Food and Agriculture Organization of the United Nations

Climate change impacts and responses in small-scale irrigation systems in West Africa

Case studies in Côte d'Ivoire, the Gambia, Mali and the Niger

Adapting small-scale irrigation to climate change in West and Central Africa (AICCA)

Climate change impacts and responses in small-scale irrigation systems in West Africa

Case studies in Côte d'Ivoire, the Gambia, Mali and the Niger

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Abbreviations and acronyms

AICCA	Adapting small-scale irrigation to climate change in West and Central Africa
CBA	Cost-benefit analysis
CBL	Land and Water Division
RCA4	Rossby Centre Regional Climate Model
CMIP5	Coupled Model Intercomparison Project - Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
CBA	Cost benefit analysis
DCF	Discounted cash flow
ET	Evapotranspiration (mm per unit time)
ETo	Reference evapotranspiration (mm per unit time)
FACE	Free atmosphere CO_2 enrichment experiments
FAO	Food and Agriculture Organization of the United Nations
FIRR	Financial Internal Rate of Return
FNPV	Financial net present value
FRR	Financial internal rate of return
GDD	Growing degree days
GHG	Greenhouse gas
HI	Harvest index
HIo	Reference harvest index (percent or fraction)
H30	Horizon 30
H50	Horizon 50
Inet	Net irrigation requirement
IPCC	Intergovernmental Panel on Climate Change
IFAD	International Fund for Agricultural Development
NPV	Net present value
O&M	Operation and maintenance
PMUs	Project management units
RCM	Regional climate models
RCP	Reference concentration pathways
SCF	Standard conversion factor
SHARP	Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists
SMHI	Swedish Meteorological and Hydrological Institute
SP3	Strategic Programme to Reduce Rural Poverty
Tx	Maximum temperature
Tn	Minimum temperature
WCA	West and Central Africa
WP	Crop biomass water productivity (tonne of biomass per ha and per mm of water transpired or kg of biomass per m^3 of water transpired)
WP*	WP normalized for ET_o and air CO_2 concentration (tonne/ha or kg/m^2)

Executive summary and main findings

The Special Report on Global Warming of 1.5 °C (2018), recently published by the Intergovernmental Panel on Climate Change (IPCC), emphasizes the urgent need for international climate action. The report outlines the likely catastrophic consequences if global warming reaches temperatures beyond 1.5 °C, including biodiversity loss, decrease of soil quality, yield reductions of staple foods and the resulting decline in food availability, and heightened poverty in already vulnerable regions. Poor people are expected to bear the brunt of the negative consequences due to their increased inequality and vulnerability. Climate change already affects the extreme poor who rely on subsistence agriculture as a result of decreases in crop production and quality, increases in crop pests and diseases, and disruptions to their social fabric and culture, e.g. through migration or conflicts over natural resources (Savo *et al.*, 2016).

Climate variability and extremes are important drivers behind the recent growth in global hunger and severe food crises around the world. The influence of climate on production and livelihoods is strongest and most complex in sub-Saharan Africa, where the heavy reliance on dryland farming and pastoral rangeland systems by more than 70 percent of the population makes the region particularly susceptible to climate shocks. This, together with the growing population and the consequent need to produce more food, poses a challenge to the way we use water and productive land, particularly in water-scarce areas where most of the world's rural poor live.

West and Central Africa (WCA) is particularly threatened by climate change and weather-related shocks, due in part to its high dependence on rainfed agriculture. The region is endowed with abundant water resources, yet less than 3 percent of its arable land is under some form of water management. Water resources are unevenly distributed across the variety of agroecological zones in the region.

Small-scale irrigation is very promising for the region as it can promote rural food security, poverty alleviation and adaptation to climate change. Improving the resilience of small-scale irrigation systems to climate change-related shocks should thus be an essential part of any effective irrigation investment plan. This report aims to provide governments, international organizations and project managers with evidence-based information on the impacts of climate change on small-scale agriculture in WCA in order to support the development of adaptation strategies that build the resilience of smallholder farmers.

The assessment underlying this report was carried out on project sites in the Sahelian and Soudanian zones of the Niger, Mali, the Gambia and Côte d'Ivoire. The sites in the Niger are located in the Sahelian zone, where the annual rainfall is less than 600 mm, while the sites in Mali and the Gambia are found in the Soudano-Sahelian zone, which has a mean annual rainfall of between 600 mm and 900 mm. The sites in Côte d'Ivoire, located in the Soudanian zone, are the rainiest areas, with an annual rainfall of more than 900 mm.

Chapter 1 of this report presents an **analysis of observed climates in the pilot sites and provides climate projections** using a selected set of regional climatic models from the Coordinated Regional Climate Downscaling Experiment (CORDEX).

The main findings are as follows:

- An analysis of observed annual mean temperature shows a mean rate of increase of about 0.5 °C every ten years in most of the project sites. The annual precipitation trend is highly dependent on the location of the site. Both a decreasing trend and an increasing trend in annual rainfall are observed in the project sites. Mean precipitation decreases are mainly observed in the Sahelian zone, but also occur in the Soudanian zone.
- Projections show that temperatures are expected to increase in all project sites in WCA, with a greater increase at sites in the Sahel than in the Soudanian zones. Temperature increases range from 0.7 °C to 2.4 °C for RCP4.5[1] and between 0.9 °C and 3.2 °C for RCP8.5. The increase in temperature is expected to be higher in Horizon 2050 (H50) than in Horizon 2030 (H30)
- No clear trend in precipitation changes is expected in the project sites. However, on average, precipitation is expected to show a relative change between -10 percent and 10 percent in a moderate scenario (RCP4.5), while a pessimistic scenario (RCP8.5) could bring about a relative change in precipitation of between -16 percent and 16 percent. Overall, the magnitude of the variability of precipitation changes is higher for the sites in the Sahel zone. Precipitation changes are expected to increase from H30 to H50.
- Projections show an increase in evapotranspiration (ET) throughout all project sites with the greatest increase in the sites located in the Sahel zone. A relative change between 1.5 percent and 8 percent is expected for RCP4.5 and between 2 percent to 10 percent is expected for RCP8.5. The highest changes are expected for H50.

Chapter 2 presents a**n analysis of the impacts of climate change on crop yields** in the pilot sites. The chapter provides a quantitative assessment of the impacts of climate change on the four main crops in the region (maize, rice, sorghum and tomato). The analysis was conducted using FAO's AquaCrop model to simulate crop yields under current conditions and future climatic scenarios (RCP4.5 and RCP8.5). The main findings of the crop yield assessment follow:

- Projections show that, under current management practices, climate change will have a negative impact on agricultural production. On average, yield is expected to decline from 5 percent to 20 percent, depending on the crop and the agroecological zone. Higher declines are likely among long-cycle cultivars of rainfed crops in the Soudanian zone.
- The current cultivars of sorghum in the Sahel zone may no longer be feasible with climate change.
- Adopting water and soil management practices can allow smallholders to cope and adapt to these negative impacts. Enhancing soil fertility is key to improving the yields of irrigated crops – such as tomato and rice – in the region. Soil fertility improvement should go hand in hand with more efficient irrigation management practices. Results show that improving the soil fertility by at least 15 to 20 percent could lead to an increase in crop yields of 8 percent for C3 crops (e.g. tomato and rice).
- Supplementing rainfed agriculture with irrigation as a strategy to enhance yields can only be effective with the improvement of soil fertility.

[1] A representative concentration pathway (RCP) is a greenhouse gas concentration trajectory adopted by the IPCC. There are four RCPs, which range from very high (RCP8.5) to very low (RCP2.6) future concentrations. For the purposes of this study, RCP4.5 (moderate scenario) and RCP8.5 (pessimistic scenario) have been used.

- In future climate change scenarios, crops can benefit from increased CO2. Under optimal conditions (no fertility or water stress), crop yields (particularly for C3 crops) can be doubled with CO2 fertilization. As a result, yield gaps (the difference between the potential yield under optimal non-limiting conditions and the actual yield under current field management conditions) increase with climate change.

Chapter 3 presents a **participatory resilience assessment** to identify how climate change is impacting smallholder farmers and describes the adaptation strategies already in place at household and community levels. The resilience assessment was conducted using the FAO-developed Self-evaluation and Holistic Assessment of climate Resilience for farmers and Pastoralists (SHARP) tool. A series of surveys helped identify the areas of vulnerability among farming families and provided a picture of the prevailing socioeconomic and environmental conditions in rural households, as well as the practices used to respond and adapt to climate change. In consultation with communities, the SHARP tool also enabled the identification of farmers' self-stated needs, which could serve as the basis for prioritizing adaptation strategies and interventions. The main results of this assessment show that the common areas in which low resilience is observed across the four pilot countries are as follows:

- Limited knowledge about field irrigation practices and the use of rudimentary infrastructure: Almost 60 percent of farmers irrigate at the surface level and 69 percent still use cans and buckets for irrigation. Water intake is carried out directly without infrastructure in 28 percent of the cases, groundwater is mostly access through traditional wells (54 percent).
- The water supply for irrigation is considered insufficient by almost half of producers (45 percent).
- Sixty-seven percent of farmers consider their water management practices to be insufficient or inadequate for increasing crop productivity.
- More than 70 percent of farmers have seen land and soil degradation increase as a result of wind or water erosion, deforestation and reduction of vegetative cover.
- Almost half of farmers (44 percent) have no non-farm income generating activities (IGAs), mostly relying on agriculture for their livelihoods.

The assessment also revealed that farmers have taken actions to adapt and overcome the negative effects of climate variability and the mismanagement of natural resources. These actions have mostly centred on the use of fertilizers and land improvement to prevent soil and land degradation. Most farmers have instituted more efficient agricultural water management practices and 54 percent of producers have made minor changes to their irrigation practices over the past decade in response to climate change.

Chapter 4 presents a **compilation and characterization of different adaptation options at the country level.** The chapter is based on a non-exhaustive consultation with national stakeholders in the four pilot countries. Countries appear to particularly favour investments in water harvesting and soil conservation practices. The introduction of pest- and drought-resistant crop varieties and the management of plant diseases and pest outbreaks are also considered to be critical for climate change adaptation.

Implementing climate change adaptation strategies requires financing. Chapter 5 analyses the financial and economic feasibility of selected practices for adapting irrigation systems and livelihoods to climate

change in the WCA region. Cost-benefit analyses of different adaptation strategies involving soil and water management were conducted on ten different irrigation sites in the four pilot countries.

The results show that soil amendments – such as the use of organic fertilizers and sustainable soil management practices - are affordable for small-scale farmers and have an effective impact on crop yields and revenues. Important investments are usually needed to put irrigation systems in place and ensure their effective functioning in the medium and long terms. However, such systems have the potential to increase farmers' incomes.

Overall, our findings are that financing climate-proof irrigation technologies improve the economic returns to farmers over the long term. The analysis determines that investing in adaptation strategies enables farmers in particular, and rural populations in general, to improve their overall resilience and wellbeing.

The report stresses the fact that the changing climate not only threatens the quality and availability of water resources, but also the livelihoods of farming families. Financing small-scale irrigation schemes and sustainable soil, land and water management practices can have a strong impact on the resilience of the livelihoods of small-scale farmers to climate shocks.

Background and objectives of the study

The *Special Report on Global Warming of 1.5 °C* (2018), recently published by the Intergovernmental Panel on Climate Change (IPCC), raises awareness of the urgent need for international climate action. The report describes the likely catastrophic consequences if global warming reaches temperatures beyond 1.5 °C; these include biodiversity loss, decrease in soil quality, yield reduction in staple foods with a resulting decrease in food availability, and greater poverty in already vulnerable regions. At 1.5 °C warming, additional negative consequences are expected for the poor, including increased inequality and vulnerability. Climate change already affects extremely poor people, who rely on subsistence agriculture, by decreasing in crop production and quality, increasing crop pests and diseases, and disrupting their social fabric and culture, for example through migration or conflicts over natural resources (Savo *et al.*, 2016).

Climate variability and extremes are already important drivers behind the recent growth in global hunger and severe food crises around the world. In Africa, the influence of climate on production and livelihoods is particularly strong and complex. More than 70 percent of the population of sub-Saharan Africa rely heavily on dryland farming and pastoral rangeland systems, making people extremely susceptible to climate shocks. This, together with the growing population and the consequent need to produce more food, presents a major challenge to how we use water and productive land, especially in water-scarce areas where most of the world's rural poor live.

The West and Central Africa (WCA) region is particularly threatened by climate change and weather-related shocks, due in part to its high dependence on rainfed agriculture. WCA is endowed with abundant water resources, yet less than 3 percent of its arable land is under any form of water management. Water resources are unevenly distributed across the variety of agroecologies in the region.

Small-scale irrigation is very promising for the region because it can promote rural food security, poverty alleviation and adaptation to climate change. Small-scale irrigation comprises a range of technologies that capture, store and distribute water in small plots owned by individuals or farmer groups and that can be part of a larger irrigated area. Small-scale irrigation accounts for most of the irrigated area in WCA, where farmers or farmers' organizations – rather than an external or government group – are responsible for managing the distribution of water.

