this century. The summary Table 1 below displays the observed past climate trends and projected future trends of different climate variables.

Table 1: Overview of changing climatic conditions for Niger.

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

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

Chapter 2 – Hydrological changes

The agricultural sector in Niger plays a vital role for the country's economy and peoples' livelihoods. Yet, due to its arid climate, water resources and precipitation are often scarce and present one of the biggest constraints to agricultural production. This chapter evaluates hydrological changes in Niger using a semi-distributed hydrological model that is driven by the GHG concentration pathway scenarios and GCM outputs presented in Chapter 1. Expected changes in vital hydrological parameters relevant to agricultural and communal water supply are then being discussed in connection with possible adaptation strategies investigated in a scenario approach.

2.1 Niger's hydrology in brief

Niger is largely a desert country with an arid climate, and scarce and highly variable precipitation (10-800 mm/y). The rainy season between June and September in the south (with rare precipitation in the north) produces a highly seasonal, intermittent runoff regime (Mahé, 2006). The main surface water artery of the country is the Niger River in the south-west of the country draining into Nigeria and thereafter into the Gulf of Guinea. Its physiological catchment covers approximately 50% of Niger's territory, even though most parts are hydrologically inactive (Figure 21). The east of the country is dominated by the largely uninhabited Sahara Desert and the Lake Chad endorheic catchment.

Due to its primarily rural and on agriculture depending population (78%) and its arid climate, Niger is considered a water-stressed country, with irrigation accounting for more than 85% of water demand. The rest is made up of communal and industrial water use concentrated in the capital region around Niamey. Groundwater is the most important source of drinking water accounting for more than 90% (Pavelic et al., 2012). Although the total nationally abstracted water volume only represents a small fraction of the estimated annual groundwater recharge with approx. 1.5%, (Martin & van de Giesen, 2005), spatial distribution and depth of the water table vary widely and are influenced by both precipitation patterns and local abstractions. The country's susceptibility to droughts gave rise to the construction of mechanised, small-scale irrigation systems predominantly along the Niger River and the southern border with Nigeria. Rain-fed agriculture still dominates the rest of the country. Since precipitation typically occurs in heavy and short events and evapotranspiration is equal to around 80-95% of annual precipitation sum, soil crusting is a frequent problem. The soil is sealed and compacted by salt deposits, favouring higher rates of overland flow and lower rates of infiltration (Descroix et al., 2009; Descroix et al., 2012).

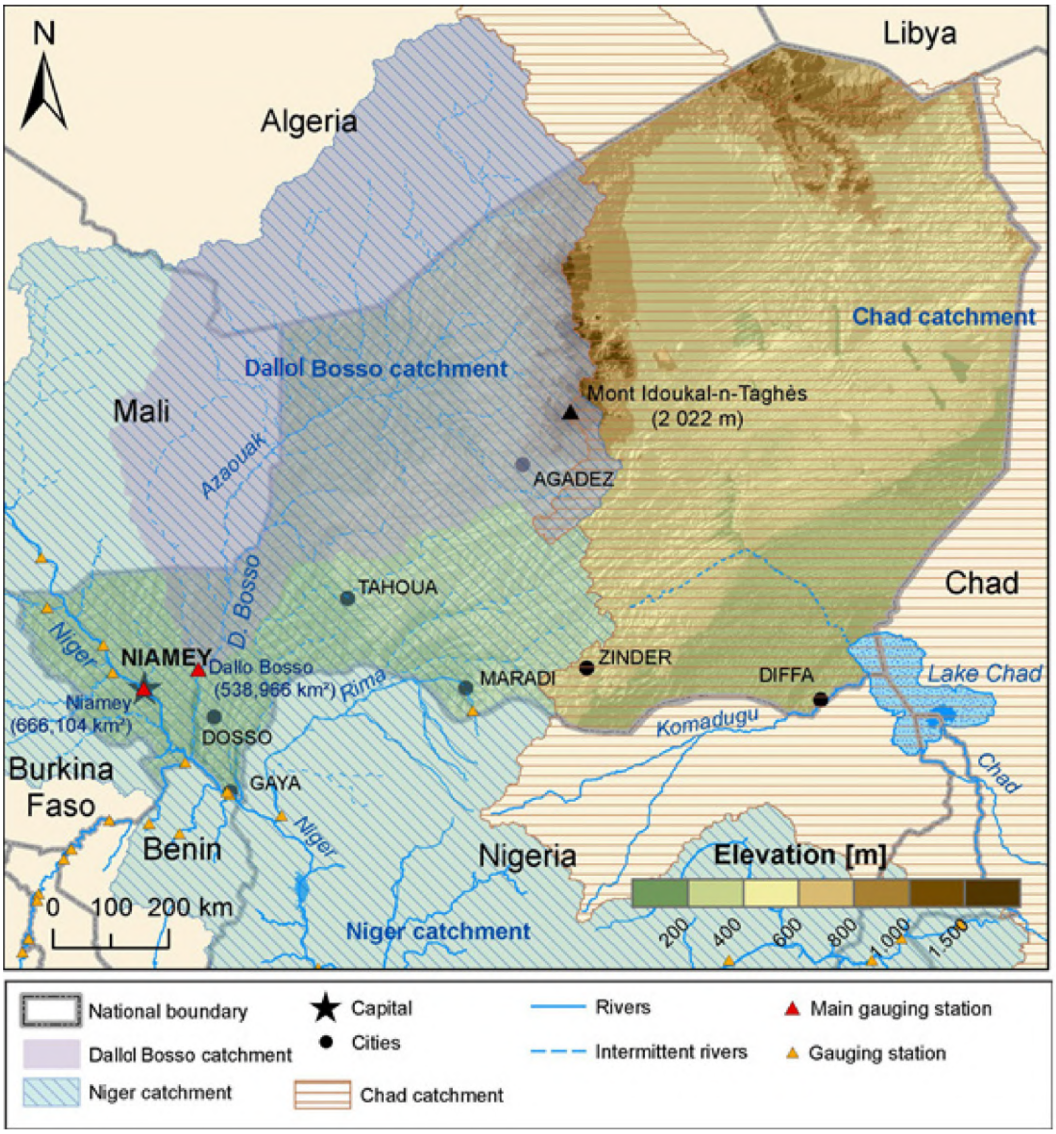


Figure 21: Map of Niger with the catchment boundary of the Niger River. The main rivers and their significant gauging stations are labelled.

2.2 Data and method

Within this study, the hydrological projections under climate change are primarily based on results of the eco-hydrological Soil and Water Integrated Model (SWIM, (Krysanova et al., 2015)) driven by the scenarios and global climate model results presented in Chapter 1, i.e. an ensemble of 10 GCMs from the ISIMIP3b project. SWIM is used to simulate the hydrological processes in the Niger basin (Niger River). This catchment covers approx. 50% of the country (the remaining desert in the east is not covered by the model). Annual absolute and relative changes in river discharge at various locations are given as well as average monthly changes in three future periods: 2021-2040, 2041-2060 and 2080-2099. Future changes are differences to the baseline 1995-2014. Different data inputs are used to setup and calibrate the model: The Shuttle Radar Topography Mission (SRTM) 90 m digital elevation model is used to delineate sub-basins. Soil parameters are derived from the Harmonised World Soil Database (HWSD v1.0) and data on land use and cover are derived from the Global Land Cover map (GLC2000). The hydrological model is calibrated and validated using daily discharge data at gauges throughout the basin in the period 1960–2010 depending on each station's data availability. Observations are provided by the Global Runoff Data Centre (GRDC). Major reservoirs as well as water withdrawals are considered in the simulations mainly relying on assumptions as detailed data are unavailable. Land use and cover are also considered to be constant without change in future periods.

2.3 Past changes

Historical hydrological changes in Niger and West Africa as a whole are dominated by interannual and decadal variability. It is generally agreed that the 1950s and 1960s were predominantly wet periods followed by a pronounced and devastating drought in the 1970s and 1980s (Conway et al., 2009; Descroix et al., 2012; Mahé et al., 2013). Since then, precipitation amounts and, accordingly, river discharges have recovered to long-term average conditions with an increasing trend since the late 1990s. For Niger, this development is shown by available long-term discharge data of the Niger River in Figure 22. The Niger River's regime has changed drastically with a shorter and lower flood peak (Figure 23). The arid to semi-arid conditions of the region cause the runoff to be highly sensitive to changes in precipitation patterns. For example, Mahé and Olivry (1999) found that a decrease of 15-20% in precipitation results in disproportionate decreases in discharge of up to 60%.

Apart from the climatic changes discussed in Chapter 1, changes in surface and groundwater resources are also strongly determined by changes in land use and water management. Both factors have changed drastically in Niger since the latter half of the 20th century (Mahe et al., 2005). Continuous population growth has led to extensive conversion of natural vegetation (bush and shrubland) in the south of the country to cultivated land that favours higher rates of surface runoff and lower rates of infiltration to recharge groundwater resources. Less permanent vegetation cover and soil compacting lead to a lower infiltration capacity. Soil compacting is due to conversion of natural vegetation to cultivated land, for instance cultivated land leads to higher soil compacting than natural vegetation. At the same time, groundwater extraction has become more mechanised with increasing rates of abstraction due to the construction of an abundance of deep wells and pumping capacity (Pavelic et al., 2012).

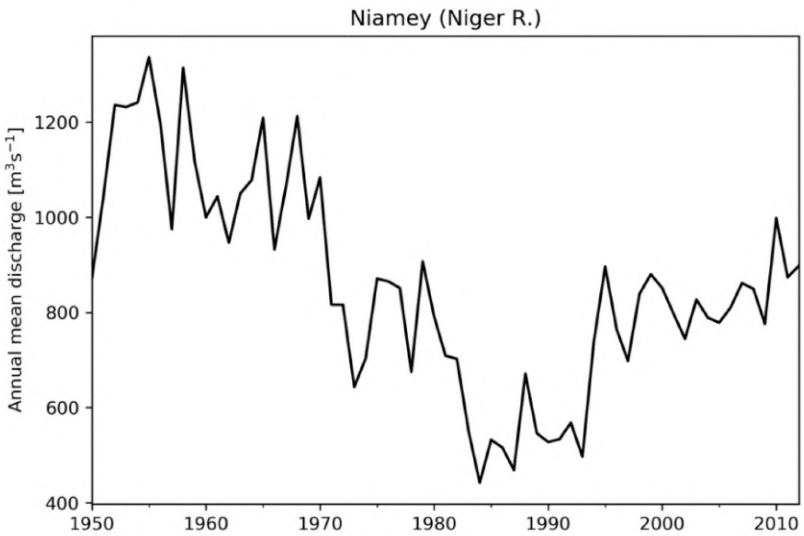


Figure 22: Long-term observed discharge of the Niger River at Niamey.

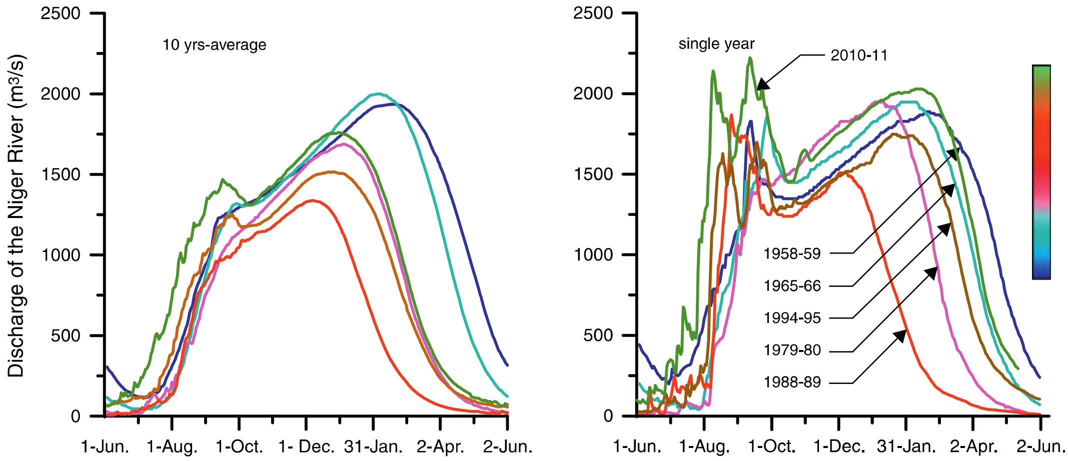


Figure 23: Changes in the discharge regime of the Niger River at Niamey, 1950-2010 (Descroix et al., 2012).

2.4 Hydrological changes under 21st century climate change

2.4.1 River discharge

In line with increasing precipitation amounts (Chapter 1, Section 1.4), river discharge is also projected to generally increase in the annual average, although not under all scenarios and GCMs (Figure 24). The country's largest river is projected to carry 8% (12%) more annual discharge in the near future (2021-2040) in the ensemble median under the low (high) emissions scenario compared to the reference period (1995-2014). Towards the middle of the century (2041-2060), both scenarios still project increases of 25% (9%) to eventually decline again to -3% (0.5%) in 2080-2099. This development is also expected for the smaller and drier catchment of the Dallol Basso, an ephemeral, left bank tributary to the Niger River draining the centre of the country. The increases in the ensemble median are much larger, with 30-45% under the SSP1-RCP2.6 scenario and up to 145% (end of the century) under the SSP3-RCP7.0 scenario, with the greatest divergence at the end of the century. Arid catchments are susceptible to large increases if most of the precipitation increases result in more infiltration, excess runoff or typically inactive parts contribute discharge to the river again. Ensemble ranges are large, however, hinting at the great variability between the GCMs. Especially under the low emissions scenario, interquartile ranges cover opposite directions of change in the Niger River at the end of the century.

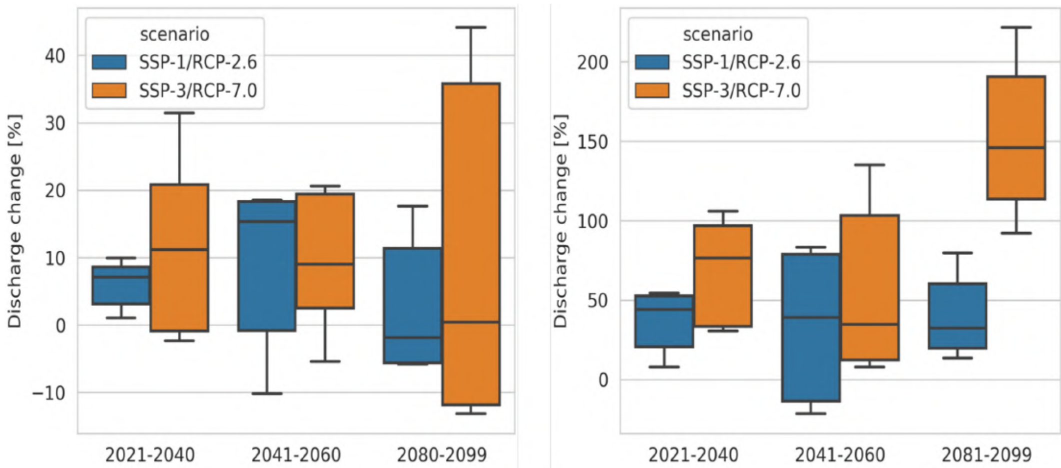


Figure 24: Projected change in annual mean discharge at Niamey (Niger River, left) and at Baleyara (Dallol Bosso, right).

In the monthly discharge regime, these annual changes are reflected mainly in the months from July to December during and after the rainy season (Figure 25). An increase in the Niger River (Dallol Bosso) discharge in the months October and November (August and September) is evident for all periods and scenarios. At the end of the century (2080-2099), discharge is projected to decline again to former levels, especially under the SSP3-RCP7.0 scenario in the Niger River. A pronounced increase in discharge at the end of the century is projected within the months of August and September in the Dallol Bosso catchment. Ensemble uncertainties (indicated by the interquartile and min.-max. ranges in Figure 24) are particularly large under the high emissions scenario and in the 2080-2099 period. Where river flows are sustained throughout the year (e.g. the main Niger River), minor changes are projected largely following the annual trend. The temporal changes are driven by the strengthening of the West African Monsoon (WAM, cf. Section 1.4) and may well spell more available surface water during the raining season, leading to larger seasonal floods and increased rates of groundwater discharge.

Figure 25: Mean monthly discharge in the reference period (blue) and the three future periods for the low emissions scenario (left) and the high emissions scenario (right) at Niamey (Niger River, top) and at Baleyara (Dallol Bosso, bottom). Error bars refer to the interquartile range (coloured) and the full ensemble range (whiskers).

2.4.2 Groundwater recharge

Apart from river discharge, groundwater recharge is an important hydrological flow which determines future groundwater resources available for groundwater dependent communities. The increases in precipitation partially also translate to greater annual rates of groundwater recharge mainly under the SSP3-RCP7.0 scenario in large parts of the Niger basin, but especially in the south of Niger (Figure 26). Under the low emissions scenario, increases are moderate and mostly not significant considering the ensemble spread.

Given the large ensemble range, much of the change is statistically not significant (comparing the period means of the baseline and the future periods). Especially the increase in the ensemble median under the low emissions scenario at the end of the century shows no significant changes. This is largely in line with the climatic variability of the region that is reflected in the disagreement of the climate models. However, the results still give important indications of general trends and clearly show the differences between the emissions scenarios.

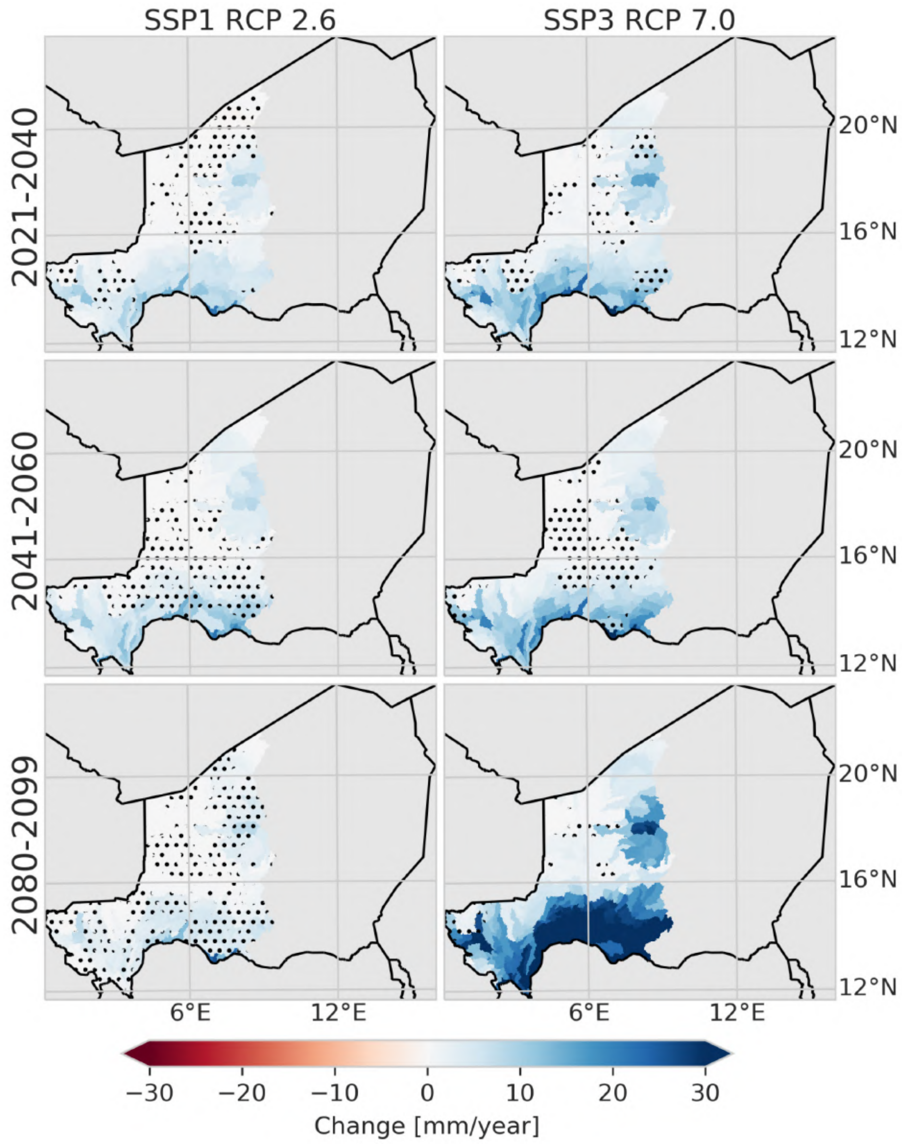


Figure 26: Median change in groundwater recharge (at subbasin level) compared to the reference period (1995-2014) for both scenarios (left/right) and the three future periods (top to bottom rows). Dotted areas indicate statistically insignificant changes (5% significance level) considering the period means of the ensemble. Areas in grey are either outside of Niger or outside of the model domain.

With the projected rise in temperature (Chapter 1) and the associated intensification of the hydrological cycle, other hydrological indicators are also projected to increase in Niger. Annual peak discharge, an indicator for the seasonal flood, is projected to increase in line with seasonal increases in discharge (Figure 25), making dangerous flooding more likely.

It is important to note that the climate of Niger is dominated by strong interannual and multi-year fluctuations, exemplified by the historical observations of very wet 1960s, dry 1970s, and very dry 1980s. This quasi-oscillation pattern is also reflected in the hydrological indicators and in many cases the amplitude is larger than the projected changes presented here. The choice of the baseline and future periods can thus have a significant influence on the projected changes, as discussed by Liersch et al. (2020) with an example of the neighbouring Volta basin. GCM results are a synthetic realisation of the weather in the baseline and future periods. Although these quasi-oscillation patterns are reflected, they are not synchronised between the models (Figure 27). That is, one model might project wet 2050s and several others very dry ones. This partly explains the large range of uncertainties and opposing signals of change.

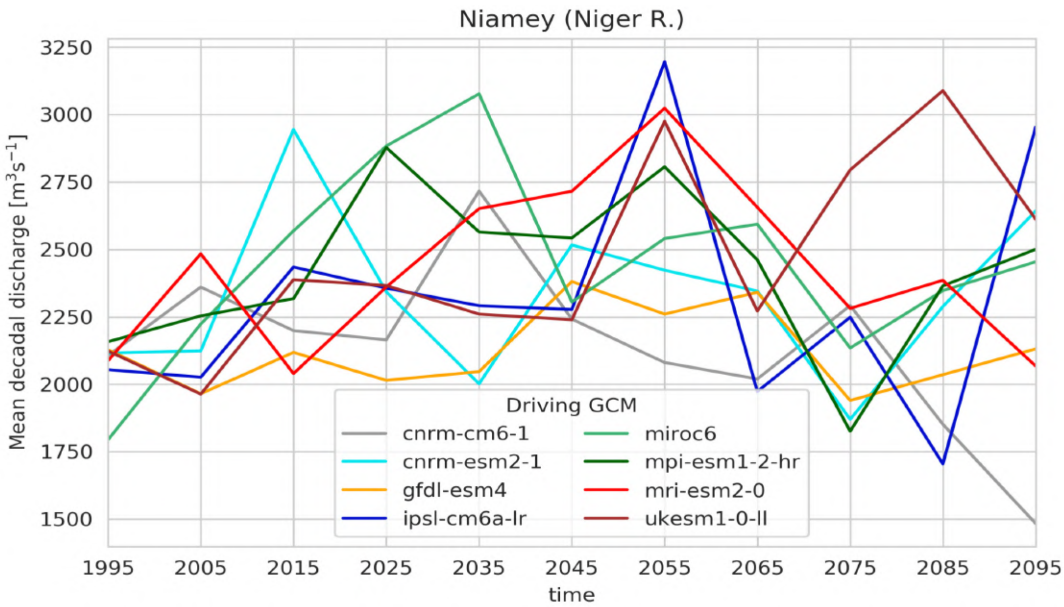
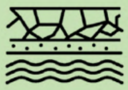
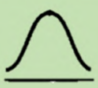


Figure 27: Decadal mean discharge at Niamey (Niger River) simulated by SWIM under SSP1-RCP2.6 scenario driven by the GCM ensemble given in the legend.

Chapter 2 Summary

This chapter evaluated hydrological changes in Niger, using a semi-distributed hydrological model that was driven by the emissions scenarios and GCM output presented in Chapter 1. It further discussed expected changes in vital hydrological parameters relevant to the agricultural and communal water supply. The trends refer to long-term annual averages and ensemble medians. Results show that a general increasing trend in the country's largest river discharge is projected towards the middle of the century with a decline again by 2090, under both emissions scenarios, yet with a stronger increase and lower decrease under SSP3-RCP7.0. Furthermore, trends are similar but stronger in their effect for smaller and drier catchments, covering a range of 30-45% under SSP1-RCP2.6 and 30-145% under SSP3-RCP7.0, with the greatest divergence at the end of the century. Increasing precipitation trends also translate into increasing groundwater recharge levels, with effects most pronounced in southern Niger under the high emissions scenario towards the end of the century.

Table 2: Summary of hydrological changes under climate change in Niger.

Impact		Trend past	Trend future	Confidence
	**Discharge**	Increasing ↗	Increasing, decreases possible under SSP1-RCP2.6 ↗	Medium
	**Groundwater recharge**	Increasing ↗	Increasing, esp. under SSP3-RCP7.0 ↗	Medium
	**Evapotranspiration**	No major change	Slightly increasing	High
	**Flood peak discharge**	Increasing since the 1990s ↗	Increasing, but shifts in regime possible ↗	Medium

Chapter 3 – Climate impacts on agricultural production

Niger is a dryland, two-thirds of it being arid, with crop production restricted to the southern part of the country. Even in the Sahelian and the Sudano-Sahelian zones, crop production is limited as they only receive 200 to 500 mm and 600 to 800 mm of rainfall per year respectively. The rainfall is usually received in only three months in a year (July, August and September) with high temperatures of up to 45 °C. Despite these limiting climatic conditions, rainfed smallholder subsistence agriculture is dominant in Niger, with irrigation covering less than a tenth of the cropped area. Major crops in the country are pearl millet, sorghum and cowpea while other crops produced include maize, cassava, rice and sweet potato. Low rainfalls with large inter-annual variability explain the low and fluctuating yields in the country coupled by low capacity of farmers, depleted soil fertility, limited extension services and lack of access to quality agricultural inputs. Climate change is adding pressure to an already depressed agricultural capacity in Niger and could worsen an already bad situation in terms of crop potential and yield. Weather, soil fertility and agricultural management, which in turn is, arguably, driven by policy incentives, resource endowment, and biophysical conditions, are the main drivers of agricultural crop yield variations. Yet, the extent to which these factors determine crop yield levels varies over time and space.

In this chapter, we therefore take a closer look at climate impacts on crop production from three perspectives. In the first part, we use the semi-statistical crop model AMPLIFY to assess the role that current day-to-day weather variability plays in determining crop yields for maize, cowpea, sorghum and millet[7] in Niger, at both national and sub-national (regional) level. The second part assesses the biophysical suitability for selected crops to be grown in specific areas of Niger, and how that suitability might change under climatic conditions towards the middle of the century. Lastly, we complement this analysis by looking also at the long-term projected impacts of climate change on agricultural yields by 2030, 2050 and 2090. For this, we use the process-based crop model DSSAT and focus on the case study of sorghum under the two future emissions scenarios SSP1-RCP2.6 (low emissions scenario) and SSP3-RCP7.0 (high emissions scenario), since millet and sorghum show similar strategies to adapt to water stress and climate change-like conditions (Choudhary et al., 2019).

3.1 Historical weather influence on crop production

3.1.1 Data and method

Crop yields in Niger are strongly influenced by weather. To determine the share of weather in crop yield variation, the study focuses on yield anomalies to avoid any influence from long-term trends in management (fertiliser application, cultivar changes etc.), which could distort the estimation of weather influences on crop yields. Anomalies are defined as variations around a local-regression trend (fitted with “loess”, a standard approach for non-parametric trend estimation). Regional time series of observed and modelled yield anomalies – obtained from WASCAL, for the years 2000 to 2018 – are aggregated to national level, using area shares as weights.

The applied modelling scheme is a variant of the AMPLIFY model (Agricultural Model for Production Loss Identification and Failures of Yields) (Gornott & Wechsung, 2016; Schauberger et al., 2017) and consists of a LASSO regression with a cross-validated variable selection and an out-of-sample (OOS) validation. For the OOS all combinatorial pairs of two years were subsequently omitted from model training and then predicted by this

[7] There are 9 different types of crop millets. The analysis focuses on pearl millet.

model, thus treating the two withheld years as 'new' data that demonstrate the capacity for generalization. This OOS performance more reliably indicates the true share of weather-explained yield variation, since estimations with the full model are prone to overfitting with the short time series available (19 years).

Weather data are extracted from ERA5 (temperature) and CHIRPS (precipitation), downloaded from Google Earth Engine in May and June 2020. Their original resolution is ~25 km and was remapped to regional level. Monthly and seasonal aggregates of daily maximum, minimum and mean temperature as well as precipitation amounts are included in the model, after shrinking highly correlated (Pearson's $r > 0.7$) variable groups to one representative variable per group. Growing seasons are adopted from the FAO cropping calendar for Niger, using June to October for cowpea and maize and July to October for millet and sorghum.

3.1.2 Results

The share of yield variation that can be explained by weather variation is high for cowpea, maize, millet and sorghum both on national (Figure 28) and regional level (Figure 29). For all four crops, more than 50% of observed yield variation at national level is found to be caused by variations in weather during the growing season, as evidenced by the out-of-sample model curves in Figure 28. Pronounced positive and negative anomalies – like the drop in maize yields in 2011 or the peak in sorghum yields in 2015 – are well captured by the temperature and precipitation-based regression model. This finding highlights that agricultural adaptation measures need to consider weather anomalies. It also opens a pathway for potential forecasts of crop yield and production if weather can appropriately be forecasted.

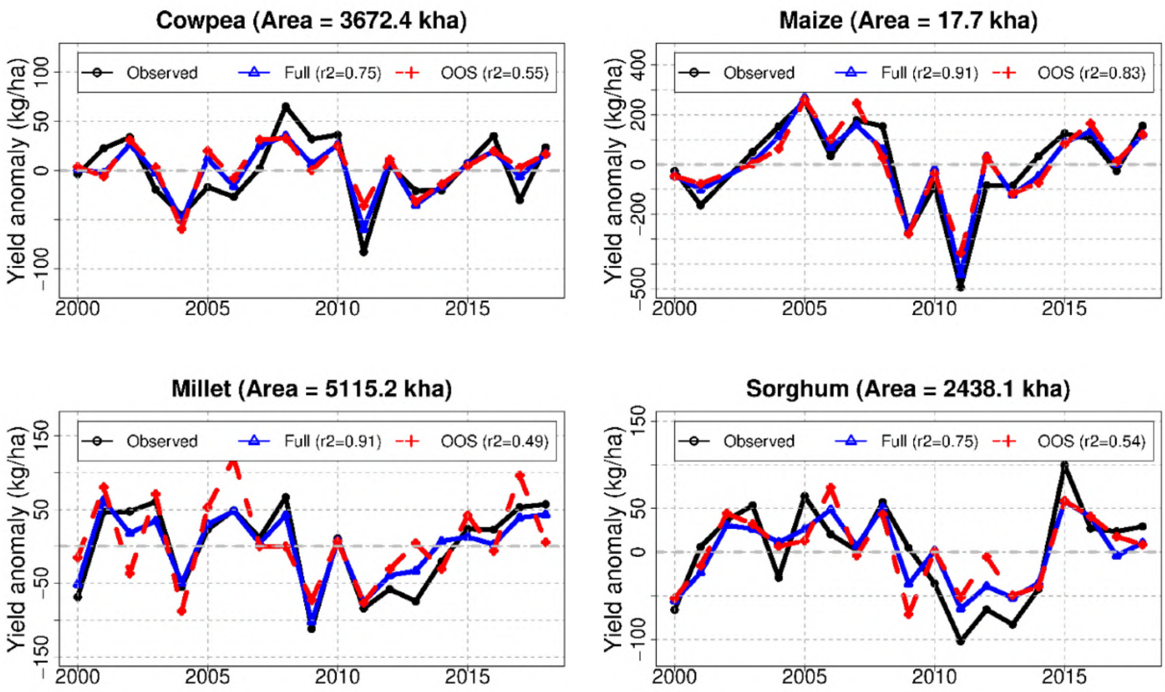
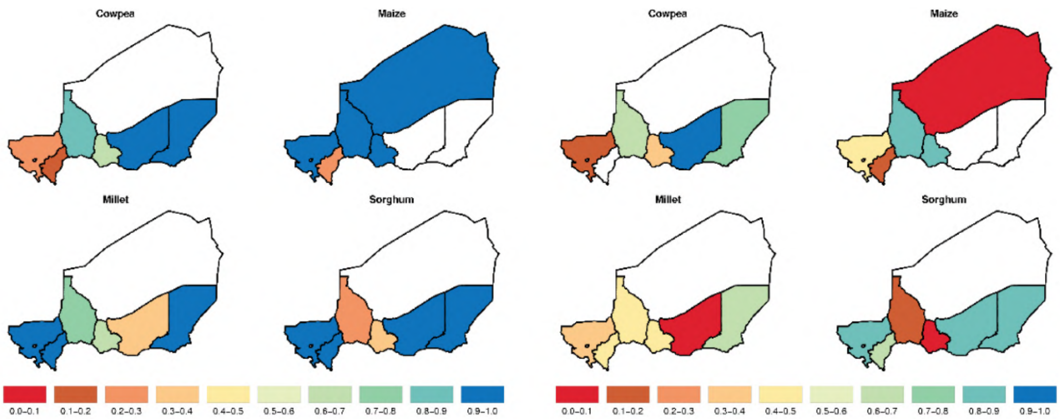


Figure 28: National time series of yield anomalies (kg/ha) for cowpea, maize, millet and sorghum. The crop growth areas per crop are indicated in the headers. Black/blue/red lines are yield anomalies as observed, modelled with full data base and modelled two-out-of-sample (OOS), respectively. The share of explained variance (R2) in yield variation due to weather variation is indicated in the legends for both model types.

The weather-driven explained share of variance on regional level, shown in Figure 29, is highlighting regional differences in modelling capacities. For most crops and regions, robust out-of-sample model estimates ($R^2 > 0.4$, corresponding to a Pearson's r of >0.63) can be achieved. In some cases, for example maize in Agadez, millet in Zinder or sorghum in Maradi, a reliable model could not be constructed. Possible reasons comprise a limited influence of weather on crop growth, errors in the yield data, insufficient quality of the applied weather data for detecting signals or that the regional-level aggregation may be too coarse as weather impacts on yield formation possibly diverge between departments. A lack of weather influences on crop growth is unlikely given the generally strong impacts, though fertiliser input or sowing windows may change between regions and could modify crop responses to weather. Regarding the quality of yield data, it is assumed to be similar across distinct crops and regions, although small growth areas (as in the case of maize in Agadez) may render crop statistics less reliable. Notably, maize yields at department level available to us– though not analysed here – contained many gaps and high variation, which may have repercussions on the regional level yield data used here, if these are compiled from department data. Yet their quality remains difficult to assess from yield data alone. With regards to weather data, it is assumed that their accuracy is equal across regions such that differences in model performance should not depend on the weather data. Finally, a strong divergence of weather impacts on crop growth between areas of the same region is possible but remains elusive without high-resolution long-term data on department level.



(a) Estimation with full data base

(b) Estimation with two-out-of-sample

Figure 29: Share of explained variance (R2) in yield variation due to weather on regional level, for (a) estimation with the full data base and (b) estimation with two-out-of-sample. Red/orange shades indicated a low influence of weather, while green-to-blue shades indicate a substantial impact of weather vagaries on crop yield formation.

3.2 Crop suitability assessment and changing climatic conditions

We conduct a crop suitability analysis in order to better understand and quantify this climate risk on major crops and to inform national adaptation planning and policy development. Crop suitability assessments are based on the understanding that the biophysical parameters (e.g. soil organic carbon) and climatic variables (e.g. total amount of precipitation received in the growing season) play an important role in determining crop production, which is true in many tropical areas where agriculture is influenced by weather. A suitability model therefore uses these variables to create a score for each crop, each period and each location depending on how the variables meet the crop requirements or conditions in known current production areas (Evangelista et al., 2013). Replacing the agronomically important climatic variables such as total amount of precipitation received in the growing season, precipitation in the crop sowing month, rainfall coefficient of variation, mean temperature growing season and temperature variability during the crop growing season with those projected under climate change shows the change in the potentially cultivatable arable land of an area for a specific crop due to climate change (Beck, 2013; Srinivasan et al., 2019). Crop suitability modelling is an assessment of the season-long and specific within-season characteristics that enable certain crops to be produced in specific places.

3.2.1 Data and method

Crop climatic suitability models have been applied to assess the impact of climate change on the potential for sorghum, millet, maize and cowpea as individual crops in Niger. Nine agronomically important biophysical parameters are used in modelling the climatic suitability of the four crops under current and future climatic conditions, following the emissions scenarios presented in Chapter 1. These are precipitation and temperature of the sowing months, precipitation and temperature of the growing season, mean annual temperature, annual temperature range, sum of annual precipitation, soil organic carbon (OC), soil bulk density (BD), with the soil factors not changed under climate change. The eXtreme Gradient Boosting (XGBoost) machine learning approach (Chen & Guestrin, 2016) was used to model suitability.