In this context, FAO, in collaboration with IFAD, the national governments of Côte d'Ivoire, Mali, the Niger and the Gambia and the Aghrymet Regional Centre, implemented the project **"Adapting small-scale irrigation to climate change in West and Central Africa - AICCA"** to improve the sustainability and climate change adaptation of small-scale irrigation systems across different agroecological systems in WCA. This report aims to provide governments, international organizations and project managers with evidence-based information on the impacts of climate change on small-scale agriculture in WCA to support the development of adaptation strategies for building the resilience of small-scale farmers.

Methodology

The project undertook a range of different studies, including:

i. analysis of climate trends and the generation of climate projections;

ii. assessment of climate change impacts on crop yields;

iii. resilience assessment in agricultural communities;

iv. identification and assessment of adaptation strategies, including their financial and economic feasibility.

i. Analysis of climate trends and the generation of climate projections

Climate studies were conducted in project sites in different climatic zones, ranging from the Sahelian to Soudanian zones in the Niger, Mali, the Gambia and Côte d'Ivoire. The sites in the Niger are located in the Sahelian zone, where the annual rainfall is less than 600 mm, while the sites in Mali and the Gambia are found in the Soudano-Sahelian zone with a mean annual rainfall between 600 mm and 900 mm. The sites in Côte d'Ivoire, located in the Soudanian zone, are the rainiest areas with annual rainfall of more than 900 mm.

Climate change data were taken from a set of regional climate models (RCM) from Coordinated Regional Climate Downscaling Experiments (CORDEX), in each of the project sites. CORDEX is an initiative led by the World Climate Research Programme that aims to coordinate international efforts in regional climate downscaling. A performance analysis was undertaken to evaluate the ability of the models to replicate observed conditions. Historical climate data and RCM outputs encompassing precipitation, temperature and derived evapotranspiration (ET) for 2 greenhouse gas emission (GHG) scenarios (RCP4.5 moderate and RCP8.5 pessimistic) were used as climate input data for the impact study on crop yields.

ii. Assessment of climate change impacts on crop yields

This assessment used the AquaCrop model developed by FAO.[2] AquaCrop simulates the yield response of herbaceous crops to different agroecological conditions, including a range of climate change scenarios. The assessment was carried out over 3 phases. The first phase focused on the calibration of four crops (tomato, rice, maize and sorghum) in the eight pilot sites located in different climatic zones in the Sahelian and Soudanian zones in the Niger, Mali, the Gambia and Côte d'Ivoire. This was done by comparing the actual yields of the farming systems (i.e. rainfed and irrigated agriculture) with the simulated yields.

The second phase of the assessment simulated future climatic conditions in two different time horizons (2030 and 2050) and based on two climate change scenarios: a moderate scenario (RCP4.5) and a pessimistic scenario (RCP8.5). A third phase involved simulating specific adaptation strategies, such as the improvement of soil fertility, to assess the benefits to crop yields.

[2] AquaCrop is a crop growth model developed by FAO's Land and Water Division that simulates the yield response of herbaceous crops to water. More information is available at www.fao.org/aquacrop.

iii. Resilience assessment in agricultural communities

A participatory and holistic resilience assessment was conducted in different communities in the pilot countries to identify how climate change is impacting smallholder farmers, as well as the adaptation strategies already in place at household and community levels. The assessment, which targeted 691 rural households across 21 irrigation sites[3] used FAO's Self-evaluation and Holistic Assessment of climate Resilience for farmers and Pastoralists (SHARP) tool.[4]

The resilience assessment also helped to identify the areas of vulnerability among family farmers and provided information on the prevailing socioeconomic and environmental conditions in rural households, as well as the practices used to respond and adapt to climate change. In consultation with communities, the tool also enabled the identification of their self-identified needs, which could serve as the basis for prioritizing the implementation of adaptation strategies and interventions.

iv. Identification and assessment of adaptation strategies, including their financial and economic feasibility

The results of the impact assessment and the resilience assessments provided the basis for country teams to identify appropriate adaptation strategies. The crop yield benefits arising from the implementation of some adaptation strategies were assessed using AquaCrop. This information was used to conduct an economic and financial analysis of the strategies.

Additional adaptation strategies were identified through consultations with national stakeholders and classified according to the level of action needed for implementation (i.e. farm-level or public), the nature of the strategy (i.e. agronomic, management or infrastructure-related), the technical difficulty, the potential costs of implementation and the scope of the benefits (i.e. local, regional or global).

The various studies were carried out in a participatory manner, working closely with national stakeholders (government, farmers and research institutions) and the Agrhymet Regional Centre. A series of training sessions, consultations and validation workshops were held in conjunction with the studies (See Annex 1).

[3] The resilience assessment reports with consolidated results and at country level are available on the project website. See www.fao.org/in-action/aicca/en/.

[4] See www.fao.org/in-action/sharp.

1. Observed climate trends and climate change projections

Introduction

This chapter provides a descriptive analysis of the climate data gathered in WCA and an analysis of future climate change scenarios. The geographical focus on WCA requires an appropriate climate modelling approach, due to the complex climate characterized by the West African monsoon cycle. For this reason, climate change datasets have been taken from the Coordinated Regional Climate Downscaling Experiment (CORDEX). A performance analysis was undertaken to evaluate the ability of the models to replicate observed conditions. The performance analysis led to the selection of a set of regional climate models (RCMs) for each of the project sites. Historically-observed climate data and RCM outputs encompassing precipitation, temperature and derived evapotranspiration (ET) for the 2 greenhouse gas emission scenarios (RCP4.5 moderate and RCP8.5 pessimistic) were used as climate input data for the impact study on crop yields, using the AquaCrop model. The AquaCrop model allows researchers to simulate crop yields under current conditions and future climatic scenarios.

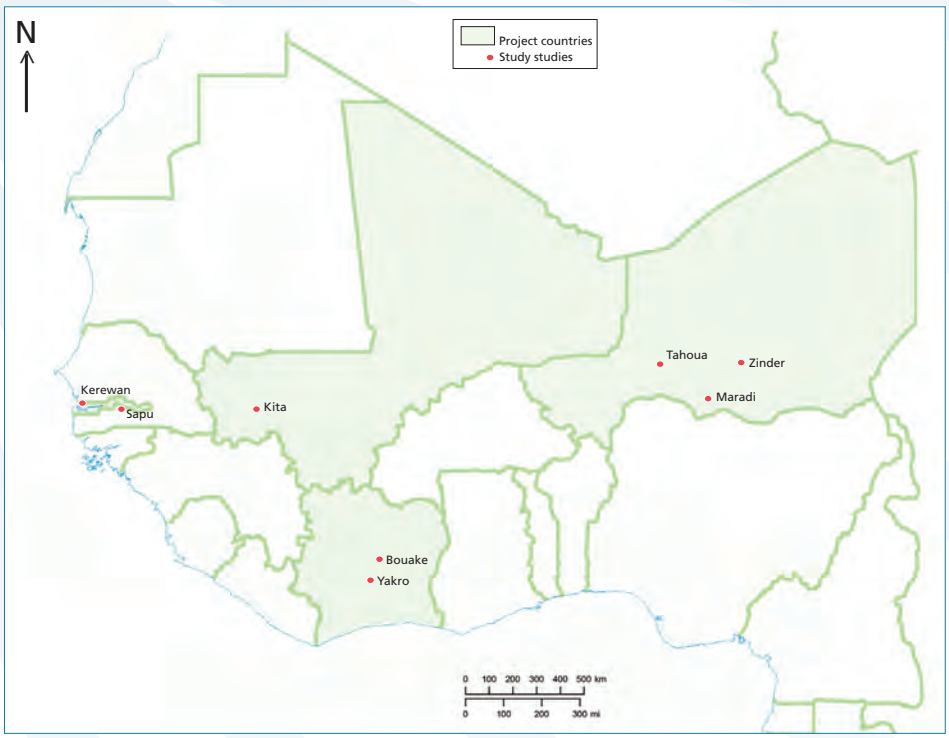
1.1 Methodology

1.1.1 Sites

A total of eight sites in Côte d'Ivoire, the Gambia, Mali and the Niger were selected for this study. The selected sites were Bouake[5] and Yakro in Côte d'Ivoire, Kerewan and Sapu in the Gambia, Kita in Mali and Tahoua, Maradi and Zinder in the Niger. Figure 1 shows the location of the study sites.

[5] Bouake was dropped from the AquaCrop simulations due to limited data availability

Figure 1. | Location of the selected sites of the AICCA project



The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers and boundaries.

1.1.2 Observed climate in the study areas

Climate data were provided by the national meteorological services in the four countries. The collected climate data in each study site came from the nearest meteorological station in order to ensure the representativeness of the data at the site level. The targeted climate variables included daily precipitation, daily maximum and minimum temperature and daily reference evapotranspiration (ETo). ETo was calculated using the FAO Penman-Monteith formula with additional variables such as relative humidity, solar radiation and wind speed. The length of the time series data used for a given site depended on the availability and quality of the data available from the nearest meteorological station.

Table 1 summarizes the climate variables and the period covered by the observed data.

Table 1. | Metadata of observed climate in the sites

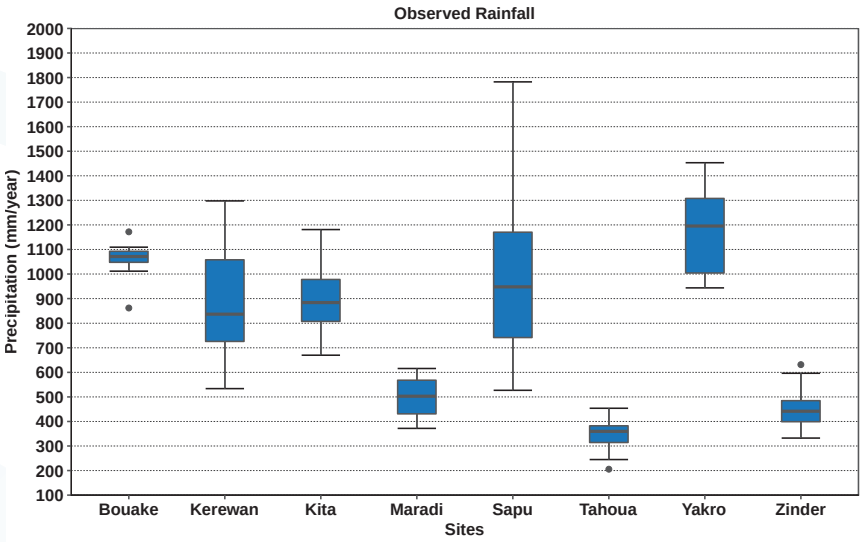
Country	Stations	Longitude (°)	Latitude (°)	Climates	Period
Niger	Maradi	7.1	13.8	Precipitation, ET_0, Tx et Tn	2000-2015
	Tahoua	5.4	14.2		
	Zinder	9.0	14.3		
Gambia	Kerewan	-16.1	13.5	Precipitation, ET_0, Tx et Tn	1990-2015
	Sapu	-14.9	13.4		
Côte d'Ivoire	Yakro	-5.4	6.9	Precipitation, ET_0, Tx et Tn	2008-2017
Mali	Kita	-9.5	13.1	Precipitation, ET_0, Tx et Tn	2008-2017

ET: Evapotranspiration, Tx: maximum temperature, Tn: minimum temperature

a) Precipitation

The project sites are located in different climatic areas in the Sahelian and Soudanian zones. The sites in the Niger are located in the Sahelian zone, where the annual rainfall is less than 600 mm, while the sites in Mali and the Gambia are located in the Soudano-Sahelian zone with a mean annual rainfall of between 600 mm and 900 mm. The sites in Côte d'Ivoire, located in the Soudanian zone, are the rainiest areas with annual rainfall more than 900 mm (See Annex 2a). In each site, a variability in high rainfall can be observed (See Figure 2).

Figure 2. | Observed annual rainfall variability for the study sites



Two seasons (a rainy season and a dry season) were observed in the project sites, with the exception of Yakro in Côte d'Ivoire, where the rainfall has a bimodal pattern with a short dry season in between. The length of the rainy season in the Sahelian and Soudano-Sahelian sites is between three and six months. In these climatic zones, a high variability of rainfall was observed during the growing season. Under mean conditions, the rainy season starts in May and finishes in October, with August as the wettest month. As noted, Yakro has 2 rainy seasons: a long rainy season from March to June and a short rainy season from September to October (See Annex 2b).

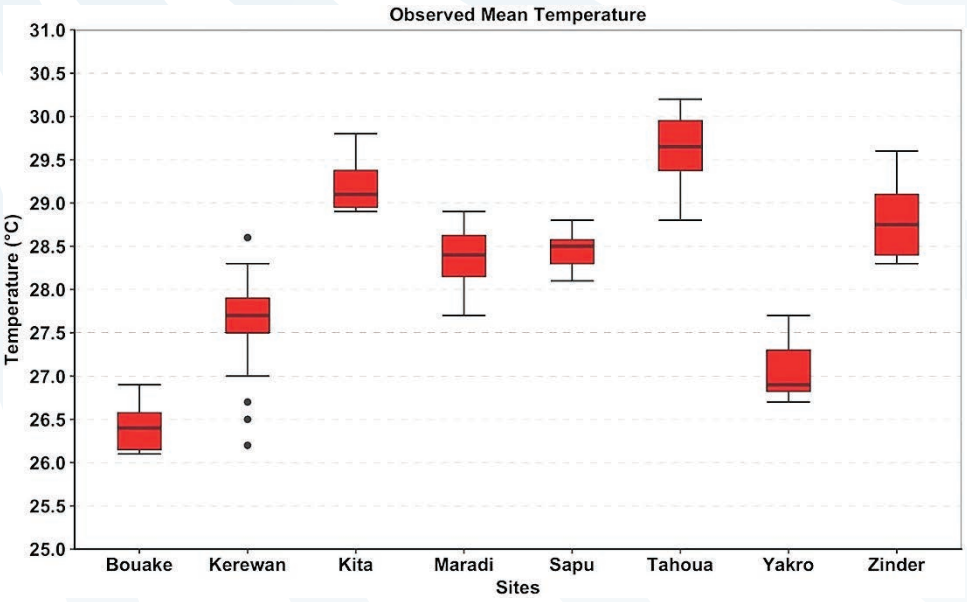
The Annual precipitation trend is highly dependent on the location of the site. For example, a decreasing trend of annual rainfall was observed in the sites in Maradi, Tahoua, Kita and Yakro; while an increasing trend in annual precipitation was seen in Zinder, Sapu and Kerewan. The greatest decrease in annual precipitation was observed in Yakro, while the smallest decrease was in Kita. Annex 2c provides more details on annual precipitation trends in the project sites.

b) Temperature

A high variability in daily mean temperature was observed in the Sahelian and Soudano-Sahelian zones. The analysis shows that for the sites located in the Niger (Maradi, Tahoua and Zinder), daily maximum temperature varies between 32 °C and 42 °C, while daily minimum temperature ranges from 12°C to 29°C. In the Soudano-Sahelian zone, covering sites in Mali and the Gambia, maximum temperatures vary between 30 °C and 41 °C, and minimum temperatures range from 16 °C to 27 °C. Temperatures in Yakro presents a low

magnitude of variability, with the daily maximum temperature varying between 30 °C and 36 °C and the daily minimum temperature falling between 19 °C and 23 °C (See Annex 2a). However, the daily mean temperature varies between 26°C and 30°C with the highest value in the Sahelian zone and the lowest value in the Soudanian zone (See Figure 3). The temperature is relatively higher during the period from March to May, while lower temperatures are observed in August (Annex 2b).

Figure 3. | Observed annual mean temperature variability in the study sites

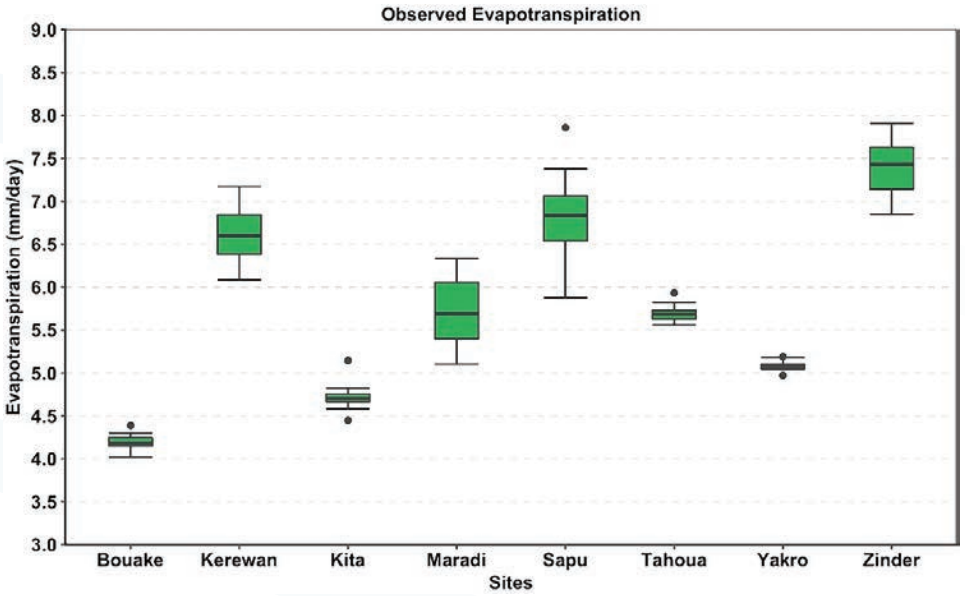


The analysis of annual mean temperature indicates an increase of temperature in all project sites (See Annex 2d). The mean rate of temperature increase is about 0.5° C every ten years for the sites in Zinder, Maradi, Tahoua, Kerewan and Yakro. However, in the sites of Kita and Sapu, only a slight increase in the annual mean temperature was observed.

c) Evapotranspiration

Daily ET_o was calculated in each site using the FAO Penman-Monteith method. The ET_o falls between 4 mm and 8 mm throughout the study area. However, ET_o decreases from the northern to the southern sites. For example, sites in the Niger have a mean ET_o of 5 mm to 7 mm per day, while daily ET_o in Yakro is less than 5.5 mm. As expected, the intra-annual variability showed that the highest ET is observed during the period between March and May, corresponding to the hottest period in most sites. During the rainy season, ET_o is 1 mm to 2 mm lower than in the dry season (See Annex 2e).

Figure 4. | Observed ETo mean variability in the study sites



1.2 Climate projections

1.2.1 CORDEX-AFRICA climate dataset

The CORDEX project provides a framework to evaluate and benchmark climate model performance and design a set of experiments to produce climate projections for use in impact assessment studies. In the climate projection framework of CORDEX, regional downscaling is taking place for 14 domains worldwide[6]. Dynamic and statistical downscaling approaches are mostly used for regional downscaling. The dynamic downscaling uses physically-based models in combination with GHG emission scenarios to produce projected future climate data at the regional scale.

CORDEX-Africa gathers ongoing simulation experiments throughout the continent. For example, the RCM group of the Swedish Meteorological and Hydrological Institute (SMHI) has used the boundary conditions of ten Global Circulation Models (GCMs)[7] (See Table 2) from the Coupled Model Intercomparison Project - Phase 5 (CMIP5) to drive the latest version of the Rossby Centre Regional Climate Model - RCA4 on the Africa domain. Table 2 presents the RCMs and institution names, with the corresponding labels used in this study.

[6] A domain is a region in which the regional downscaling takes place.
[7] More detail can be found at www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5.

Table 2. | RCMs and institution country names and the corresponding labels used in this study

RCMs	Countries	Labels
RCA4 (CanESM2)	Canada	CCCma
RCA4 (CNRM-CM5)	France	CNRM
RCA4 (EC-EARTH)	Europe	ICHEC
RCA4 (MIROC5)	Japan	MIROC
RCA4 (HadGEM2-ES)	United Kingdom of Great Britain and Northern Ireland	MOHC
RCA4 (MPI-ESM-LR)	Germany	MPI
RCA4 (NorESM1-M)	Norway	NCC
RCA4 (GFDL-ESM2M)	United States of America	NOAA
RCA4 (CSIRO MK2)	Australia	CSIRO
RCA4 (IPSL-CM1-4)	France	IPSL

1.2.2 Selection of RCMs

The selection of RCMs was based on an analysis of RCM data from the SMHI CORDEX-Africa. The selected models were then used to conduct an impact assessment study using the AquaCrop model (See Chapter 2). The selection of models was conducted in 2 steps. First, the Pairwise comparison method was used to analyse the means of precipitation, temperature and ET for each site to determine whether they were significant differences. The selection of the most suitable RCM was based on the capacity of the control runs of the different RCMs to reproduce the observation pattern, at least during the crop growing season. This method used the intra-annual cycle of the 3 climate variables (See Annexes 3a, 3b, 3c), which helps us to compare and select the RCMs with similar patterns to the observed variables, and the Taylor diagram approach (See Annexes 4b, 4b, 4c). This first step allowed the selection of a subset of RCMs.

The second step used the Taylor diagram, which provides a statistical summary of how well RCMs and observation (reference) patterns match each other in terms of their correlation, their root-mean-square difference and the ratio of their variances. This diagram provides a graphical framework that allows a set of variables from one or more RCMs to be compared to observations in the reference data.

The analysis of Taylor diagrams for the three variables (precipitation, temperature and ET) guided the final selection of the best RCMs, which were used in the AquaCrop simulations. Table 3 presents the three RCMs that were selected on the basis of the two-step selection process described above.

Table 3. | Selected RCMs by site

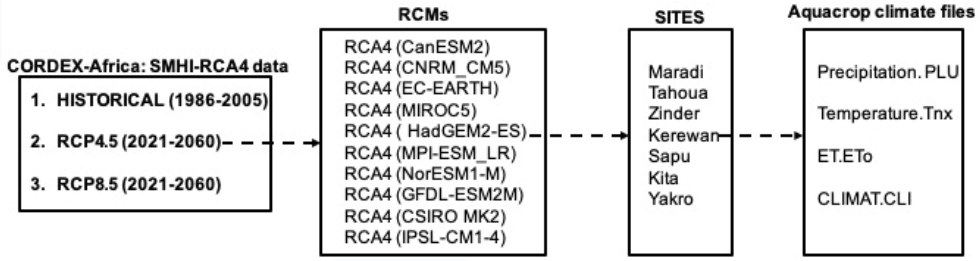
COUNTRIES	SITES	RCM Labels
NIGER	Maradi	CCCma, CNRM, MPI
	Tahoua	CNRM, MPI, MOHC
	Zinder	CNRM, MPI, MOHC
GAMBIA	Kerewan	CNRM, MIROC, MPI
	Sapu	CNRM, MIROC, MPI
MALI	Kita	CCCma, CNRM, MPI
CÔTE D'IVOIRE	Yakro	CCCma, CNRM. IPSL

1.2.3 Climate change data simulation

CORDEX Africa data have a resolution of 0.44° x 0.44° and include precipitation, minimum and maximum temperature and ET on a daily basis. The dataset consists of control runs (CTRL) and projections based on the GHG emission scenarios, called reference concentration pathways (RCPs). The RCPs are prescribed GHG concentration pathways throughout the twenty-first century and correspond to different radiative forcing stabilization levels expected to be reached by the year 2100. Two scenarios were considered in this study: a moderate scenario in which temperature is projected to increase by 1.5 °C (RCP4.5)[8] and a pessimistic scenario, where temperature is projected to exceed 2 °C by the end of the century (RCP8.5).[9]

A climate dataset for RCP4.5 and RCP8.5 was retrieved from the CORDEX-AFRICA repository. The retrieved data range from 1986 to 2005 for the control runs (historical), and from 2021 to 2060 for the two RCPs. The retrieved climate data have been reshaped and formatted to produce climate input data for AquaCrop model simulations. In view of the objectives of the project, a future (2021-2060) climate dataset has been divided into two time horizons: Horizon 30 (H30) corresponding to climate change data for the period 2021-2040 and Horizon 50 (H50), which corresponds to the period 2041-2060. From the historical range (from 1986 to 2005), climate data, including precipitation, minimum and maximum temperature and ET, have been formatted and set up to be used as climate input data for AquaCrop simulations for the two time horizons. The following flowchart provides an overview of the steps involved in formatting climate data for the simulation using the AquaCrop model.