The crop production data for each of the four selected crops was split into four groups (optimal, moderate, marginal and limited) using percentiles of the average yield. For example, areas with optimal suitability are defined as areas that are above the 75th percentile of the long-term average crop yield, representing areas with no significant limitations to sustained production and stability over time. Moderate suitability corresponds to areas allowing for crop production within the 50th to 75th yield percentile, marginal suitability to the 25th to 50th yield percentile, and limited suitability to areas with less than the 25th percentile of long-term average yield, thus indicating that the biophysical conditions in these areas are not apt for the crop under analysis.

The models were evaluated before application using leave-one-out cross validation. In addition to the class based performance indicators for each crop such as specificity, sensitivity and balanced accuracy, we calculate the multi-class area under the receiver operating curve (AUC) for assessing overall model performance as defined by Hand & Till (2001).

The results of the four crops are also combined to identify how the potential for multiple cropping will change under climate change, as an indicator of diversification or crop switching potential. In order to determine the climatic suitability for cultivation of the four key staple crops for Niger, the suitability of the individual crops is combined in order to understand which areas will have multiple crop suitability now and under climate change conditions using the method by Chemura et al. (2020). In this approach, the individual suitability maps are stacked to determine the number of crops that were suitable for each cell and then the cells with the levels of suitability for each crop are counted. Changes in suitability proportion and distribution between the current and the projected climatic conditions were assessed by comparing areas between time periods and climatic scenarios.

3.2.2 Determinants of crop suitability in Niger

The relative contribution of each variable used in the model to the suitability of each crop was established using permutation importance (Figure 30). This ranked the variables as determinants for sorghum, millet, maize and cowpea. The most important variable for sorghum suitability was the amount of precipitation in the growing season while for millet annual rainfall amount was the most important factor. Temperature variables were the most important for maize (growing season temperature - 19%) and cowpea (sowing months temperature - 44%). Overall, the suitability of the crops is influenced by different factors, with rainfall being the most significant one for sorghum suitability while temperature variables are most important for millet, maize and cowpea. The significance of soil factors was evident for maize (27%) and millet (21%), which in both cases were lower than rainfall and temperature variables.

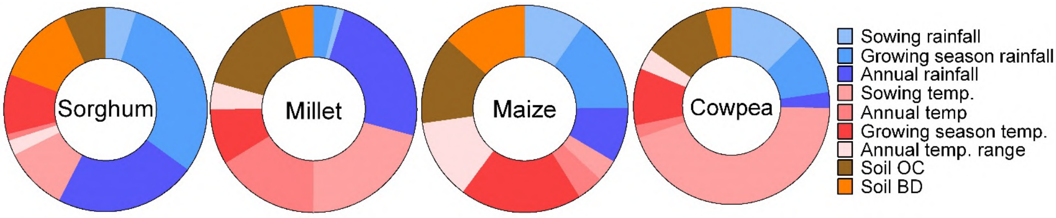


Figure 30: Importance of variables in modelling the suitability of sorghum, millet, maize and cowpea in Niger.

3.2.3 Current crop suitability

Sorghum is suitable in the southern regions of Niger with 6.9% and 6.1% of the country classified as optimally and moderately suitable for sorghum under current climatic conditions. These areas are found in all provinces except for Agadez, which has the largest area with limited suitability for sorghum (Figure 31). Our model shows that millet is suitable on 6.4% of the country under current climatic conditions. The largest areas suitable for millet are in the Tillabery region. Maize has the least area suitable under current climatic conditions (2.7% moderately suitable and 1.7% with optimal suitability). This is the lowest value of the four crops being considered in this study. Cowpea has the largest proportion of area that has optimal suitability (9.8%) under current climatic conditions.

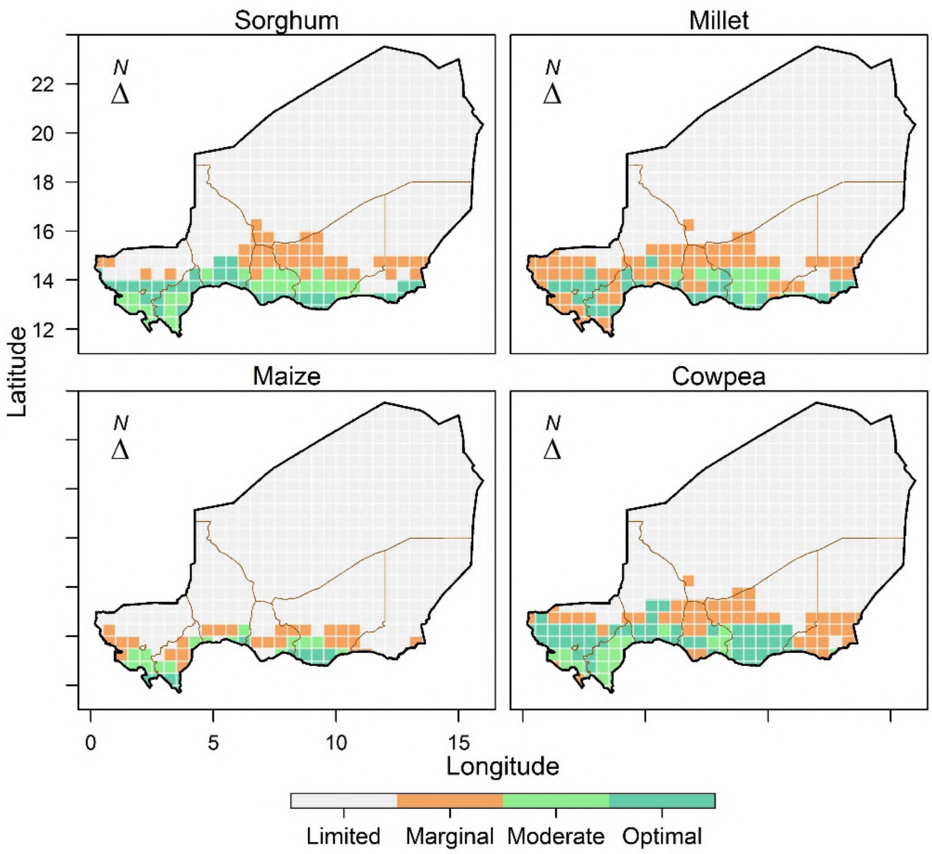


Figure 31: Maps showing the current climatic suitability for sorghum, millet, maize and cowpea in Niger as modelled from observed yields.

3.2.4 Sorghum suitability

A slight increase can be projected in the areas that have optimal suitability for sorghum by 2030, 2050 and 2090 mainly in the central southern Zinder and Diffa regions. As a rising number of areas become more suitable with time, the areas that will have reduced suitability are also increasing from 1.5% in 2030 to 2.5% in 2090. A northward shift in suitability is predicted with a concurrent reduction in the areas with limited suitability that will turn marginally and moderately suitable for sorghum under climate change (Figure 32). This will occur in areas which are currently suitable for sorghum production as rainfall amounts are projected to increase (see Chapter 1). These results mean that the season-long conditions for sorghum production will improve to make sorghum more suitable to be grown in some areas. Similar increases in the suitability of sorghum under climate change in the Sudano-Sahelian regions have been reported by Ramirez-Villegas et al. (2013). This increase in suitable areas is explained by projected increases in rainfall amounts and through the fact that sorghum is generally adapted to a wide range of environmental conditions, including many that are marginal for other cereals. In addition, Akumaga (2018) reported that sorghum will respond positively to climate change in the Niger basin with changes being confounded by soil fertility. Our model identifies seasonal and annual rainfall patterns as the two most important determinants of sorghum suitability, and these are projected to increase in the southern and western parts of the country under climate change.

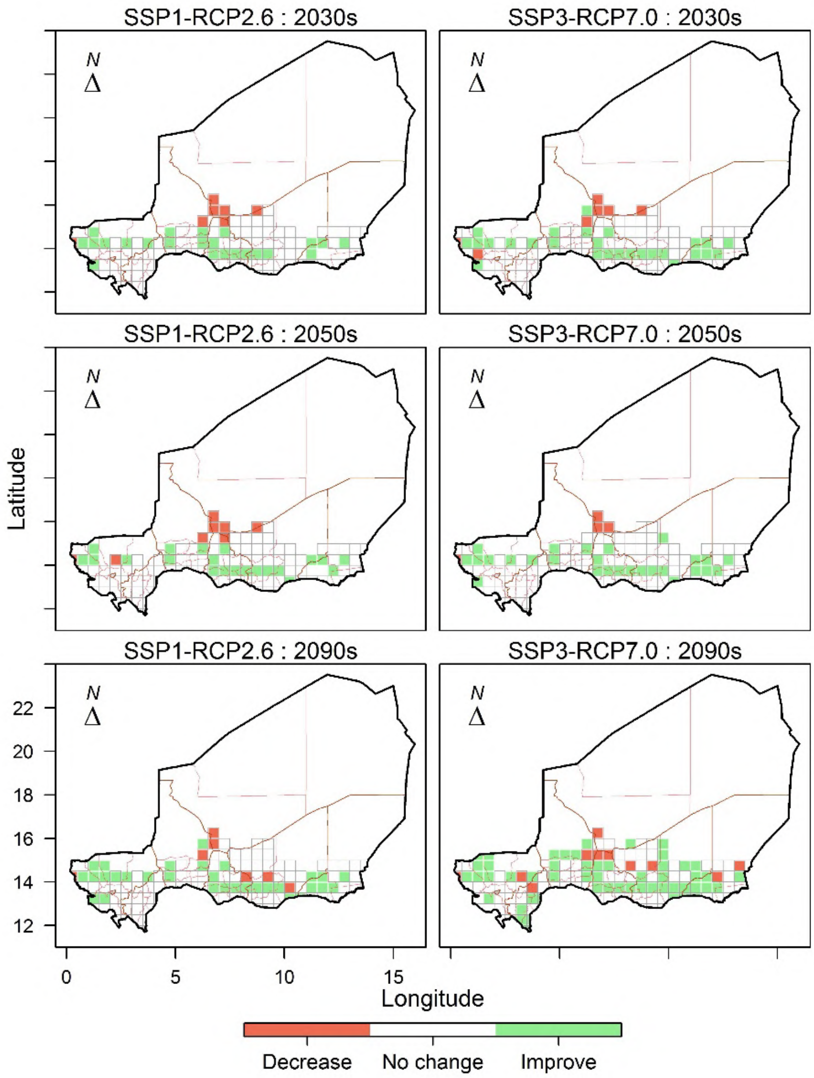


Figure 32: Maps showing the modelled changes in climatic suitability for sorghum in Niger for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. The grey boxes represent the areas of sorghum suitability under current climatic conditions.

3.2.5 Millet suitability

A northward increase in millet suitability is projected with suitable areas increasing by 4.5% (SSP3-RCP7.0) and 3.5% (SSP1-RCP2.6) by 2050 and up to 3.8% under SSP1-RCP2.6 and 11.9% under SSP3-RCP7.0 by 2090 (Figure 33). Significant suitability gains are projected in the Tahoua region, most of which is categorised as having moderate and marginal suitability for sorghum under current climatic conditions. Like sorghum, the projected increases in rainfall amounts (see Chapter 1) in the southern parts of the country explain the modelled improved suitability of millet in Niger. With millet having a shorter growing period and higher tolerance to lower rainfall amounts, the results confirm expectations. We project that the greatest part of the country will not have a change in millet suitability. Egbebiyi et al. (2020) explains the northwards expansion in suitability of millet in the region as explainable by the interaction between rainfall and temperature, with rainfall being the most limiting of the two factors. Further, the current suitability level represents relatively low yields for millet especially because of soil fertility limitations, and therefore increased suitability should be assessed together with the yield gaps in the region which are large. In addition, it is important to note that some parts (although small) of Niger are projected to lose their suitability under climate change and adaptation strategies are required for these regions.

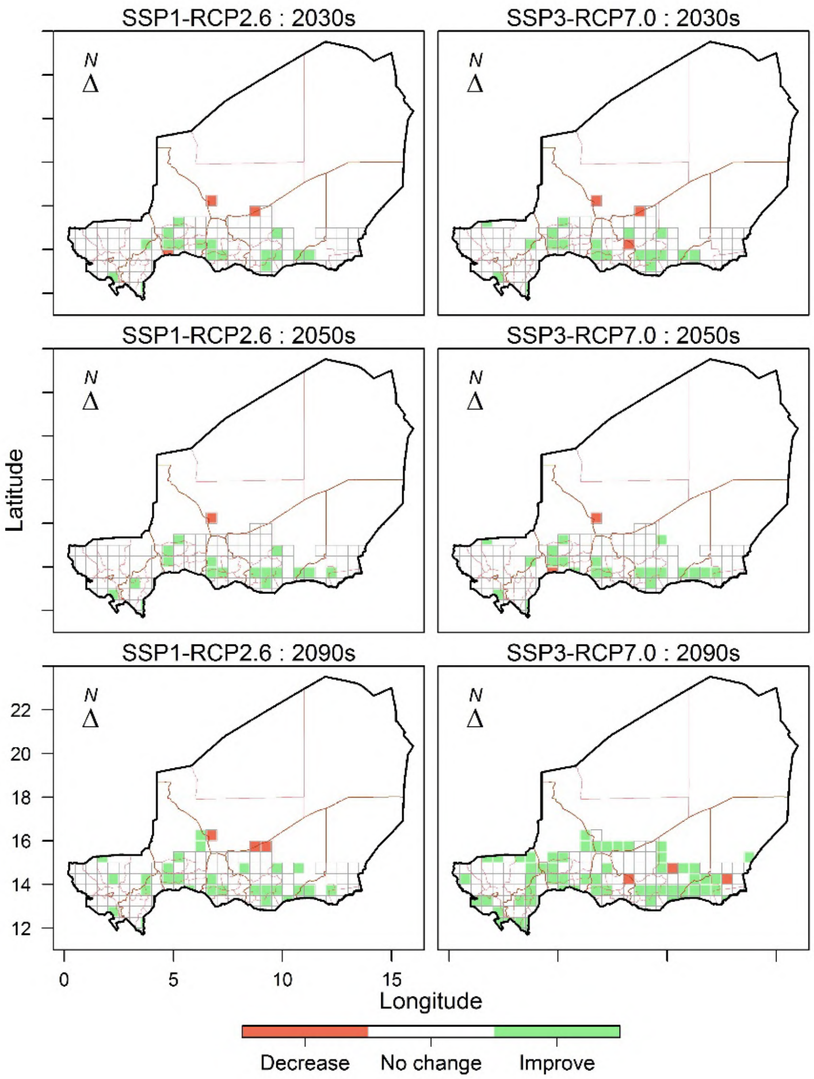


Figure 33: Maps showing the modelled changes in climatic suitability for millet in Niger for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. The grey boxes represent the areas of millet suitability under current climatic conditions.

3.2.6 Maize suitability

The production range for maize in the country is projected to remain the same (<2% net change for all categories) by 2050. As larger areas become more suitable for maize production, more areas are also turning marginal for the crop with net slight improvements projected for the regions of Zinder and Maradi and decreases in maize potential in Tillabery and Dosso regions (Figure 34). The major crop producing areas in the western parts are projected to be impacted by climate change and yet they are key agricultural regions. Consistent changes in maize suitability are also projected for Southern Maradi and parts of Tillabery from the mid-century onwards. In the far future under the high emissions scenario, the conditions for maize production will deteriorate for the southern parts of Zinder and Maradi, which are the main growing areas. These areas may require adaptation or switching to other and more suitable crops.

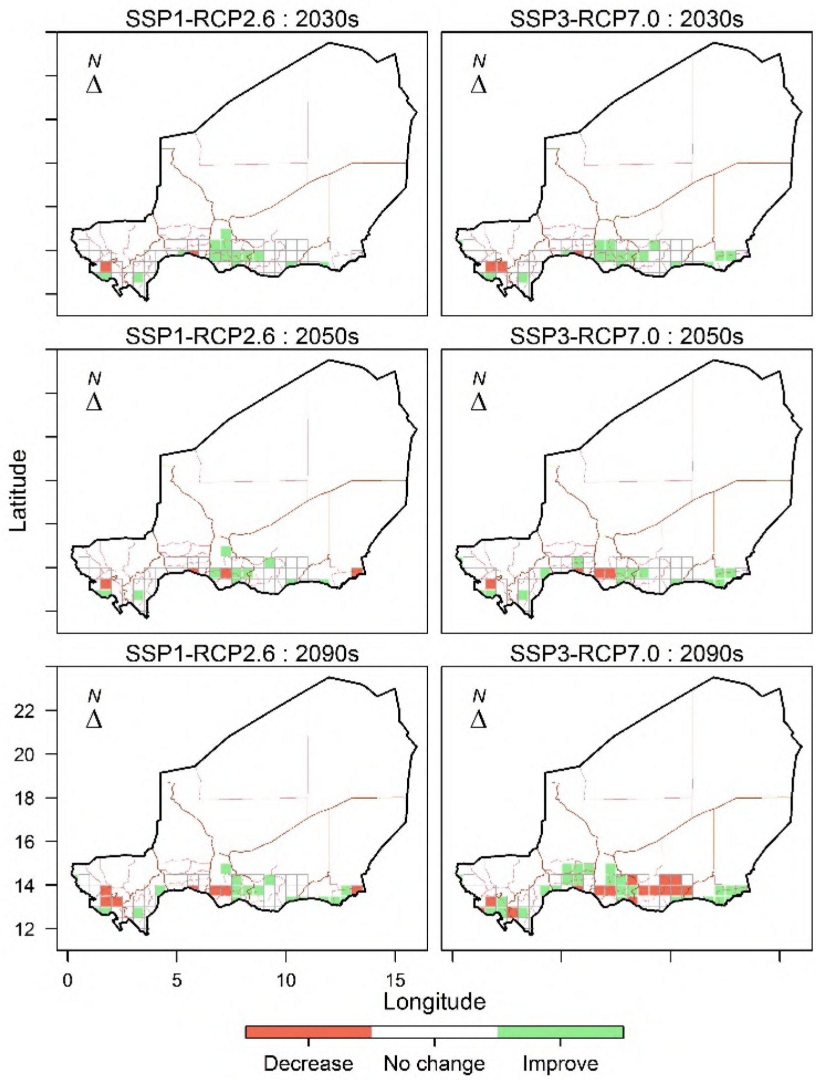


Figure 34: Maps showing the modelled changes in climatic suitability for maize in Niger for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. The grey boxes represent the areas of maize suitability under current climatic conditions.

3.2.7 Cowpea suitability

The models project that the area suitability for cowpea will remain stable in Niger under climate change but there will be shifts in terms of the areas suitable for growing the crop (Figure 35). We project a net increase in the suitable area for cowpea of 1.3% (SSP1-RCP2.6) and 2.0% (SSP3-RCP7.0) by 2030, 1.8% (SSP1-RCP2.6) and 2.5% (SSP3-RCP7.0) by 2050 and 0.8% (SSP1-RCP2.6) and 4.0% (SSP3-RCP7.0) by 2090 (see Table 3). Under SSP3-RCP7.0, the suitability of cowpea will decrease by 2.2%, 2.7% and 4.2% in 2030, 2050 and 2090 respectively. A regional assessment shows that the suitability will decrease in Zinder while increasing in Tahoua and Tillabery regions. Under the high emissions scenario, the projected decrease in cowpea suitability for southern parts of Zinder by 2090 is substantial. Cowpea is mainly produced under shade, and as identified in our model importance parameters, sowing and growing season temperatures explain over half the suitability of cowpea in the country, unlike other crops where rainfall is more important. The crop is sensitive to temperature changes and therefore the projected impacts are not surprising for cowpea. Other studies (e.g. Hall, 2011; Carvalho et al., 2019) have also reported that climate change modification of temperatures during the growing season pose the greatest threats to cowpea.

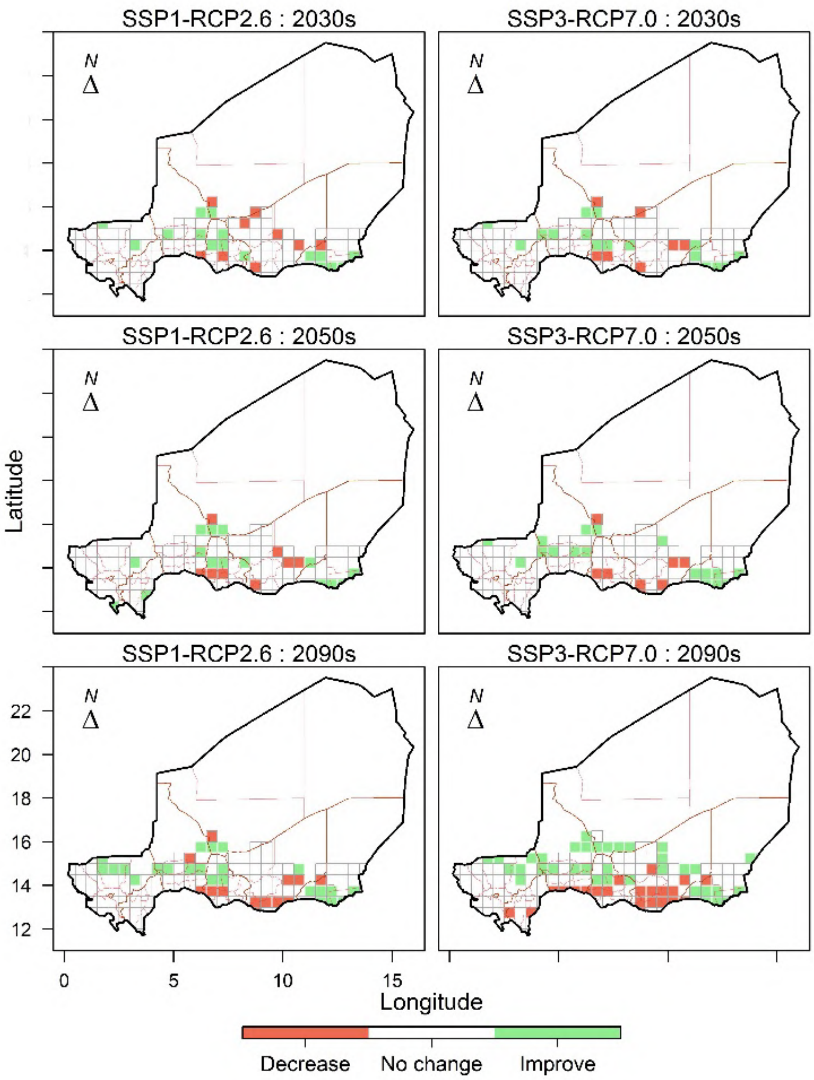


Figure 35: Maps showing the modelled changes in climatic suitability for cowpea in Niger for the 2030s, 2050s and 2090s under the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. The grey boxes represent the areas under current climatic conditions.

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

Crop		2030		2050		2090	
		RCP2.6	RCP7.0	RCP2.6	RCP7.0	RCP2.6	RCP7.0
Sorghum	Decrease	1.5	0.7	1.5	1.5	1.7	2.5
	No Change	92.8	92.8	92.1	91.3	93.3	86.1
	Increase	5.7	6.4	6.4	7.2	5.0	11.4
Millet	Decrease	0.5	0.2	0.7	0.7	0.2	0.7
	No Change	95.5	95.0	94.8	93.3	95.8	86.6
	Increase	4.0	4.7	4.5	5.9	4.0	12.6
Maize	Decrease	0.2	0.7	0.5	1.5	0.7	3.2
	No Change	97.0	96.8	96.3	95.8	97.5	92.1
	Increase	2.7	2.5	3.2	2.7	1.7	4.7
Cowpea	Decrease	2.2	1.7	1.7	2.7	2.0	4.2
	No Change	94.3	94.6	94.8	92.1	94.8	87.6
	Increase	3.5	3.7	3.5	5.2	3.2	8.2

3.2.8 Multiple crop suitability

The suitability of multiple crops as a proxy for evaluating diversification potential under current and projected climatic conditions by stacking the individual suitability maps has been evaluated. This crop diversification has the potential to reduce crop failure and yield loss, and therefore has a positive impact on nutrition, pastoralism, economics and soil rehabilitation, as well as strengthening farmers' resilience (Moussa & Abasse, 2020). There is high potential for multiple crops in Zinder, Tillabery and parts of Dosso under current climatic conditions. However, the areas that are optimal for all of the four selected crops under current climatic conditions are very limited, accounting for less than 1% of the country. When the optimal and moderate suitability areas for producing all four crops are combined, about 3.7% of the country is defined as suitable for multiple cropping. Considering that individual crop suitability under current climatic conditions is larger than this, there is a spatial distribution to crop suitability in the country where certain areas are suitable for some crops and not for others, all of which are in the southern and western areas. Under climate change the potential for multiple cropping will decrease under the high emissions scenario from mid-century while it is projected to increase up to 2050 under the low emissions scenario and decrease thereafter (Figure 36 and 37). Losses in crop suitability under climate change can mainly be found in the Tillabery region with some gains in the Zinder and Maradi regions. Figure 36 shows the potential for crop diversification or switching in different parts of Niger under current and projected climatic conditions.

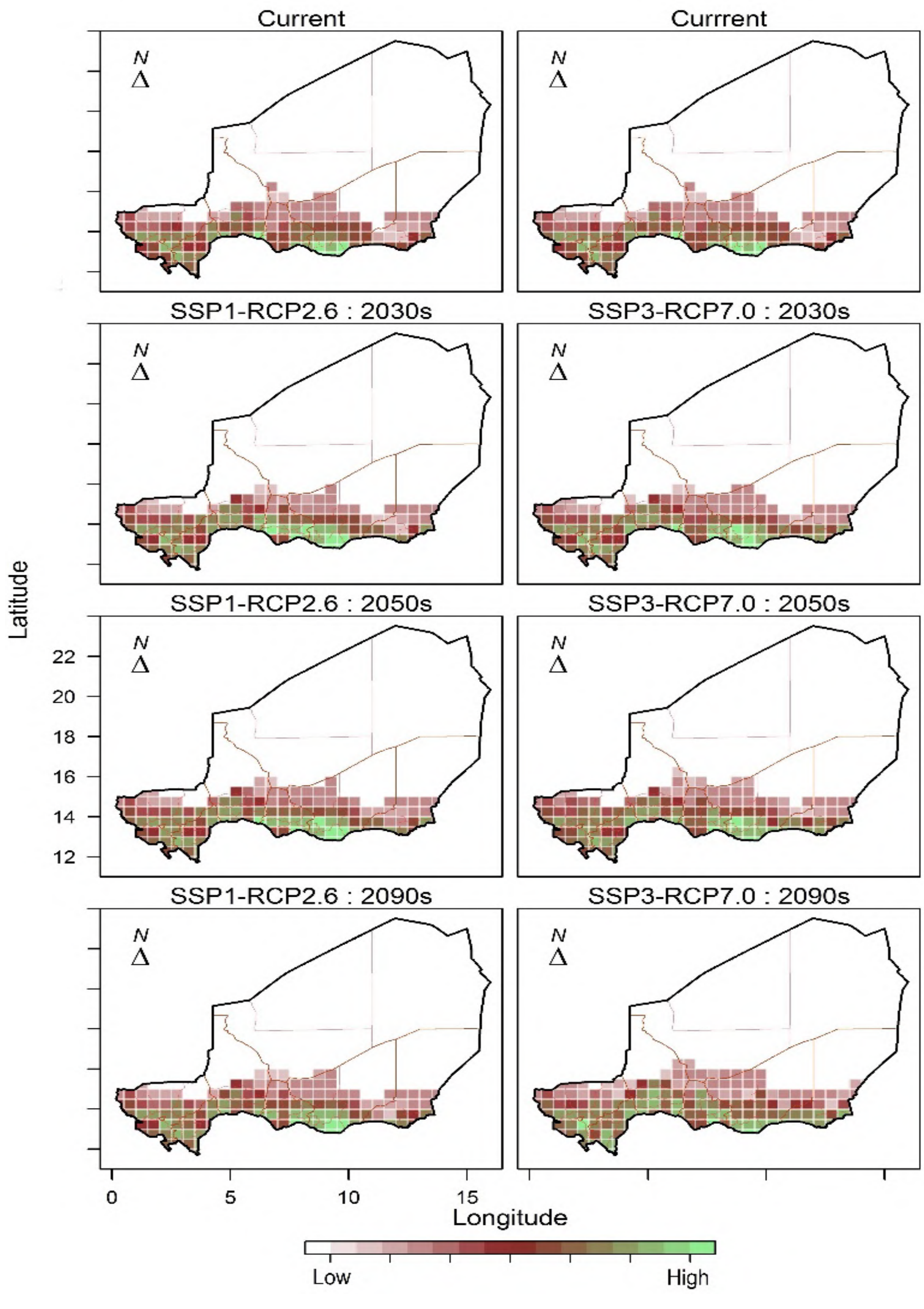


Figure 36: Potential for multiple crop suitability under current and selected climatic conditions for 2030, 2050s and 2090s, under SSP1-RCP2.6 and SSP3-RCP7.0 scenarios in Niger. Dark green shades show areas where the 4 crops are suitable while the white show where none of the 4 crops is suitable.

The area which is optimally suitable for producing all four crops will gradually decrease under climate change, while areas optimally suitable for three crops will increase (Figure 37). Projections show that the least suitable areas for production of all four crops are expected to emerge under SSP3-RCP7.0 in 2090, where only 0.2% of the country will be suitable for sorghum, millet, maize and cowpea, down from 0.7% under current climate conditions. Optimal areas for producing only one crop will decrease from 7.9% under current climatic conditions to 6.2% (SSP1-RCP2.6) or 6.7% (SSP3-RCP7.0) by 2030, 6.7% (SSP1-RCP2.6) or 6.2% (SSP3-RCP7.0) by 2050 and 5.7% (both scenarios) by 2090 as crop suitability shifts (Figure 37).

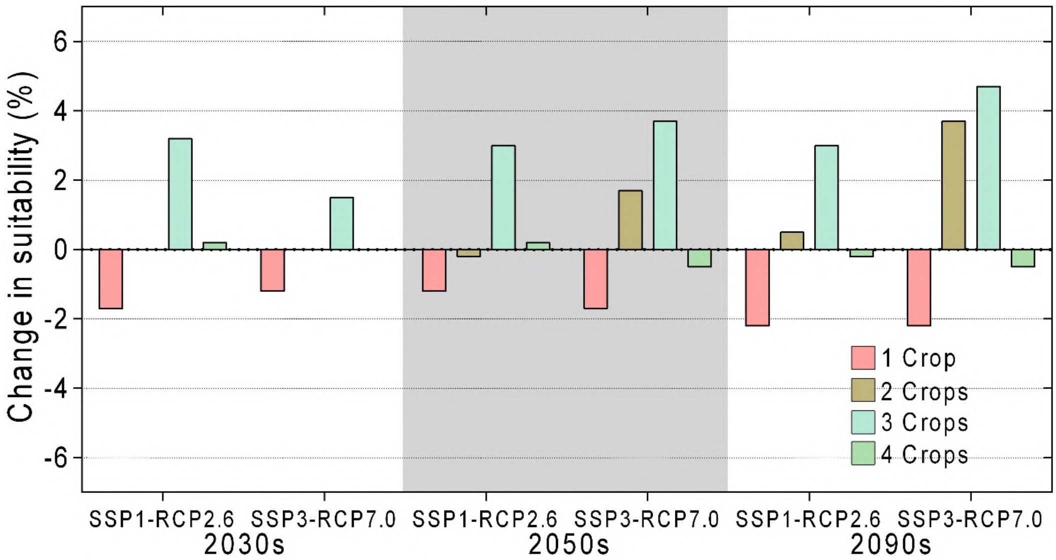


Figure 37: Changes in optimal suitable areas for multiple crops in Niger under current and projected climatic conditions for 2030, 2050 and 2090 under SSP1-RCP2.6 and SSP3-RCP7.0 scenarios.

3.3 Sorghum yield loss assessment under future climate conditions

While the previous section provided a general assessment of the suitability of different crops under future climate scenarios, this section focuses on biophysical mechanistic modelling of climate change impacts on agricultural yields of sorghum in regions where this crop is currently grown.

3.3.1 Data and method

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

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

For the assessment, we assume rain-fed conditions and no fertilizer application as a default management strategy in sorghum and use the DSSAT model's default West African sorghum variety for model calibration. The sowing date is automatically calculated by the model when the field meets at least 10% of soil moisture, and the temperature is between 10 and 40 °C. Simultaneously, harvest dates are also automatically calculated by DSSAT, indicating when the crop has reached maturity. Planting depth was set to 3 cm, row spacing to 45 cm, and plant density to 13 plants/m², according to common practice in Niger (White et al., 2015). We rely on yield statistics provided at the province level by the Ministry of Agriculture in Niger for model calibration (MAAH/DGESS, 2020). Only four regions' observations were used (Maradi, Niamey, Tillabery, and Zinder), which are major sorghum growing regions, for the calibration due to the data availability and the area of productivity. Therefore, the simulation confidence level is higher in the four regions (Maradi, Niamey, Tillabery, and Zinder) than in other regions of Niger, although simulation was done for the whole country. The national-level analysis was made by aggregating the simulations from the regions.

The simulated yields correspond to observed yields with a Pearson's correlation of r=0.53, an index of agreement (Willmott's d) of 0.61, and a Root Mean Square Error (RMSE) of 63 kg/ha between observed and simulated yields over 16 observations (2001-2016) at the national scale and the regional-level simulation error (difference between simulated and observed yield values) of ±30-60 kg/ha.

The yield is calculated from the specific response to weather variables and other field inputs such as soil and farmer's practices, formed as equations representing a crop's physiological responses to environmental variables (Jones et al., 2003).

3.3.2 Results

Current sorghum yields in Niger reach on average 0.33 t/ha in observed data and 0.36 t/ha in simulated data. The range of current yields within the country lies mostly within 0.24-0.5 t/ha in observed data. Figure 38 shows the current distribution of absolute yield levels in Niger together with projected future changes for 2030, 2050, and 2090 under SSP1-RCP2.6 and SSP3-RCP7.0.

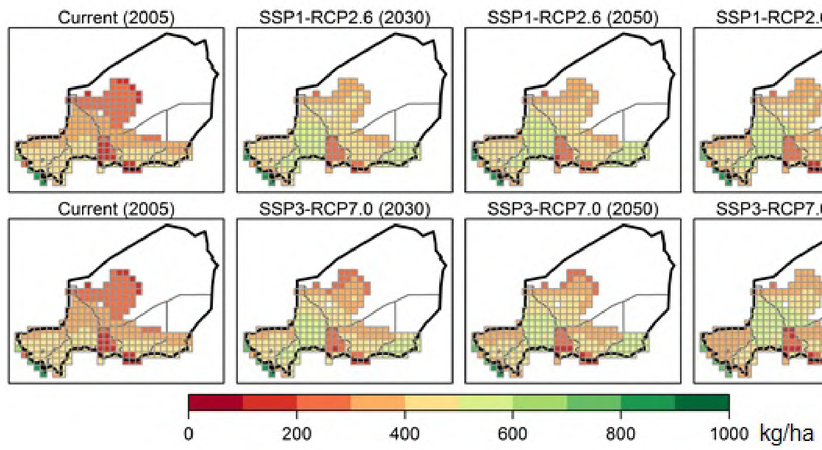


Figure 38: Current and future projected sorghum yields under the scenarios SSP1-RCP2.6 and SSP3-RCP7.0.

As it can also be seen from Figure 39, yields on national level are projected to increase under SSP1-RCP2.6 in 2030, 2050 and 2090 (around 15 to 17%), compared to the current level. Under SSP3-RCP7.0, nationally averaged yields are also projected to increase by about 14% by 2030, but then decline again to an overall increase of about 11% (2050) and 10% (2090) for the second half of the century.

Furthermore, the regional distribution of yield impacts becomes especially evident in Figure 39, indicating overall negative impacts under both emission scenarios in Niamey and Tillabery and strongly positive impacts in Agadez, Tahouha and Diffa. An analysis of climate indicators suggests that most of the projected yield losses in SSP3-RCP7.0 can be explained by temperature increases of up to 4 °C over time (Figure 11). Precipitation amounts and their distribution throughout the season have little impact on yields, as both indicators are projected to remain relatively unchanged at first and pursue an increasing trend in the future (see also Chapter 1). Looking at the projections for sorghum yields and sorghum suitability in Agadez (see igure 32), it is clear that yields will increase in the future, while suitable areas will decrease. This is mainly due to the fact that the suitability modelling looks at the general conditions for the crop's requirements. The yield model, on the other hand, takes factors such as management practices and interactions between different parameters into account that can have a positive impact on sorghum yields. Overall, our results are consistent with other studies that show that yields for cereals like sorghum and maize may increase or remain stable under climate change in the region due to projected rainfall increases, despite warming (Akumaga et al 2018, Parkes et al. 2018). However, the crop yield responses are different between regions. For example, the predicted sorghum yield losses of up to 8% for Tillabery confirm similar findings by Akumaga et al. (2018) for the same area. Regional studies for West Africa however show average yield losses under climate change because of the expected warming, irrespective of whether precipitation amounts increase or decrease (Sultan et al., 2013, Raes et al., 2021).