Figure 5. | Flowchart of AquaCrop climate input formatting steps



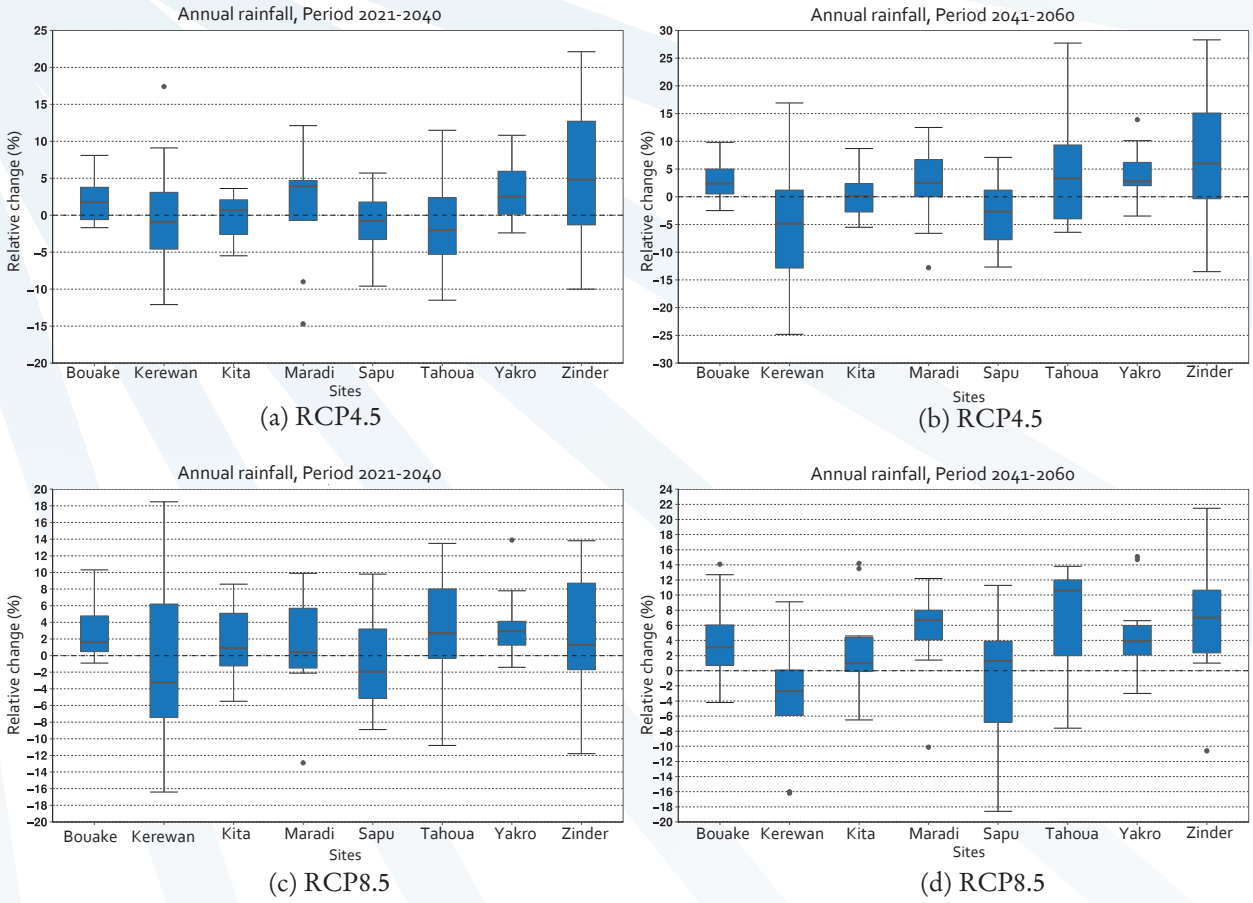
1.2.4 Precipitation changes for RCP4.5 and RCP8.5

Precipitation data for the two scenarios (RCP4.5 and RCP8.5) were analysed for every site. Annual precipitation was computed for the control run and the two RCPs by considering all RCMs. Then the changes in precipitation (expressed as a percentage) between RCPs and control runs were computed in order to obtain the magnitude of future changes expected, considering the two time horizons (H30 and H50) separately. Figure 6 shows the relative changes in precipitation for each site.

[8] RCP4.5 is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the radiative forcing target level 4.5 W/m2 (650 parts per million (ppm) CO2 eq).

[9] RCP8.5 is a high emission scenario (i.e. increased GHG emissions over time) corresponding to a rising radiative forcing pathway, leading to 8.5 W/m2 (1370 ppm CO2 eq) by 2100.

Figure 6. | Expected relative change of precipitation for RCP4.5 (a, b) and RCP8.5 (c, d) for H30 and H50



(a) RCP4.5 (b) RCP4.5

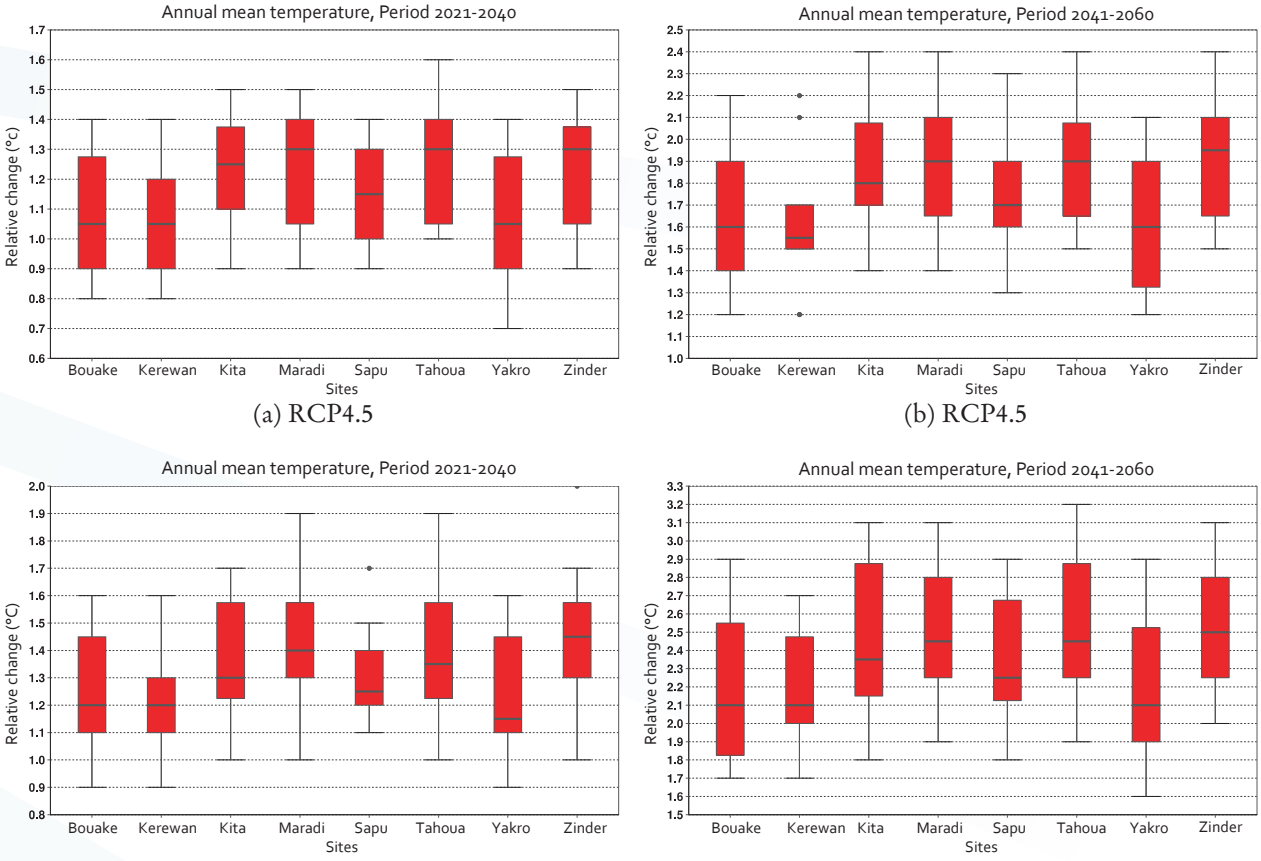
(c) RCP8.5 (d) RCP8.5

Overall, an average relative change in precipitation between - 10 percent and 10 percent is expected for a moderate scenario (RCP4.5), while in a pessimistic scenario (RCP8.5), precipitation is expected to vary between -16 percent and 16 percent. The magnitude of change is 50 percent lower for RCP4.5 than for RCP8.5 in all sites. No clear trends are evident among the RCMs.

1.2.5 Temperature changes for RCP4.5 and RCP8.5

In general, an increase in mean temperature is expected in future (H30 and H50). In fact, the analysis of the data for all sites presented a relative change of between 0.7 °C and 2.4 °C for RCP4.5 and between 0.9 °C and 3.2 °C for RCP8.5 (See Figure 7). For each RCP, the increase in temperature is higher for the H50 than for the H30. All RCMs showed a clear positive change in temperature in all sites. It was also observed that the spread is about 0.8 °C above 0.7 °C among RCMs, showing a high variability in the projected changes.

Figure 7. | Expected relative change in mean temperature for RCP4.5 (a, b) and RCP8.5 (c, d) for H30 and H50



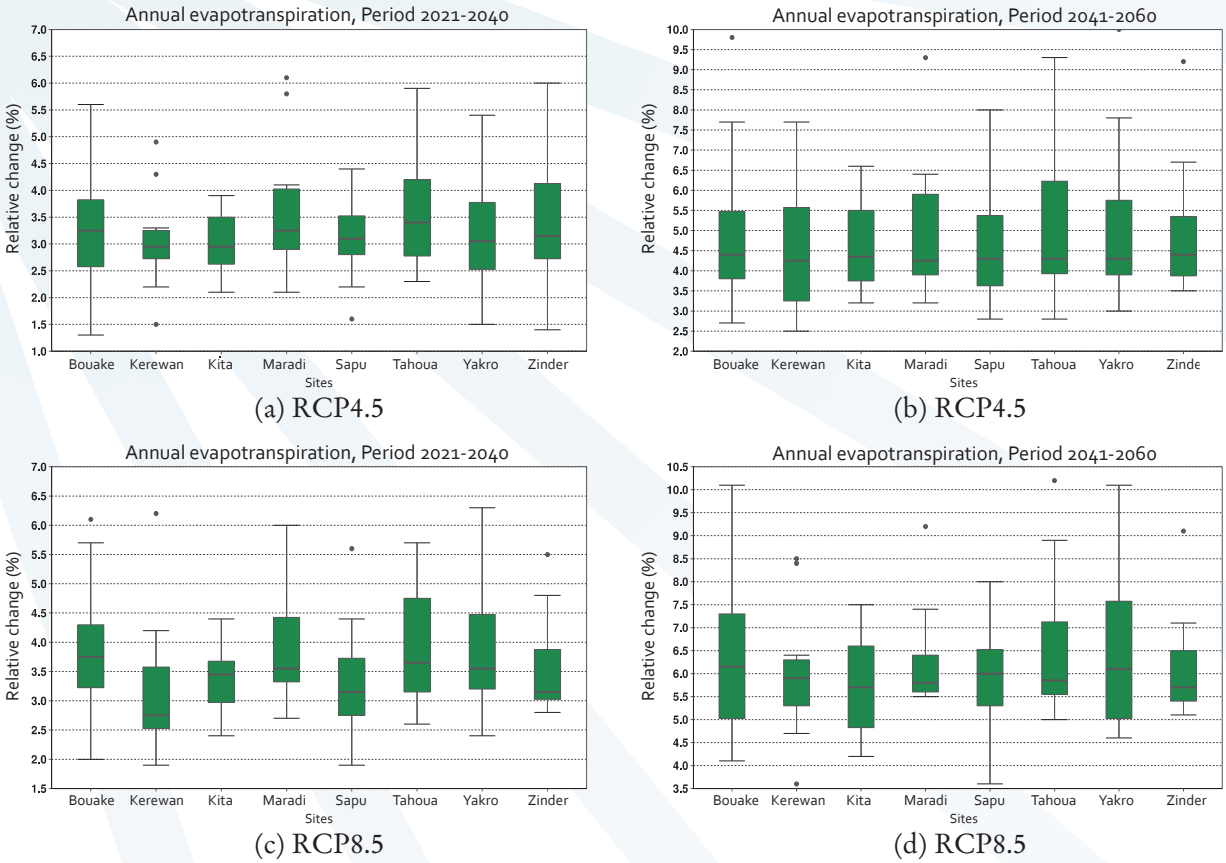
(a) RCP4.5 (b) RCP4.5

(c) RCP8.5 (d) RCP8.5

1.2.6 ET changes for RCP4.5 and RCP8.5

As is the case for temperature, an increase is also expected in the future ET. All projections from RCMs revealed positive changes in the ET trend. A relative change between 1.5 percent and 8 percent is expected for RCP4.5 and between 2 percent to 10 percent for RCP8.5. The mean changes are about 3 percent to 4.5 percent for RCP4.5 and 3.5 percent to 6 percent for RCP8.5. The highest changes are expected for H50. Figure 8 presents the magnitude of ET changes for each site.

Figure 8. | Expected relative change in ET (mm/day) for RCP4.5 (a, b) and RCP8.5 (c, d) for H30 and H50



(a) RCP4.5 (b) RCP4.5

(c) RCP8.5 (d) RCP8.5

1.2.7 Planting date shifts for RCP4.5 and RCP8.5

In the project sites, planting dates are only determined for rainfed crops using the rainfall data, since predefined dates are used for planting irrigated crops. Given the high seasonal precipitation variability in the project sites, the success of crop production strongly depends on when farmers proceed to planting. Therefore, crop planting date is a key factor in the choice of crop varieties and land preparation work. One strategy that farmers can use to sustain or improve their crop yields in the face of climate variability and climate change is to adjust planting dates. Thus, it is useful to know how planting dates might shift in the future.

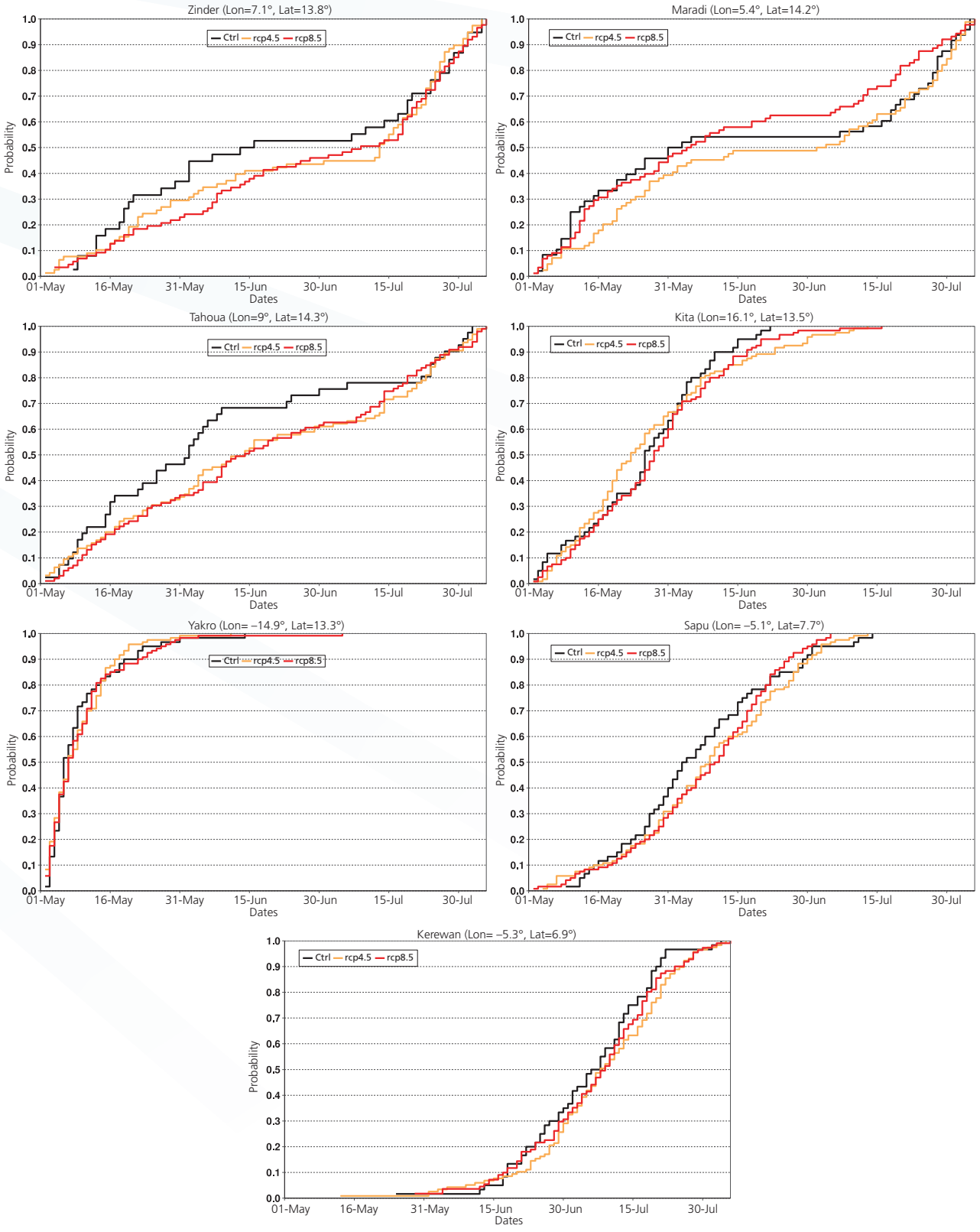
For this study, the following well-known rainfall-based method was selected to compute the planting date: the date after 1 May, when rainfall has accumulated over three consecutive days, is at least 20 mm and when no dry spell of more than ten days occurs within the next 30 days. These criteria are currently used by farmers in West Africa.

For a given site, planting dates were determined using daily rainfall data from the three selected RCMs. The control runs dataset (Ctrl) was used as reference to mimic the current planting dates, while the RCP4.5 and RCP8.5 datasets were used to estimate the projected planting dates. The projected planting dates are therefore an empirical cumulative distribution function derived from the time series of the planting dates.

Figure 9 presents the probability of non-exceedance of planting dates for the Ctrl and RCP4.5 and RCP8.5 scenarios. For a specific date on the x-axis, the corresponding probability on the y-axis indicates the chance of planting the crop before the given date. In general, it is noticeable that planting dates occur earlier in the

southerly sites than in the northern sites. The analysis shows that in Zinder and Tahoua, the probability of planting crops before the end of July is higher for the Ctrl than for the RCP4.5 and RCP8.5 scenarios. This means that, a delay of planting is expected in the future for RCP4.5 and RCP8.5 crops in those sites. However, no clear difference in planting date is observed in the other sites.

Figure 9. | Planting dates shifting for the scenarios RCP4.5 and RCP8.5 in the project sites



2. Impact of climate change on crop yields and adaptation needs at crop production level

Introduction

Climate variability and changes in weather patterns are likely to affect crop yields, because they affect the availability and quality of crucial resources such as water and soil.

The objective of this study was to determine the impact that future climatic conditions may have on crop yields in WCA. The study was carried out on four crops, which were selected by country teams: tomato (irrigated agriculture), sorghum (rainfed agriculture), and rice and maize which are cultivated under both irrigated and rainfed agriculture. The study considered different crop management strategies in order to assess differences in yield gap and irrigation water requirements. Crop yields were simulated under actual irrigation and field management conditions, as well as improved and optimal management conditions (i.e. unlimited soil fertility and absence of weed infestation).

The study used the AquaCrop model[10] to simulate crop yields under current conditions and future climatic scenarios. To do so, the model used climatic data obtained from ten different meteorological stations, climate change projections (See Chapter 1), regional observed crop and soil data, and various field and water management practices.

[10] AquaCrop model is a crop growth model developed by FAO. AquaCrop simulates the yield response of herbaceous crops to water. For more information, visit www.fao.org/aquacrop

The study was conducted in two different phases. The first phase focused on the calibration of AquaCrop to current climatic conditions. This was done by comparing the actual yields of the farming systems (i.e. rainfed and irrigated agriculture) with simulated yields under different management conditions.

The second phase involved simulating climatic conditions in two future time horizons (2030 and 2050) and based on two climate change scenarios: a moderate scenario (RCP4.5) where temperature is projected to exceed 1.5 °C, and a pessimistic scenario (RCP8.5) where temperature is projected to exceed 2 °C by 2100. The analysis considered the effect of the atmospheric CO_2 concentration on crop yields, since it might increase the productivity of some crops (C3) and could lead to higher yields (CO_2 fertilization). The combined effect of CO_2 fertilization, altered weather conditions and different management practices on future crop yields were studied with AquaCrop.

The impacts of a number of adaptation strategies were also studied, including improved soil fertility and the use of complementary irrigation for rainfed crops such as maize, rice and sorghum.

2.1 Data collection

2.1.1 Crop data

The study considered four crops and two cultivation methods: tomato (irrigated agriculture), sorghum (rainfed agriculture), and rice and maize which are cultivated under both irrigated and rainfed agriculture..

a) Combination of crops, cultivation method and sites

The combination of crops, cultivation methods and sites used in the different simulations are presented in Table 4.

Table 4. | Combination of crops, cultivation method and sites

Crop	Cultivation method	Country			
		Niger	Mali	Côte d'Ivoire	Gambia
Tomato	Irrigated	Falki	Kita	Kpato	-
Rice	Irrigated	-	-	M'bé	Sapu [1]
Maize	Irrigated	Soumarana	-	-	-
Rice	Rainfed	-	Kita [2]	-	-
Maize	Rainfed	-	Kita	-	Kerewan
Sorghum	Rainfed	Fachi	-	-	-

[1] Tidal irrigated rice;
[2] Shallows (bas-fond)

b) Crop files

Information on the plant density, the length of the various growth stages in calendar days, rooting depth and the harvest index (HI) linked to the crop cultivar was used to fine-tune the default files available in AquaCrop's database on the six target crops. The crop cycle, expressed in calendar days, was subsequently converted to growing degree days (GDD) by considering the average thermal time required in the various years and sites. Since the thermal regime in the cold dry season for maize (irrigation season) is different from the thermal

regime in the wet season (rainfed cultivation), two GDD crop files were created for maize. Although both irrigated and rainfed rice are cultivated in the wet season, two files were created since the cycle length of the rice cultivar under irrigation differs from the cycle length under rainfed agriculture (See Table 5).

In the absence of information on the development of canopy cover, the variation of the soil water content and the amount of biomass produced at regular intervals during the growth cycle, general crop characteristics were used to supply these data.

The characteristics included in the six crop files are presented in Annex 5. The files include information on plant density, the reference harvest index (HIo), crop response to water, temperature and salinity stresses, and other variable used for the calibration.

Table 5. | General characteristics of the six general crop files

Crop	Cultivation		Plant density	Cycle length	Cultivar	
	Season [1]	method			Type	HIo [2]
			plants/m^2	days		%
Tomato	Cold dry season	Irrigated	4	120	High yielding	63
Rice	Wet season	Irrigated	25	120	High yielding	43
Rice	Wet season	Rainfed		135	Inbred	37
Maize	Cold dry season	Irrigated	2	90	Landrace	35
Maize	Wet season	Rainfed				
Sorghum	Wet season	Rainfed	4	90	Landrace	30

[1] Cold dry season from October to January; Wet season from June to September;
[2] HIo: the reference harvest index.

c) Reference crop yield

For reference yields, the values presented in the FAO Irrigation and Drainage Paper No. 66, *Crop yield response to water* for high yielding cultivars were used to calibrate the different crops (See Table 6).

Table 6. | Global reference yields

Crop	Reference yields
Tomato	A good commercial fresh fruit yield ranges up to more than 150 tonnes/ha for fresh market cultivars.
Rice	Irrigated: Under continuously flooded conditions, short duration (100 – 115 days) modern tropical cultivars can yield 6-8 tonnes/ha in the wet season.
	Rainfed: In good conditions, average yields of rainfed lowland rice range from 4 tonnes/ha to 5 tonnes/ha. With frequent abiotic stresses (mainly drought), however, yields are considerable lower, around 2 tonnes/ha.
Maize	Farm yields between 11 tonnes/ha and 14 tonnes/ha are normally achieved under full irrigation and high fertility. The average country yields are generally much lower. Average yields in Argentina, China and South Africa were only about a half of this (6 tonnes/ha), and in Brazil slightly above one-third (4.5 tonnes/ha); but all show clear rising trends over time.
Sorghum	The average yield of sorghum varies wildly from high productivity countries, which present yield averages of 4.7 tonnes/ha in the Unites States and Argentina, and 4.3 tonnes/ha in China, to productivity levels of 0.6 tonnes/ha in Sudan, and 1.0-1.5 tonnes/ha in India, Burkina Faso or Ethiopia.

Source: FAO Irrigation and Drainage Paper No. 66.

2.1.2 Planting dates

Irrigated tomatoes and maize are cultivated in the cold dry season, while irrigated rice is cultivated in the wet season. The reported planting/sowing dates shown in Table 7 represent all of the years of the simulation period.

The rainfed crops (rice, maize and sorghum) are typically planted/sown at the start of the wet season. Due to variations in the onset of the wet season, we cannot use the same sowing day for all of the years of the simulation period. For this reason, the planting/sowing dates were based on a rainfall level criterion for each year considering the reported planting periods (See Table 8). For example, rainfed rice cultivated in basins requires a level of precipitation compared to maize and sorghum, since the top soil has to be close to saturation when planting. For maize and sorghum, the first day of the sowing period was set for 1 May and for rice, it was set for 1 June to guarantee sufficient pre-wetting. Table 8 summarizes the planting/sowing periods and the rainfall criteria used to generate the planting/sowing dates.