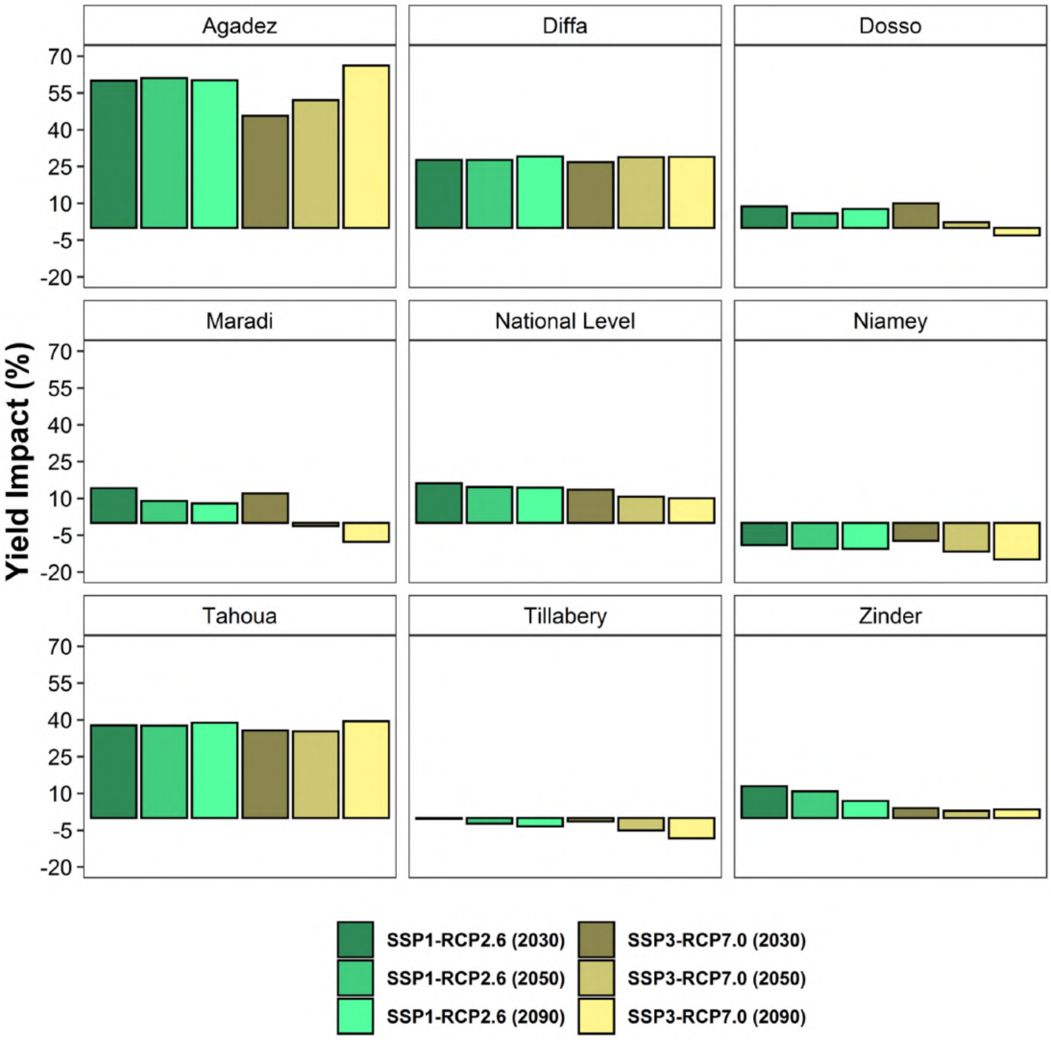


Figure 39: Simulated yield change by administrative region in Niger for 2030s, 2050s and 2090s under SSP1-RCP2.6 and SSP3-RCP7.0.

A limitation in our analysis of future climate impacts on sorghum production is rather low agreement of simulated and observed yields in the historical time range. This could question the adequacy of our results. We argue, though, that any modelling study would likely suffer from the same problem, as there are several reasons that could explain the low correlation: data quality of observations, statistical effects of low mean yields, inadequate representation of sorghum management in Niger in the DSSAT model, or, finally, a modest impact of weather on yields due to other more imminent limiting factors (lack of nutrients, weed competition, herbivores etc.). See also the related discussion in section 3.1.

Chapter 3 Summary

This chapter assessed climate impacts on crop production in Niger from three perspectives: the first part showed that weather influence plays a key role in determining crop yields. For maize, millet, cowpea and sorghum, more than 50% of observed yield variation at national level is found to be caused by variations in weather, with maize even reaching a value of 83%. Broken down to the sub-national level, the share of weather influence in yield variation differs between regions for all crops, yet poor data quality at sub-national level means caution is needed when interpreting results.

Secondly, our models show that areas suitable for sorghum and millet production will increase in Niger while those for maize and cowpea production will remain stable under climate change conditions until 2090. The reasons for this increase in suitability are related to the interactions of the projected changes in temperature and rainfall, where the increase in rainfall amounts will surpass the evaporative pressure of temperature increases resulting in positive suitability changes in some areas. From these results, a potential for transformational change under climate change has been observed, where there are likely going to be shifts in locations for production of sorghum, millet, maize and cowpea. Multiple crop suitability is projected to decrease especially under the high emissions scenario which will limit the potential for diversification or crop switching under climate change conditions.

Requisite technical and policy plans which include the expansion of agricultural production in the regions that will become more suitable are recommended. Awareness raising and training need to be provided to farmers to increase willingness and knowledge to cultivate only the new/more suitable crops. Adaptation planning should be mainly designed and focused on areas where suitability is projected to decrease. However, it should be noted that this modelling considered only the average temperature conditions and rainfall amounts and not the extreme events, such as heat waves or floods that may impact the crops growth. Therefore, the results should be interpreted together with the section on extreme events and on yield changes.

Lastly, an in-depth analysis of sorghum yield projections under two emissions scenarios (SSP1-RCP2.6 and SSP3-RCP7.0) by 2030, 2050 and 2090 indicated an increase of sorghum yields on national level towards the end of the century. The increase is higher under SSP1-RCP2.6 than under SSP3-RCP7.0. In two of the four major sorghum growing regions, namely Tillabery and Niamey, the yield impacts are negative under both emission scenarios. This can be mainly explained by increased temperature extremes during sowing and at germination stage.

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

Impact		Current	Trend future	Confidence
	Weather influence in sorghum yields	Medium 54%	-	High
	Sorghum suitability	Medium 6.9%	SSP1-RCP2.6 Increasing +3.3 to +4.9% SSP3-RCP7.0 Increasing +5.7 to +8.9%	High
	Sorghum yields	Low 0.24-0.5 t/ha	SSP1-RCP2.6 Increasing +15 to +17% SSP3-RCP7.0 Increasing +10 to +14%	Medium
	Weather influence in millet yields	Medium 49%	-	High
	Millet suitability	Medium 6.4%	SSP1-RCP2.6 Increasing +3.5 to +3.8% SSP3-RCP7.0 Increasing +4.5 to +11.9%	High
	Weather influence in cowpea yields	Medium 55%	-	High
	Cowpea suitability	Medium 9.8%	SSP1-RCP2.6 Relatively stable +1.2 to 1.5% SSP3-RCP7.0 Relatively stable +2.0 to +4.0%	High
	Weather influence in maize yields	High 83%	-	High
	Maize suitability	Low to medium 1.7%	SSP1-RCP2.6 Relatively stable +1.0 to +2.7% SSP3-RCP7.0 Relatively stable +1.2 to +1.8%	High

Chapter 4 – Climate impacts on livestock production

The livestock sector plays a critical role for the agricultural sector and the food and nutrition security in Niger. With more than 15 million cattle, Niger has one of the largest cattle population in the Sahel region (FAOSTAT, 2019b). The main animal breeds kept in Niger are goats, sheep, cattle and chicken (FAOSTAT, 2019a). Six production systems are common: the agro-pastoral system, semi-modern dairy farms/semi-intensive farms, re-organized traditional system (where cattle raising is abandoned for camels and goats), enhanced traditional system (i.e., livestock keepers maintain specific bovine breeds and mobility), small producers (large number of farmers using livestock as "live bank" and large land owners (owned by large traders as safety assets for trade activities (Rhissa, 2010))).

One way to understand how livestock is impacted by climate change is to study possible changes in fodder availability under future emissions scenarios. This chapter assesses the impacts of climate change on grassland productivity and grazing-based livestock production in Niger using the dynamic global vegetation model LPJmL.

In addition, we provide an excursion on how climate change can have an impact on the security situation in Niger looking specifically at the potential of conflicts between sedentary farmers and nomadic pastoralists and recruitment by extremist groups present in the region.

4.1 The livestock sector in Niger

Given the country's dry climate and limited crop production potential, the livestock sector in Niger plays a major role in sustaining national food and nutritional security of dependent populations (Ashley, 2020). According to recent estimates, the sector contributes approximately 12% to the national GDP and about 35% to the agriculture GDP (Ashley, 2020; Enahoro et al., 2019). A total of 13 million farmers (42% of the population) own livestock to secure their livelihoods. Different livestock management systems prevail, most of which employ a form of pastoralism. Of these, agro-pastoralism is the most common livestock system. In the arid and semi-arid regions of Niger, farmers move with their livestock in search of pasture and water. In recent times, studies have reported the livestock sector in Niger to be under increasing threat due to a variety of drivers, such as expansion of agricultural land leading to change in land tenure (Catholic Relief Services, 2020) and growth of human population and urbanisation coupled with an enormous increase of the global demand for livestock products and climate change (Nwosu & Ogbu, 2011).

A substantial diversity of ruminant and non-ruminant animals occurs in Niger with its major constituents being cattle, sheep and goats. As the demand for livestock production is increasing, a simultaneous growth can be noticed in the livestock numbers for cattle, sheep and goats over recent decades (Figure 40). For these three main livestock types a dip can be observed in 2010, likely due to the severe droughts in 2009 and 2010 which led to dramatic livestock losses (Ickowicz et al., 2012). Overall, goats make up the largest livestock population in Niger with an annual growth rate of 3.6%.

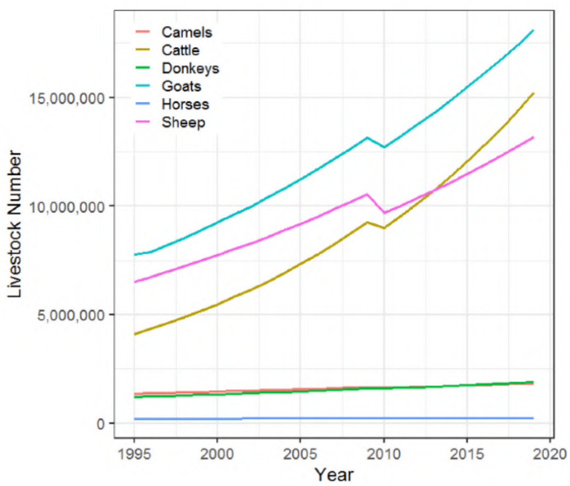


Figure 40: National trends for livestock numbers from 1995-2020.

The cattle-population growth rate increased substantially after 2010, with the highest growth rate of ~6% making cattle the second largest livestock population. Sheep form the third largest livestock type in Niger, with a population growth of 3% since 1995. However, the national-averaged livestock numbers spread unevenly across the regions and provinces in Niger (Figure 41).

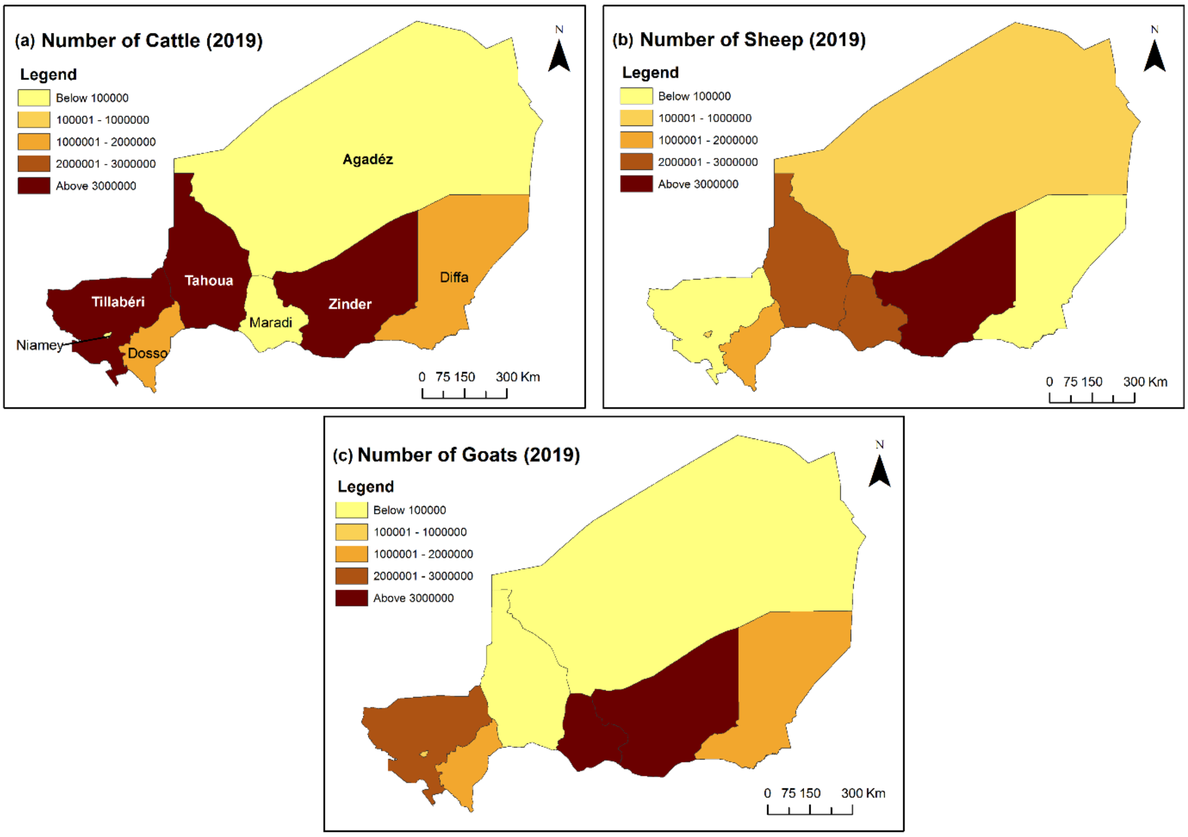


Figure 41: Spatial distribution of (a) cattle, (b) sheep and (c) goats for the 36 departments of Niger in year 2019.

Changing climatic and weather patterns are expected to cause a net decrease in yield of grain, forage and pasture crops for livestock as well as changes in the epidemiology and dynamics of livestock diseases, pests and vectors (Mendelsohn & Seo, 2007; Rust & Rust, 2013). Climate risks are resulting in loss of livestock production in multiple ways. Climate change is already affecting livestock number, forage quality and pasture composition in the region (Pfeifer et al., 2020). Shortage of fodder is being increasingly reported to limit the livestock system productivity as current livestock farming systems in Niger (sedentary or transhumant) depend heavily on the availability of grazing land and fodder. Given that grassland systems are highly vulnerable to climate fluctuations (Knauer et al., 2017), it is important to understand how grassland productivity has changed in the past and how it is expected to change under future climate change scenarios. Moreover, it is critical to understand the implications of future fodder availability for livestock production in Niger.

Climate Change as a Driver of Conflict in Niger

Intercommunal violence and extremist militancy have taken hold of the Sahel in recent years (Amnesty International, 2020; Human Rights Watch, 2018; International Crisis Group, 2020b; People´s Coalition for the Sahel, 2021). While Mali has been grappling with instability since a coup 2012, ethnic tensions have grown and violence has erupted in the neighboring Burkina Faso and in Niger. Underlying grievances related to cattle raiding and socio-economic conditions have provided homegrown extremist groups, who have aligned themselves with the Islamic State and Al Qaida, fertile ground for recruitment. Already socially marginalized pastoralist communities are particularly affected by inter-communities conflicts (International Crisis Group, 2020).

Classic conflict drivers such as socio-economic inequalities, ethnic fragmentation, and a lack of government resources and capacities, are still considered to be more influential in the development of security threats than climate change itself. Moreover, the expansion of agricultural land into areas that have traditionally served as transhumant corridors as well as the co-existence of traditional and modern land tenure systems have also been identified as crucial conflict drivers (Catholic Relief Services, 2020). However, experts increasingly agree that climate change has a significant impact on the development of armed conflict (Scheffran et al. 2020; Kelley et al., 2015; Mach et al., 2019; Schilling et al., 2010; Schleussner et al., 2016; Von Uexkull et al., 2016) and will become increasingly more relevant in armed conflict genesis as well as armed conflict prolongation. Moreover, these classic conflict drivers increase the possible consequential damage of extreme weather or hydrological events caused by climate change. For example, due to their negative impacts on food supplies, droughts can represent a substantial potential for conflict (Von Uexkull et al., 2016). A high level of dependence of a large part of the population on agriculture harbors an additional risk, since the consequences of climate change in agriculture directly threaten the existence of large population groups and can also force them to migrate (Kelley et al., 2015). Already marginalized groups are exposed to additional risks in conflict situations due to existing structural inequalities.

While many of the classic drivers of conflict are at play regarding Niger´s current security challenges, already observable climate change is another factor further aggravating existing tensions. The country is highly exposed to climate change impacts, while exhibiting a low adaptive capacity. Farmers and pastoralists are the first to feel these impacts and bear the brunt of the burden, being affected by food insecurity and ever diminishing livelihoods opportunities. The agricultural sector provides livelihoods for 80% of the population. Additionally, the sector overwhelmingly relies on rain-fed agriculture and primarily revolves around subsistence farming and herding (Tomalka et al., 2020). Rising temperatures can lead to heat stress and health risk, particularly in very exposed sectors such as agriculture and construction, negatively impacting human security (International Labour Organisation, 2019). In addition, increasing patterns of drought and flood adversely impact both sectors, which depend on one another. While nomadic pastoralism has served as a viable option for the already challenging local climatic conditions, changing patterns of precipitation increasingly challenge the annual transhumance (Kiema et al., 2015). Considering the high reliance on rain-fed agriculture within Niger, these climatic developments act as an additional stressor on people´s livelihoods.

For pastoralists, who are increasingly vulnerable to recruitment by extremist groups, this is not only a threat to their livelihoods but indeed a threat to their group identity, which is inherently connected to pastoralism and the transhumance. Much of the recruitment on behalf of these armed, extremist non-state actors is undertaken among the local population (International Crisis Group, 2020; Human Rights Watch, 2018). The more marginalized have been particularly vulnerable to recruitment efforts, chief among them cattle herders. Considering their nomadic/semi-nomadic lifestyle, pastoralists are particularly susceptible to climate impacts as they not only depend on precipitation but indeed follow the rain on their annual transhumance (Traore & Owiyo, 2013). This brings them in contact with local farmers as well as other pastoralists along the way. While these relationships can be cooperative, changing patterns of precipitation also mean changing routes on the quest to follow the rain and find pasture. Relations with farmers of likely different ethnic groups have to be established, which bears conflict potential, particularly during the growing season (Von Uexkull et al., 2016). NGO reports have shown that in Niger as well as surrounding Burkina Faso and Mali, pastoralists are inextricably linked to recent instability

(Benjaminsen & Ba, 2019; Human Rights Watch, 2018; International Crisis Group, 2020). Cattle theft among different pastoral groups is an aggravating factor causing grievances. As are intercommunal relations between farmers and pastoralists as well as military abuse targeting pastoralists. Furthermore, impunity in regards to cattle theft and the heavy-handed response by security forces sow intercommunal distrust (International Crisis Group, 2020).

In addition to intercommunal tensions, Niger´s security challenges are threefold: instability due to the presence of extremist groups and bandits in Tillabery to the West, instability due to extremist groups in the Lake Chad border area to the South-East, and finally trafficking and banditry in the migration transit hub of Agadez to the less populated Center-North. While both border regions are struggling with an onslaught from locally grown as well as internationally notorious extremist groups, the city and department of Agadez deals primarily with trafficking as it serves as a transit migration hub for migrants headed to Libya, Algeria as well as Europe (Molenaar et al., 2017).

The complex state of security in the country along with its low adaptive capacity with respect to climate extremes, climate change impacts on the development of violent conflict require further research. This will aid policymakers and implementing organization in identifying the best suited and conflict-sensitive adaptative solutions for Niger. This is particularly needed in the crucial agricultural sector and should have a special focus on already marginalized groups. If done right, such measures may aid in transforming intercommunal relations by creating more socio-economic equity. The Islamic State poses a security threat to Niger as well as to the entire region. Furthermore, the organization has positioned itself as an alternative to existing state structures, providing governance services to communities. As pastoralists are particularly vulnerable, more emphasis should be put on identifying and enforcing transhumance routes, including fodder and watering spots along the way. One of the main challenges regarding intercommunal relations in Niger is cattle raiding. Considering issues and delays relating to the carrying out of justice, security forces should increasingly work on cattle raiding issues in order to foster trust with pastoralist communities.

4.2 Data and methods

Our approach to assess impacts of climate change on grassland productivity and therefore grazing-based livestock production in Niger is based on the dynamic global vegetation model LPJmL (Lund-Potsdam-Jena with managed land), which is developed mainly at PIK (Schaphoff et al., 2018; Von Bloh et al., 2018). LPJmL is a process-based model and simulates key ecosystem processes such as photosynthesis, plant and soil respiration, carbon allocation, evapotranspiration and phenology of natural as well as managed vegetation, as coherently linked through their carbon, water and nitrogen fluxes (Schaphoff et al., 2018; Von Bloh et al., 2018). Dynamic global vegetation models are often used to study the impact of climate change on vegetation. In addition, LPJmL features a representation of different grassland management schemes, enabling it to simulate the impacts of grazing, grazing intensities and mowing systems in managed grasslands (Rolinski et al., 2018). Other sources of animal fodder such as agricultural wastes or fodder crops are not analysed. Following the spatial resolution of the climate data, the model simulates the land surface as discrete grid cells with a size of 0.5° x 0.5°, roughly 55 km x 55 km.

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

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

Livestock species	Number of TLUs
Cattle	0.8
Sheep	0.15
Goat	0.15
Asin	0.5
Camel	1
Horse	1

In the model simulations, the effect of grazing by livestock is represented as a daily partial removal of the leaf biomass of grasses. Grazing is assumed to always leave a minimum stubble height of about 1 cm. On the demand side, the amount of biomass removed depends on the density of grazing animals (number of TLUs per hectare). On the supply side, available biomass changes between seasons and between years in response to weather, but also in response to previous grazing. There are no spatially and temporally explicit data available of the actual livestock grazing density in Niger for the historical period. Therefore, we systematically test a range of livestock densities (between 0 and 5 TLU/ha) and select in each grid cell and year the livestock density that produces the highest annual grass yield. This approach is designed to estimate the upper limit of livestock density that avoids overgrazing and represents a grazing potential. Figure 42 illustrates the procedure for one cell and year. Note that grazing supply does not necessarily fulfil the demand of the selected livestock density (1.0 TLU/ha in the example) at all times during the year.

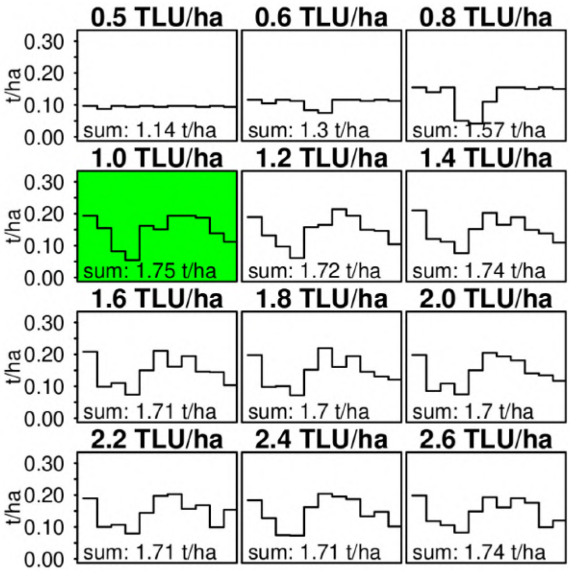


Figure 42: Monthly grass yields under different livestock densities in one cell and year; livestock density with highest annual yield is considered as grazing potential (marked in green in plot).

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

4.3 Results

4.3.1 Historical grazing potentials

Figure 43 shows the multi-model ensemble median of annual grazing potential for the historical period 1995–2014. Grazing potentials are highest in the Dosso region, exceeding 2.5 t dry matter per hectare and year along the border with Benin. Grazing potentials decrease towards the north following the decreasing precipitation gradient across Niger. The lowest grazing potential is found in the Agadez region, going down to almost zero in the desert regions. Besides the spatial differences, grazing potential varies substantially between seasons and years, as illustrated in Figure 44 for the monthly grazing potential in the eight region*s* of Niger. In this figure, the colour gradient from light to dark green denotes the variability across the 10 GCMs and 20 years making up the multi-model ensemble median. Even in the most productive regions, in Dosso and Maradi, there is a pronounced difference between grazing potential during the dry and wet season. Since ruminants require a relatively constant forage intake, supplemental fodder from other sources such as crop residues would be required during the dry season in order to utilise the full annual grazing potential.

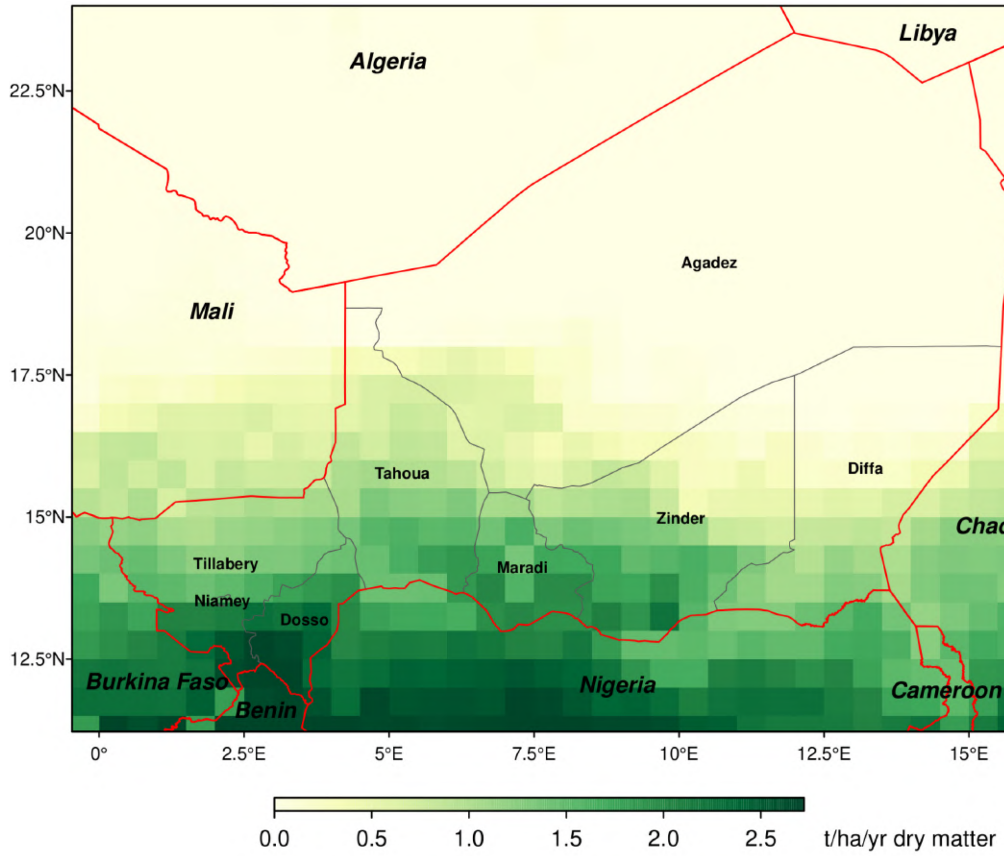


Figure 43: Multi-model ensemble median of simulated annual grazing potential for the historical period 1995-2014 in Niger.

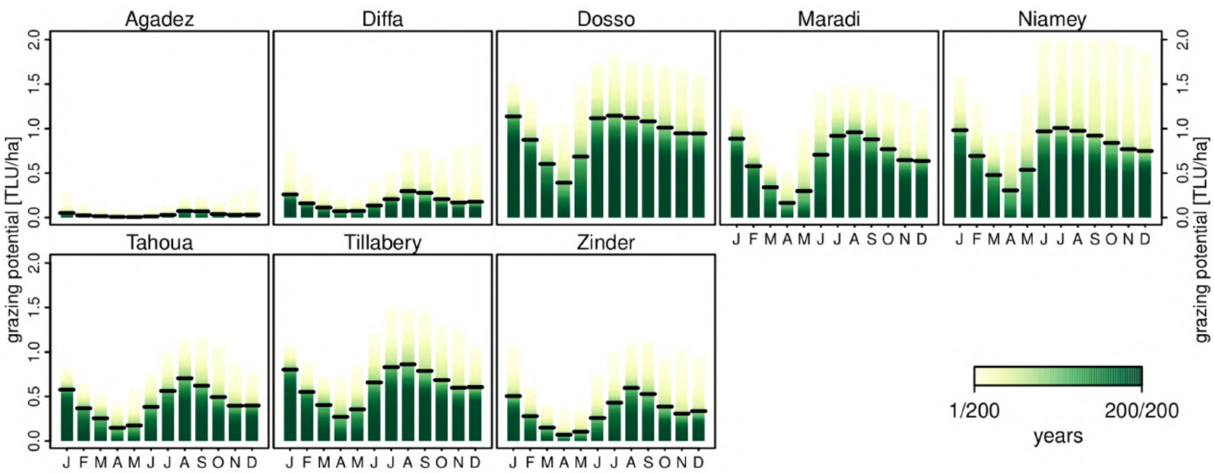


Figure 44: Variability of historical grazing potential within and across years in the multi-model historical ensemble. Each bar represents the range of monthly grazing potential across 20 years over 10 GCMs. Lighter colours denote high values reached only in a few regions in specific months.

4.3.2 Projected long-term changes

Looking at projected future changes in grazing potentials over the course of the 21st century there is no clear, uniform trend for Niger. Under the low emissions scenario SSP1-RCP2.6, the multi-model median is projected to fall about 3% below the historical grazing potential until 2030 (Figure 45), with an overall model range between -19% and +19% and 6 GCMs showing an increase while the other 4 GCMs show a decrease. Grazing potentials increase by about 6% compared to the historical period until 2050, with an even larger range of -19% to +34% and 3 GCMs still projecting a decrease compared to the historical period. Grazing potentials are projected to fall again to 5% below historical levels by 2090 in the multi-model median but the range across GCMs continues to increase. Under SSP3-RCP7.0, the multi-model median shows increasing grazing potentials over the course of the 21st century, going from +20% in 2030 to +17% in 2050 and +57% in 2090. There is very high model agreement on the sign of change, with only one GCM projecting a decreasing grazing potential until 2050. Yet, there is a large uncertainty range across GCMs regarding the size of the increase in grazing potential.

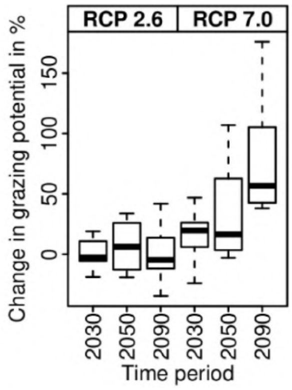


Figure 45: Change in country-scale annual grazing potential for two scenarios and three time periods. Boxplots show range over 10 GCMs.

The aggregation to the country scale presented in Figure 45 hides substantial regional differences. This becomes evident when looking at Figure 46. The most productive regions of Dosso and Maradi are projected to experience losses of about 10-12% by 2030, 14% by 2050 and almost 20% by 2090 under SSP1-RCP2.6. There is very high GCM agreement on the sign of change but substantial uncertainty regarding the magnitude of change. While the multi-model median shows slightly positive trends of grazing potentials in the regions of Tahoua, and Zinder until 2050, between 3 and 6 GCMs project a negative trend in these regions. There is medium to high GCM agreement on positive change in grazing potential in the Agadez and Diffa regions. The multi-model ensemble mean shows a 23% increase over the historical period in Diffa and 86% increase in Agadez by 2050. The trend positively reverses in the second half of the 21st century but grazing potentials are still 4% and 41% above historical levels by 2090.

The Dosso and Maradi regions are also projected to experience a decrease of grazing potential under SSP3-RCP7.0 (Figure 46, right column), although the loss is smaller than under SSP1-RCP2.6. By 2090, 6 out of 10 GCMs agree on a slight increase in grazing potential in Maradi. There is medium to very high GCM agreement on positive trends in grazing potentials in Tillabery and very high GCM agreement on positive trends in grazing potentials in the remaining regions, namely Agadez, Diffa, Tahoua and Zinder, over the course of the 21st century.

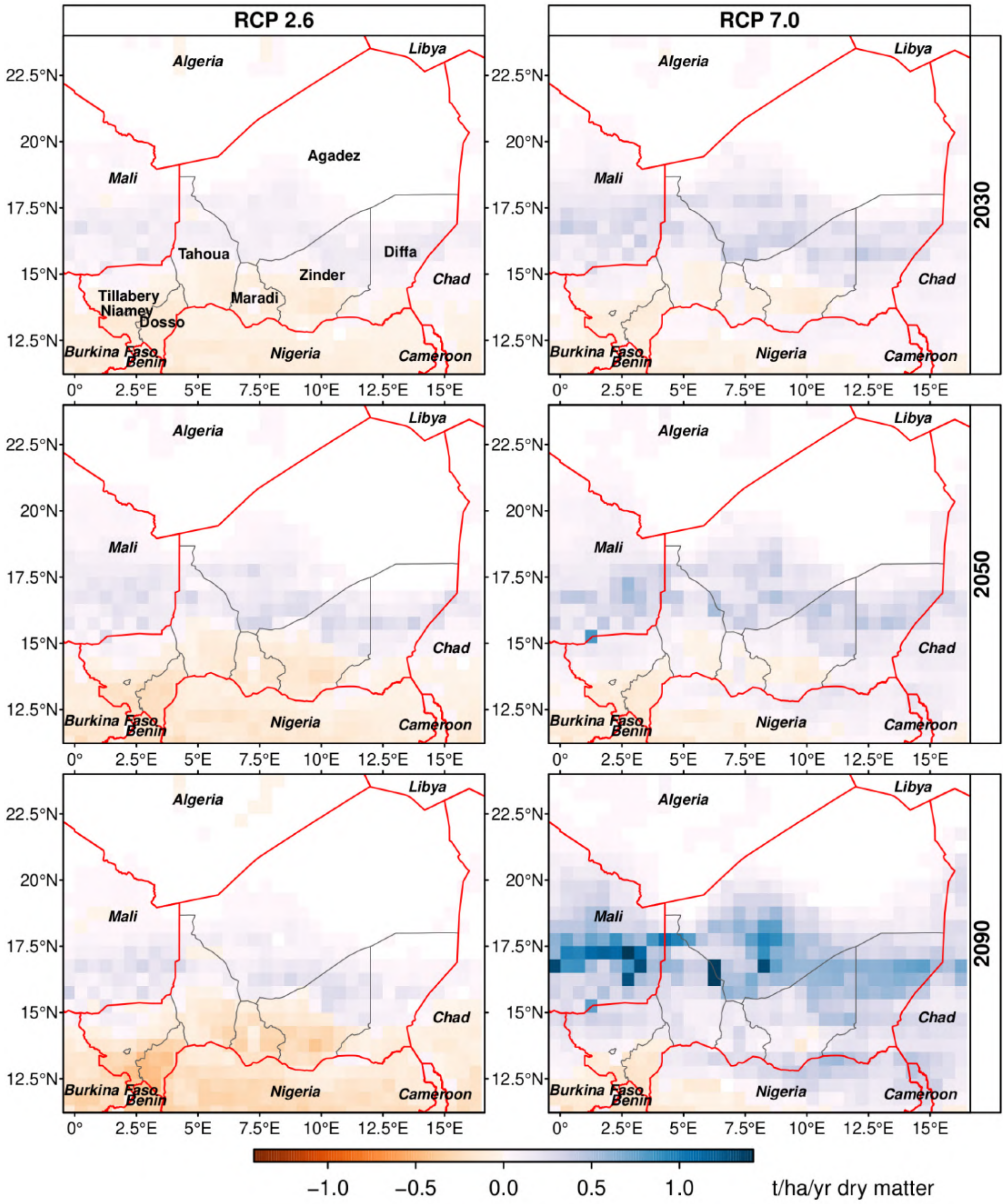


Figure 46: Multi-model ensemble median of change in annual grazing potential for three time periods (2030 top, 2050 middle, 2090 bottom) and two emissions scenarios (SSP1-RCP2.6 left, SSP3-RCP7.0 right). Changes are relative to historical period shown in 43.