Table 7. | Reported planting/sowing dates for the irrigated crops at the various sites

Crop	Site	Country	Planting date
Irrigated tomatoes	Falki	Niger	1 October
	Kita	Mali	15 October
	Kpato	Côte d'Ivoire	1 October
Irrigated rice	Sapu	Gambia	20 July
	Mbe	Côte d'Ivoire	1 June
Irrigated maize	Soumarana	Niger	1 October

Table 8. | Reported period of planting/sowing and selected rainfall criteria for the determination of the planting/sowing dates for rainfed crops at the various sites

Crop	Site	Country	Period of planting/ sowing	Rainfall criterion
Rice	Kita	Mali	1 June - 31 July	40 mm in 5 days (second occurrence)
Maize	Kita	Mali	1 May - 31 July	20 mm in 2 days (second occurrence)
	Kerewan	Gambia		
Sorghum	Fachi	Niger	1 May - 31 July	2 m in 2 days (second occurrence)

2.1.3 Soil characteristics

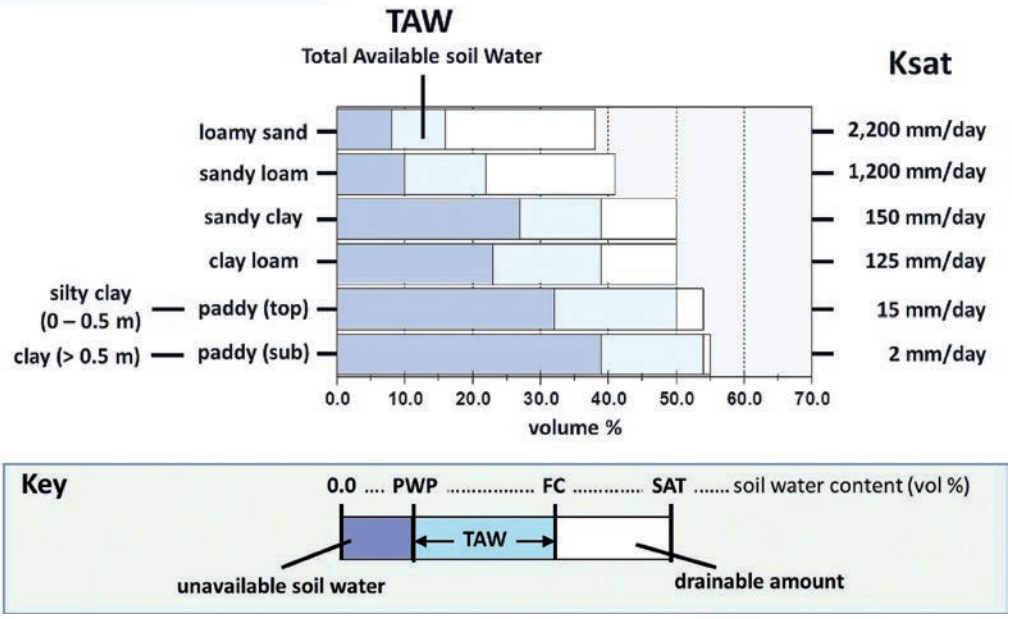
Table 9 presents the reported soil types on the project sites. The default characteristics available in the AquaCrop database were considered in the absence of a full description of the soil profile or detailed information about the soil texture (See Figure 10).

Table 9. | Reported soil types at the 8 sites for the various crops

Crop	Site	Soil type
Irrigated tomatoes	Falki (Niger) and Kpato (Côte d'Ivoire)	loamy sand
	Kita (Mali)	clay loam
Irrigated/rainfed rice	Sapu (Gambia), M'bé (Côte d'Ivoire) and Kita (Mali)	paddy soil [(1)]
Irrigated maize	Soumarana (Niger)	sandy loam
Rainfed maize	Kita (Mali)	sandy clay
	Kerewan (Gambia)	sandy loam
Rainfed sorghum	Fachi (Niger)	sandy loam

[(1)] The fields are surrounded by soil bunds with a height of 0.3 m

Figure 10. | Saturated hydraulic conductivity (Ksat) and soil water content at permanent wilting point (PWP), at field capacity (FC), and total pore volume at soil saturation (SAT), with indication of the unavailable soil water for crops, the total available soil water (pore volume between PWP and FC) and the drainable amount of water (pore volume between SAT and FC) for the various soil types



2.1.4 Irrigation management

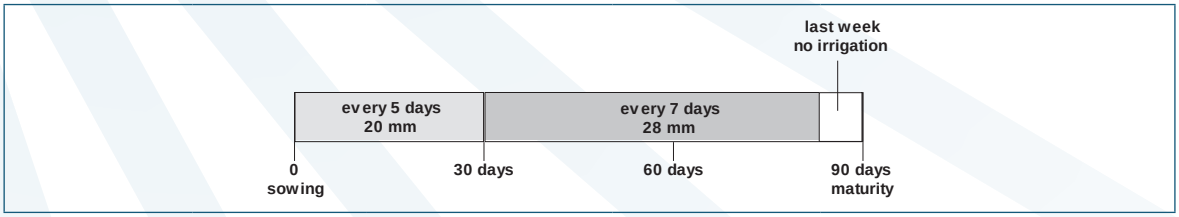
Irrigation schedules specific to each of the irrigated crops were developed based on the selection of (i) the irrigation method), (ii) a fixed irrigation interval; and (iii) a fixed net irrigation application dose.

In the case of tomatoes, a fixed irrigation interval of five days was selected in the absence of reported data. The fixed net application dose for each site was obtained by considering the mean ETo during the irrigation season (See Table 10).

Irrigated rice is cultivated in basins surrounded by soil bunds with a height of 0.30 m. To avoid water stress, irrigation water is applied to the fields when the standing water between the bunds drops below a minimum level (10 mm of standing, water was selected as minimum depth). Since the deep percolation of the saturated paddy soil is only 2 mm/day (See Figure 10), soil water stress can be avoided. To study the possible contribution of rainfall, only 10 mm of water is applied each time the water level between the soil bunds drops below its minimum depth (See Table 10). By keeping the water level low, a maximum amount of rainfall can be stored between the soil bunds on rainy days.

For maize, in the absence of reported data, a fixed irrigation interval of five days was selected for the first month, and of seven days for the remaining part of the irrigation season (See Table 10). The fixed net application dose was 20 mm in the first month and 28 mm in the later period. Irrigation was not applied during the week before harvest.

Table 10. | Characteristics of irrigation management for the various crops

Irrigation management for tomatoes (furrow irrigation)			
Characteristic	Falki (Niger)	Kita (Mali)	Kpato (Côte d'Ivoire)
Average ETo (October – February)	6 mm/day	4 mm/day	5 mm/day
Irrigation interval	5 days	5 days	5 days
Net application dose	30 mm	20 mm	25 mm
Irrigation management for paddy rice (basin irrigation)			
	0.30 m soil bunds surround the basins; Apply 10 mm of water each time the water level between the bunds drops below its minimum depth of 10 mm.		
Irrigation management for maize (furrow irrigation)			
			

2.1.5 Field management

Reported crop yields are low in all irrigation sites, especially when compared to yields that could be obtained under excellent field management conditions (See Table 6). This is mainly attributed to non-optimal field management for both the irrigated and rainfed crops, and, to some extent, to a poor irrigation schedule. Low yields can be also explained by losses due to pest and diseases, harvesting methods, and post-harvest practices, including low-quality transportation and storage processes.

Field management was used to calibrate AquaCrop for crop yield given its strong effect on crop productivity. The calibration consisted of adjusting the levels of soil fertility and the degree of weed management until the simulated crop yield matched that of the reported yield. The greatest reported yield was selected for calibration, assuming that the losses due to pests and diseases, harvest and post-harvest practices are minimal.

Crop yields in line with the greatest reported yield were simulated by considering the soil fertility and weed management practices presented in Table 11. The considered classes of soil fertility were determined using the maximum biomass production that can be obtained in the absence of any stress other than soil fertility (B_{rel}). These classes are as follows: near optimal (80 percent B_{rel}), moderate (60 percent B_{rel}) and poor (40 percent B_{rel}). Soil fertility is assumed to be good to moderate under irrigation, and moderate to poor for rainfed crops. Weed management was assumed to be very good (5 percent weed infestation) under irrigation, and only moderate (15 percent weed infestation) for rainfed crops.

Table 11. | Calibrated field management

Crop	Site and country	Soil fertility	Weed management
Irrigated tomato	Falki (Niger), Kita (Mali), Kpato (Côte d'Ivoire)	Moderate	Very good
Irrigated rice	Sapu (Gambia)	Near optimal	Very good
	M'bé (Côte d'Ivoire)	Moderate	Very good
Irrigated maize	Soumarana (Niger)	Poor (*)	Very good
Rainfed rice	Kita (Mali)	Poor	Moderate
Rainfed maize	Kita (Mali)	Moderate	Very good
	Kerewan (Gambia)	Poor	Moderate
Rainfed sorghum	Fachi (Niger)	Poor	Moderate

(*) Yields of irrigated maize in line with the reported yields could only be simulated by assuming poor soil fertility, although under irrigation the soil fertility is likely to be good.

2.2 Simulations under current climatic conditions

Simulations were run for each site using historical climatic data and the characteristics of crop, soil and irrigation and field management in a number of successive years.

2.2.1 Climatic data input

The climatic data included historic daily data for rainfall, the minimum and maximum air temperature, and reference ETo computed using the FAO Penman-Monteith method for 10 up to 26 successive years (See Table 12).

Table 12. | Selected sites and characteristics of the representative climatic stations

Country	Site	Climatic Station	Coordinates	Period	Number years
Niger	Falki	Zinder	13°48'N; 8°59'W; 460 m.	2000-2015	16
	Soumarana	Maradi	13°29'N; 7°6'W; 340 m.	2000-2015	16
	Fachi	Tahoua	14°54'N; 5°16'W; 389 m.	2000-2015	16
Mali	Kita	Kita	13°03'N; 9°29'W; 340 m.	2008-2017	10
Côte d'Ivoire	Kpato Mbe	Yakro	6°49'N; 5°17'W; 220 m.	2008-2017	10
Gambia	Sapu	Sapu	13°34'N; 15°56'W; 20 m.	1990-2015	26
	Kerewan	Kerewan	13°30'N; 16°04'W; 20 m.	1990-2015	26

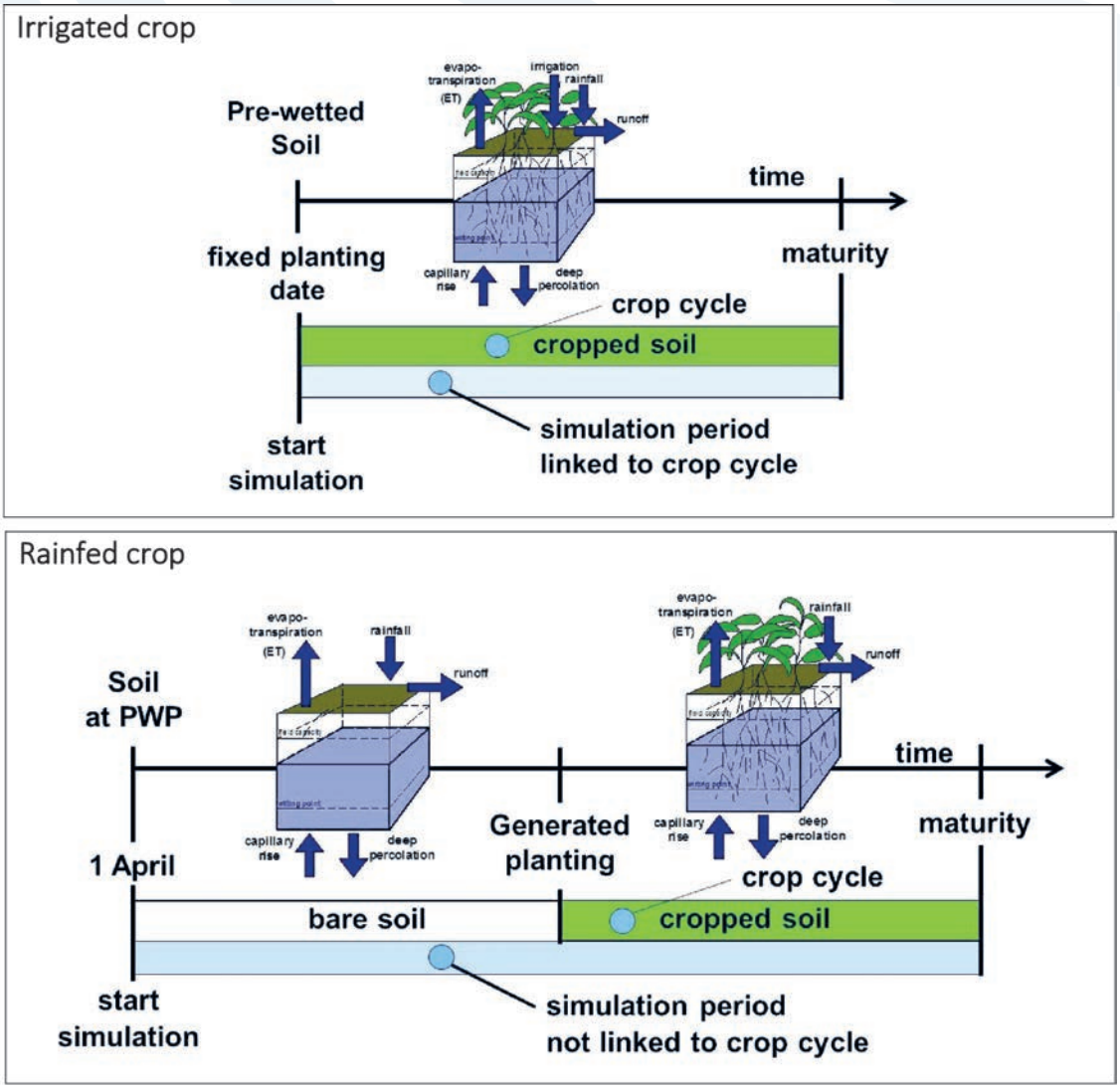
2.2.2 The simulation period and initial conditions

The simulation period for irrigated crops is linked to the crop cycle, and thus it was set to start in each year at the fixed planting date (See Table 7) and to end at crop maturity. A pre-wetted top soil was assumed at the start of the simulation period (See Figure 11) resulting from pre-irrigation and/or rainfall.

Since rainfed crops should be planted/sown in soil that has been sufficiently rendered wet by rain, the planting/sowing date varies annually. The dates for the simulation were generated at the onset of the wet season, based on a rainfall criterion (See Table 8). Since the water content in the soil profile at the time of the planting/sowing is unknown, the simulation started well before the crop cycle on 1 April during the hot-dry season, with a soil profile at permanent wilting point. Between 1 April and the moment of planting/sowing, the water content in the soil profile was adjusted by the simulation process on a daily basis. Namely, it was

considered that the water content reduces due to soil evaporation and deep percolation, and it increases with the amount of rainfall that infiltrates the soil profile on a particular day. Considering this, the initial soil water content was generated at the moment of planting/sowing (See Figure 11).

Figure 11. | Simulation period and crop cycle for irrigated and rainfed crops. By starting the simulation with a bare soil at permanent wilting point (PWP) at 1 April, the soil water content at the start of the growing cycle of the rainfed crops can be obtained

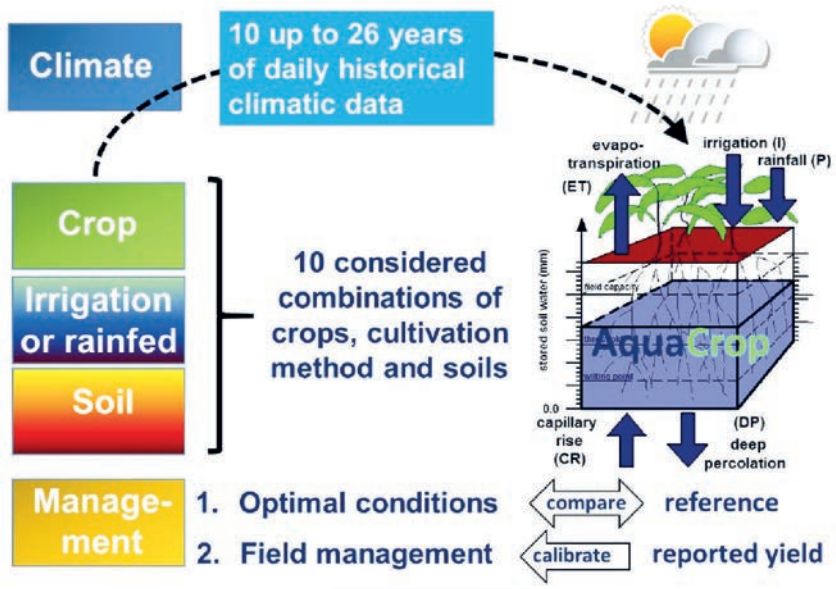


2.2.3 Overview of the simulation runs

a) Optimal management conditions

Optimal management conditions are found in a scenario with unlimited soil fertility and the absence of weed infestation. Based on these conditions, simulations were done to calculate the maximum potential yields (See Figure 12) and compare them with the reference yields reported in Table 6. The simulated crop yields in this set of runs provide information on the maximum yields that can be expected in the region in the absence of soil water and soil fertility stress for irrigated crops, and in the absence of soil fertility stress for rainfed crops.

Figure 12. | Overview of simulation runs for the current climatic conditions



Simulation runs were also used to calculate the net irrigation requirement (Inet) for the irrigated crops. Running simulations to estimate Inet guarantees that the soil is well-watered during the season. In AquaCrop, the net irrigation requirement is determined by the soil water content in the root zone above a specific threshold (i.e. the acceptable root zone depletion). The threshold was selected based on the soil water content at which the leaf expansion growth of the crop starts to be affected by water stress. The determined Inet does not consider the extra amount of water that has to be applied to the field to account for conveyance losses or uneven distribution of irrigation water on the field.

b) Actual management conditions

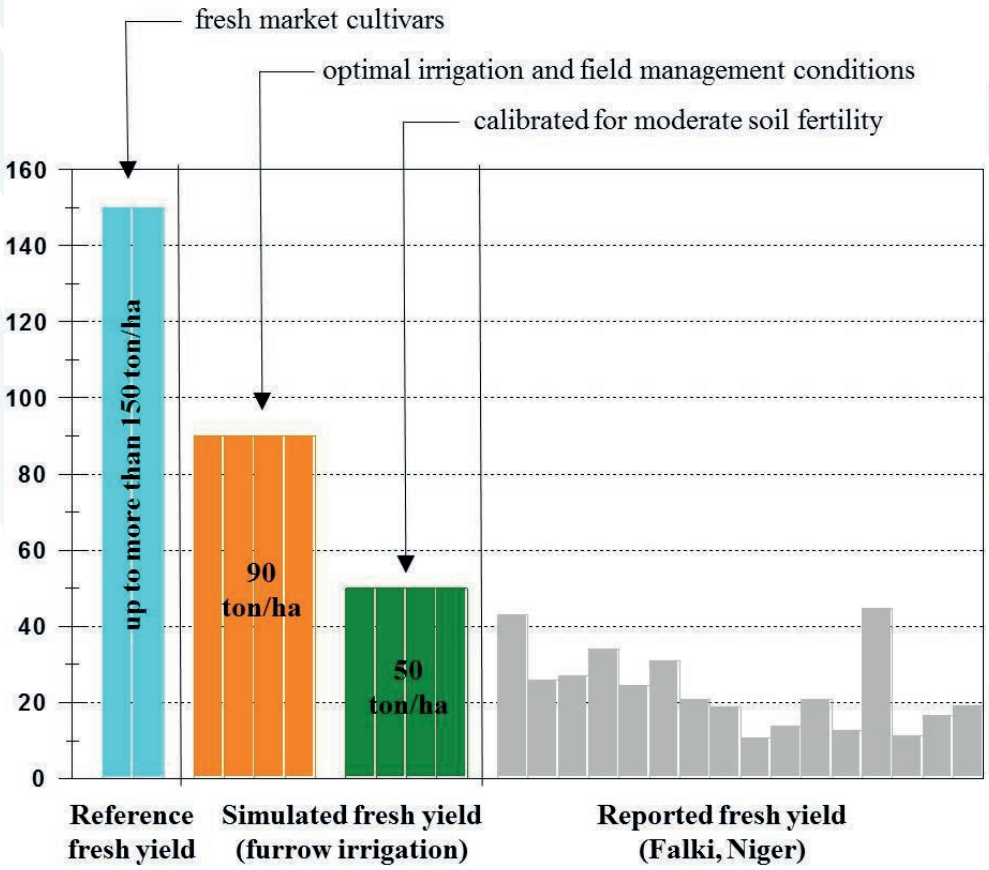
Simulations were used to calculate the yield that is obtained under actual irrigation and field management conditions (See Figure 12). Simulations for irrigated crops used the appropriate irrigation schedule as presented in Table 10, while for rainfed crops, rainfed conditions were considered. This set of runs was used to calibrate the field management practices that matched the simulated crop yield with that of the maximum reported yield for each of the irrigated and rainfed crops (See Table 11).

2.2.4 Simulation results for current climatic conditions

Figures 13 to 18 present the results of the reference yield, the simulated yield-assuming optimal and actual management conditions, and the reported yields for irrigated tomato, rice and maize and for rainfed rice, maize and sorghum. By comparing the simulation results under actual management conditions with the results obtained under optimal conditions, we were able to formulate recommendations for the soil fertility management practices that might improve actual crop yields (See Annex 6). Annex 6 also includes an analysis of the net irrigation requirements and desired planting/sowing dates.

2.2.4.1 Reference, simulated and reported yields for irrigated tomato

Figure 13. | Reference yield, average simulated yield under optimal (maximum yield) and moderate (calibrated yield) field management, and reported fresh yield (2000-2015) for irrigated tomatoes

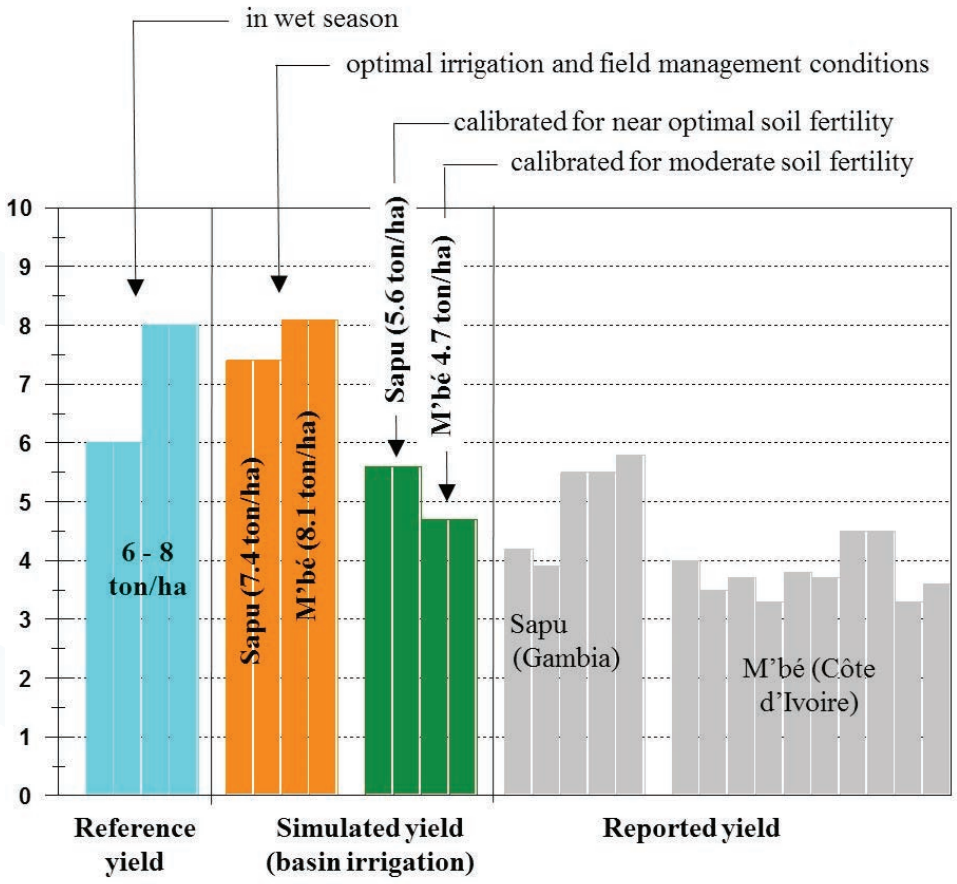


The average simulated yield (90 tonnes/ha) under optimal conditions for the 120-day high-yielding cultivar of tomato, is only 60 percent of the reference for fresh market cultivars (up to more than 150 tonnes/ha). By selecting tomato cultivars with a longer cycle length, higher yields can be obtained under irrigation.

Simulations with moderate soil fertility and a very good weed management regime are likely to give good indicative values for the reported yield currently obtained in the region for the 120-day high yield tomato variety.