Chapter 4 Summary

This chapter analysed the consequences of climate change on the livestock sector, with the aim to understand the spatiotemporal dynamics in livestock number and grassland productivity in order to assess the current and future grassland capacity for livestock. A detailed analysis of the changes in livestock numbers in Niger were presented, followed by an analysis of the changes in grassland productivity and its implications for future fodder availability for livestock production under two future climate change scenarios (SSP1-RCP2.6 and SSP3-RCP7.0). The results suggest that there is no clear trend for future fodder availability and grazing potential in Niger. Under both future emissions scenarios, there is a slightly decreasing trend for the south and a slightly increasing trend for the central areas of the country up to 2050. By 2090, there is an increase in grazing potential projected under the high emissions scenario for the whole country, with relatively strong effects projected for the central belt of the country.

Table 6: Climate impacts on livestock production.

Impact		Trend past	Trend future	Confidence
	**Livestock number**	Increasing	- no data -	-
	**Fodder availability, grazing potential**	Decreasing	SSP1-RCP2.6 Decreasing (south) and increasing (centre) SSP3-RCP7.0 Increase towards end of the century	High

PART II – ADAPTATION

The first part of the comprehensive climate risk analysis focused on the impact dimension, starting with climate impacts on temperature and precipitation, moving on to impacts on water availability and, finally, looking at impacts on crop and livestock production. In the second part of the study, these findings will inform the assessment of four selected adaptation strategies in the context of Niger's agricultural sector. The four adaptation strategies – namely irrigation for counter-season agriculture, integrated soil fertility management, agroforestry and farmer managed natural regeneration (FMNR), and improved fodder and pasture management – were carefully selected based on thorough consultations with a wide range of Nigerien stakeholders and local experts. In addition, they are based on insights from Niger's Nationally Determined Contribution (NDC), the country's National Adaptation Programme of Action (NAPA) as well as the National Strategy and Plan for Agricultural Adaptation to Climate Change (SPN2A).

In its NDC, Niger highlights the AFOLU (Agriculture, Forestry and Other Land Use) sector as one of two priority sectors, with the other being energy (Republic of Niger, 2015). Adaptation in the AFOLU sector is meant to follow a Climate Smart Agriculture approach and, among other measures, tap the unexploited potential of irrigation in the Niger River valley, which is particularly important for expanding rice production (Republic of Niger, 2015). The NAPA emphasises the exposure of the agricultural sector to the effects of climate variability and climate change (Republic of Niger, 2006). It rates the agricultural sector as one of eight most vulnerable sectors in the country, among cattle breeding, forestry, water resources, wildlife, fisheries, health and wetlands, all of which are interconnected and depend on each other. Hence, Niger's NAPA recognises the importance of adaptation to climate change, identifying 14 adaptation goals, nine of which are directly related to crop and livestock production, e.g. intensification of irrigation or switching to crop types that can better adapt to a changing climate (Republic of Niger, 2006).

The SPN2A (République du Niger, 2020) is among the latest national strategy plans specifically targeting the agricultural sector's vulnerability to climate change. It highlights the need to rehabilitate and preserve the productive potential of agro-ecosystems, by promoting sustainable management of natural soil, water and plant biomass resources, and by ensuring the protection of vulnerable ecosystems (République du Niger, 2020). The country's Economic and Social Development Plan identifies food security and sustainable agricultural development as one of eleven programmatic areas and highlights food and nutritional security as well as adaptation of agricultural production systems to climate change as major challenges (Ministère du Plan du Niger, 2017b). In a similar way, the Strategic Framework for Sustainable Land Management and Investment Plan ("Cadre Stratégique de la Gestion Durable des Terres (CS-GDT) au Niger et son plan d'investissement 2015-2029") highlights the development and implementation of adaptation strategies for the agricultural sector and vulnerable rural populations in particular (Ministère de L'environnement, de la Salubrite Urbaine et du Developpement Durable, 2014).

Chapter 5 – Methods and data for adaptation assessment

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

To ensure the suitability of our study results for decision-makers and to achieve a continuous engagement of local experts and stakeholders despite travel restrictions for PIK scientists due to the Covid-19 pandemic, we closely collaborated with a regional partner organization throughout the entire study process: the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). In the following, the methods applied for the selection and assessment of adaptation strategies will be described in more detail.

5.1 Selection of adaptation strategies

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

In the first phase of the process, a stakeholder workshop was held in Niamey in June 2020. Participants came from government, academia, civil society and development organizations with backgrounds in the field of climate change, agriculture, livestock, forestry, water management and development. Due to prevailing health and safety as well as international travel restrictions during the Covid-19 pandemic, the workshop was organized by WASCAL repeatedly over several days with a limited number of participants attending each day and abiding to strict social distancing and hygiene rules. PIK scientists joined virtually from Germany for a 2-hour discussion every day. Despite these challenging circumstances, a total of 46 stakeholders were able to join the workshop. The main objectives were to introduce the study approach, to jointly discuss with stakeholders' crucial design elements of the study and to foster a common understanding of the relevance of the study. In addition, the workshop served to discuss and prioritize four adaptation strategies to be included in the study. For this purpose, an initial list with possible adaptation strategies was presented to the local stakeholders, which they could discuss in groups and prioritize through a final selection exercise.

Niger's NDC and NAPA as well as the official report in support to the concerted formulation of the SPN2A (Hauswirth et al., 2020) served as a starting point for creating the initial list of possible adaptation strategies. The authors of this study made a pre-selection of adaptation strategies that aligned with the identified climate risks, matched the purpose of our analysis (crop and livestock related) and that were suitable for analysis with our crop and economic models. This generated a list of eight potential adaptation strategies, of which stakeholders then selected four strategies to be included in the analysis (Figure 47).

Across all documents, the term “adaptation strategy” was used in different degrees of specification. For the long list of adaptation strategies and the prioritization process with local stakeholders, several specific technologies were subsumed under umbrella terms. For example, the term “Integrated soil fertility management” was defined to encompass different specific single or combination technologies with the purpose of soil conservation such as use of compost, creation of Tassa (or zaï) pits, half-moons, contour stone walls or infiltration basins. This served to ensure that priorities of stakeholders were captured regarding overall problem areas and not with regard to preferences of specific technologies within these problem areas. Stakeholders were invited to discuss the current use, state of knowledge and potential of each adaptation strategy in the context of Niger in small groups, before voting individually for the four strategies they deemed most relevant for the analysis. The preselection was done based on literature review of national strategies such as the NDC document. After the selection process, the four adaptation strategies were further specified together with WASCAL, using concrete interventions subsumed under the general adaptation strategies to enable model-based analysis. The four final adaptation strategies are:

- irrigation for counter-season agriculture
- integrated soil fertility management
- agroforestry and farmer managed natural regeneration of trees, and
- improved fodder and pasture management.

These four strategies will be assessed individually in the Chapters 7 to 10, following eight assessment criteria that will be further presented in the next section.

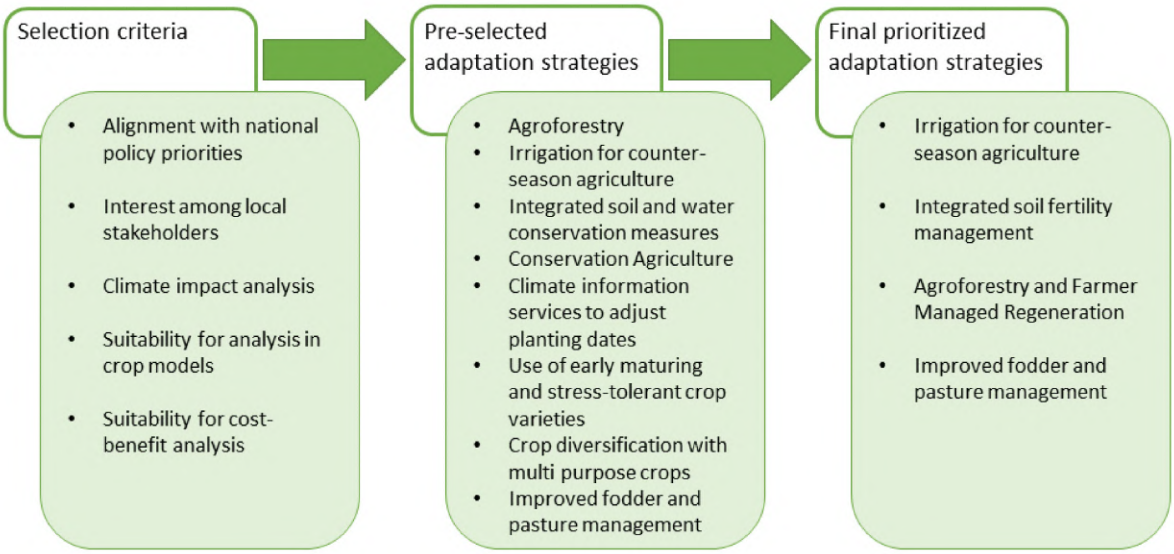


Figure 47: Overview of the selection process of adaptation strategies assessed in the study.

5.2 Multi-criteria assessment of adaptation strategies

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

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

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

5.3 Biophysical assessment of risk mitigation potential

Following the model-based assessment of climate impacts on sorghum yields, adaptation measures were evaluated for their effectiveness in climate buffering yields in Niger. To do this, parameters in the models were modified to represent the characteristics of the adaption strategies. Four different farming adaptation strategies (without CIS) were implemented in the model to assess the yield impacts under current and future climatic conditions. These were Integrated Soil Fertility Management (ISFM) to mimic the Tassa system, automatic irrigation, improved varieties for fodder management and agroforestry system. The yield impact of the adaptation measure was considered as the difference between production with and without the adaptation measures for each period and scenario. This approach can show the potential for adaptation measures to reduce negative impacts or enhance positive impacts of climate change in Niger.

The effect of mowing in Chapter 10 is represented using the LPJmL model as the complete removal of the leaf biomass of grasses down to a stubble height of roughly 5 cm on pre-determined mowing days. We tested four different mowing regimes: one single mowing event per year on October 1st (M1), two mowing events per year on August 1st and October 1st (M2), three mowing events per year on May 1st, August 1st and October 1st (M3), one single late mowing event on November 1st (M4). The four tested mowing regimes are completely generic and mowing dates in May, August and October are very roughly aligned with the beginning, peak and end of the rainy season.

5.4 Cost-benefit analysis

A cost-benefit analysis (CBA) has been conducted to evaluate the economic costs and benefits of the selected adaptation strategies at farm level. Land tenure and plot size were considered as only the land where the analysed crop was cultivated, was used for the calculation and the farmer was explicitly asked to determine this exact plot size. Whether higher costs arise from scattered plot farming or are due to other reasons, is not evident, since this was not asked in the survey. If the land was not owned, but rented by the farmer, these costs were also included into the calculation. A CBA applied in the context of adaptation examines the expected costs and benefits of implementing a specific adaptation strategy and allows to compare it with the costs and benefits of a business-as-usual production system or with alternative adaptation strategies. In this way, the analysis allows a direct comparison and helps to identify the adaptation strategy with the highest net economic benefits compared to potential alternative strategies or a business-as-usual scenario. The CBA is done by monetising all expected costs and benefits associated with implementing a specific adaptation strategy over a certain period of time. The costs of an adaptation strategy at farm level may include costs related to agricultural input, labour, tools and machinery, whereas the benefits derived from an adaptation strategy at farm level are mainly concerning an increase in yield or additional income from a diversified production. For a CBA, the costs and benefits of adaptation strategies that are linked to different time periods are discounted at an appropriate discount rate to take into consideration the timely value of money (Boardman et al., 2011). This is necessary, as we typically value current benefits (and costs) more than benefits in the (distant) future, which is integrated into the calculation using a discount rate.

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

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

The CBA for each adaptation strategy is based on selected case studies from different villages in Niger. For each strategy, we collected detailed cost and production data from 10 farmers who were implementing the technology as well as from 10 control farmers who did not. Local yield levels were used as baseline values for the no-adaptation scenario. Future yield changes resulting from climate impacts under different emissions scenarios are calculated from our crop model outputs in the case of sorghum. Against this background, the following CBA case studies were conducted:

- Agroforestry and farmer managed natural regeneration of trees
- Implementation of soil fertility and water management technologies in rain-fed millet and cowpea intercropping
- Irrigation for counter-season agriculture
- Improved fodder management: Improved varieties, irrigated alfalfa production and mowing

Chapter 6 – Adaptation and adaptive capacity in Niger

Since the beginning of this century, research on adaptation to climate change has soared, with the abstract and citation database Scopus returning 35,034 results for the search terms "climate change adaptation". 88% of the results are not older than 2010. The majority of studies has focused on factors which either enable adaptation or pose barriers to adaptation (Eguavoen & Wahren, 2015; Moser & Ekstrom, 2010; Nielsen & Reenberg, 2010; Sanou et al., 2019; Yaméogo et al., 2017). Understanding the ways in which adaptation functions is important for the design, implementation and evaluation of respective adaptation strategies. Therefore, this chapter seeks to provide an introduction to climate adaptation in the agricultural sector, with a particular focus on the social and institutional factors which determine adaptive capacity.

6.1 Adaptation and adaptive capacity

Moser and Ekstrom define adaptation as follow: "Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting nonclimatic changes. Adaptation strategies and actions can range from short-term coping to long-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities" (Moser & Ekstrom, 2010, p. 22026). In a similar way, Adger et al. (2005) say that adaptation to climate change can be motivated by many factors, including economic well-being and safety.

Adaptation can involve both building adaptive capacity, thereby increasing the ability of individuals, groups, or organisations to adapt to changes, and implementing adaptation decisions, i.e. transforming that capacity into action. Both dimensions of adaptation can be implemented in preparation for or in response to impacts generated by a changing climate (Adger et al., 2005).

Successful adaptation requires not only the selection of suitable adaptation strategies but also increasing the adaptive capacity of human and natural systems since this will determine the potential for sustainably implementing adaptation strategies. The IPCC defines adaptive capacity as "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2014, p. 118). While the historical underpinnings of adaptive capacity lie in sociology and organisational and business management, the term has become integral in addressing climate change. As the definition above already shows, there are different types of adaptive capacity. Engle (2011) distinguishes between reactive and anticipatory adaptation. While the former refers to the ability to adapt to a changing environment, i.e. responding to a stress that has occurred in the past, the latter means the ability to anticipate future stresses, based upon "one's ability to understand what the future might resemble [and] influenced by one's ability to have learned from past experiences" (Engle, 2011, p. 648). This is exactly the rationale of the climate risk analysis, i.e. to model the future climate based on historical data and in this way select suitable adaptation strategies.

Gender in national plans and policies

The majority of national strategies barely touch upon gender and women's situation in the face of climate change. In its NDC, Niger states the intention to reduce the load of household duties traditionally assigned to women, such as fetching water or firewood (Republic of Niger, 2015). The Sustainable Development and Inclusive Growth Strategy outlines a medium-term development strategy for the country, recognizing existing inequalities between men and women. It makes several references to the vulnerable situation of women, particularly regarding education, health and sanitation, however, without calling for any form of gender mainstreaming or making other suggestions on how to overcome these inequalities (Ministère du Plan du Niger, 2017b). Similarly, the strategy does not address other vulnerable groups, defined by, for example, age, ethnicity or migrant status. The Economic and Social Development Plan, adopted in 2017 for the period 2017-2021, acknowledges Niger's underperformance in terms of gender – "la contre-performance du Niger en termes du genre" (Ministère du Plan du Niger, 2017a, p. 46) – and the ways in which it is reflected in existing inequalities between men and women. It is thereby relating e.g. to access to education and healthcare, and participation in economic activities and decision making, however, also without any specific measures on how to overcome these. Only the 2017 National Gender Policy goes into detail about the situation of women, particularly in the agricultural sector, where women tend to be primarily involved in crop production, particularly in that of vegetables, and less so in management positions (Ministère de la Promotion de la Femme et de la Protection de l'Enfant de Niger, 2017). The National Gender Policy also acknowledges the limited access to land, finance and agricultural inputs, such as seeds and fertilisers. Finally, it lays out a vision for tackling gender disparities and does so along four strategic axes aimed at improving (1) the socio-cultural environment for greater gender equity, including in the areas of reproductive health and education; (2) the institutional and legal framework for effectively implementing women's rights; (3) economic empowerment and inclusive growth; and (4) frameworks and partnerships for the coordination and evaluation of gender interventions.

6.2 Factors in adaptation planning

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

6.2.1 Access to resources

Several studies mention the lack of access to resources as the main barrier to effective climate change adaptation. Resources are important at every stage of the adaptation process and include natural, financial and technical resources, information and expertise regarding climate change and adaptation options, labour, transportation and time (Acquah, 2011; Moser & Ekstrom, 2010; Shackleton et al., 2015; Sorgho et al., 2020). According to Moser and Ekstrom (2010), inadequate resources are often the first response to the question why practitioners have not yet begun to plan for climate change adaptation.

A household analysis that was conducted as part of this climate risk analysis, based on a World Bank data set collected in 2011 from about 4,000 households (ECVMA, 2011), shows that having a bigger household and larger size of land has a significant positive effect on farmer's action against climate change (see annex Table 1). A larger household and land size can indicate better availability of human resources and financial capacity which increases adaptive capacity. Asfaw, Di Battista and Lipper (2014) found that besides greater plot size also land ownership increases the likelihood that farmers adopt adaptation strategies. Ownership, in particular, increases the likelihood of adopting those strategies which will see returns from investment in the long term. On the other hand, they observed that the distance between the household and the plot was negatively correlated with the adoption of adaptation strategies, with the explanation relating mostly to higher transportation costs.

Another farm household study in Niger found that the adoption of adaptation strategies, such as improved seeds or inorganic fertilisers, was determined by the level of household wealth, with wealthier households being more likely to adopt adaptation strategies (Djibo & Malam Maman, 2019). Similarly, Asfaw, Di Battista and Lipper (2014) found that wealthier households in Niger were more inclined to use practices that required more initial capital, while being less likely to use practices which required minimal initial investment, such as crop residues, which were rather used by poorer households. Other constraints to climate change adaptation include poor market access and insufficient property and/or insecure property rights, which can limit farmers' scope of action and planning periods (Shackleton et al., 2015). Finally, both Murken et al (2020) and Shackleton et al. (2015) mention shortages in water availability as a frequent challenge to adopting adaptation strategies, e.g. irrigation.

6.2.2 Local context and diversity

The design and implementation of adaptation strategies frequently fails to adequately recognise local contexts and the heterogeneity inherent to them. Local contexts are shaped by culture (e.g. values, norms and beliefs), different levels of governance and political systems, ecosystems and social networks. These interacting factors are crucial in planning for climate change adaptation (Shackleton et al., 2015). They can either serve as enablers or as barriers for successful adaptation strategies. For example, in northern Burkina Faso, different ethnic groups and, accordingly, different cultural values allowed one and prevented another group from diversifying their livelihood strategies, i.e. by taking advantage of development projects, gardening and engaging women in economic activities (Nielsen & Reenberg, 2010). Different factors, including gender, age, class, religion and ethnicity, influence people's adaptive capacities and choice of adaptation strategies (Biesbroek et al., 2013; Shackleton et al., 2015). Nielsen and Reenberg (2010, p. 142) refer to these factors as "varied sensitivities": Different groups experience climate impacts and opportunities for adaptation differently. Poor and marginalised people in low-income countries are likely to face barriers to adaptation, such as lack of access to credit, decision-making power, information and natural resources, such as land or forests (Engle, 2011; Shackleton et al., 2015). This is particularly true for women who, due to a combination of these factors, produce, on average, 20% less per hectare of land than their male counterparts (World Bank, 2019). Also, women but also other groups, such as older people, will find it more difficult to migrate and hence rely more on agricultural production (Shackleton et al., 2015). As Asfaw, Di Battista and Lipper (2014) find, crop productivity tends to decrease with the age of the farmer, which can further increase the risk of food insecurity. "An explicit focus on intersecting dimensions of inequalities would help identify the complex drivers that prevent certain groups of disadvantaged people from successfully adapting to climatic change, while others may be more fortunate or even benefit" (Shackleton et al., 2015, p. 338). And even if adaptation strategies are in place, their mere existence does not guarantee equal access: According to Ludi et al. (2012), the establishment of irrigation infrastructure can serve to maintain social exclusion, in particular that of women, who may lack the money to pay for bribes or the social status necessary to make claims to it.

And while from an external perspective, climate change may seem a pressing issue in countries around the world, including those of the Sahel region, several scholars argue that there may be other, possibly more immediate problems (Brockhaus et al., 2012; Shackleton et al., 2015). Other issues are related to, for example, population growth, resulting competition over resources, ethnic conflicts or health risks (e.g. HIV/AIDS) (Shackleton et al., 2015). For example, in the climate risk analysis conducted in Ethiopia, informants identified population growth as a major pressure, increasingly reducing farmland size and leading to farmland fragmentation (Murken et al., 2020). These are often more immediate and more short-term stressors and are, therefore, given priority.

6.2.3 Knowledge and information

According to Shackleton et al. (2015), climate uncertainty and variability, an overall lack of information and a lack of tailored information regarding extreme weather events, and poor predictive capacity at the local level present frequent barriers to climate adaptation. Hence, knowledge and information on climate risks are key in designing and implementing the right adaptation strategies. Local value and belief systems determine the ways in which people understand and interpret climate risks (Moser & Ekstrom, 2010). Concrete experience with climatic stressors and responses to these stressors also play an important role: On the one hand, experience with climatic stressors, such as droughts, can serve as a critical trigger and motivate people to invest in adaptation strategies

(Shackleton et al., 2015). This is particularly true when yields are negatively affected, since, according to Akponikpè et al. (2010), farmers do not perceive climate in meteorological terms but in terms of agricultural activities. Asfaw et al. (2014) confirm this in their study of conditioning factors regarding adaptation strategies: Greater variability in precipitation and greater maximum temperature during the growing season increased the use of risk-reducing practices, such as for example crop residue management. On the other hand, phenomena like climate variability have been an integral part of many people's lives across the Sahel. Therefore, they may view it as a natural phenomenon and beyond human control, and as a result underestimate the severity of a changing climate (Shackleton et al., 2015). Therefore, effective communication about climate risks is important to increase awareness and understanding. Traditionally, agricultural extension services have played an important role here. However, it turns out that farmer access is often low. According to a study conducted in two rural communities in Niger, 32% of respondents had never been visited and 55% have rarely been visited by extension officers (Assoumana et al., 2016). Assoumana et al. (2016) explain this poor access with a gradual decline of public extension services since around 1998. Information, however, is crucial, e.g. relating to weather and climate forecasts: Mubaya et al. (2012) found that farmers with access to weather information were more likely to be aware of changes and to make adjustments accordingly. This was also found by a study of fifteen villages around Niger's capital Niamey: 10-days forecasts led to positive income changes in more than 75% of cases, with the biggest positive income changes for those farmers with access to fertilisers and more arable land (Roudier et al., 2016).

One of the major problems underlying climate information is that it relies on knowledge about long-term impacts, and "this knowledge is riddled with uncertainties" (Vink et al., 2013, p. 1). Also, the long-term character of adaptation to climate change requires several policy cycles before the effects of adaptation strategies can be evaluated. This temporal dimension and the (perceived) uncertainty attached to it complicate prioritisation and decision making in adaptation planning (Hovi et al., 2009; Lazarus, 2009).

6.2.4 Governance, institutions and networks

Governance, institutions and networks are considered as core elements in responding to climate change (Adger et al., 2005; Biermann et al., 2010; Brockhaus et al., 2012; Moser & Ekstrom, 2010). These core elements are characterised by multiple actors, levels, scales, sectors and degrees of decision-making power, all of which interact with each other. According to Amaru and Chhetri (2013), adaptation to climate change should draw attention to and actively engage a broad set of stakeholders, including farmers, their supporting organisations, communities, public institutions, civil society (e.g. NGOs), international agencies and the private sector. These interdependent stakeholders bring different interests, responsibilities and problem framings to the table, some of which may conflict with each other (Rodima-Taylor, 2012; Vink et al., 2013). At the same time, they contribute insights, knowledge and resources which can greatly facilitate successful adaptation planning. Adger et al. (2005, p. 79) say that adaptation to climate change involves "cascading decisions" across this stakeholder landscape. While it is important to bring different stakeholders together, it is also important to bring and think together different sectors. (Brockhaus et al., 2012) conducted several studies at different levels in Burkina Faso and Mali and observed strong sectoral thinking among government actors who did not see climate adaptation as a cross-sectoral activity but looked at sectors like water and forests independently.

The design and implementation of adaptation strategies is also conditioned by existing policies, laws, rules, regulations, programs and mandates (Moser & Ekstrom, 2010). These institutional frameworks, Brockhaus et al. (2012) argue, are needed to shift from a reactive response to climate impacts, often happening on the local level, to sustainable and systematic climate action. However, more macro-level adaptation planning, such as at the national or international level, must ensure planning across scales, also including the location-specific adaptation needs and capacities of local communities: "While the institutions operating at the macro level may be able to create an enabling environment for adaptation at the national level, their levels of engagement tend to leave large gaps in adaptive responses at the local level, ignoring important actors in understanding the relationship between climate trends and adaptation outcomes at the local level" (Amaru & Chhetri, 2013, p. 129). Furthermore, it is important to note that institutional frameworks can serve as enablers of climate adaptation but, in some cases, also serve as barriers, for example in the case of time-limited or otherwise insecure tenure rights (Adger et al., 2005).

Finally, in addition to governance and institutional frameworks, it is important to include local communities in adaptation planning to create ownership, taking into account informal networks which are organised around kinship and friendship, and customary institutions such as locally accepted resource management practices, norms and taboos (Amaru & Chhetri, 2013; Yaméogo et al., 2018). Informal networks can provide quick and more easily accessible help in climate adaptation, for example, through shared information and knowledge. These networks can also serve as financial resources for credit, either informally from relatives or friends or more formally through farmers' associations (Yaméogo et al., 2018). Social connectivity can have also negative effects: If exclusive and rigid, social networks can serve to reinforce existing power structures, further marginalise already disadvantaged groups and limit access to external networking opportunities and knowledge. Social networks can also serve as a barrier to learning, if conventional wisdom is left unchallenged (Newman & Dale, 2004; Wolf et al., 2010).

6.3 Gender, vulnerability and climate change adaptation in Niger

A growing body of literature recognises the fact that different social groups experience different levels of vulnerability to climate change and different levels of adaptive capacity (Alston, 2013; Arora-Jonsson, 2011; Perez et al., 2015; Rao et al., 2019). Differences exist regarding, for example, assets and skills available to different groups as well as different responsibilities and roles within families and communities (Carr & Thompson, 2014). This is particularly true for women. At the same time, their different responsibilities and roles, particularly with regard to agricultural practices and natural resource management, make them powerful agents in facing climate change, highlighting thus the importance of acknowledging gender differences in decision making. Although gender is not the only factor, it is regarded as critical in determining vulnerability to climate change and adaptive capacity (Ahmed et al., 2016). "In the vulnerable space following disasters, it appears that gender inequalities are being consolidated and legitimated in ways that reduce women's adaptive capacity," says Alston (2013, p. 8).

6.3.1 Determining factors of gender-specific vulnerability to climate change

Assets and resources

Women tend to have poorer access to and control over income and production factors, such as seeds, fertilisers or ploughs (Ahmed et al., 2016; Alston, 2013; Kakota et al., 2011; Tall et al., 2014). According to a recent World Bank study of gender inequality in Niger, female-managed farm plots produced, on average, 20% less per hectare of land than plots managed by men (World Bank, 2019). Factors influencing this gender gap included lack of labour and non-labour inputs, such as pesticides and fertilisers, as well as lower incidence of intercropping and irrigation (World Bank, 2019). On average, organic fertilisers were used on 1 out of 5 female-managed plots, compared to 2 out of 5 male-managed plots (Backiny-Yetna & McGee, 2015). A gender gap also exists with regards to the amount of organic fertiliser used: While male-managed plots benefited from an annual value per hectare of 3,300 CFA (~ 6 USD), it was only 1,800 CFA for women (Backiny-Yetna & McGee, 2015). A FAO report estimates that if women had the same access to resources as their male counterparts, they could increase their crop yields by 20–30% (FAO, 2011).

Land and tenure insecurity

The increasing pressure on land in Niger is reflected in women's access to it. For example, the distance between the household and farm plots tends to be higher for women than for men (World Bank, 2019), while the average size of farm plots managed by women (1 ha) tend to be smaller than for men (1.7 ha) (Backiny-Yetna & McGee, 2015) and are becoming increasingly smaller (Monimart & Tan, 2011). Monimart and Tan (2011) explain this trend with the increasing scarcity of agricultural land in Niger and the need to divide existing farm plots among family members, with priority given to men. As a result, women's labour is needed less and women are increasingly being excluded from farming activities, making them more reliant on older generations for access to land and other assets (Monimart & Tan, 2011). Diarra and Monimart (2006, p.2) refer to this development as the "de-feminisation of agriculture".

Tenure insecurity is another major issue which results in few women owning land, yet again reinforcing gender inequalities (Backiny-Yetna & McGee, 2015; Diarra & Monimart, 2006; Perez et al., 2015). Participants in a multi-national study, including Niger, report that, according to customary land rights, only men own and inherit land, while women cultivate land that is given to them by their husbands or which they rent from their community (Perez et al., 2015). Only under Islamic Law, women inherit half the share of a male family member of the same position (Bron-Saïdatou & Yankori, 2016). Hence, restricted access to and control of land keep women from making longer-term investments, such as implementing adaptation strategies, which they would otherwise consider (Bryan et al., 2018; Jost et al., 2016).

Access to information

Women also face barriers when accessing climate information, e.g. due to insufficient literacy, lack of a radio or mobile phone, which translates into limited decision-making power (Bryan et al., 2018; Rigg et al., 2016): According to a study in Niger's Aguié district, women (66.7%) were less aware of climate change effects than men (80.5%) (Ado et al., 2019). Needs with respect to climate information can also be gendered: In a rural community in Senegal, women farmers specifically required information on precipitation because men were planting their plots first, only later assisting the women (Tall et al., 2014). Hence, it was particularly important for women to know about potential dry spells and the end of the rainy season (Tall et al., 2014). While agricultural extension services provide important technical advice, many services tend to work exclusively with men. This was the case in a farming village in south-eastern Niger, where women were excluded from extension services, although they were the primary producers of sesame, groundnuts and cowpeas (Goudou et al., 2012).

Social customs and household responsibilities

Due to social customs, patterns of household responsibility and labour are also highly gendered, with women often taking on a triple role in productive, reproductive and community-managing activities (Moser, 1993; Rigg et al., 2016). In a study conducted in Burkina Faso, women reported that men worked 14 hours and women 11 hours a day, however, they did not include the time for household chores, collecting wood or water (Kieran et al., 2012). In Burkina Faso like in Niger, these are almost exclusively women's responsibilities (Dickin et al., 2020; WFP & USAID, 2017). The gender-water nexus is also reflected in a study by Goudou et al. (2012): Men and women were asked to map their village and none of the men mentioned the water well. The explanation for this difference was that men do not go there because fetching water is defined as a women's responsibility. Adding this chore to other household responsibilities and work on the fields, including travel time to water wells, women are presented with multiple burdens. This is particularly true for the dry season, when travel time to water wells increases and when especially men migrate for work, either to larger cities, irrigated farms or abroad, with major destinations being Nigeria, Benin and Côte d'Ivoire (IDMC, 2019; UNDESA, 2019). Due to its high prevalence, this type of seasonal migration is locally referred to as "exodus" and, by the IDMC (2019, p. 5), classified as a form of "distress migration" since it is not of a voluntary and strategic nature but a short-term response to external environmental shocks.

These are all factors limiting women's mobility, agricultural productivity and income sources. Hence, women's livelihoods heavily depend on farming and livestock, which are increasingly sensitive to climate impacts and heavily constrained by the gendered differences in resource access as outlined above (Alston, 2013; Belcore et al., 2020).

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

6.3.2 An intersectional perspective

It is not only gender which determines vulnerability to climate change. Instead of focusing exclusively on gender, Ahmed et al. (2016, p. 2) adopt a broader lens, speaking of “a landscape of vulnerability where diverse social descriptors including disability, social class, ethnicity and value systems create heterogeneous conditions” for climate adaptation. Factors, such as marital status (e.g. married, divorced, widowed), a growing family, poor health, an advanced age or a particular livelihood activity can all increase people’s vulnerability (Nation, 2010; Van Aelst & Holvoet, 2016). Nyantakyi-Frimpong (2019, p. 1545) carried out research on smallholder farmers’ vulnerability to climate extremes in northern Ghana, highlighting the importance of an intersectional perspective by considering different social factors. She gave the example of a woman farmer, who was “not just a woman, but also a woman who is HIV-positive, poor and widowed, with no spouse to handle the everyday village politics of securing a plough”.

Info Box: Potential of adaptation strategies to increase agricultural production

Based on household level data collected in 2011 from about 4 000 households in Niger as part of the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) program of the World Bank (ECVMA, 2011), we assessed the existing adaptation management by Niger’s farmers to understand the impact of implemented adaptation strategies on the level of agricultural production. The dataset has a national coverage, including both urban and rural areas in all regions of the country and contains a range of information on households’ agricultural production, implemented adaptation practices and existing knowledge on the farm as well as households’ characteristics, such as the total number of people in a household and gender and education of the household head.

First, we identified the adaptation practices implemented by farmers in response to changes in temperature and rainfall in 2011 (see annex Table 2): Diversifying sources of income, changing seed varieties, and migration appeared to be among the most frequently implemented strategies. While some of the adaptation strategies such as changing seed varieties have a direct benefit to enhance food production, other strategies such as diversifying income sources and migration can have an indirect role in food production and climate resilience overall: financial constraints are reduced which enables the implementation of innovations such as improved seed and irrigation.

While 57% of the sampled households have not taken any action against climate change, 16% of the households implemented a single adaptation strategy and 28% implemented a combination of adaptation strategies (Figure 48). However, the percentage of households that implemented more than four adaptation strategies is very low.

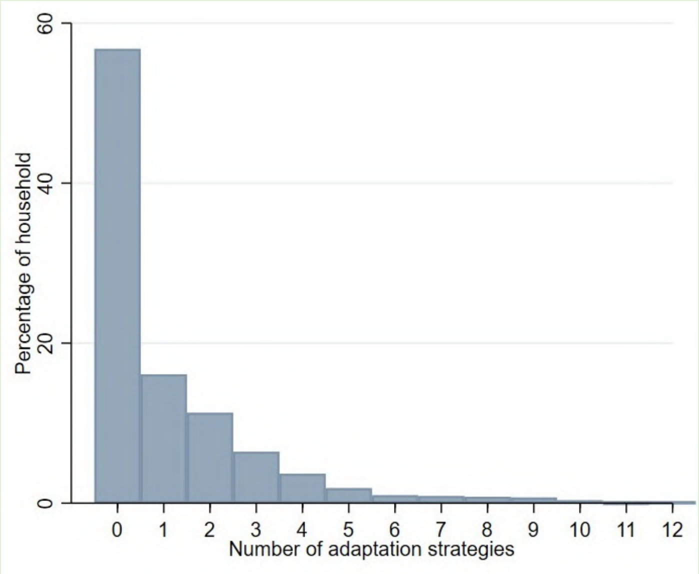


Figure 48: Number of adaptation strategies implemented by households.

Then a regression analysis was conducted to evaluate the impact of adaptation on agricultural production. The analysis suggests that the implementation of adaptation strategies has a positive relation to the level of food production (see annex Table 3). Households that implemented one or more adaptation strategies have a relatively higher level of production than households who did not implement any strategy. However, the effect is not found to be statistically significant. This suggests that even though adaption strategies provide some benefits, they are not yet significant enough. Other characteristics such as education level of household heads, size of the household, land area and herd size, land tenure security, a constant availability of an extension agent and specific weather conditions (e.g. precipitation level) show a significant positive relation to the level of agricultural production, whereas female headed households have a significant negative relation with the production level. As argued in the previous Chapter (5.3), gender is an important issue to consider when it comes to adaptation management. Regarding all the factors mentioned above (assets and resources, access to information, etc.), women generally are affected by inequality and gender related constraints diminishing their adaptive capacity and resilience towards climate change.

Therefore, these first results point to the importance of understanding the gender dimension and related constraints in order to assess and improve the adaptive capacities of smallholder farmers. As most farmers are not taking any adaptation actions against climate change, there is also a need for policy intervention to increase their capacity for adaptation. Besides the implications of gender related constraints, further effort is needed to identify innovative adaptation practices that can produce stronger and more significant positive impacts than those currently being practiced by smallholder farmers in particular.

Chapter 7 – Agroforestry and farmer managed natural regeneration of trees

7.1 Context and description of the technology

Agroforestry is defined as "the integration and use of trees in crop fields, farms and agricultural landscapes" (Dinesh et al., 2017, p. 11). More specifically, it is "a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels." (FAO, 2015a). In Niger, along with other Sahelian countries in Western Africa, thanks to this practice, areas that were once semi-desert are re-greening and marginal production areas are restoring (Vira et al., 2015; Binam et al., 2017; Bayala et al., 2020). Listed as one of ten best bet innovations for adaptation in agriculture (Dinesh et al., 2017), agroforestry is highly promising to alleviate many of the challenges of traditional low-input cropping systems, while also buffering adverse impacts of climate change and variability. Decades of research and experience have shown that integrating trees into these cropping systems enables agricultural landscapes to generate yields and revenues increasingly sufficient to sustain the livelihoods of the rural poor (Boffa, 1999; Francis et al., 2015; Garrity & Bayala, 2019; Haglund et al., 2011; Smale et al., 2018).

Agroforestry in Niger is mostly practiced in the form of Farmer Managed Natural Regeneration (FMNR), a tree management practice that, instead of planting tree seedlings into farmlands, is based on the identification, active protection and regrowth of wild tree and shrub stumps in fields (Reij & Garrity, 2016). Trees are integrated into fields or agricultural landscapes (then often referred to as agroforestry parklands) otherwise used for cultivation of annual crops as well as for grazing and feeding of livestock (Boffa, 1999). There are several steps involved in the practice of FMNR (Garrity & Bayala, 2019): when clearing lands for grazing or crop production, farmers identify the stumps of those wild tree species they wish to retain on their fields. As stumps grow from an already developed and living root system, their survival and growth under dryland conditions is much higher than from planted tree seedlings. Farmers then actively manage the growth of the selected stumps into full canopy trees, with tree density varying from some 40 to 150 trees per ha (Pye-Smith, 2013; Smale et al., 2018).

First established in Niger in 1983, the promotion of FMNR was a decisive response to the droughts of the 1970s and 80s that together with mounting demographic pressure had seriously disrupted the existing ecological balance. 34 years later, agroforestry parklands are reported to cover over 7 million ha of lands in Niger, a success bearing witness to the many benefits that trees provide to farmers' livelihoods (Francis et al., 2015; Smale et al., 2018). Niger's agroforestry parklands are mostly found in the agricultural zone that stretches across the southern part of the country, commonly along the Niger river and in territories with a marked human presence. The highest concentration is found in the Tahoua, Maradi and Zinder regions (Pye-Smith, 2013).

Favoured species differ from place to place. According to Garrity and Bayala (2019), the most common tree species for FMNR practice in African drylands include the baobab tree (*Adansonia digitata*), which provides nutritious fruits and leaves; the shea tree (*Vitellaria paradoxa*) that provides butter used in cooking, in chocolate and cosmetics; gum arabic (*Acacia senegalensis*) that provides a gum used in many food items; and the white acacia tree (*Faidherbia albida)*, which enriches soils and provides valuable pods and foliage for fodder. *Faidherbia albida,* a leguminous nitrogen-fixing tree, thereby has a unique property in exhibiting a reverse phenology that makes it especially attractive to farmers in Niger and Western Africa. Unlike other trees, it sheds its leaves at the onset of the rainy season, thus providing timely soil fertilization and only limited shading that allows farmers to grow their crops underneath the tree canopy in the rainy season (Pye-Smith, 2013).

Agroforestry systems provide multiple **adaptation benefits** to local livelihoods. The most direct stem from the diversification of farm system produce resulting from the provision of fruits, nuts, timber or firewood which farmers can use or sell at local markets. Well-established tree canopies create favourable micro-climates underneath, reducing peak temperatures by several degrees and alleviating heat stress for temperature-sensitive crops and livestock (Dinesh et al., 2017). A sufficiently high density of trees can contribute to the recharge of groundwater levels, whereas in less dense systems, deep-reaching tree roots can still pump water from deep layers to surface soil strata that can help sustain crops during prolonged dry spells (Garrity & Bayala, 2019). Trees on fields also act as windbreaks, offering protection to crops from strong winds and sandstorms, and are an effective measure for controlling soil erosion from winds and floods.

Given that Niger is experiencing the effects of a changing climate already today through rising temperatures, erratic precipitation amounts and higher frequency of extreme events such as droughts or floods, the further promotion of agroforestry systems through FMNR holds great potential in increasing the resilience of local livelihoods against climate change. In the following sub-chapters, the biophysical and socioeconomic potential of FMNR as adaptation strategy under climate change are further assessed and discussed.

7.2 Biophysical risk mitigation potential

Modelling tree-crop interaction in DSSAT is limited. However, the effects of agroforestry, mainly in soil properties, can be emulated in the model. Therefore, we increased Soil Organic Carbon (SOC) and soil nitrogen content by 20% based on a meta-analysis which showed that this was the mean benefit of agroforestry across different systems, agro-ecological zones, soil types and climates (Kuyah et al., 2019). Agroforestry can increase SOC by photosynthetic fixation of carbon from the atmosphere and by transferring it to the soil. This is the first meta-analysis that indicates that agroforestry systems in sub-Saharan Africa can increase crop yields while maintaining and regulating soil properties.

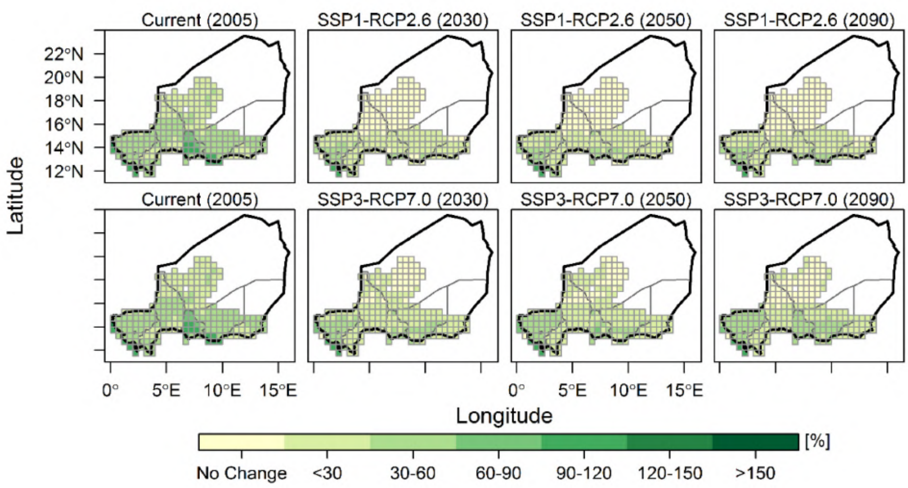


Figure 49: The spatial distribution map for sorghum yield change with agroforestry emulation compared to current yields without the intervention in Niger.

The spatial distribution map shows the yield impacts of agroforestry implementation in Niger (Figure 49). Overall, results show that agroforestry can increase the yields up to 150%, especially in the south of Niger (Zinder and Maradi regions). The southern region's SOC is already high compared to other regions of Niger, and an additional 20% increase in SOC has an extensive impact on sorghum yields compared to other regions where soil fertility may already be too low. Thus the response in sorghum yields from agroforestry is from the combination of the shading and the increased fertilisation effects, which are important for many areas in the country that have low fertiliser use.

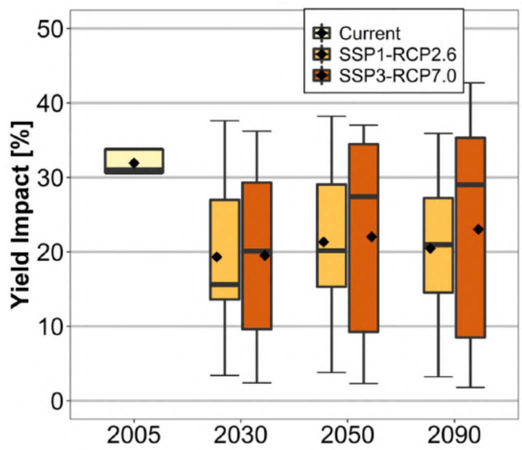


Figure 50: The intercomparison of the yield impacts between different time steps with agroforestry.

Figure 50 shows the yield impact variability over time for different scenarios. Both low and high emissions scenarios have similar impacts (up to 40% increase in yield) over time. Unlike other adaptation strategies, the yield impact of agroforestry increases with increasing emission levels and with time, with the highest increase under the high emissions scenario in 2090, although in all cases the benefit is lower than that realised under current climatic conditions. This response pattern shows that agroforestry is very promising for yield benefit under climate change in Niger.

Figure 51 shows the regional-wise yield impacts of agroforestry for both the emissions scenarios and different time-steps. All regions have yield impacts up to 60%. The regions with already higher SOC compared to other regions have a projected increase of up to 60% in yield, while other regions have a projected yield increase of up to 30%. In Zinder, Maradi and Tillabery, the yield impacts of agroforestry are higher at higher emissions scenarios and later periods when climate impacts are projected to be worse, while they are relatively similar for the other regions. This is because of the simulated benefit of keeping the crop canopy temperature within plant tolerable limits especially when high emission scenarios project as higher temperature changes as 4 °C by the end of the century. The low response in sorghum yield to agroforestry compared to the current in Diffa and Tahoua is because these two regions have been projected to have positive yield changes under climate changes while other regions were projected to have negative changes. Therefore, the shading in agroforestry will reduce this benefit much more than the benefit from fertilisation in agroforestry.

Different studies have been conducted to assess the impact of FMNR on crop yields. In 2009, Reij et al. (2009) estimated an average sorghum yield increase of 100 kg/ha in Niger across the areas where FMNR was practiced. At five million ha with practiced FMNR at the time, they calculated this to be leading to 500,000 extra annual tonnes of cereals produced that could feed an additional 2.5 million people. However, these high percentage yield increases can be realised in areas with low productivity already, and even with 300% increases in yield, this will be still below potential production when all crop production limitations are eliminated.

As demonstrated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Niger, yield increases from FMNR depend on local context and management of agroforestry systems. Nevertheless, the overall effect of adopting agroforestry will likely result in positive crop yield gains, for sorghum but also for millet and cowpeas, provided that the compost and NPK-fertilizer input is not too high/remains low.

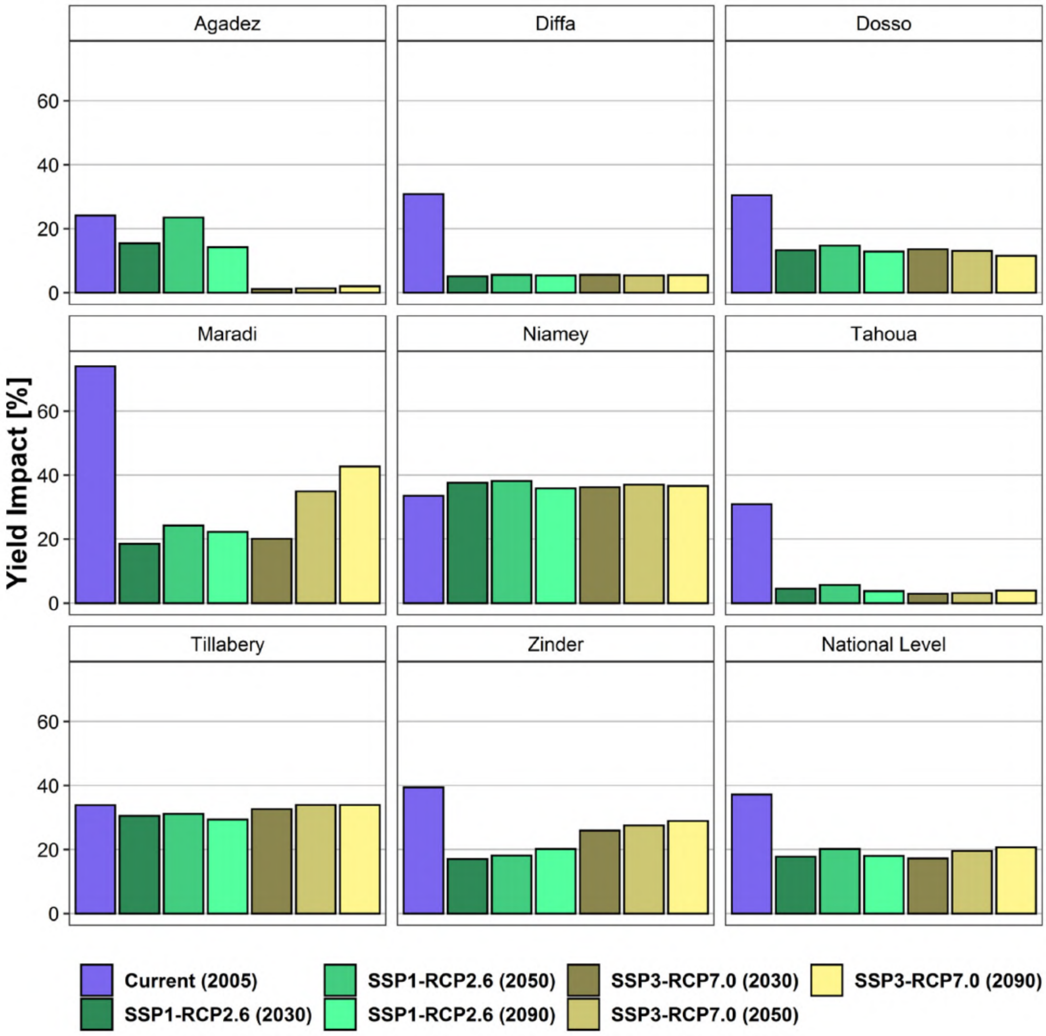


Figure 51: Regional-wise yield impacts with agroforestry over different emissions scenarios and time-steps.

7.3 Cost-benefit analysis: using FMNR for integrating *Bauhinia rufescens* trees into millet and cowpea production

Previous experiences have shown that integrating agroforestry in an intercropping system strengthens the resilience of those systems and can significantly improve yields. We analysed the economic feasibility of millet-cowpea-agroforestry systems with *Bauhinia rufescens* trees, and compared the costs and benefits of those systems with a conventional millet-cowpea intercropping system that did not adopt agroforestry. Two different climate change scenarios were compared, each projected until 2050 with reference to a baseline scenario describing the status quo as of today.

7.3.1 Baseline and scenarios

The baseline and the scenarios are defined as follows:

Baseline (no action, no climate impacts): Rainfed millet and cowpea production in an intercropping system without agroforestry under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under low and high emissions scenarios): Rainfed millet-cowpea intercropping without agroforestry. The market revenues and production costs of the system are extrapolated until 2050 assuming a climate change yield impact based under a low emissions scenario and a high emissions scenario.

Adaptation (action, climate change impacts under low and high emissions scenarios): Rainfed millet-cowpea production with *Bauhinia Rufescens* trees in an agroforestry system. The market revenues and production costs of the system are extrapolated until 2050 assuming a similar climate change yield impact as under "non-adaptation" under low and high emissions scenarios.

7.3.2 Survey data

The household data on which the assessment is based was collected from ten farms in Southern Niger in the region of Maradi (department Aguié). The farming families were supported by the project *Projet de Développement Rural de l'Arrondissement d'Aguié* (PDRAA) in adopting agroforestry on their fields. Most of the analysed agroforestry systems have been installed more than 20 years ago, combining millet and cowpea with 200 *Bauhinia rufescens* trees on an average farm size of 1.7 ha, planted at five- meters intervals. However, following the standards in farm economics and for better comparison across scenarios, we analysed the average market revenues and production costs associated with one hectare. The farmers provided detailed information on costs for installation of the trees in the first and subsequent years, on millet and cowpea yields before and after adaptation, on tree product yields and on market prices in the region. To determine the changes of market revenues and production costs due to adaptation, the following aspects are considered for the farmers who adopt.

- The cost side includes labour costs for the installation of the system, which involves twelve days of planning, land and nursery bed preparation, sowing, tree transplantation, fencing, tree pruning and input application. Some of the farmers hired external workers, but most of the work was done by family members. By using the mean value of the average daily labour rate for the externally hired farm workers retrieved from the survey, which is 1,080 CFA (~ 2 USD[8]), we arrive at total labour costs of 8,639 CFA (~ 16 USD) in the first year of installation, and of 2,880 CFA (~ 5 USD) for maintenance in the second and third year respectively. Since farmers reported to harvest tree products from the fourth year onwards, costs for harvesting fodder, firewood and leaves are added, resulting in 3,403 CFA (~ 6 USD) per ha in the same year, and rising up to 4,778 CFA (~ 9 USD) in the fifth year and for all subsequent years (WASCAL, 2020a).
- The largest cost factor, however, are the costs for inputs, such as tree seedlings, manure,

[8] All exchange rates were retrieved on 19.4.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en

UREA, NPK, pesticides and fungicides, accounting for 32,369 CFA (~ 59 USD) in the first year, but reduced to 24,430 CFA (~ 45 USD) from the second year on, because fewer new tree seedlings are needed. *Bauhinia Rufescens* trees have an average lifespan of 67 years, therefore the total renewal of the agroforestry system lies outside the period under consideration. However, every year some of the trees have to be renewed by the farmers (ibid.).

- The higher yields of millet and cowpea induced by the new growing system lead to an increased workload for harvesting, drying and stocking. The labour costs for these activities are therefore annually adjusted using the ratio between the yield with adaptation and the reference yield prior to adaptation (WASCAL, 2020a).
- Costs for equipment are not included into the calculation, since all tools, which are needed for the agroforestry system, are also used for growing millet and cowpea and therefore do not produce additional costs.
- Opportunity costs, or lost income respectively, are calculated for the working time spent on the installation and maintenance of the agroforestry system. The daily rate, which is used, is an average daily price for different on- and off-farm activities such as oil production, tailoring, breeding and more is 2,648 CFA (~ 5 USD). The opportunity costs are therefore highest in the year of installation, being 30,165 CFA (~ 55 USD), reducing to 17,008 CFA (~ 31 USD) from year 2025 on (ibid.).
- To calculate the revenues, we use a market price of 257 CFA (~ 0.47 USD) for one kg millet and 263 CFA (~ 0.48 USD) for one kg cowpea. The prices are average values of the market prices indicated in the household survey. According to the interviewed farmers, the millet yield increased by 260 kg per hectare between the first year of adaptation and the fifth year. For cowpea, the yield gain after adaptation is 85 kg compared to the baseline yields of 215 kg/ha for millet and 130 kg/ha for cowpea. Based on the revenues gained from the yield surplus, we extrapolated the additional market revenues and extra labour costs until 2050 (WASCAL, 2020a).

7.3.3 Assumptions

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

- Climate change induced yield developments on millet in the Maradi region are derived from PIK projections using sorghum as proxy under a SSP1-RCP2.6 and a SSP3-RCP7.0 scenario including a positive effect on yield developments with adaptation. The climate change effects on cowpea were calculated using the IMPACT model (IFPRI, 2015), which assumes a demographic and economic growth trajectory under SSP2 and a low emissions scenario under RCP4.5 and a high emissions scenario under RCP8.5. In the following CBA calculations, the yield development of millet under SSP1-RCP2.6 and the cowpea yield development under SSP2 and RCP4.5 are summarized under a “low emissions scenario”, while the combination of millet under SSP3-RCP7.0 and cowpea under SSP2 and RCP8.5 are merged under a “high emissions scenario”.
- It has been assumed that the farmers’ area productivity increases due to autonomous technological change by 1.63% per annum for millet and by 7.90% for cowpea. These are extrapolations of millet and cowpea yield increases between 2000 and 2018 in the target region (WASCAL, 2020b).
- To depict the inflation rate, we calculated the exponential growth rate of the GDP per capita of Niger from the last 30 years, its value is 2.35% (FAOSTAT, 2021b).

7.3.4 Results

Calculating the above listed costs and revenues for the installation of an agroforestry system in intercropping with millet and cowpea shows, that within the analysed time horizon until 2050, the adaptation strategy becomes beneficial for the farmers, as it has a positive return on investment. This applies to both climate change scenarios, whereby the high emissions scenario performs better than adaptation under the low emissions scenario, due to the embedded additional climate change related yield effects. In particular, the following key figures shall be discussed:

- As it can be seen in Figure 52, the net present value (NPV) is negative for a couple of years, starting with -71,327 CFA (~ -131 USD) in 2020.The NPV even decreases during the first years due to a negative cash flow until 2022 for the high emissions scenario and until 2023 for the low emissions scenario. This can be explained by high establishment costs and the delayed revenues from tree products.
- However, for both scenarios, the net cash flow for the farmers becomes positive in year 2023 letting the NPV steadily increase, and thus becoming positive in year 2026, marking the break-even point between accumulated net costs and net benefit. In other words: the investment pays off after five years. In 2050, the NPV of the low emissions scenario is 841,563 CFA (~ 1,550 USD) and 1,173,579 CFA (~ 2,157 USD) for the high emissions scenario.
- Accordingly, the internal rate of return (IRR) is positive and yields almost 24% for adaptation under the low emissions scenario and even 28% for an adaptation under the high emissions scenario. To indicate a profitable investment, the IRR must be higher than the local interest rate. According to the survey, this is 5% for our case study site (WASCAL, 2020a).[9] As the IRRs for both scenarios are much greater, the switch from millet-cowpea production without agroforestry to a millet-cowpea system with agroforestry is profitable for the farmers
- This is also directly reflected in the cost benefit ratio (BCR) of the adaptation investment, which in 2050 is 1.71 for the low emissions scenario and 1.99 for the high emissions scenario (see Table 7).

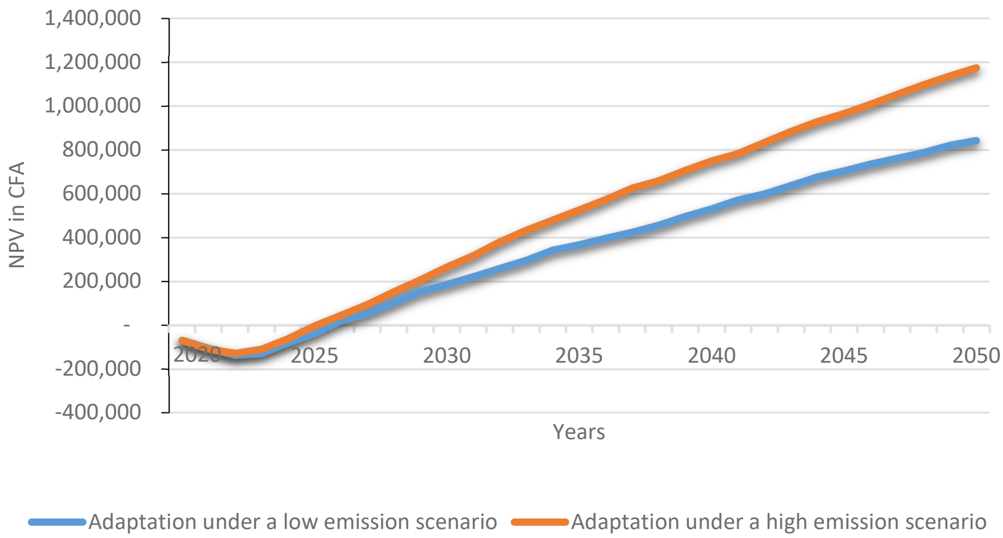


Figure 52: Development of the net present value of switching to millet and cowpea production in an agroforestry system with Bauhinia rufescens.

9 Considering a global rentability perspective, which is often taken for local CBAs, any IRR higher than 6 percent is seen as a profitable investment.

Table 7: Summary of major CBA indicators for switching to millet cowpea intercropping with agroforestry.

	Adaptation under the low emissions scenario	Adaptation under the high emissions scenario
IRR	23.46%	28.10%
NPV	841,563 CFA (~ 1,550 USD)	1,173,579 CFA (~ 2,157 USD)
BCR	1.71	1.99

7.4 Multi-criteria assessment

7.4.1 Upscaling potential

The previous sections showed that FMNR is both cost-effective and a strategy that can directly revert some of the negative consequences of climate change on crop yields. Yet, its beneficial impacts especially on crop yields is only achieved under an adequate management, ensuring that shading of crops does not exceed a certain threshold of and in specific locations where high temperatures and changing climate conditions are projecting a yield loss for the future periods. Given its easy and cheap establishment, multiple benefits, decades-long experience and high stakeholder interest, there is great potential for further upscaling of this practice across Niger.

Given that the UNCCD together with a wide range of stakeholders from the African and international donor and development community support the establishment of a "Great Green Wall" across the Sahel, there is also significant momentum for scaling up this practice. It is a Pan-African initiative to plant trees and re-green a 15 km wide and 7 000 km long stretch of land across 11 countries (including Niger) in the Sahel, with the goal to halt desertification, restore ecosystems and improve livelihoods of populations in partaking countries (Goffner et al., 2019). First launched in 2008, the initiative has recently entered a new phase in support of reaching the Sustainable Development Goals (SDGs) by 2030, to which it can contribute on several fronts, e.g. through directly supporting SDGs 2 (Zero Hunger), 13 (Climate Action) and 15 (Life on Land), among others. FMNR is one of the practices that directly contributes to achieving the goals of this initiative and hence can attract additional funding and programme support from development actors (UNCCD, 2020).

7.4.2 Development of co-benefits

Additional development co-benefits besides strengthening resilience to climate change and increasing incomes and livelihoods of farmers are also evident. In particular, the additional biomass from trees increases carbon capture and storage, contributing significantly to mitigation actions, as agroforestry systems accumulate between 1.1 and 28.2 t CO_2 ha^{-1} yr^{-1} in biomass and between 3.7 and 27.3 t CO_2 ha^{-1} yr^{-1} in soils (Dinesh et al., 2017).

Agroforestry systems contribute positively to health and nutrition. As Dinesh et al. (2017, p.16) suggest in an overview study of adaptation options, "a positive relationship between indicators of dietary quality of children under five years of age and landscape scale tree cover has been found in Africa, associated with maximum fruit and vegetable consumption at an intermediate level of tree cover". A strengthened economic position of women has been found in communities where women have been able to become tree owners and earn additional incomes from selling tree products (Reij et al., 2009). The easy availability of firewood from trees also significantly reduces the workload of women who are typically spending several hours per day in collecting firewood or dry manure for use in cooking. By using more high quality firewood (especially of *Faidherbia albida* trees) instead of dry manure, women are less exposed to hazardous smoke during meal preparation, which contributes to better health (Larwanou et al., 2006). Francis et al. (2015) found that children that would usually spend hours herding livestock for grazing could now feed animals with easily accessible tree products and find time to attend school or for recreation instead.

The production and sale of timber also creates lucrative income sources in rural areas, thus reducing incentives for migration of young farmers.

Additional income also creates multiplier effects in village communities by supporting the establishment of small businesses that provide employment and supply rural communities with construction material, medicinal products and fodder (Larwanou et al., 2006). Also, additional income sources due to the created resilience when climate shocks destroy or reduce the year's harvest, while edible fruits and nuts are also of particular value during the lean season before the harvest when food is typically scarce. Agroforestry systems also provide valuable inputs for farm production, such as animal feed, bio-fertilization in the form of tree leaves or nitrogen fixation, or shading for crops and livestock (Garrity & Bayala, 2019; Reij & Garrity, 2016). Overall, the establishment of agroforestry systems present a landscape resilience approach for whole farming communities, increasing social capital and reducing socio-economic and environmental pressures and concerns.

7.4.3 Potential negative outcomes

There is a multitude of forms in which agroforestry and FMNR systems can be implemented, and often it depends on the specific local context how they need to be designed in order to reap the greatest benefits. A careful selection of tree species and tree density according to the local social and environmental context is adamant for an efficient integration with local farming systems. Sometimes the degree of shading or competition for nutrients and water resources from trees can also result in undesired yield reduction of other crops or livestock.

In some cases, there might be competition for land between agroforestry and other user groups. For example, protecting agroforestry tree seedlings from roaming animals can reduce available grazing areas and fodder for livestock in the initial development stage of agroforestry systems, creating potential conflict between different groups of land users (Garrity & Bayala, 2019). Adequate planning and the creation of livestock corridors can avoid such conflicts.

7.4.4 Barriers for implementation

In Niger (and other African countries), private possession and utilization of trees and their products has long been illegal or required specific permits from the state that were difficult and costly to obtain. Farmers were threatened with imprisonment for even pruning a tree, and have often been faced with extortion from foresters wrongly accusing farmers of 'breaking the law' (Garrity & Bayala, 2019). That practice was gradually suppressed, but only a reform of Niger's forest legislation in 2004 finally lifted the ban for farmers to utilize trees and their products (ibid.). This reform prompted the spread of FMNR practice among farmers, yet many farmers continue to fear that they will not benefit from the care given to the trees, reducing their motivation to engage in FMNR (Fritz & Graves, 2016).

Nowadays, a common barrier to implementing agroforestry systems is the large time-gap of several years between the investment in establishing the trees and obtaining returns, which is often difficult for smallholder farmers who cannot afford to wait several years to generate revenue from an investment (Dinesh et al., 2017). In FMNR, the initial cost of the investment is comparably low as almost no external inputs are required, yet if farmers decide to introduce new tree species to their fields that require purchase of seedlings and equipment for planting, this can become a challenge. In this case, farmers need to be able to access required inputs and tree seedlings as well as necessary financial resources, the absence of which might hinder adoption.

7.4.5 Institutional support requirements

Farmers need institutional support to clarify land tenure status, which commonly hinders many to make any long-term investments into their lands. Information and education campaigns at grassroot level such as farmer-to-farmer extension and organized farm demonstration visits have proven to be powerful tools in promoting the adoption of FMNR (Garrity & Bayala, 2019). Additional and tailored information campaigns using e.g. farm radio programs and a better-equipped and well-trained extension service are needed to create further awareness on the benefits of FMNR on the local level. The establishment of rural wood markets where farmers can sell their tree-derived products can go great lengths in further spreading the adoption of the practice (Garrity & Bayala, 2019; Reij & Garrity, 2016). During the stakeholder workshop we conducted, it was highlighted that strengthening the capacity of women's organizations can have a great impact on environmental protection and especially on promoting agroforestry and FMNR.

7.5 Conclusion

Considering all mentioned criteria, agroforestry presents a high-risk mitigation potential and various positive benefits as an adaptation strategy with a high upscaling potential (Table 8). However, institutional support to e.g. clarify land tenure status would be needed where appropriate to increase the adoption by smallholder farmers.

Table 8: Summary of multi criteria assessment of agroforestry.

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

Chapter 8 – Integrated soil fertility management

8.1 Context and description of the technology

Farmers in Niger are facing various challenges, including low-fertility sandy soils, variable rainfall amounts, and changing social and political situations. Agriculture increasingly relies on marginal or even degraded land, as rapid population growth and limited availability of fertile land is putting pressure on natural resources (Fatondji et al., 2006). Water and wind erosion, nutrient depletion, salinization and soil crusting are among the most important land degradation processes. Soil moisture is a major limiting factor for crop production resulting mainly from loss of rain water through surface runoff and evaporation (Fox & Rockström, 2003; Hoogmoed, 1999). Water and soil conservation should therefore constitute a priority in Niger.

Integrated Soil Fertility Management (ISFM) is defined as "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions in aim of maximizing the agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles" (Vanlauwe et al., 2010). ISFM is applied in response to soil degradation and nutrient depletion and requires interventions to be aligned with prevalent biophysical and socio-economic conditions at farm and plot level (Vanlauwe et al., 2015). It is not characterised by specific field practices, but can be considered as "a fresh approach to combining available technologies in a manner that preserves soil quality while promoting its productivity" (Sanginga & Woomer, 2009, p. 13) and therefore requires an in-depth understanding of the resources available and their alternative uses, as well as continuous assessment and response of the implemented practices' effects on the environment and yields. Common for ISFM in drylands, the set of management practices applied in Niger are based on the following objectives: 1) maximising water capture and decreasing surface runoff, 2) reducing water and wind erosion, 3) managing limited available organic resources and 4) strategically applying mineral fertilisers (Sanginga & Woomer, 2009). Suitable interventions include Tassa, half-moons, stone bunds, filter bunds, grass strips, mulching, bocage system, etc. In the following section some of those interventions will be described in more detail.

Originally re-discovered by farmers in neighbouring Burkina Faso after a period of severe drought in the Sahel in the early 1980s, the traditional water harvesting technique **Tassa** (also known as Zaï) spread at a surprising rate to Niger towards the end of the 1980s and is now a commonly applied ISFM technique in the country. It is implemented with the goal to rehabilitate degraded, crusted land. Farmers dig small planting pits that are 20-30 cm in diameter, 20-25 cm in depth and about 1 m apart in each direction (Liniger et al., 2011).

Half-moons work similarly, but involve digging pits of about 2 m in diameter and 15-20 cm in depth in a crescent shape with a distance of around 8 m (Savadogo et al., 2011). Both traditional practices have the goal to accumulate water before subsequent planting to improve infiltration and increase the soil moisture content. In many cases and often depending on availability, manure is added to each pit, such as millet straw, cattle manure or their composted form, thereby combining water harvesting with nutrient management to rehabilitate degraded lands (Hassane & Reij, 2020). This can further improve the performance of Tassa and Half-moons (Sawadogo, 2011). A method called micro-dosing that involves adding small amounts of mineral fertilisers to planting points within fields where water conservation is practiced is also often used in the Sahel (Sanginga & Woomer, 2009). In Niger, millet is the most common crop grown in Tassa and half-moon pits, but some farmers also cultivate a mixture of millet and sorghum.

Tassa are often combined with stone lines along the contour to enhance water infiltration, reduce soil erosion and siltation of the pits (Liniger et al., 2011). **Stone bunds**, also called stone lines ("cordon de pierres" or "cordon pierreux") are erosion control structures that involve piling stones at close spacing along contour lines. Stone bunds are built at the height of 20-30 cm from the ground and along the natural contour of the land after 10-15 cm of the soil has been removed from the line where they are to be built. The distance between the stone rows is around 20-50 cm depending on the slope of the land. Stone bunds work best when combined with biological measures, such as growing grass, live hedges and tree planting, as well as with organic manure and mulching (Nill et al., 2014). Well-vegetated stone bunds, for example, can reduce soil temperature and protect the soil from wind erosion. Growing grass between the stones can further increase infiltration and accelerates the accumulation of fertile sediment (Liniger et al., 2011).

The lifespan of a stone bund is over 20 years. There is a progressive build-up of sediment behind the bunds, resulting in the formation of terraces. Although the capacity of the bunds to retain water declines as the sediment builds up, soil infiltration capacity increases, thanks to improved soil structure, and the slope becomes gentler thanks to the terracing effect. The best results are achieved when contour stone bunds are used in combination with biological measures (planting of grass, trees and hedges) and the use of organic fertiliser and mulching (Nill et al., 2014).

Implementing ISFM has shown to improve water use efficiency, prevent erosion and restore degraded lands, and can therefore be considered as a promising climate change adaptation strategy. In an eight year project implemented in Tahoua, a total of 5,765 ha of severely degraded land has been restored to productive land not including spill-over effects to farming community that were not part of the project but also adopted ISFM technologies (Hassane & Reij, 2020). By improving water use efficiency, ISFM also helps farmers become more resilient against drought and related food shortages. Those aspects are particularly important in a context like Niger, where a rapidly increasing population is putting pressure on available land resources.

8.2 Biophysical assessment of risk mitigation potential

The Tassa technology has been used as a case study to showcase the biophysical risk mitigation potential of ISFM in the case of sorghum production. Since the adaptation strategy (Tassa) is not directly available as an option in DSSAT, we generated initial soil conditions using DSSAT internal module by keeping water availability of 60% and nitrogen content of 62 kg/ha (Fatondji et al., 2012; Faye et al., 2018).

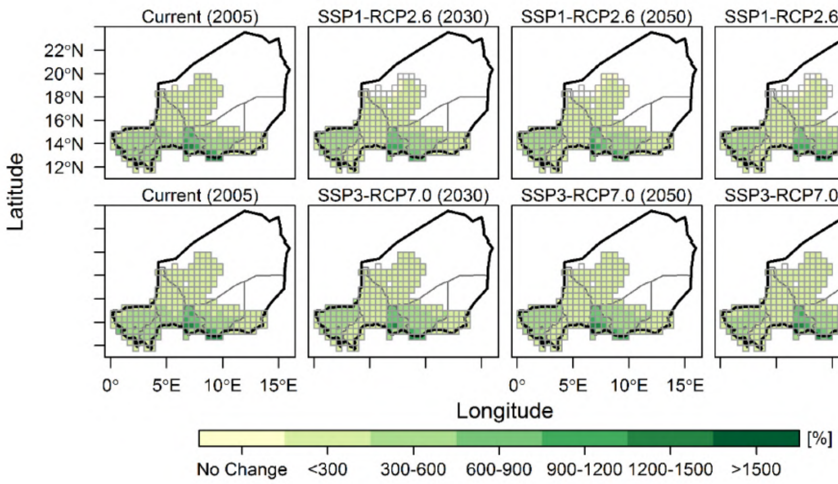


Figure 53: The spatial distribution map for impact analysis with integrated soil fertility management.

As visualised in Figure 53, applying Tassa as an ISFM increases sorghum yield over all grids significantly up to 1500%, especially over Southern Niger under both emissions scenarios. The higher soil organic carbon (SOC) in the southern part could be a reason for extremely improved yield values (up to 1500%). With the implementation of Tassa, there are on average between 300% and 600% of yield increases in Niger except for the southern regions in Zinder and Maradi.

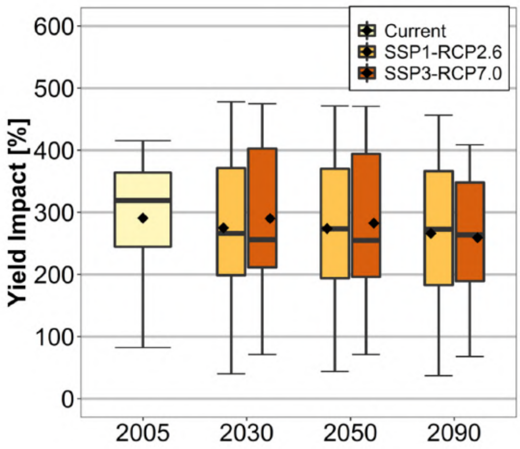


Figure 54: The intercomparison of the yield impacts between different time steps.

Figure 54 shows the variability of yield impacts over different time steps at the regional level. Both low and high emissions scenarios have maintained standard yield impacts over time of up to 400%. The range of positive impacts in yields under climate change is higher compared to potential yields under current climate conditions for both emissions scenarios. This could be because of climatic conditions becoming more optimal for the growth of sorghum in the future than under current circumstances.

Figure 55 shows the region-specific yield impacts of the Tassa technology for both emissions scenarios and different time-steps. All regions experience positive yield impacts of at least up to 100% compared to the baseline year 2000. In most regions, both high and low emissions scenarios have similar yield impacts. In comparison, southern regions (Maradi, Zinder, Niamey and Tillabery) experience a more positive impact than other parts of Niger, such as Agadez and Diffa. Overall, the results show that the Tassa technology can increase sorghum yields by over 350% compared to non-adoption of this technology and that this increase remains stable under changing climate conditions.

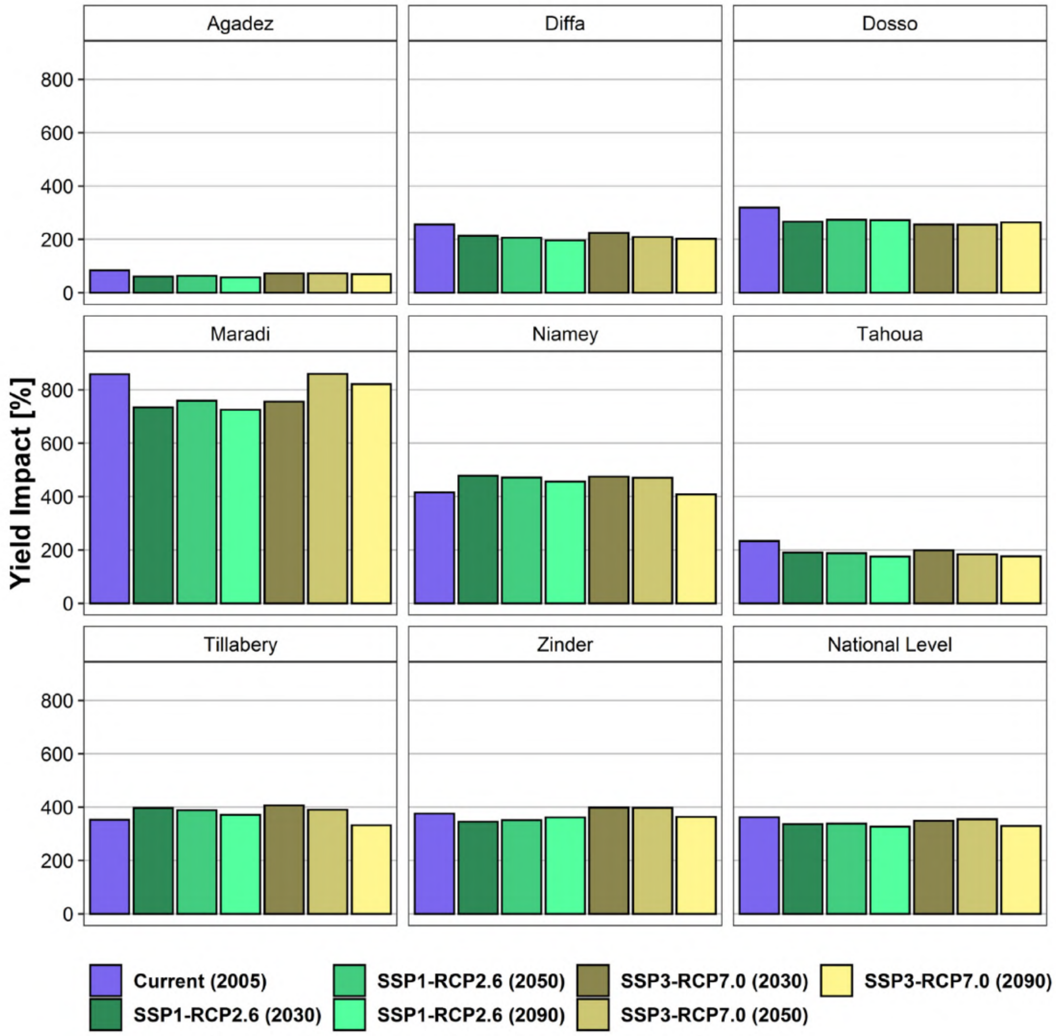


Figure 55: Regional wise yield impacts with integrated soil fertility management over different scenarios and time-steps.

8.3 Cost-benefit analysis for ISFM for millet and cowpea intercropping

To analyse the economic feasibility of ISFM as an adaptation strategy, the costs and benefits of a millet and cowpea intercropping system that adopted the use of an ISFM with a conventional millet-cowpea intercropping system that did not adapt to an ISFM strategy were compared. For this analysis, ISFM includes Tassa holes and contour bunds installed on the fields to conserve soil and water. Two different climate change scenarios were compared, each projected until 2050 with reference to a baseline scenario describing the status quo as of today.

8.3.1 Baseline and scenarios

The baseline and the scenarios are defined as follows:

Baseline (no action, no climate impacts): Rainfed millet and cowpea production in an intercropping system under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under low and high emissions scenarios): Rainfed millet-cowpea intercropping without the use of ISFM. The market revenues and production costs of the system are extrapolated until 2050 assuming a climate change yield impact under a low and a high emissions scenario.

Adaptation (action, climate change impacts under low and high emissions scenarios): Rainfed millet-cowpea intercropping system with the use of an ISFM. The market revenues and production costs of the system are extrapolated until 2050 assuming a similar climate change yield impact under "non-adaptation" under a low and a high emissions scenario.

8.3.2 Survey data

The economic data used as basis for the CBA calculations were collected from 13 farms in Keita, in Tahoua region in southern Niger. The surveyed farmers installed stone contour bunds in the fields to check runoff and to control erosion. Tassa holes were dug into the fields to improve rainwater harvesting, and infiltration into the soil and to collect compost and manure. On average, each farmer cultivates an area of 12 ha, of which around seven hectares are under a millet and cowpea intercropping system using ISFM. However, following the standards in farm economics and for a better comparison across scenarios, the average market revenues and production costs were analysed associated to one hectare. The farmers provided detailed information on costs for installation of the techniques, on yields before and after the adaptation, as well as on market prices in the region. To determine the changes of market revenues and production costs due to adaptation, the following aspects are considered for the farmers who adopt.

- Once installed, the contour bunds have to be maintained only every subsequent year. For the initial installation, the farmers need less than half a day for planning and training per year and hectare. For contour plotting one day in the first year and only a quarter of a day in each subsequent year is needed. For collecting pebbles and stones they allocate six days in the first year and only two days in the following years. Other than the contour bunds, Tassa holes must be rebuild every year. For the whole process of land preparation and digging holes, the farmers need between five and six days per year and hectare. Using the mean value of the average daily labour rate for farm work retrieved from the survey, which is 2.188 CFA (~ 4 USD[10]), we arrive at labour costs of 27,321 CFA (~ 50 USD) in the first year and of 19,834 CFA (~ 36 USD) in each subsequent year (WASCAL, 2020a).
- The new fertilization strategy doubles the need for manure and urea as it is used to fill the Tassa holes. The total costs for inputs increase by 33,040 CFA (~ 60 USD) per year and hectare. However, as contour bunds and Tassa holes are constructed from naturally occurring materials such as sand and stones which are collected from the fields, no additional costs occur in this regard (ibid.).
- Small digger, cart, spade, rake, shovel, wheelbarrow and hammer is equipment which is required for the constructions. These hand machines are renewed at certain intervals retrieved from the survey. In total, they produce rather minor costs, as they are not mechanized and therefore can be acquired at comparably low costs.
- The higher yields induced by improved soil fertility and water management, however, lead to an increased workload for harvesting, threshing and seed conservation. The labour costs for these activities are therefore annually adjusted using the ratio between the yield with adaptation and the reference yield prior to adaptation (WASCAL, 2020a).
- To calculate the revenues, we use a market price of 295 CFA (~ 0.60 USD) for one kg millet and 272 CFA (~ 0.50 USD) for one kg cowpea. The prices are average values of the market prices indicated in the household survey adjusted for the mean common market price level of past five years in the region (FEWS NET, 2020). According to the interviewed farmers, the millet yield increased by 525 kg per hectare in the first year of adaptation and again by additional 24 kg in the second year. For cowpea, the yield gain after adaptation is 190 kg. Based on the revenues gained from the yield surplus, we extrapolated the additional market revenues and extra labour costs until 2050 (ibid.).

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10 All exchange rates were retrieved on 15.4.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en

8.3.3 Assumptions

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

- Climate change induced yield developments on millet in the Tahoua region are derived from PIK projections using sorghum as proxy for millet under a SSP1-RCP2.6 and a SSP3-RCP7.0 scenario including a positive effect on yield developments with adaptation. The climate change effects on cowpea were calculated using PIK projections, which assumes a demographic and economic growth trajectory under SSP2 and a low emissions scenario under RCP4.5 and a high emissions scenario under RCP8.5. In the following CBA calculations, the yield development of millet under SSP1-RCP2.6 and the cowpea yield development under SSP2 and RCP4.5 are summarized under a "low emissions scenario", while the combination of millet under SSP3-RCP7.0 and cowpea under SSP2 and RCP8.5 are named "high emissions scenario".
- We assume that the farmers' area productivity increases due to autonomous technological change by 1.3% per annum for millet and by 7.9% for cowpea. These are extrapolations of millet and cowpea yield increases between 2000 and 2018 in the target region (WASCAL, 2020b).
- To depict the inflation rate, the exponential growth rate of the GDP per capita of Niger from the last 30 years was calculated with 2.35% (FAOSTAT, 2021b).

8.3.4 Results

The CBA results show, that implementing the ISFM techniques would be beneficial for the farmers in 2050, as it has a positive return on a rather small-scale investment (Figure 56). This applies to both emissions scenarios, whereby the high emissions scenario performs considerably better, due to the embedded additional climate change related yield effects. In particular, the following should be highlighted:

- Starting with a negative net present value (NPV) of -104,319 CFA (~ -189 USD) in 2020, the net cash flow for the farmers and so the NPV become positive from the second year on. The comparably low initial investment and reinvestment costs lead to a steadily increasing NPV right from the beginning accumulating to 4,999,427 CFA (~ 9,065 USD) for the low emissions scenario and 5,656,315 CFA for the high emissions scenario (~ 10,256 USD) in 2050. In other words: the break-even point between accumulated net costs and net benefits for both scenarios is reached already in year 2021, the second year of investment.

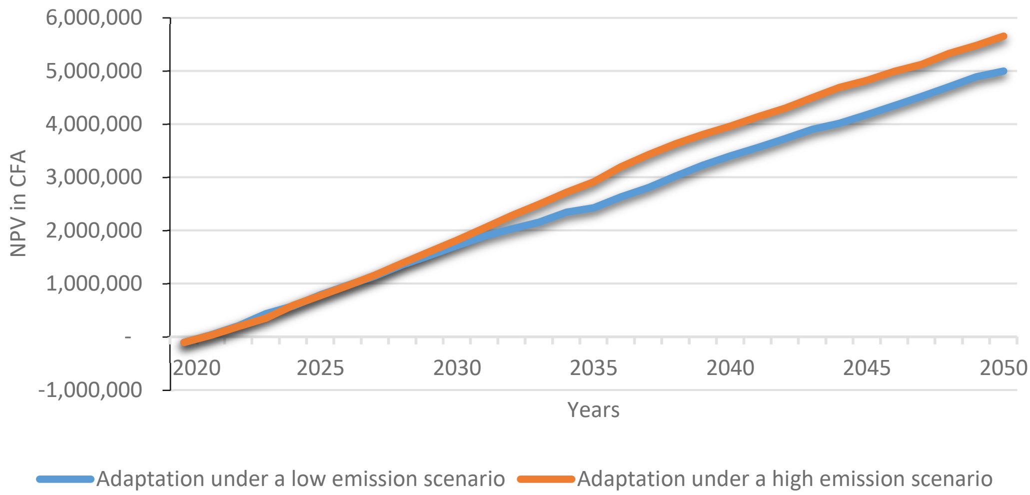

Figure 56: Development of the net present value of switching to millet cowpea intercropping using ISFM.

Consequently, the internal rate of return (IRR) is highly positive and yields 159% for an adaptation under the low emissions scenario and 150% for an adaptation under the high emissions scenario. Assuming a global rentability perspective, which is often taken for a local CBA, any IRR higher than 6.0%, is considered a profitable investment. This is also evident in the benefit cost ratio (BCR) of the adaptation investment, which in 2050 is 4.79 under the low emissions scenario and 5.29 under the high emissions scenario (Table 9). The very positive results of the CBA can be explained by comparably low installation costs at remarkable yield increases and high market rates for millet and cowpea.

Table 9: Summary of major CBA indicators for switching to millet cowpea intercropping with ISFM.

	Adaptation low emissions scenario	Adaptation under high emissions scenario
IRR	158.93%	150.12%
NPV	4,999,427 CFA (= 9,065 USD)	5,656,315 CFA (= 10,256 USD)
BCR	4.79	5.29

8.4 Qualitative assessment of integrated soil fertility management

8.4.1 Upscaling potential

National policies and donor programmes have given increasing attention to water harvesting, stemming mostly from the country's prioritization of food self-sufficiency, particularly as a response to the 1968-73 major drought (Di Prima et al., 2012). Considering the rather limited extent of irrigation coverage, rain-fed agriculture still plays a significant role in Niger. As of 2017, according to the FAO, only 33% of the irrigable land in Niger was irrigated, corresponding to 0.5% of the total national cropland (FAO, 2017; FAOSTAT, 2017).

While consistent data is lacking on the adoption rate of ISFM technologies in Niger, anecdotal successes are well documented showing the great potential of ISFM to restore degraded lands and increase the water holding capacity for the soils. Several ISFM projects have been implemented with successful outcomes over the past decades, even beyond the project timeline, most notably the soil and water conservation project implemented by the International Fund for Agricultural Development (IFAD) between 1988 and 1995 in Niger's Illéla District. Di Prima et al. (2012), report that even 16 years after project activities ended, farmers continued to integrate the rainwater-harvesting technologies into their agricultural system and the area has consequently seen a remarkable environmental transformation. The significant potential of micro-dosing as a form of ISFM has been highlighted by Sanginga and Woomer (2009). The 2005 food shortfalls that led to a devastating famine could have been eliminated, if only a quarter of Niger's farmers had applied fertilizer micro-dosing.

8.4.2 Potential co-benefits

ISFM entails different social and environmental co-benefits that help to promote numerous aspects of sustainable development. A soil and water conservation project supporting the implementation of Tassa and half-moon, which was implemented from 1988 to 1995 in the Illéla District in Niger's Tahoua Region, reports various co-benefits for sustainable development, including increased purchase of degraded lands to bring them back to life, increased food security and income from labour (Hassane & Reij, 2020).

Furthermore, various studies confirmed positive environmental outcomes of ISFM. Nill et al. (2014), for instance, reported various positive observed ecological impacts of implementing contour stone bunds in Niger, including decreased surface runoff and soil loss, decreased wind velocity and increased soil moisture, and increased plant diversity.

Additionally, some studies find that the implementation of ISFM can also lead to an increase in income, for example from labour or the purchase and selling of land. The high labour intensity of implementing some of those ISFM techniques, has helped to create new employment in rural areas, as farmers often rely on hired labour to construct Tassa (Di Prima et al., 2012). In the Tahoua project the land restoration successes led to increased land purchase of severely degraded lands that would then be restored and sold at higher prices. A household survey conducted as part of the project found that 40% of the household heads interviewed had bought degraded land with the goal of restoring it for crop production (Hassane & Reij, 2020).

ISFM has also proven to have a positive impact on food production and thereby indirectly on food security. On the one hand, this is due to an increase of cropland on which food can be produced, as degraded land is restored. On the other hand, the land that is being farmed becomes more productive. Field trials of Tassa conducted between 1999 and 2000 in Sadoré showed a 3- to 4- fold increase (in some cases even a 19-fold increase) in grain yield. When adding organic fertilizer, such as manure, the yield even increased up to 68 times. Moreover, water use efficiency of millet doubled (Fatondji et al., 2006).

8.4.3 Potential negative outcomes

The literature cites very few maladaptive outcomes. Di Prima et al. (2012) point to the potential of conflicts between farmers and pastoralists that may occur when communal land that is used as pasture land is rehabilitated for the purpose of agricultural production. At the same time, Hassane and Reij (2020) report, as one of the long-term impacts of implementing ISFM, that sedentary pastoralists in the village of Batodi do not need to move their herds to bordering Nigeria anymore, because there is now enough fodder to keep the livestock close to the village all year around.

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

All in all, the few references made to potential maladaptive outcomes suggest that ISFM is a promising technology for climate change adaptation that may help to overcome some of the obstacles posed to agricultural production in Niger.

8.4.4 Barriers for implementation

The implementation and upscaling of ISFM techniques may face some barriers including high labour requirements, access to fertilizers, insufficient access to knowledge or awareness, and inadequate policies (Sanginga & Woomer, 2009). Estimated labour requirements for Tassa, for example, vary between about 300 hours (Roose et al., 1999) to 600 hours per hectare of hard work of digging holes and an additional estimated 300 hours for the production of manure and its transport and spreading into the pits (Kabore-Sawadogo et al., 2013). The digging of the pits also must be redone every three years. Nevertheless, a study conducted in the Tillabery Region of Niger found that despite the hours of labour required to implement ISFM, labour availability does not appear to be a constraint for adoption, as the digging of holes is done during the dry season when there is no need for other field activities (Wildemeersch et al., 2013).

Another potential barrier for the implementation of ISFM frequently cited in literature is the availability of input, such as manure needed to fertilise the planting holes, agricultural equipment and transport facilities (Fatondji et al., 2006; Wildemeersch et al., 2013), in addition to weak access to fertilizer credit and insufficient flows of information to farmers (Sanginga & Woomer, 2009). Furthermore, low levels of literacy among some smallholder farmers can be a main constraint to effective communication and dissemination of ISFM information (Sanginga & Woomer, 2009).

Wildemeersch et al. (2013) find that while most farmers are well aware of ISFM techniques and their direct benefits, such as improved yields, the long-term environmental benefits of implementing ISFM are less well known. Most farmers in the study had little awareness of the causes and effects of erosion and therefore did not relate ISFM techniques to the indirect benefits.

8.4.5 Institutional support requirements

Experience from Niger has shown that the promotion of ISFM requires complementary institutional support and market linkage. An experiment assessing the adoption of ISFM technologies in 180 villages in Niger suggests that while training alone can be a cost-effective way to get farmers to use the technology, upfront cash transfers are essential to farmers to help them overcome immediate credit constraints associated with hiring labour (Aker, 2018). Another strategy that has proven successful is the support of "warrantage", farmer's cooperatives which help farmers to organize themselves as a response to increased yields due to the implementation of ISFM. Incomes of farmers in Niger accessing the *warrantage* system increased between 52% and 134% as a result of the improved farm produce prices (Sanginga & Woomer, 2009).

Perceptions and access to information also play an important role in the adoption of ISFM. A study conducted in the Illéla district of Niger found that higher percentages of degraded farmland, extension education, lower risk aversion, and the availability of short-term profits are important factors for increasing the adoption and intensity of ISFM (Baidu-Forson, 1999). Wouterse (2017) suggest that the perceived increase of drought can lead to an increased adoption of ISFM. Households that are better educated, more experienced, and empowered are also more likely to implement ISFM (Wouterse, 2017). There is the need to provide extension education that demonstrate not just the immediate positive impacts of ISFM, but also the long-term environmental and socio-economic advantages (Wildemeersch et al., 2013), as well as risk reduction capacities of the technologies (Baidu-Forson, 1999). Empowerment programmes can also be an important tool to help with the uptake of ISFM technologies. This may include leadership trainings or encouraging membership of producer groups or rotating savings schemes (Wouterse, 2017).

It is important to recognise that the technologies described as ISFM are originally traditional practices from the region. Osbahr & Allan (2003) who conducted a study in the Fandou Béri village to compare local and scientific understandings of soils, suggest that farmers draw on varied ecological knowledge and experiences to make complex and dynamic farming decisions. Individuals' capabilities, perceptions of constraints and opportunities, and their ability to mediate access to different types of resources influence local soil fertility management. There is also a great variability between the soil fertility status of individual fields, even within the same communities that are important to consider when implementing ISFM (Vanlauwe et al., 2010). This suggests that there is a need to leverage the benefits of traditional knowledge by integrating social and natural science (Osbahr & Allan, 2003).

Nevertheless, there are some barriers to implementation, such as scarcity of inputs, access to capital and markets, labour and to some extent access to knowledge, that can only be overcome at a policy level. Strategic policies are therefore needed to stimulate institutional and market response toward ISFM and resulting crop surpluses (Sanginga & Woomer, 2009). Policies towards sustainable land use intensification, as well as the rehabilitation of degraded soils and the necessary mechanisms to implement and evaluate these can help to promote the uptake of ISFM (Vanlauwe et al., 2010). Policies that incentivise credit and loan schemes and subsidy programmes for the production of organic inputs could address the issue of lack of access to equipment and input (Roobroeck et al., 2015).

8.5 Conclusion

ISFM, especially considering the traditional practices like Tassa and halfmoons, is a promising adaptation strategy. In a context like Niger, where there is significant population pressure on land resources, the upscaling of ISFM holds great potential for climate change adaptation offering farmers a cheaper method to more efficiently use rainwater and thereby limiting the impacts of negative climate impacts. In addition, the strategy holds various socio-economic co-benefits including increased agricultural-production, food security and restoration of degraded land and biodiversity.

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

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

Chapter 9 – Irrigation for counter-season agriculture

9.1 Context and description of the technology

The agricultural sector in Niger is heavily dependent on water from precipitation. Since precipitation is increasingly erratic due to climate change, irrigation can help smallholder farmers to adapt to these changing conditions. Irrigation can be defined as the artificial process of applying water to crops or land in order to support plant growth. The FAO distinguishes between three types of irrigation: surface irrigation, where water flows over the land; sprinkler irrigation, where water is sprayed under pressure over the land; and drip irrigation, where water is directly brought to the plant (FAO, 2001). Irrigation is not yet widely implemented in Niger, which is reflected in a largely unexploited irrigation potential - only 33% of the total irrigable land area were irrigated in 2017 (FAO, 2017) and the scientific interest in irrigation: a literature search with the database Scopus returned only 25 results on the terms "Niger" and "irrigation"[11].

Irrigation systems in Niger can be classified into four types: (1) state-financed irrigation systems under full water control, also referred to as "aménagements hydroagricoles" or "AHA" (14,000 ha); (2) off-season irrigation systems under partial water control, which are supervised by district agricultural services (18,000 ha); (3) private small-scale irrigation systems, which usually comprise only a few hectares, sometimes even less than one hectare (68,000 ha); and (4) traditional types of run-off collection, such as zaïs or half-moons (Ministère de l'Agriculture et de l'Élevage, 2015; Ministère du Développement Agricole, 2005).

State-led irrigation systems in Niger are overseen by the national irrigation agency ONAHA (Office National des Aménagements Hydro-Agricoles), which provides monitoring and support to the local irrigation associations. The majority of state-led irrigation systems are located along the banks of the Niger River. Compared to other neighbouring countries, such as Burkina Faso, the size of state-led irrigation systems in Niger is several times larger. While irrigation systems comprise, on average, 50 ha in Burkina Faso, the average size of irrigation systems in Niger is 230 ha (Abernethy & Sally, 2002). State-led irrigation systems in Niger are characterised by modern technologies: They usually consist of concrete-lined canals, which deliver water from motorised pumping stations to the plots. Also, at 3 to 5 litres per second and hectare, water-delivery capacities are high (Abernethy & Sally, 2002). These factors, among others, result in high water user fees which are based on an exact calculation of true costs in the previous season per hectare cultivated (Abernethy & Sally, 2002). Different from off-season and private small-scale irrigation systems, which produce primarily vegetable crops, state-led irrigation systems focus on the production of rice, which is grown in two cropping cycles year-round (Abernethy & Sally, 2002).

Off-season irrigation systems were developed by the Nigerien government as a result of recurring droughts in the early 1980s and the subsequent cereal deficit (Ehrnrooth et al., 2011). This type of irrigation system focuses on irrigated crops in the dry season, which runs from October to May and which is a time of the year when food insecurity is particularly high. After the end of the rainy season, plots are usually left to rest for a couple of weeks and then tilled with off-season crops, which typically include vegetables, such as onions, tomatoes and chili peppers (Cochand, 2007). Plots are less than a hectare in size and supervision is provided by agricultural extension services. Water comes from wells, cesspools, ponds or boreholes. While this type of irrigation spanned more than 60 000 ha by the end of the 1990s and scientific literature continues to distinguish this type of irri-

[11] The literature search was conducted by excluding the search terms „Nigeria" and "office". "Office" was excluded due to a Malian government agency called "Office du Niger". Office du Niger administers a large irrigation scheme in the Ségou Region of Mali and appears in many scientific articles.

gation, (Ehrnrooth et al., 2011) note that, in reality, such a distinction is no longer obvious, since many off-season irrigation plots have been divided and transferred onto individual farmers, who now farm these plots according to their personal preferences.

Private small-scale irrigation systems are initiated by farmers themselves and managed either individually or in small groups (Ehrnrooth et al., 2011). Irrigated areas are as small as less than a hectare and, according to (Cochand, 2007), usually no more than 15 ha. Technologies are low-cost: In most cases, irrigation is done manually with the help of manual pumps, shadoofs[12] or water buckets (Cochand, 2007). This type of irrigation is very labour-intensive. Hence, the land area which can be irrigated in this way is limited and so are opportunities for more commercial crop production. Increasingly, however, motor pumps are being used, allowing farmers to cultivate larger areas of land and to intensify crop production (Cochand, 2007). Water typically comes from wells, which tap on groundwater, or shallow water points, which collect surface runoff during the rainy season (Cochand, 2007). Since private small-scale irrigation systems do not operate under a government or NGO initiative, statistical figures are difficult to obtain (Cochand, 2007).

Traditional types of runoff collection include zaïs and half-moons. As an off-season farming technique, zaïs are constructed by digging small pits and filling them with organic matter, which, in combination with collected water, fosters the retention of soil moisture and increases soil nutrients (Wouterse, 2017). Half-moons are semi-open structures, which, in the shape of a half-circle, are dug into the soil. They help to keep surface runoff in place, allowing it to seep into the soil and improve fertility of the encrusted soil. However, Wouterse (2017) notes that, compared to zaïs, which can be planned more autonomously, half-moons present a more expensive adaptation strategy which is promoted by the Nigerien government and NGOs.

The development of modern irrigation systems in Niger dates back to the colonial period. In the mid-1930s, colonial companies first implemented irrigation systems in order to satisfy the food needs of the local colonies, in particular regarding rice, and to export high-value products back to France such as onions and other leafy vegetables (Ehrnrooth et al., 2011). However, an expansion and more rapid development of irrigation systems only occurred after independence and in particular after the severe droughts in the 1970s and 1980s, which caused food shortages across the entire Sahel region (Jaubert et al., 2010). This period of droughts, in turn, strengthened the commitment to irrigation, including that of the Nigerien government, farmers' organisations and international donors, such as the European Union (at the time: European Economic Community) and foreign governments, most prominently China (Ehrnrooth et al., 2011; Moussa et al., 2020). However, as in other countries in the region, public investments were reduced in the 1990s as a result of structural adjustment programmes, shifting the focus away from subsistence farming and towards market-oriented agricultural production, in particular that of vegetables and fruits (Jaubert et al., 2010). Key to this process was the adoption of the document "Guiding Principles for a Rural Development Policy" (original title: "Principes directeurs pour une politique de développement rural") in 1992, which advocates for the disengagement of the state and the promotion of the private sector (Ehrnrooth et al., 2011). In this context, the World Bank took a renewed interest in irrigation in Niger and initiated the Private Irrigation Promotion (PIP) project which provided grants to farmers so they could cover the initial investment costs (Jaubert et al., 2010). Initiated in 1998 and terminated in 2008, the PIP project was deemed successful by the World Bank (2009), particularly for its contribution to yield and irrigated land increases, while also being criticised for its exclusion of smallholder farmers, due to a variety of barriers, which are discussed in Chapter 9.4.4 (Jaubert et al., 2010).

Today, irrigation presents a priority area in agricultural development in Niger, which is reflected in several national policies and initiatives taken by the government. The 2005 National Strategy of Irrigation Development and Runoff Water Collection lays out a detailed strategy for increasing the share of irrigated agriculture in the agricultural GDP (MDA, 2005). The proposed framework aims at attracting private-sector investments and, in this way, at improving the productivity of irrigation facilities and the diversification of agricultural production. The 2015 Strategy of Small-Scale Irrigation focuses on the development of small-scale irrigation in order

[12] A shadoof is an irrigation tool, which consists of a pole with a bucket and a counterpoise to raise water from wells or other water bodies.

to improve food and nutritional security (Ministère de l'Agriculture et de l'Élevage, 2015). Furthermore, several other documents, including the Rural Development Strategy (République du Niger, 2003), the Accelerated Development and Poverty Reduction Strategy (République du Niger, 2007), the 3N Initiative (République du Niger, 2015) and the Agricultural Policy (Ministère de l'Agriculture et de l'Élevage, 2016), recognise the potential of irrigation as a means to improving food security, reducing poverty and contributing to overall economic growth.

9.2 Biophysical assessment of risk mitigation potential

As illustrated in Chapter 1, climate change leads to increased temperatures, evapotranspiration rates and increasingly uncertain precipitation amounts. In addition, the number of dry spells, even during the rainy season, and the onset and length of the latter are becoming more and more uncertain. These climatic changes and uncertainties translate into uncertainties regarding water availability and agricultural production. Irrigation can help to compensate for these uncertainties and significantly reduce climate risks and therefore constitutes a promising adaptation strategy. In the rainy season, irrigation can mitigate the impact of dry spells, while in the dry season, it can compensate for crop failures from the rainy season through the cultivation of for example vegetables. In this way, irrigation can help to stabilise agricultural production and food security year-round.

Different studies have been conducted to assess the impact of irrigation on crop yields. Since the literature on irrigation in Niger is scarce, we drew on studies from neighbouring countries which are characterised by similar socioeconomic and biophysical patterns. For example, a study by Zongo et al. (2015) assessed the impact of supplemental irrigation from small man-made reservoirs on cereal production in Burkina Faso. The results show that smallholder farmers were able to increase maize yields by 68% (2.5 t/ha on experimental plots and 1.7 t/ha on control plots) and even grow a second crop with the water surplus from the reservoir. Another study by Zongo et al. (2019) modelled the economic impact of supplemental irrigation in Burkina Faso, showing that in a dry year, supplemental irrigation of maize, sorghum and millet would increase incomes by 27%, compared to the situation without irrigation. Opata et al. (2019) compared irrigated and rain-fed rice farms in Nigeria and found that the mean net farm income of irrigated farms was more than double of that of rain-fed farms. Fox et al. (2005) confirm this picture for Burkina Faso and Kenya, noting that supplemental irrigation is economically viable, however, only when combined with cash crop production during the dry season.

To analyse the risk mitigation potential of irrigation as an adaptation strategy, we used sorghum as a case study and chose the option "automatic irrigation when required" in DSSAT. In this option, we set the irrigation flood depth for 5 cm.

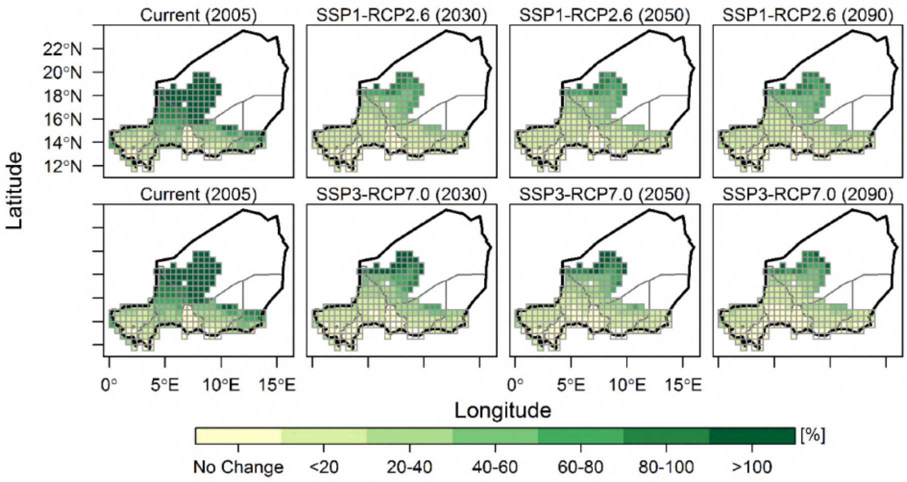

Figure 57: The spatial distribution map for impact analysis with automatic irrigation.

Overall, irrigation increased yield over most of the grids significantly up to 100%, especially over northern Niger in both emissions scenarios. Comparing the two emissions scenarios, the high emissions scenario has produced higher yields than the low emissions scenario in all time steps, mainly in Niger's northern part (Figure 57). In both emissions scenarios, the southern part of Niger remains unchanged, but the northern region had higher positive impacts in the high than in the low emissions scenario. The lack of response in the southern regions is because the projected rainfall trends could satisfy the crop water requirements for sorghum and therefore no irrigation was triggered. However, overall, both scenarios have produced significantly positive impacts in yields with irrigation application.

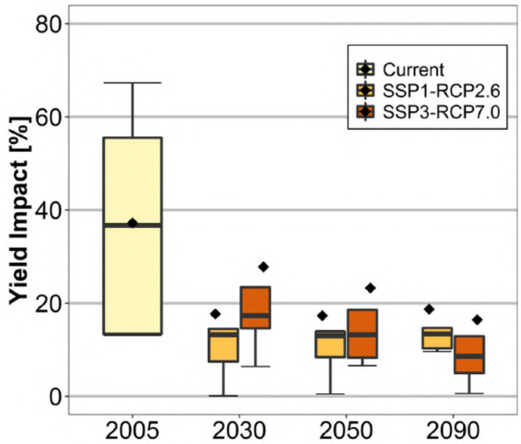

Figure 58: The intercomparison of the yield impacts between different time steps with automatic irrigation.

Figure 58 shows the variability of yield impacts over different time steps with irrigation application. Comparing both scenarios, the low emissions scenario has maintained standard yield impacts over time, whereas the high emissions scenario shows a decreasing trend over time, but with higher yield impacts than SSP1-RCP2.6. Irrigation performs very well in yield impacts under current conditions with increasing yields by over a third, but this benefit is not directly translated to projected climatic conditions as the yield impacts will be lower. In both scenarios, some of these unchanged yields can be explained by the processes of unproductive soil evaporation, interception losses, deep percolation, and surface runoff due to a combination of higher rainfall in SSP3-RCP7.0 than in SSP1-RCP2.6 and irrigation in southern Niger (Rockström, 2000).

Figure 59 shows the regional-wise yield impacts of automatic irrigation for both emissions scenarios and different time-steps. Comparing all the time-steps, the northern regions of Niger have higher sorghum yields under irrigation than the southern regions in both scenarios. Compared with future scenarios, current yields are higher with irrigation in all regions, indicating that climate change (specifically warming) will reduce the potential of irrigation to provide yield benefits though excessive evapotranspiration.

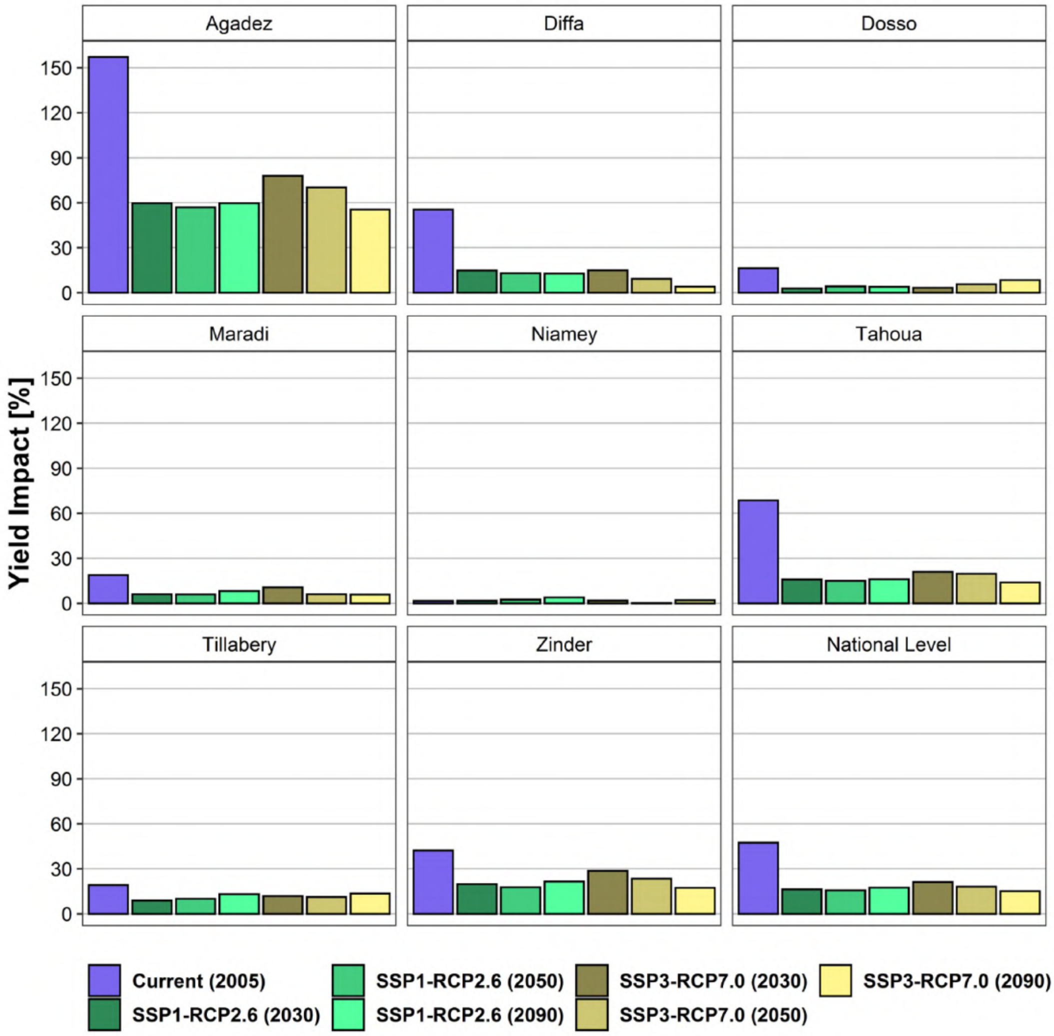

Figure 59: Regional-wise yield impacts with automatic irrigation over different scenarios and time-steps.

9.3 Cost-benefit analysis for irrigated counter-season vegetables and crop production

Irrigated off-season agriculture enables farmers to generate an income from agriculture during the dry season of the year, when cultivation is normally not possible and many farmers turn to other sources of income instead. To assess whether counter-season agriculture is economically viable, costs and benefits of this cultivation system were compared with a scenario where farmers generate their income with off-farm work. For the adaptation scenario, we analyse two different climate change scenarios each projected until 2050 with reference to a baseline scenario describing the status quo as of today.

9.3.1 Baseline and scenarios

The baseline and the scenarios are defined as follows:

Baseline (no action, no climate impacts): No agricultural production during dry season. Instead, farmers engage into off-farm labour under current climatic and technological conditions in the region.

Non-adaptation (no action): No agricultural production during dry season. Instead, farmers engage into off-farm. The market revenues and production costs of the system are extrapolated until 2050.

Adaptation (action, climate change impacts under RCP4.5 and RCP8.5): Irrigated off-season agriculture. The market revenues and production costs of the system are extrapolated until 2050 assuming a climate change yield impact under RCP4.5 and RCP8.5.

9.3.2 Survey data

The data on which the calculations are based was collected from ten farms in Maradi, a Southern region of Niger. The here analysed farmers cultivate irrigated plots with an average size of 0.3 ha with different vegetables, such as pepper, eggplant, onions, tomatoes, anise and cucumber and with staple crops such as maize, wheat and cassava. While vegetables are sold at the market, the crops are commonly used for own consumption. Most of the farmers do so since more than 20 years. Apart from counter season farming, they also engage into rainfed agriculture during rainy season, which is not subject to this analysis, but influences the cost side of the CBA. To follow the standards in farm economics and for better comparison across scenarios, the average market revenues and production costs associated to one hectare were analysed. The farmers were asked to provide detailed information on costs of cultivation, irrigation, yields and market prices. To determine the changes of market revenues and production costs due to adaptation, the following aspects are considered for the farmers who carry out dry season agriculture.

- On the cost side, the famers must bear the costs for the irrigated farming plots, which is 95,072 CFA (~ 175 USD[13]) per hectare and year.
- In addition, the production requires certain equipment, such as cart, seed drill, daba[14], sprayer, rake, axe and hoe which are acquired newly in the first year and renewed at certain intervals depending on the specific lifetime retrieved from the survey. Assuming, that the farmers use the same equipment for cultivation during rainy season, too, the costs for the tools are halved.
- Vegetable production is labour intensive, and especially water intensive. Accordingly, 180 days per hectare and year are needed only for irrigation. 28 days are spent on weeding, 36 days on land. Some of the farmers hired external workers, but most of the work was done by family members. By using the mean value of the average daily labour rate for the externally hired farm workers retrieved from the survey, which is 958 CFA (~ 1.76 USD), we arrive at total labour costs of 268,056 CFA (~ 491 USD) per hectare and year (WASCAL, 2020a).
- The costs for input are one of the major cost factors of vegetable production. In sum, seeds, manure, and NPK, cause costs of 572,256 CFA (~ 1,052 USD) (ibid.).
- Opportunity costs, in other words lost income from other sources, are applied with the help of a control group which was not involved into off-season farming. A sample of ten farmers from the same village were asked to provide information on their income from labour work such as trading, brick laying or farm work on other farms during the dry season. The so determined revenues of 488,632 CFA (~ 898 USD) per hectare and year were then set as opportunity costs for the surveyed farmers (WASCAL, 2020b).
- For each crop and vegetable, the market price indicated in the household survey was used. The prices were weighted according to the yields achieved and the area cultivated under each crop. The determined price was then used to calculate the average revenues for one hectare across the surveyed farmers. Based on these revenues, we extrapolated the additional market revenues and extra labour costs until 2050 (WASCAL, 2020a).

13 All exchange rates were retrieved on 22.4.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en

14 A daba is a tool used by farmers in parts of Western Africa.

9.3.3 Assumptions

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

- Climate change effects are directed from PIK projections, which assumes a demographic and economic growth trajectory under SSP2[15] and a low emissions scenario under RCP4.5 and a high emissions scenario under RCP8.5. Yields of all vegetables and crops other than staple crops, including anise and moringa, were summarized under "vegetables", which means that due to the absence of data, climate change impacts on vegetables were also applied to moringa and anise. For cassava, wheat and maize, the IMPACT model provides crop specific data on yield developments under RCP4.5 and RCP8.5.
- To depict the inflation rate, we calculated the exponential growth rate of the GDP per capita of Niger from the last 30 years, its value is 2.35% (FAOSTAT, 2021b).

9.3.4 Results

The results of the CBA show that in comparison to the no adaptation scenario switching to an agricultural production during off-season (adaptation scenario) will be economically beneficial from the year 2044 on under the low emissions scenario and from 2047 on under the high emissions scenario. From then on, the switch has a positive return on investment. The following figure shows this development of the net present value (NPV) from 2020 to 2050.

- During the first ten years, the net cash flow is negative for a RCP4.5 climate change scenario, i.e. the NPV of adopting the switch decreases. This changes after 2030, when the NPV is -3,935 CFA (~ -7.2 USD). From now on, the net cash flow is positive. Hence, the NPV starts to increase. Finally, the NPV becomes positive in the years 2044 and 2047 respectively and further increases until 2050. The corresponding NPVs in 2050 consequently are 1,478,894 CFA (~ 2,710 USD) under RCP4.5 and 549,717 CFA (~ 1,007 USD) under RCP8.5.
- The corresponding internal rate of return (IRR) for an adaptation scenario under RCP4.5 amounts to 6.05% and under RCP8.5 to 3.88% in 2050. To indicate a profitable investment, the IRR must be higher than the local interest rate. According to the survey, this is 5% for our case study site (WASCAL, 2020a).[16]
- This means that for a production under RCP4.5 the investment to switch from no agricultural production to irrigated vegetable and crop production is profitable from a farmer's point of view in the long run because the IRR is higher than the local interest rate. However, under RCP8.5 this is not the case anymore, as the IRR is lower than 5%.
- This can also be expressed with the BCR: For a scenario under RCP4.5, the BCR is 1.05 after 30 years (in 2050). For a scenario under RCP8.5, the BCR is 1.02 (see also Table 11). In other words: The farmer's investment in the income source switch will pay off after over 24 and 27 years only, when the break-even points between accumulated net costs and net benefits are reached.

[15] This includes an increase of the farmers'` area productivity due to autonomous technological change.

[16] Considering a global rentability perspective, which is often taken for local CBAs, any IRR higher than 6 percent is seen as a profitable investment.

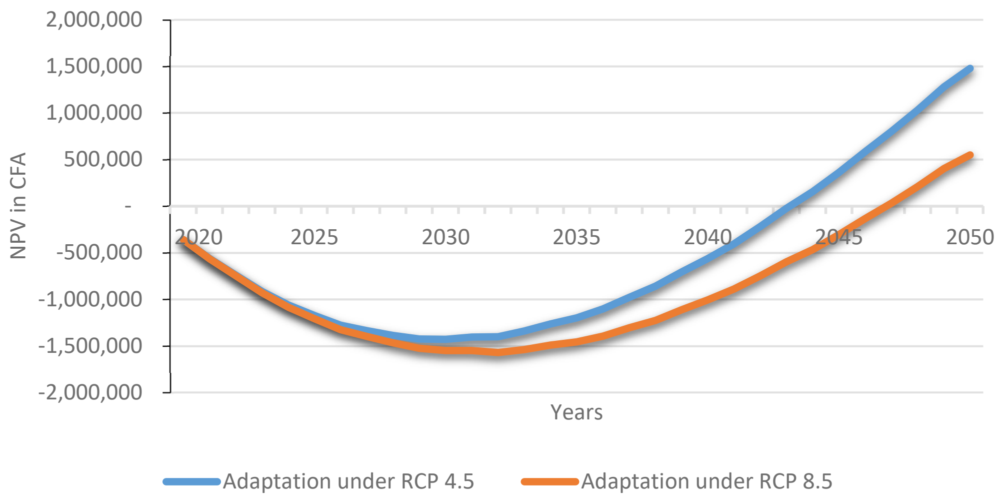

Figure 60: Development of the net present value of switching from no agricultural production to an irrigated production of vegetables and crops during the dry season under future climate change and over time.

The late break-even point suggests that switching to irrigated off-season farming can be recommended in the future, but rather in the medium to long term. One major reason is that off-farm labour work in most cases is better paid than farm work, suggesting a careful consideration of all factors before giving recommendations regarding crop switching in order to avoid maladaptive outcomes.

Table 11: Summary of major CBA indicators for switching to irrigated off-season farming.

	Adaptation under the low emissions scenario	Adaptation under the high emissions scenario
IRR	6.05%	3.88%
NPV	1,478,894 CFA (~ 2,710 USD)	549,717 CFA (~ 1,007 USD)
BCR	1.05	1.02

Switching to an irrigated off-season production of vegetables and crops is economically meaningful, because the partial change of the production system leads to a high IRR and a BCR above 1.0. That means that attributable additional revenues to the change are higher than the associable additional costs. However, the particular outcome does not mean that the entire production system is profitable in terms of internationally standardized calculation of economic margins. The household survey data shows, that the production of irrigated vegetables and crops in the baseline (no action, no climate impacts) scenario, i.e., counter-season production under current climatic and technological conditions in the region is characterized by a negative gross and net margin. In other words: variable and fixed costs are higher than market revenue. The major costs are produced by input and labour. In addition, opportunity costs are high, because off-farm labour is well-paid and therefore generates high incomes.

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

9.4 Multi-criteria assessment

9.4.1 Upscaling potential

According to the FAO, Niger had an estimated irrigation potential of 270 000 ha of irrigable land in 2017 (FAO, 2017). As of the same year, only 33% of this potential was irrigated (aggregate data), which corresponded to 0.5% of the total national cropland in 2017 (FAO, 2017; FAOSTAT, 2017). Much of Niger is arid desert. Nevertheless, there are various types of water resources through which the irrigation potential could be further exploited. In terms of surface water, the most important resource is the Niger River, which flows around 550 km through the south-western part of the country, passing through the capital Niamey. The Niger is a perennial river and usually reaches its highest level in the early dry season, i.e. in December and January, which is when pumping is easiest and also when demand is the highest (Abernethy & Sally, 2002). Before reaching Niger, the river crosses through Guinea and Mali. Especially Mali has been developing irrigation at a faster pace than Niger, which increases Niger's vulnerability to potential water scarcity (Abernethy & Sally, 2002). In the rest of the country, people rely on smaller water resources, such as surface water reservoirs and ponds, of which there are around 1 000 nation-wide, amounting to a total capacity of nearly 100 million m^3 (Cochand, 2007). Some of these ponds are located in shallow depressions, which retain water even after the end of the rainy season and, depending on their depth, width and the type of soil, sometimes even year-round (Cochand, 2007). Therefore, these ponds present an important water resource for both farmers and pastoralists. Nevertheless, Niger's climate presents a limiting factor for irrigation, which is characterised by hot temperatures, limited amounts of precipitation and high rates of evapotranspiration (Lange, 2016). According to Abernethy & Sally (2002), precipitation exceeds evapotranspiration on average for only two months a year. Niger has a single rainy season (unimodal precipitation regime), receiving almost all of its annual precipitation amounts between June and September. The length of the rainy season is decreasing towards the north, with annual precipitation sums of only 10 mm in the desert areas of the north. Soil quality is another limiting factor: Soils in many regions of Niger are poor in nutrients and sandy, which makes them vulnerable to drying, erosion and flooding, due to the weak water-holding capacity (Touré et al., 2019; Wildemeersch et al., 2015).

9.4.2 Development of co-benefits

If developed in a planned and equitable manner, irrigation bears several development co-benefits. Irrigation allows to produce non-traditional, high-value crops, such as vegetables, which can be sold at the market. Market-oriented production can help to increase farmer household incomes and reduce poverty (Cochand, 2007; Jaubert et al., 2010; Mounir et al., 2013). Access to irrigation in Niger can help farmers to grow, for example, vegetables and fruits for household consumption and for sale on the local market during the dry season. Hence, irrigation can help to diversify diets and ensure food security at times when famine is most common, thereby contributing to good health. Moreover, irrigation can also create new jobs: Depending on the size and the degree of mechanisation of an irrigation facility, labour is required for the construction, operation and maintenance of facilities. Hence, irrigation facilities can create employment opportunities for non-farming households as well as for farming households during the dry season. Larger commercial irrigation facilities, such as those irrigating onions for export[17], can contribute to overall economic growth and stability (Jaubert et al., 2010). For example, the region around Gaya in southern Niger has turned into an important trading centre supplied by producers, cooperatives and traders from both Niger and neighbouring Benin and Nigeria (Cochand, 2007; Dambo, 2007). In this way, irrigation can also help to prevent rural exodus, which is common in Niger, where especially younger people migrate to cities or neighbouring countries, such as Benin, Nigeria or Côte d'Ivoire (IDMC, 2019; UNDESA, 2019). This is particularly true for the dry season, when food stocks run low. However, irrigation not only has socio-economic benefits. Irrigation facilities can also act as protective infrastructures to control seasonal floods: North of the town of Kaya in central Burkina Faso, Boelee et al. (2009) found that a cluster of 12 reservoirs reduced the flood flow from 38 m^3/s to 23 m^3/s.

[17] Niger is the largest exporter of onions in West Africa (Jaubert et al., 2010).

9.4.3 Potential maladaptive outcomes

The adoption of irrigation can also produce negative effects and maladaptive outcomes. Especially larger irrigation systems come with high operating and maintenance costs (Abernethy & Sally, 2002; Jaubert et al., 2010). These are frequently covered by water fees or contribution of labour to operation and maintenance activities, however, not all farmers are able or willing to pay fees or contribute otherwise to the functioning of irrigation systems. Hence, conflicts can develop between those paying for water abstractions and those not paying for it (De Fraiture et al., 2014; Evans et al., 2012). Uncontrolled irrigation development and water abstractions can also affect other livelihoods, such as fishery or pastoralism (Dambo, 2007). For example, agricultural production close to water bodies can limit access for livestock, for example through the erection of fences, which is increasingly common. In turn, straying livestock can become a threat to irrigation infrastructure, damaging pipes and canals (Dambo, 2007). Irrigation can also have negative impacts on the environment, for example, it can exacerbate soil degradation by salinity and lead to inefficient water use and overexploitation of water resources, especially if irrigation facilities are old and have poor drainage systems (Moussa et al., 2020). The expansion of irrigation can also increase energy needs and lead to higher GHG emissions from agriculture (Zou et al., 2013), conflicting with efforts for climate change mitigation. Finally, irrigation can have a negative impact on human health: The construction of water reservoirs can create new aquatic ecosystems in previously semi-arid or arid areas and foster the development of water-related diseases, such as cholera, schistosomiasis or malaria, which is, for example, the leading cause of infant mortality in the southern region of Gaya (Dambo, 2007).

9.4.4 Barriers to implementation

The development of irrigation faces several barriers and constraints. Depending on the type and the size of the irrigation system, high institutional, technical and financial support may be required. While small-scale irrigation on a few hectares of land may be more easily initiated and operated by farmers themselves, larger areas require, among other factors, machinery, technical expertise and labour, some of which may be too expensive or not available (Dambo, 2007; Mounir et al., 2013). According to Jaubert et al. (2010), the average price for a motor pump is 276 USD and the drilling of a borehole costs between 18 and 166 USD. Mounir et al. (2013) provide much higher quotes for the construction of a well, saying that it can easily cost between 5 000 and 15 000 USD because of a shortage of private companies offering well construction. For smallholder subsistence farmers, it is usually hard to access the credit required to cover initial investment costs (Cochand, 2007). Many of Niger's larger irrigation facilities have, even by international standards, high operating costs due to the amount of electrical energy needed for the pumps (Abernethy et al., 2000; Abernethy & Sally, 2002). Hence, they come with high user fees, which can only be afforded by a small fraction of farmers. This was true in the case of the Private Irrigation Promotion (PIP) project funded by the World Bank. This project supported individual irrigation initiatives, providing grants, which covered 80% of the initial investment costs, e.g. for drilling a well or building irrigation canals (Jaubert et al., 2010). The remaining 20% had to be paid by beneficiaries, which resulted in a high proportion of beneficiaries being civil servants and merchants, versus a l ow proportion of farmers, who were unable to afford the personal contribution and the price for equipment, which was set by the project and which was often far above market prices (Jaubert et al., 2010).

Furthermore, there are biophysical constraints to setting up irrigation facilities, such as water availability (Cochand, 2007). Oftentimes, rivers and reservoirs dry out for several months in a row, limiting the potential for irrigation. Another limiting factor can be salinity (Dambo, 2007; Moussa et al., 2020). Excessive irrigation can lead to waterlogging, especially when drainage systems are not functioning (Moussa et al., 2020). Waterlogging, in turn, can lead to soil and water salinization, including in lower soil layers and groundwater, and threaten crop production. Finally, available land is becoming increasingly scarce, due to population growth, unsustainable agricultural practices, soil erosion and poor soil properties (Cochand, 2007). Another important issue relating to land is tenure insecurity, which is persistent in Niger and which makes it difficult to access both land and water resources (Monimart & Tan, n.d.; USAID, 2016). Jaubert et al. (2010) note that in the PIP project, beneficiaries were asked to present a land ownership title, which many smallholder farmers were unable to provide since they cultivated land on a loan or lease basis or simply did not have access to a formal title. Furthermore, many smallholder farmers were unable to prepare the technical files required for the application to the PIP project. One explanation for this can be the low level of literacy and schooling of many smallholder farmers (Jaubert et al., 2010).

Since the development, operation and maintenance of irrigation systems comes with high financial costs, it may prevent certain social groups of farmers to participate in and benefit from this adaptation strategy. Social factors, such as gender, marital status, migration status, age or health, still largely influence farmers' access to assets and resources (Alston, 2013; Backiny-Yetna & McGee, 2015; World Bank, 2019). This differential access also translates into access to irrigation systems. This is particularly true for women: In a study conducted in the regions of Gaya and Bengou in southern Niger, the author was unable to find any women's groups practicing irrigation, saying that only very few women owned land in these regions (Cochand, 2007). Diarra & Monimart (2006) confirm this picture, saying that Nigerien women have been traditionally disadvantaged when it comes to land rights and that the current pressure on land is further exacerbating their situation. Nevertheless, irrigation can help to improve the lives of different social groups, especially those of women, who are traditionally engaged in small-scale vegetable gardening to enhance food security, household health and incomes (Reliefweb, 2012). These aspects are particularly important in the dry season when the food reserves from the main harvest have been consumed and the men leave to find off-season jobs in cities or abroad. Hence, provided that women are given equal access to irrigation facilities, respective training, financing tools and technological equipment, irrigation can help promote gender equality.

9.4.5 Institutional support requirements

Depending on the type of irrigation, institutional support is required in different domains. For example, small-scale private irrigation is usually initiated and managed by farmers themselves, requiring as little as a watering can or low-cost technologies, such as hand pumps or treadle pumps (Jaubert et al., 2010). However, manual technologies are very labour-intensive. Therefore, farmers are increasingly using motor pumps, the access to which has been facilitated through the Fadama Project in northern Nigeria, which is supported by the World Bank and has contributed to easier access to motor pumps in neighbouring Niger (Jaubert et al., 2010). Hence, the initial investment costs and expertise required for small-scale private irrigation may be relatively low. Furthermore, maintenance for these irrigation systems may be performed by smallholder farmers themselves or small cooperatives, although such efforts often turn out defective or fail to materialise due to lack of clarity about responsibilities (Abernethy et al., 2000). The picture is different for larger, more mechanised irrigation systems, which require technical guidance and have high operating costs (Abernethy et al., 2000). These systems are usually managed by ONAHA, however, as Abernethy et al. (2000) note, the services provided by ONAHA have been gradually reduced by the government, with its main roles being advisory services and repairs of pumping equipment. During the stakeholder workshop we conducted, the role of the private sector in participating in irrigation improvement strategies was also highlighted.

9.5 Conclusion

Considering all mentioned criteria, the adaptation strategy "irrigation" presents in fact a medium risk mitigation potential and has several positive co-benefits, for instance applying irrigation can help to diversify diets and ensure food security (Table 12). However, there are numerous barriers for a sustainable implementation and despite the numerous still unirrigated surfaces the upscaling potential is rather medium as water resources are rare in Niger (Ibbi and Timothy, 2012). Institutional support would be needed where appropriate to support the access and maintenance of equipment to increase the adoption by smallholder farmers. In addition, irrigation can easily cause the development of various maladaptive outcomes, as in water scarce countries such as Niger, water use has to be carefully managed to prevent groundwater table decrease and associated consequences. As the investment for irrigation is high, farmers apply irrigation only for rentable production systems. According to the CBA, irrigation may only be suitable as a long-term perspective. In addition, farmers do not traditionally irrigate sorghum, which was used as a case study in our modelling. All in all, it is indispensable to consider the traditional techniques and management practises of farmers as well as the water availability in the local context to recommend irrigation as suitable adaptation strategy.

Table 12: Summary of multi criteria assessment of irrigation.

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

Chapter 10 – Improved fodder and feed management for livestock

10.1 Context and description of the technology

Inadequate quantity and quality of feed resources are major factors limiting the productivity of livestock systems in Niger (Kashongwe et al., 2017; Amole & Ayantunde, 2016). Besides natural pastures, crop residues and agro-industrial byproducts are the main livestock feed sources (ibid.). However, in recent years, a reduction in the quantity of available residues and a degradation of natural pasture lands have been observed (FAO, 2014), making alternative feed sources and improved fodder management more important.

Hay and silage making are common methods of preserving fodder around the world. The nutritional value and economic considerations make them the most practical options in many tropical areas (Olorunnisomo, 2015). Its positive effect on milk yields in pastoral cow and camel herds has been subject of several studies (Kashongwe et al., 2017).

The purpose of haymaking is to reduce the moisture content of green fodder to a low enough level to inhibit the actions of enzymes and microorganisms, so that it can be stored for a long time. Best harvesting time is at the time in the early flowering stage, when the maximum nutrient levels are reached. However, this is also the time with the highest humidity content. Harvesting at the right time is a balancing act between sufficient forage growth and dry weather conditions (FAO, 2020). To date in Niger, hay is mostly produced from naturally occurring forage grass species such as *Pennisetum pedicellatum* and *Digitaria ciliaris* (Ayantunde et al., 2009). Unlike hay, silage is a technique for preserving forage in the absence of oxygen and in an acid environment. It involves placing chopped green grass (natural or cultivated) in an airless conditioner (package or silo), which enables the anaerobic fermentation process. Acidification is achieved by the lactic acid bacteria present in the forage (Olorunnisomo, 2015). Apart from fodder grasses, most crop residues can be conserved as silage. Silage is also still an option, when the moisture content of grass would compromise the quality of the hay and therefore not allow for hay making anymore (Bhandari, 2019).

In Niger, the source for fodder depends to a large extent on the agroecological zones. In the agricultural zone in the south, fodder is mainly produced from agricultural residues, while in pastoral and agropastoral systems in the desert zone agricultural residues are less available (Rhissa, 2010). In 2011, the Nigerien government set up an emergency program for the promotion of fodder crops, particularly bourgou, fodder sorghum, cowpea and alfalfa. The program was a response to the fodder deficit in 2011 and 2012 (Ayantunde, 2017), which had mainly affected the pastoral zones. In this regard, the Irhazer, Tamesna and Aïr Agricultural Development Support Project (PADA/ITA) especially promoted the cultivation of alfalfa on the irrigated perimeters of its intervention zone in Agadez, which is subject to this analysis. With support of the project, 50 ha of alfalfa have been installed on the pilot sites (Regional Chamber of Agriculture of Agadez, 2016). This has also contributed to the fact that, by now, the production of irrigated alfalfa has also been adopted in other parts of the region. One advantage is that the cultivation of fodder crops and grasses allows the maximum exploitation of irrigation systems outside the main season, when crops cannot be cultivated (WASCAL, 2021).

10.2 Biophysical risk mitigation potential

Improved varieties for sorghum fodder

Improved sorghum variety was chosen based on its selection history, phenology (maturity and photo-period sensitivity), and grain yield productivity to represent contrasting sorghum types cultivated in West Africa (Adam et al., 2018). In this study, we used Fadda, a single-cross hybrid with Guinea-race-derived parents and grain yield productivity exceeding that of farmers' local varieties (Rattunde et al., 2016). The Fadda variety is an improved hybrid with medium maturity days (100–135), high-yielding (>3t/ha). One of its key advantages over traditional varieties is that is has intermediate plant height and also moderate photo-period sensitivity. The Fadda variety is dual purpose as it can be used for both (biomass and grain) as its leaves remain green until physiological maturity. They are characterized by short internodes and improved digestibility by animals.

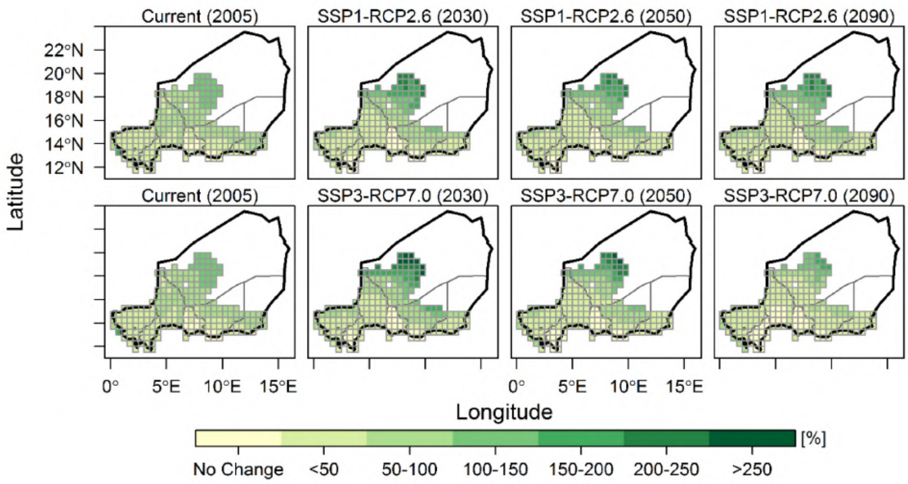

Figure 61: The spatial distribution map for impact analysis with improved variety.

Overall, the improved variety shows significantly increased yields over all the grids, in some areas up to 250%, especially over northern Niger in both emissions scenarios. In the high emissions scenario, the south-western and central parts of the Niger region have lower positive yields, but the northern region has higher positive impacts. The Crop Water Requirement (CWR) of the crops in the Northern region of Niger is optimal, respective to higher rainfall than southern region rainfall which is why higher yields can be reached. However, both emissions scenarios have produced significantly positive impacts in the yields with improved variety.

Figure 62 shows the yield impact variability with improved varieties for both emissions scenarios and different time-steps. The low emissions scenario has maintained standard yield impacts over time, whereas the high emissions scenario has a decreasing trend over time, meaning that with increasing climate change forcing the benefits of an improved variety are reduced by almost half. The variability of response also increases with time over the high emissions scenario.

Figure 63 shows the regional-wise yield impacts of improved variety for both emissions scenarios and different time-steps. All regions have yield impacts between 10 and 80%, except for Agadez which has over 90% yield increases with the improved variety. Comparing all time-steps, the northern regions of Niger have higher yields with the improved variety than the southern regions in both emissions scenarios.

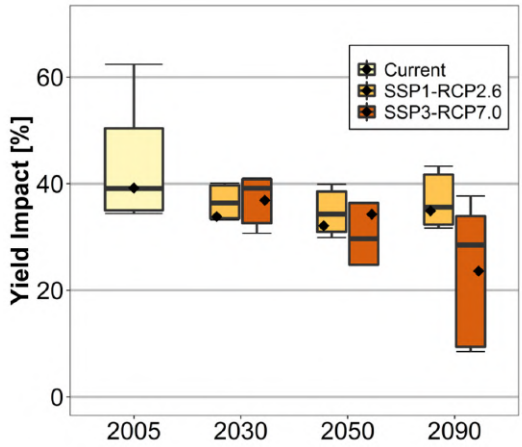

Figure 62: The intercomparison of the yield impacts between different time steps with improved variety.

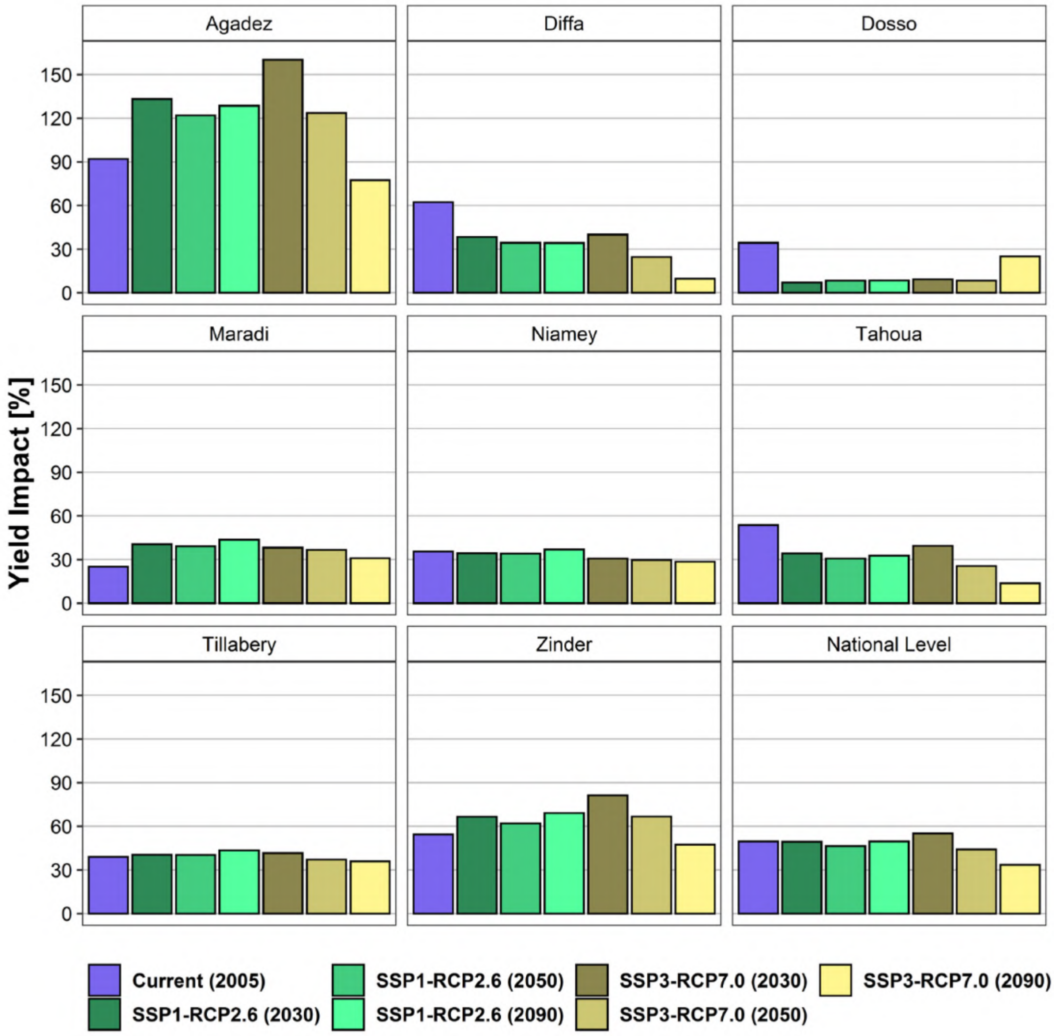

Figure 63: Regional-wise yield impacts with improved variety over different scenarios and time-steps.

Mowing as an adaptation option

In addition to the previous evaluation of improved varieties for sorghum as improved fodder management option, this excursion evaluates mowing and storage of fodder as a good pastoral practice for sustainable land management, therefore contributing to an improved fodder management. One of the main purposes is to improve the availability of fodder in terms of quantity and quality during the dry season.

Figure 64 compares annual grass yields in five Départements of Niger under grazing management (marked "G" in the Figure) and four different mowing management regimes (marked "M1" to "M4"). The first column presents results for the historical period (1995–2014). The other columns are for the future periods. Mowing regimes M2 and M3 (with two and three mowing events per year, respectively) provide higher yields than mowing regimes M1 and M4 in all Départements and all time periods. Compared to grazing, mowing generally leads to lower annual yields in all but the Dosso Département. During the historical period, mowing yields are about 30% lower than grazing potentials (as calculated in Chapter 4) in the Maradi Département and the Tillabery Département, and about 45% lower than grazing potentials in the Tahoua Département.

In addition to a generally lower performance, mowing also shows a larger uncertainty than grazing, as illustrated by the length of the boxplots in Figure 64. Each row shows results for one Département. Each panel in a row is for one time period and emissions scenario. Within each panel, the first boxplot shows annual yield values under grazing, the other four boxplots show yields for the four different mowing regimes. The length of each boxplot illustrates the spread across 10 GCMs and 20 years and can be considered a measure of uncertainty. The horizontal dashed line in each row denotes the average grazing yield during the historical period and provides a visual guide to quickly assess whether yields increase or decrease under the mowing regimes or under climate change.

This suggests that mowing yields are more sensitive to inter-annual variability and differences between the GCMs than grazing potentials. Given these circumstances, mowing does not seem to present an attractive alternative to grazing in most parts of Niger. Combined with storage, mowing does offer an opportunity to increase fodder availability during the dry season. However, this requires proper treatment of forage to avoid losses during storage, as well as dedicated storage facilities.

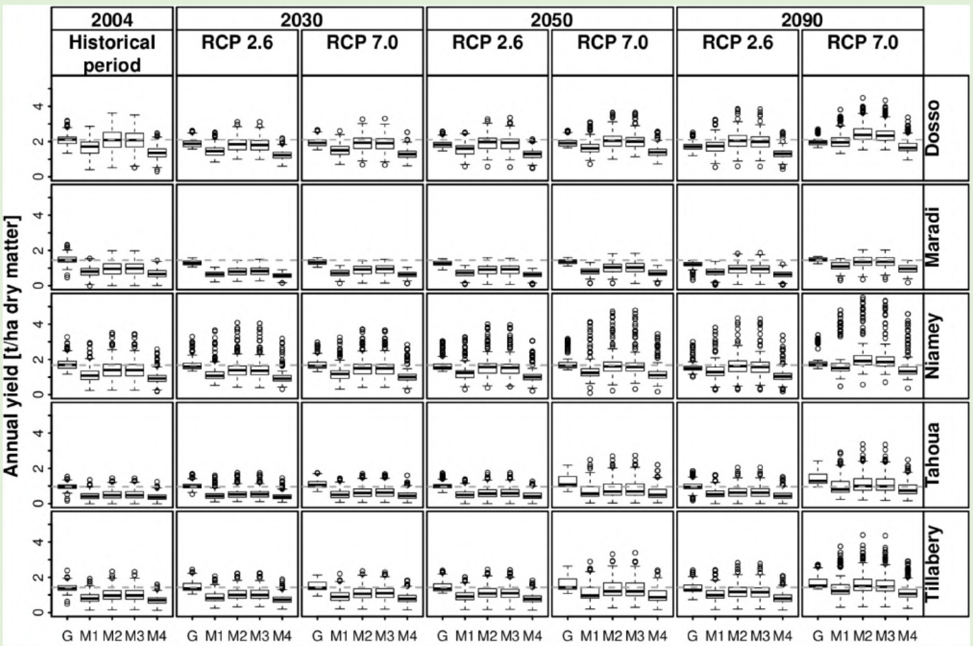

Figure 64: Yields under grazing and mowing management with one single mowing event per year on October 1st (M1), two mowing events per year on August 1st and October 1st (M2), three mowing events per year on May 1st, August 1st and October 1st (M3), one single late mowing event on November 1st (M4).

10.3 Cost-benefit analysis for improved fodder and feed management for livestock – irrigated alfalfa fodder banks

The economic feasibility of irrigated alfalfa fodder banks as adaptation strategy is tested by offsetting the attributable additional revenues to the change with the associable additional costs. Therefore, we analyse the costs and benefits of camel herders for implementing the strategy in comparison with camel herders who do not engage into alfalfa production. We compare two different climate change scenarios each projected until 2050 with reference to a baseline scenario describing the status quo as of today.

10.3.1 Baseline and scenarios

The baseline and the scenarios are defined as follows:

Baseline (no action, no climate impacts): Camel husbandry with grazing as the main feed source under current climatic and technological conditions in the region.

Non-adaptation (no action, climate change impacts under low and high emissions scenarios): Camel husbandry with grazing as the main feed source, without growing own alfalfa fodder banks. The market revenues and production costs of the system are extrapolated until 2050 assuming a climate change yield impact based under RCP4.5 and RCP8.5.

Adaptation (action, climate change impacts under low and high emissions scenarios): Camel husbandry with irrigated alfalfa fodder banks for supplementary livestock feed and sale. The market revenues and production costs of the system are extrapolated until 2050 assuming a similar climate change yield impact as under RCP4.5 and RCP8.5.

10.3.2 Survey data

The economic data used as basis for the CBA calculations were collected from eleven camel herders in Agadez region in the center of Niger. All farmers cultivate alfalfa on land with preinstalled irrigation schemes, which they rent from the government, that installed the irrigation system in collaboration with the Irhazer, Tamesna and Aïr Agricultural Development Support Project (PADA/ITA). The Californian system is a network of pipelines buried in the soil to deliver water from the source to farmer fields, where alfalfa is grown on an average field size of 0.25 ha. However, following the standards in farm economics and for better comparison across the emissions scenarios, we analyse the average market revenues and production costs associated to one hectare. The farmers provided detailed information on production costs, on alfalfa yields, as well as on local market prices. To determine the changes of market revenues and production costs due to adaptation, the following aspects are considered for the farmers who adopt.

- As most of the irrigation systems were preinstalled (except for one farmer) and the costs were covered by the project, the farmers do not bear the costs for installation. However, they pay an average yearly rent of 14,840 CFA (27 USD[18]) to the project. Furthermore, for some of the interviewed farmers additional costs for irrigation during rainy season incur, which amount to 1,740 CFA (3 USD) per year and hectare.
- Alfalfa is produced throughout the year and harvested ten times. Therefore, the production is labour intense and comprises next to the regular production steps also many days for irrigation, fodder transformation, stocking and transport to the sales market. Also, mechanical pest control such as weeding requires comparably high labour input. The work is carried out by family members and external workers. In total, the farmers spend 430 days per hectare on alfalfa cultivation. Using the mean value of the average daily rate for the external labour retrieved from the survey, which is 2,269 CFA (~ 4 USD), we arrive at labour costs of 975,996 CFA (~ 1,783 USD) per year and hectare being the second largest cost factor (WASCAL, 2020).

[18] All exchange rates were retrieved on 15.4.2021 from: https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en

- The main cost driver of the production system is related to inputs, i.e., manure, UREA and seeds. The total costs for the farmers accumulate to 1,591,755 CFA (2,907 USD) per year (ibid.).
- As the alfalfa production in Agadez region is government-subsidised, most of the equipment needed for production is donated to the farmers. For this reason, most of the surveyed farmers could only provide information on the number of tools they needed and the specific lifetimes of them, but not on costs. However, to draw a realistic picture of adaptation costs, we intended to include equipment costs and therefore used average values from the other adaptation case studies. In that way we calculated the initial purchasing and renewal costs for plough, wheelbarrow, shovel and hoe.
- According to the survey, the farmers use the minor part (26%) of the alfalfa harvest or camel fodder and sale the major part of 74% on the local market. However, to be able to monetize the part of alfalfa which is fed, we also allocated the market price of 205 CFA (~ 0.37 USD) for one kg hay to it. The prices are average values of the market prices indicated in the household survey. To calculate the total revenues, we take the average alfalfa yield amount from the project site, which is 2,400 kg of fresh matter indicated per hectare and harvest. The alfalfa is sold as hay and therefore reduces to 1,100 kg dry matter per hectare and cut manually.[19]. This value was then multiplied with the number of harvests (ten) per year retrieved from the survey (WASCAL, 2020).

10.3.3 Assumptions

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

- Due to missing information on the effects of climate change on alfalfa yields, we developed a proxy from climate change induced yield developments on papilionaceous plants, i.e., chickpea, cowpea and groundnuts using the PIK projections, which assumes a demographic and economic growth trajectory under SSP2, a low emissions scenario under RCP4.5 and a high emissions scenario under RCP8.5 (Aschenbrenner et al., 2021).
- To depict the inflation rate, we calculated the exponential growth rate of the GDP per capita of Niger from the last 30 years, its value is 2.35% (FAOSTAT, 2021b).

10.3.4 Results

The CBA results, as depicted in Figure 65, show, that in 2050, the adaptation strategy of producing alfalfa on irrigated fodder banks would be beneficial for the farmers, as it has a highly positive return on investment. This applies to both climate change emissions scenarios, whereby RCP4.5 performs only little better, than RCP8.5. In particular, the following shall be highlighted:

- Starting with a negative net present value (NPV) of -1,166,980 CFA (~ -2,156 USD) in 2020, the net cash flow for the farmers and so the NPV become positive from the second year on. The comparably low initial investment and reinvestment costs lead to a steadily increasing NPV right from the beginning accumulating to 35,812,578 CFA (~ 65,243 USD) for RCP4.5 and to 34,349,506 CFA for RCP8.5 (~ 62,578 USD) in 2050. This means that the break-even point between accumulated net costs and net benefits for both emissions scenarios is already in year 2021, the second year of investment.

[19] The data was provided by WASCAL and relates to official data on the here analysed project site.

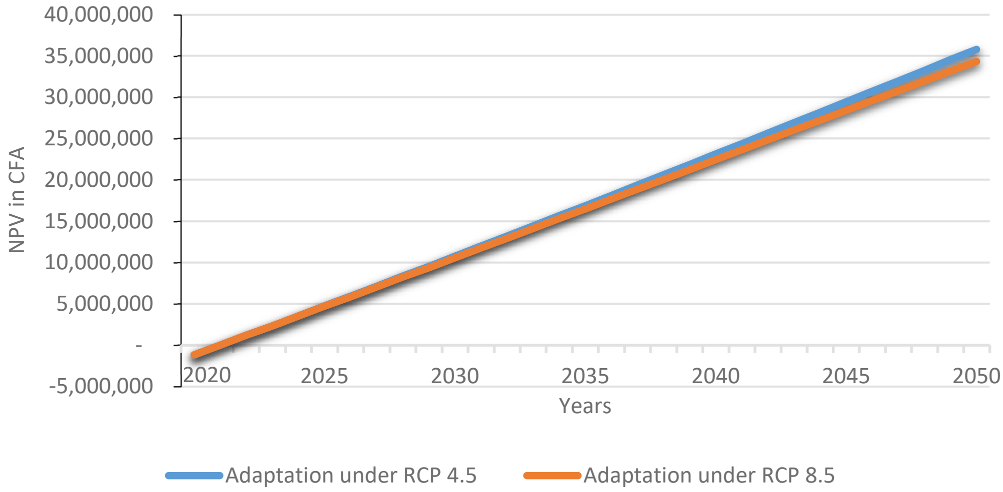

Figure 65: Development of the net present value of switching to irrigated alfalfa production.

As a consequence, the internal rate of return (IRR) is very positive and yields 105.97% for an adaptation under RCP4.5 and 105.6% for an adaptation under RCP8.5. Assuming a global rentability perspective, which is often taken for a local CBA, any IRR higher than 6.0%, is considered as a profitable investment. This is also evident from in the cost benefit ratio (BCR) of the adaptation investment, which in 2050 is 2.44 under the low emissions scenario and 2.38 under the high emissions scenario (see also Table 13).

Table 13: Summary of major CBA indicators for switching to alfalfa fodder production on irrigated fodder banks.

	Adaptation under the low emissions scenario	Adaptation under the high emissions scenario
IRR	105.97%	105.61%
NPV	35,812,578 CFA (~ 65,243 USD)	34,349,506 CFA (~ 62,578 USD)
BCR	2.44	2.38

10.4 Multi-criteria assessment

10.4.1 Upscaling potential

The production of alfalfa fodder stocks has several benefits for building up the climate resilience of traditional livestock farming systems in Niger. It provides fodder during dry season and is therefore an effective alternative to pastoral activities carried out by livestock keepers in search of abundant forage resources. Apart from producing fodder for self-consumption, income can also be increased through the sale of the fodder surplus. This creates significant economic benefits and offers the opportunity to develop stall-fed animals which in turn again generates additional income.

In addition to the economic benefits, alfalfa can be grown on large scale increasing the vegetative cover of an area and thus contribute to soil protection and rehabilitation. As the technology is easy to apply and requires no academic training, it offers great potential for upscaling, provided that there is strong support from policy makers in education and the facilitation of irrigation schemes. However, the implementations requirements with regard to irrigation should be also considered, as it may affects the applicability of this strategy (see results of previous chapter).

10.4.2 Development of co-benefits

Besides strengthening resilience to climate change and increasing incomes and livelihoods of farmers there are several more co-benefits coming with the production of alfalfa. One major positive effect is the provision of employment opportunities for women in the communities. An analysis of gender roles showed that, in general, women are more involved into fodder production and management than men to support their families and income (Ayatunde et al., 2017). Farmers from the household survey confirmed unanimously the positive effect on women and youth employment in their communities. In addition, they emphasised the positive effect on the community cohesion and on their relationships to neighbours. The survey also showed that with the implementation of alfalfa fodder banks the overall farm workload has decreased (WASCAL, 2021). Compared to other forage crops such as maize and soya, alfalfa constitutes also an inexpensive source of protein. Depending on the timing of the cutting, 18 to 20% of the dry weight is protein (FAO, 2014). It is a low fiber fodder which is well suited for cattle as it easily digested and contains essential amino acids, potassium and more calcium than other forage crops. From an agronomic perspective it is also a valuable crop due to its high yields (dry matter yields may range between 10 and 20 t/ha) as well as its steadiness and relatively good drought tolerance or water efficiency due to its deep roots (Naylor, 2003). The crop's water use in relation to its production is high when comparing it to other forage crops such as maize (FAO, 2014). Another important advantage is its contribution to soil fertility through nitrogen fixation, which makes it important in cropping rotations. Alfalfa is well suited for conservation agriculture as it prevents soil erosion, improves soil health and offers wildlife benefits. Alfalfa is usually grown for three to five production years and harvested mechanically or manually according to the farm size (Ahmed and Faki, 2020).

10.4.3 Potential maladaptive outcomes

Fertile agricultural land is a scarce resource. The cultivation of alfalfa brings multiple benefits to herders and pastoralists in Niger, however, it decreases the availability of land for other agricultural purposes such as the production of staple crops or vegetables for human consumption. Adequate planning and the careful selection of land suitable for fodder production can avoid such conflicts (Olorunnisomo, 2015). Another reverse effect of the improved fodder availability is, that it could lead to an increased number of animal and hence contribute to more greenhouse gas emissions and therefore reinforce climate change. Again, appropriate planning of stocking of livestock can remedy this effect.

10.4.4 Barriers for implementation

One major technical obstacle concerns the packaging and transportation of dried alfalfa grass, as the low density of traditional packaging increases transportation costs. However, the problem has already been captured by the above mentioned PADA/ITA project. Together with other Nigerien research institutions such as the *Ecole des Mines de l'Aïr (EMAIR)* and the *Centre de Formation Professionnelle et Technique (CFPT)* of Agadez, the project developed an innovative manual hay press, which was then provided to the alfalfa intervention site by the Regional Chamber of Agriculture (CRA) of Agadez. Further institutional support is now needed to assure the wide availability of the press to other alfalfa producers. If this problem is not addressed and the cost for packaging and transportation will continue to be high, this could become a barrier for the farmers to adopt to the strategy. In addition, alfalfa has a high water use in relation to its production when compared to other crops (Djaman, 2020). Access to irrigation facilities or irrigated plots is therefore indispensable. From the survey responses it emerged that the main reasons for not producing alfalfa are of financial nature. Even when irrigated plots are accessible, many farmers lack financial means for the rent or, if plots are not available, to install their own system. However, the lack of information was also named as one major reason for not adapting the strategy. If more educational work could be done here, better results could be achieved.

10.4.5 Institutional support requirements

Although women and youth are key actors in the production of fodder, they face a number of challenges in terms of access to and control over resources related to fodder and feed production. These obstacles stem from cultural and socio-economic barriers, including the fact that cultivated land in much of the Sahel is inherited from father to son, which means that women get access to land only through marriage. Also, at household level, cultivated land resources are under the control of the household head, who is usually a man. The fact that women do not own the land on which they cultivate, means that they are mostly excluded from decision-making processes. By increasing the rights of women and their participation in decision making, important opportunities to improve the sustainability and productivity of the fodder value chain can be tapped (Ayantunde, 2017).

10.5 Conclusion

Considering all mentioned criteria, the adaptation strategy improved fodder management with the option improved varieties has in fact a high-risk mitigation potential. Irrigated alfalfa production is a rentable strategy and has several positive co-benefits (Table 14). Combined with storage, mowing does offer an opportunity to increase fodder availability during the dry season. However, fodder crop production has to be carefully planned in order to avoid negative outcomes such as conflicts about suitable areas for staple crops or e.g. for the use of water resources. Institutional support would be needed where appropriate to support the access and maintenance of equipment to increase the adoption by smallholder farmers. Furthermore, all requirements that have to be considered for irrigation management play also a relevant role.

Table 14: Summary of multi criteria assessment of improved fodder management.

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

Chapter 11 – Uncertainty

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

11.1 Climate model data

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

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

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

The ten models cover a wide range of climate sensitivity[20] with equilibrium climate sensitivity (ECS)[21] values of 1.53-5.41 °C (Nijsse et al., 2020). Nevertheless, the selection of models shows a bias towards higher ECS, with five out of ten models having an ECS higher than 4.5 °C, which is, according to various studies, very unlikely (Nijsse et al., 2020). This means that the displayed temperature increases from five models show unlikely high future temperature values under increasing greenhouse gas concentrations and also the multi model median will shows a bias towards warm future projections.

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

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

11.2 Hydrological model

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

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

- Data availability of observed river discharge data in terms of the number of stations, available periods and the many gaps in the time series are limiting hydrological model calibration and validation.
- Climate data for the Niger basin are needed for the parametrisation of SWIM. Therefore, (gridded) global climate data sets (WFD-ERA40 and W5E5, depending on the availability of observed discharge data) were used in the calibration of SWIM. Where precipitation (spatial and temporal) distribution is uncertain, verification of these data using observed data would be necessary.
- There is a lack of information on water resources management (irrigation and reservoir management and parameterisation). Especially data availability for all dams in the Middle/ Lower Niger basin (downstream of Inner Niger Delta) is scarce. Another source of uncertainty is the (future) water/land management in the Upper Niger and the Inner Niger Delta, such as potential (new) dams and irrigation for agriculture.
- Furthermore, it would be good to employ more advanced quality checks for the input data (soil parameterisation including, for instance, an adaptation of soil depth, land use/cover parameterisation combined with a validation on vegetation cycles etc.).

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

11.3 Crop models

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

11.4 Cost-benefit analysis

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

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

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

Chapter 12 – Conclusion and policy recommendations

12.1 Conclusion

This study provides a comprehensive climate risk analysis for Niger that aims to provide an in-depth basis for national and local decision-makers on current and future climate risks for the agricultural sector to guide suitable adaptation planning and implementation in the country. The whole impact chain was modelled from climate and hydrological changes to resulting impacts on agricultural and livestock production. The changing climate and weather-related risks were analysed from a historic, current and future perspective, based on two different greenhouse gas (GHG) emissions scenarios: SSP1-RCP2.6, a low emissions scenario following strong mitigation in line with the Paris Agreement and SSP3-RCP7.0, a high emissions scenario without climate policy and considerable GHG emission cuts.

Climate change puts additional challenges on Niger's agricultural sector, which is mainly characterized by smallholder subsistence farming systems. Livelihoods depend to a large extent on rainfed crop and pastoralist livestock production. In addition to natural variability, the climate in Niger is showing a clear changing trend, with as well as temperature extremes clearly projected to rise continuously. Furthermore, annual precipitation sums and extreme precipitation events are also expected to increase. Under the low emissions scenario, the climate is projected to stabilize after 2050, while the changing trends are projected to still continue under the high emissions scenario during the second half of this century. However, there is less statistical confidence in the projected precipitation changes than in the temperature changes.

For both emissions scenarios, a general increasing trend in the country's largest river discharge is projected towards the middle of the century with a decline again by 2090, yet with a stronger increase and lower decrease under the high emissions scenario. Trends are similar yet stronger in their effect for smaller and drier catchments, covering a range of 30 to 45% under the low emissions scenario and 30 to 145% under the high emissions scenario, with the greatest divergence at the end of the century.

Moreover, hydrological changes in the Niger basin, which covers approximately half of the country, were analysed. Increasing precipitation trends translate into elevated groundwater recharge levels, with effects most pronounced in southern Niger under the high emissions scenario towards the end of the century. The projections show a general increase in the country's largest river discharge towards the middle of the century and a decline by 2090, under both emissions scenarios, with a stronger increase and lower decrease under the high emissions scenario.

Yield variability of major crops in Niger can mainly be attributed to weather influences which makes their production particularly exposed to the impacts of climate change. An in-depth analysis of sorghum yield projections in the areas that are currently producing sorghum shows that yields will decrease under the high emissions scenario, mainly due to temperature increases. Crop suitability models have shown that the areas suitable for sorghum and millet will increase in Niger by 2050, while areas suitable for maize and cowpea will shift to other regions, but on average remain stable. Furthermore, multiple crop suitability is projected to decrease, specially under the high emissions scenarios, which will limit the potential for diversification or crop switching under future climate change conditions.

Due to the importance of livestock for Niger's economy and food and nutrition security, climate impacts on livestock production have also been analysed, specifically looking at fodder availability and grazing potential. Under both emissions scenarios, a slight decrease in fodder availability and grazing potential in the south of the country and a slightly increasing trend for the central areas until 2050 is projected. By 2090, there is an increase in grazing potential projected under the high emissions scenario for the whole country, with relatively strong effects projected for the central belt of the country.

Based on these projected climate change impacts as well as interests expressed by involved stakeholders, we assessed four adaptation strategies for an implementation in those areas, where climate change will have negative impacts: agroforestry, integrated soil fertility management (ISFM), irrigation and improved fodder management. These adaptation strategies were evaluated regarding their risk reduction potential, their cost-effectiveness, as well as other socio-economic evaluation criteria, such as upscaling potential and potential co-benefits. The assessment was conducted within a multi-criteria framework, combining assessment indicators from a biophysical mode, economic analysis and soft assessment indicators based on a literature analysis. An overview of the results has been summarised in table 15.

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

Adaptation strategy	Agroforestry	ISFM	Irrigation	Improved fodder management
Risk mitigation potential	High	High	Medium	High
Risk-gradient	Risk-independent	Risk-independent	Risk-independent	Risk-independent
Cost effectiveness	Medium to high	High	Low	Medium to high
Upscaling potential	High	High	Medium	Medium to high
Potential co-benefits	High	High	Medium	Medium
Potential maladaptive outcomes	Low	Low	Medium to high	Medium
Barriers to implementation	Medium	Medium	High	Medium
Institutional support requirements	Medium	Medium to low	Medium	Medium

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

The adaptation strategies entailed all yield increases, even without projected climate change, as well as a range of co-benefits that should be taken into consideration. Carefully assessed combinations of multiple adaptation strategies can often be an option to tap into the merits of more than one strategy.

The biophysical evaluation of the adaptation strategies for Niger showed that there is scope for increased sorghum yields in Niger currently as well as under projected future climate change conditions. Overall, the Tassa method, an ISFM technique, was found to be the most promising adaptation strategy as it increases sorghum yields the most and functions in more marginal areas that are projected to be impacted the most by climate change. This is followed by improved sorghum variety for fodder management, which also works in the northern areas. Agroforestry is the third strategy in terms of yield impact but unlike the other adaptation strategies it has higher impacts in the southern regions as well as under higher emissions scenarios and later periods. Irrigation comes last in terms of yield impacts, nevertheless with significant yield increases over most of the grid cells in Niger.

The cost benefit analyses showed that all adaptation strategies bring positive returns under both emissions scenarios, but the period until which the net cash flow for the farmers becomes positive varies. Agroforestry, ISFM and the production of alfalfa on irrigated fodder banks for improved fodder management all show positive net returns for the farmers relatively quickly, in the case of ISFM and alfalfa already after the second year of investment. This can mainly be explained by the comparably low investment and reinvestment costs. Irrigation has a much longer pay-back period due to the high initial investment costs and is therefore only profitable for farmers in the long run.

Adaptation strategies can also have potential negative outcomes that need to carefully be considered when promoting their implementation. Some adaptation strategies need more institutional support in form of enabling policies and access to markets and credits than others, but all adaptation strategies need at least accompanying knowledge transfer and access to information.

It is important to notice that the various benefits that come with the implementation of the suggested adaptation strategies ultimately depend on the concrete design of those strategies, which should be tailored to the local context and farmers' needs. The actual impact of the projected climatic changes is not only shaped by the actual hazard, but also by the vulnerability and exposure of the affected farming communities. Differing social characteristics like gender, age, education and health can substantially shape farmers' vulnerability and therefore their exposure to climate change. Taking these characteristics into consideration is an important prerequisite for the implementation of these strategies, to avoid potential maladaptive outcomes and to fully leverage the great potential climate change adaptation at farm-level can hold to build resilience across farming communities.

Furthermore, it is important to underline that the suggested four adaptation strategies are not exclusive nor prescriptive, but that adaptation measures (and a prioritization thereof) would ultimately depend on the respective local context, accounting for both socio-economic and biophysical conditions.

12.2 Policy recommendations

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

12.2.1 Agroforestry

Agroforestry, with its high risk-mitigation and high upscaling potential, constitutes a promising adaptation strategy in Niger. The Farmer Managed Natural Regeneration (FMNR) technique, already practiced in the Tahoua, Maradi and Zinder regions, is beneficial for local livelihoods, as it contributes to climate-resilience, income diversification, favourable soil properties, as well as improvements in women's and children's health and nutrition, among others. Crop yields can increase up to 150%, notably in the southern regions (Maradi, Zinder), where soil organic carbon is comparably high. On the national level the yield impacts of agroforestry are projected to increase with emission level and time. Implementing agroforestry systems can therefore be recommended across Niger for their various socio-economic and environmental benefits. The economic analysis has shown that millet-cowpea intercropping with agroforestry is a profitable investment for local farmers and has a positive return on investment after five years. Yet, this time-gap may hinder its implementation if farmers do not have the financial means to wait until the investment pays off.

Based on these results, the following specific recommendations can be provided for Niger:

- Implementing agroforestry systems can be recommended across Niger for their various socio-economic and environmental benefits.
- Investments and policies related to the "Great Green Wall" initiative could be leveraged to promote further FMNR practice.
- Women should be involved in the establishment of agroforestry systems, as their health, workload and economic situation are impacted positively by them.
- Tree species and tree density should be carefully chosen, and agroforestry planned according to the local context, including land use competition.
- Access to tree seedlings, equipment for planting and financial resources should be ensured for local smallholder farmers.
- Land tenure status needs to be overhauled through more institutional support.
- Awareness raising about FMNR can be expanded for instance through information material for various target groups, e.g. farm radio programs, and the establishment of rural wood markets.

12.2.2 Irrigation

Irrigation has a high risk-mitigation potential but nevertheless constitutes a complex adaptation strategy in Niger. On the one hand, irrigation can help smallholder farmers to compensate for the negative impacts of erratic and insufficient precipitation amounts and significantly stabilise agricultural production. But on the other hand, water resources are very scarce in Niger, with irrigation requiring a significant investment and only becoming profitable in the mid- or long-term perspective, depending on the type of irrigation system and the farm location. Continuous institutional support is therefore usually required, and care has to be taken to avoid potential maladaptive outcomes from irrigation.

Specific recommendations regarding irrigation in Niger are therefore:

- Low-cost irrigation options with low maintenance requirements can be promoted across Niger, where water resources (for instance surface water) are available.
- Awareness raising about water-saving irrigation management is crucial to ensure a responsible long-term use of natural resources.
- Irrigation may only be recommended as a long-term adaptation strategy due to its high investment and depending on local water availability as well as traditional farming practises.
- Ideally, water saving equipment such as drip irrigation, smart irrigation systems or other innovative irrigation systems suitable for the respective crops are promoted and supported by extension services to encourage farmers to use sustainable and environmentally responsible techniques.
- Provision of support services is needed to ensure the ability of farmers to further operate the technology and take care of their maintenance.
- For upscaling irrigation, all user interests in water and energy should be carefully considered. Dispute settlement mechanisms could be implemented to address potential conflicts between upstream and downstream users.
- The development of financing mechanisms, such as access to loans or credits, can support the accessibility for irrigation equipment.

12.2.3 Integrated soil fertility management (ISFM)

The implementation of ISFM is a promising climate change adaptation strategy that helps to improve soil health, water use efficiency, prevent erosion and restore degraded lands. In addition, ISFM shows great economic and food security potential, as models are predicting that especially the Tassa technique can lead to increases in sorghum yield up to 1,500% under both emissions scenarios. The high emissions scenario performs considerably better, due to the embedded additional climate change related yield effects. To promote ISFM as an adaptation strategy and leverage the various co-benefits, the following policy recommendations can be given for Niger:

- Education and empowerment campaigns are key for the dissemination ISFM. Considering that ISFM is an approach indigenous to the region, its promotion should build on and leverage existing knowledge.
- Awareness raising of the advantages of ISFM, in particularly the long-term socio-economic and environmental benefits through trainings, information days can help to increase the adoption of the adaptation strategy.
- To fully benefit from the yield increases caused by ISFM, farmer cooperatives ("warrantage" systems) are a good way for farmers to organise themselves to ensure stable produce prices.
- Policies that incentivise credit and loan schemes and subsidy programmes to produce organic inputs could address the lack of access to equipment and input.
- Policies towards sustainable land use intensification, rehabilitation of degraded soils and necessary mechanisms to implement and evaluate these can help to promote the uptake of ISFM.

12.2.4 Improved fodder management

Improved fodder management with the presented options of improved varieties for sorghum production, irrigated alfalfa production and mowing show a high risk-mitigation potential and various positive outcomes. Combined with storage, mowing offers an opportunity to increase fodder availability during the dry season. Moreover, irrigated alfalfa production is a very cost-beneficial strategy that becomes profitable already from the second year on. However, all technologies require proper treatment and careful planning as well as institutional support for successful implementation.

The following specific recommendations can be given for Niger:

- The choice of appropriate varieties and crop rotation as well as the number of cuttings (with regard to the adaptation strategy mowing) depends on local conditions and is important in order to ensure a sustainable and successful fodder crop production.
- All recommendations given for irrigation with regard to water saving techniques and awareness raising approaches should be considered in order to ensure the protection of scarce water resources in Niger and promote implementation of irrigation management for fodder production only when water resources are sufficiently available.
- Providing innovative and low-cost equipment, with low maintenance for fodder storage and production, to municipalities and farmer co-operatives can improve the problematic packaging and transportation of fodder crops.
- Pilot plots of sufficient coverage conducted for instance by local authorities can foster acceptance of farmers for improved varieties or new management techniques such as irrigated crop production.
- Women empowerment through awareness raising across gender can help to sensitize about the participation of women in decision making, which in turn presents an important opportunity to improve the sustainability of fodder management.
- It is also important to highlight the value of local landraces as they are a pillar for safeguarding local traditions, agronomic practices, and accompanying knowledge. Safeguarding of seeds and practices could be institutionalized by in-situ conservation projects, local seed banks, corporations with national or international gene banks and diversity fairs.
- A better communication and interaction of seed sector stakeholders can help to improve seed and knowledge dissemination on a local, regional, and national level.

12.2.5 General recommendations

In addition to the specific recommendations for the four presented adaptation strategies, some general recommendations regarding adaptation in Niger can be drawn from this analysis:

- Climate change impacts vary markedly across the country. Considering the increasing and switch of crop suitability in some of the regions, it is important to support local farmers with knowledge and awareness raising about the opportunity to grow certain crops that were not suitable to grow before. Participatory and context-specific policies and investment planning is needed to expand agricultural production to those regions.
- The effect of adaptation strategies can differ depending on the crop and region. Adaptation planning should therefore be designed and focused on areas where crop suitability will decrease.
- Improved soil and water management should be a priority for agricultural development planning and should be mainstreamed in all adaptation activities and be considered wherever possible.
- Rich and diverse indigenous and traditional knowledge systems are prevalent across Niger, which should be tapped into for successful adaptation. However, since scientific literature on these knowledge systems remains scarce, more research is needed to reactivate and harness indigenous adaptation strategies that have received only minor attention in the past.
- Smart adaptation incentives are key to induce uptake of suitable adaptation strategies. Such incentive structures are for instance build around land tenure systems, credit accessibility and market access.
- In general, all four adaptation strategies directly contribute to achieving the goals of the “Great Green Wall” initiative and hence can attract additional funding and programme support.
- It is important to ensure that smallholder farmers have market access to sell potential surpluses harvested due to the implementation

of adaptation strategies. Additionally, as switching to the suggested adaptation strategies requires investments, farmers need financial support in the form of subsidies, micro-credits or loans. This needs to be complemented by trainings and extension services, also in the long-term, in order to ensure continued implementation.
- Adaptation measures can help to fight instability, conflict and terrorism, which are issues, that are often multiplied by climate change. Nevertheless, more research with regard to the complex interplay of climate change impacts and security and migration issues is needed, in particular between pastoralists and farmers.
- Adaptation design should be inclusive. All community groups and income strata, includeing women and marginalized groups, should be engaged at all planning and implementation stages, for instance through community conversation sessions. Gender-disaggregated data and gender-sensitive approaches can help design gender-responsive adaptation strategies and ultimately foster women empowerment.

12.2.6 Available programs

In order to implement adaptation strategies, there is an urgent need to provide financial and material resources and thus strengthen the capacities of stakeholders. During the stakeholder workshop in December 2021, several national strategies and programs were identified in which the four adaptation measures could be included.
- Economic and Social Development Plan (PDES 2022-2026) (FMNR, ISFM, irrigation, improved fodder management)
- Sustainable Development and Inclusive Growth Strategy (SDDCI 2035) (FMNR, ISFM, irrigation, improved fodder management)
- The National Strategy and Plan for Agricultural Adaptation to Climate Change (SPN2A 2020-2035) (FMNR, ISFM, irrigation, improved fodder management)
- 3N Initiative Strategy (2021-2025) (FMNR, ISFM, irrigation, improved fodder management)
- National Environmental Plan for a Sustainable Development (PNEDD) (FMNR, ISFM, irrigation, improved fodder management)
- Nationally Determined Contribution (NDC) (FMNR, ISFM, irrigation, improved fodder management)
- The Great Green Wall in Niger (FMNR, ISFM, irrigation, improved fodder management)
- Strategic Framework for Sustainable Land Management (SFLM) in Niger and its Investment Plan (2015-2029) (FMNR, ISFM, irrigation, improved fodder management)
- The Small-Scale Irrigation Strategy in Niger (SPIN) (FMNR, ISFM, irrigation, improved fodder management)
- Integrated Project for the Modernization of Agriculture and Livestock for the Transformation of the Rural World (PIMELAN) (ISFM, irrigation, improved fodder management)
- Rural Land Policy in Niger - Action Plan (2021-2027) (FMNR, ISFM, irrigation)
- National Action Plan for Integrated Water Resources Management (PANGIRE) (Irrigation)
- Water Hygiene and Sanitation Sector Program (PROSEHA 2016-2030) (Irrigation)
- National Strategy for Irrigation Development and Stormwater Harvesting (SNDI/CER) (Irrigation)
- Sahel Irrigation Initiative Regional Support Project (PARIIS) (2013-2024) (Irrigation)
- Millennium Challenge Account (MCA) (Irrigation)
- Small Scale Irrigation and Food Security Program (PISA) (Irrigation)
- The Integrated Water Security Platform Program (PISEN) (2021-2028) (Irrigation)
- Sustainable Livestock Development Strategy (SDDEL-2013-2035) (Improved fodder management)
- The Association for the Revitalisation of Livestock in Niger (AREN) (Improved fodder management)
- National Program for Genetic Improvement / Local Cattle (PNAG/BL) (Improved fodder management)

We strive to consider these programs within the outreach strategies.

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ANNEX

Chapter 6 – Adaptation and adaptive capacity in Niger

6.2.1 Access to resources – p.67.

Table 1: Probit regression on factors affecting the likelihood of adapting to climate change (ECVMA, 2011)

Dependent variable	Household implemented adaptation strategy
HH characteristics	
HH head female=yes	-.154
HH head age in years	-.011
HH age in years # HH age in years	0.000
HH head attended education= yes	-.022
Total number of people in the household	.029***
Farm characteristics	
Land area in log	.058***
Constant	-.098
Observations	2225
Pseudo R^2	0.009

6.3.2 An intersectional perspective

Info Box: Potential of adaptation strategies to increase agricultural production – p.71.

Table 2: Commonly practiced adaptation strategies against changes in temperature or rainfall

Adaptation strategies	Percent* of households implementing the strategies
Practice(diversity)more often other non-agricultural activities (diversify source of revenue)	49
Change seed varieties	29
Migration of certain members of the household	27
Engage in contre-saison agriculture	25
Terrace the soil or use other methods to protect against erosion	23
Raise less livestock in order to increase agriculture	23
Raise fewer sheep and switch to goat	19
Plant trees	18
Raise fewer small ruminants and switch to cattle	13
Adopt specific technique to regenerate the grass cover favored by livestock	12
Irrigate more intensively	12
Raise fewer cattle and switch to camels	8

Info Box: Potential of adaptation strategies to increase agricultural production – p.72.

Table 1: The impact of adaptation on food production

Dependent variable	Total wet season crop production
Number of adaptation strategies	0.000
HH characteristics	
HH head female=yes	-0.627***
HH head age in years	0.002
HH age in years # HH age in years	-0.000
HH head attended education= yes	0.130**
Total number of people in the household	0.028***
Farm characteristics	
Land area in log	0.268***
Soil type= Sandy	
Silty	0.168
Clay	0.154*
Rocky	-0.076
Topography =Hill	
Plain	0.036
Gentle slop	-0.014
Steep slope	0.212
Valley	0.145
Other	2.082*
Agroecology= Tropic-warm/arid	
Tropic-warm/semiarid	0.286**
Agro-ecological zone= Urban	0.000
Agricultural	0.068
Agropastoral	0.032
Pastoral	0.127
Total herd size	0.010***
Biophysical	
Total rainfall (mm) in 2011	0.002***
Temp in °c	-0.151*
Other controls	
Region fixed effect	yes
Distance to market in log	-0.037
There is an agriculture extension agent who lives in the village = yes	0.224**
Constant	8.443***
Observations	1662
R^2	0.305

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$