2.2.4.2 Reference, simulated and reported yields for irrigated rice

Figure 14. | Reference yield, average simulated yield under optimal (maximum yield) and near optimal to moderate (calibrated yield) field management, and reported yield in Sapu (Gambia) for 5 years in the period 1989-1998 and M'bé (Côte d'Ivoire) for the period 2008-2017 for irrigated rice

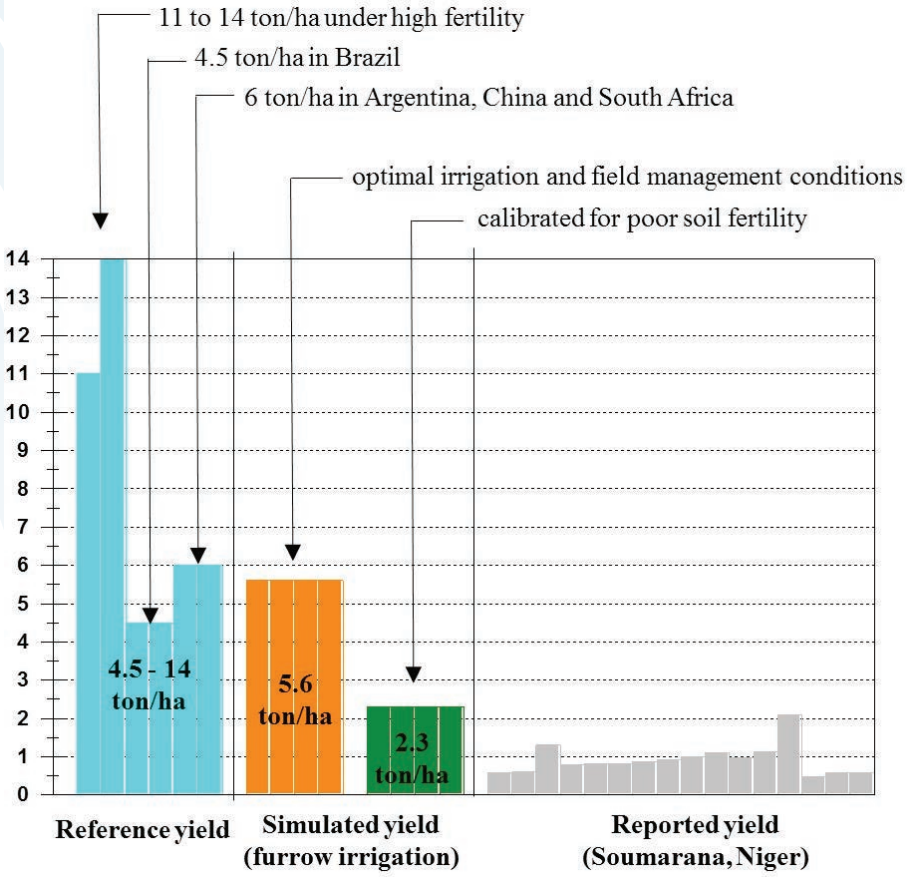


The average simulated yield (8 tonnes/ha) under optimal conditions for the 120-day high-yield variety corresponds with the reference yield (See Table 6) for flooded rice during the wet season.

Simulations with the 120-day high yielding variety, with near optimal (Sapu, the Gambia) and moderate (M'bé, Côte d'Ivoire) fertilizer applications and very good weed management practices are likely to give good indicative values for the yield of flooded rice that is currently obtained in the region.

2.2.4.3 Reference, simulated and reported yields for irrigated maize

Figure 15. | Reference yield, average simulated yield under optimal (maximum yield) and poor (calibrated yield) field management, and reported yield (2008 – 2017) in Soumarana (Niger) for irrigated maize

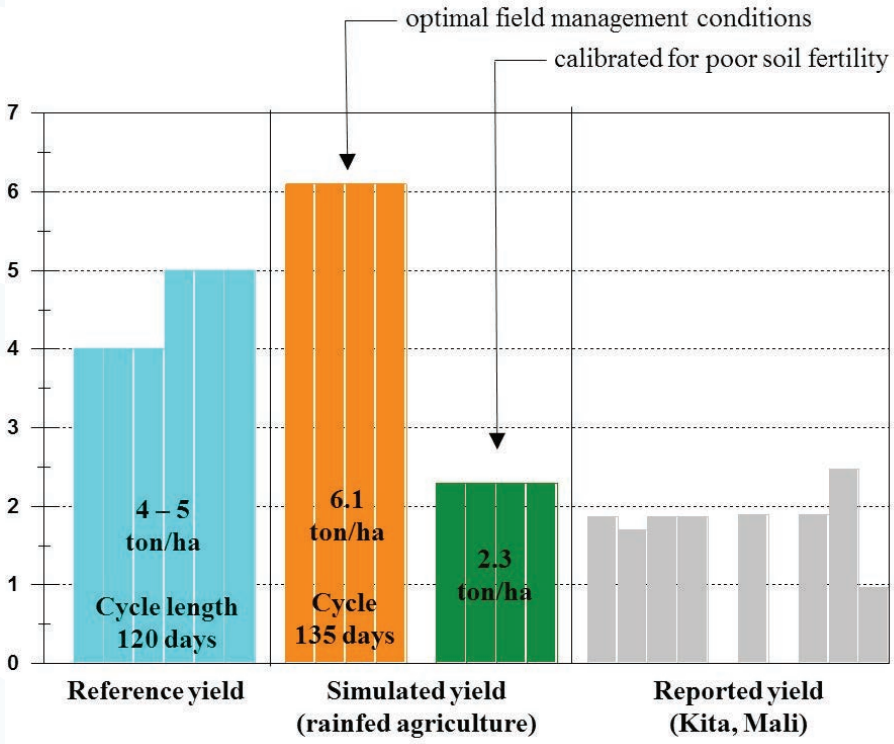


The average simulated yield for the 90-day landrace variety of maize under optimal conditions corresponds with the reported reference yield in most countries. However, it is significantly below the maximum yield that can be obtained with the use of high yielding varieties (See Table 6). Replacing the landrace variety with higher performing crop varieties, could double the yield.

Simulations for the 90-day landrace variety of maize with poor soil fertility and a very good weed management regime are likely to give good indicative values for the yield of irrigated maize that is currently obtained in the region.

2.2.4.4 Reference, simulated and reported yields for rainfed rice

Figure 16. | Reference yield, average simulated yield under optimal (maximum yield) and poor (calibrated yield) field management, and reported yield (2008-2017) in Kita (Mali) for rainfed rice

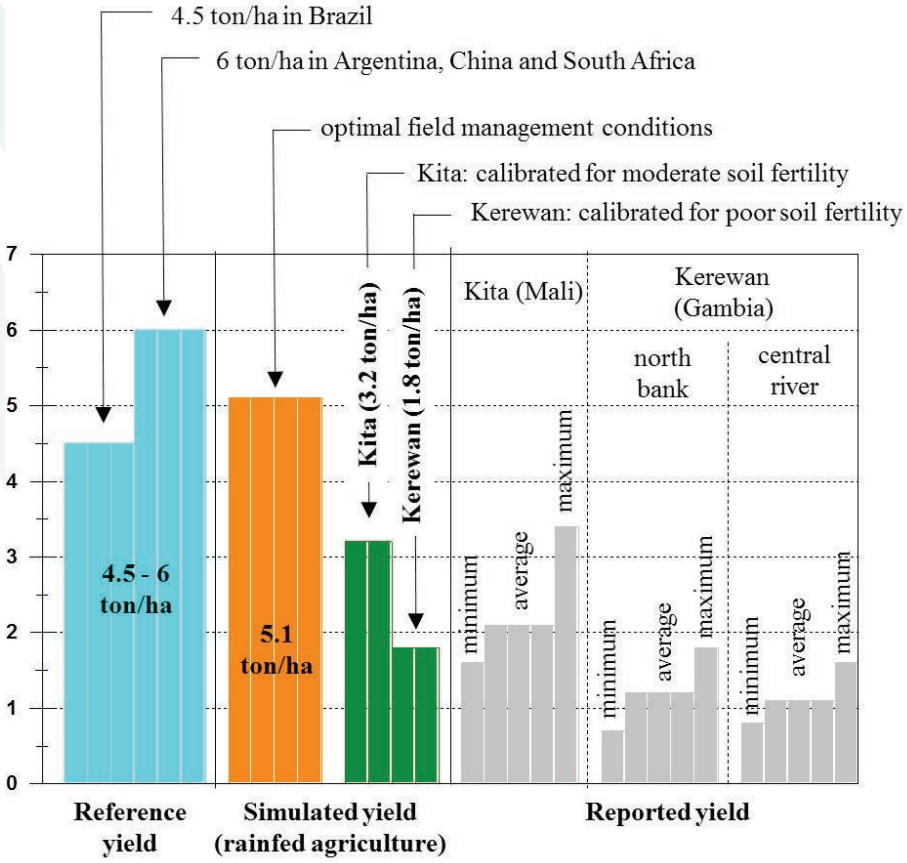


The average simulated yield under rainfed agriculture for a 135-day inbred rice cultivar, under optimal field management, is in line with the reference yield (See Table 6), which corresponds to the 120-day rice cultivar. In wet years, a maximum of 7 tonnes/ha was obtained. while in drier years the crop yield was restricted to 4 tonnes/ha.

Simulations for the 135-day inbred rice cultivar, with poor fertilizer applications and moderate management, are likely to give good indicative values for the yield of rainfed rice that is currently obtained in the region (See grey bars in Figure 16).

2.2.4.5 Reference, simulated and reported yields for rainfed maize

Figure 17. | Reference yield, average simulated yield under optimal (maximum yield) and moderate to poor (calibrated yield) field management, and reported yield in Kita (Mali) in the 2008-2017 period and Kerewan (Gambia) in the 1990-2015 period for rainfed maize

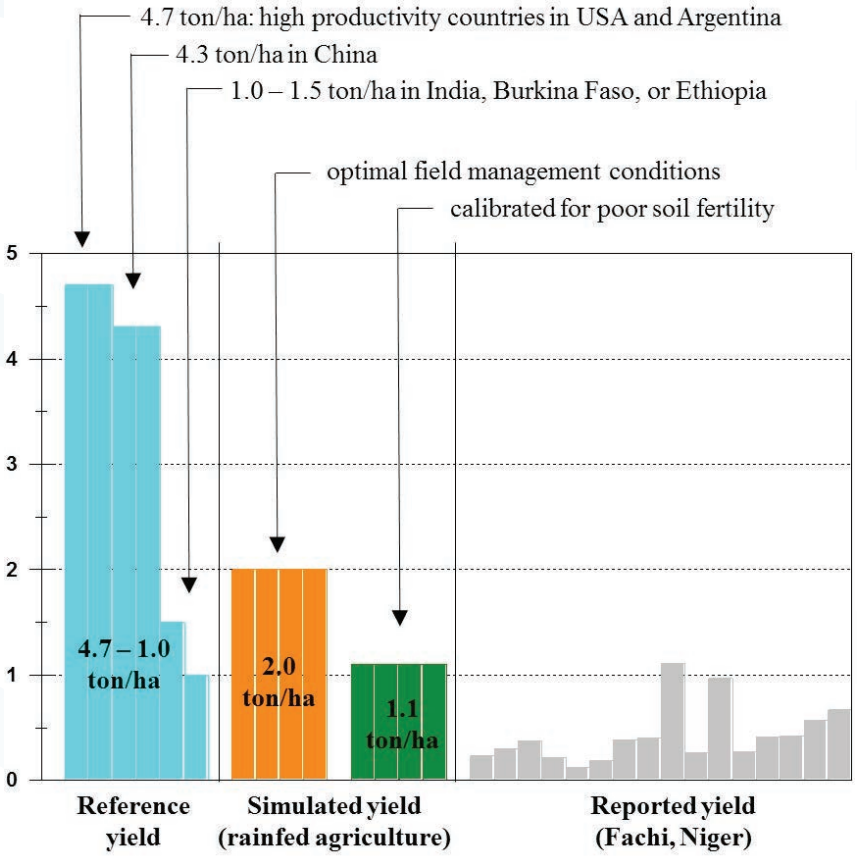


The average simulated yield of the 90-day landrace maize cultivar under optimal conditions corresponds to the reported reference yield in most countries (See Table 6). The length of the growth season of 137 days in Kita (Mali) and of 119 days in Kerewan (the Gambia) is suitable for the cultivation of a 90-day maize cultivar.

Simulations with moderate to poor fertilizer applications and a very good to moderate management regime are likely to give good indicative values for the yield of the 90-day landrace maize cultivar that is currently cultivated under rainfed agriculture in the region.

2.2.4.6 Reference, simulated and reported yields for rainfed sorghum

Figure 18. | Reference yield, average simulated yield under optimal (maximum yield) and poor (calibrated yield) field management, and reported yield (2000-2015) in Fachi (Niger) for rainfed sorghum



The average simulated yield of the 90-day landrace sorghum cultivar under optimal conditions is high when compared to reference yields in India, Burkina Faso and Ethiopia, but less than half of the reference yields in countries using highly productive cultivars. Given the low rainfall, the landrace cultivar is a better option then high yielding cultivars. The wet season is too short for the 90-day sorghum cultivar. The soil water stress affecting the crop yield was high (up to 51 percent) and the variation of the yield over the years is very high (88 percent).

Simulations with poor fertilizer application and moderate management are likely to give good indicative values for the yield of the 90-day landrace sorghum cultivar that is currently obtained in the region.

2.3 Considerations with respect to climate change

2.3.1 Effect of climate change on crop production

The increase in atmospheric CO_2 concentration ($[CO_2]$) should be borne in mind when simulating future crop yields. The effect of elevated $[CO_2]$ on crop production is being studied around the world in FACE (Free-Air CO_2 Enrichment)[11] experiments. These experiments are conducted in control and experimental crop

[11] Free-Air Carbon dioxide Enrichment (FACE) is an experimental method that raises the concentration of CO_2 in a specified area and allows researchers to measure the response in plant growth.

fields. In the experimental fields, CO_2 is administered through pipes with the holes facing the plot to keep the [CO_2] relatively uniform across the experimental area. The effect of elevated [CO_2] on crops is studied using field data from plots with and without enriched CO_2. The results show a robust response of biomass water productivity (WP) to elevated [CO_2] for C3 crops (i.e. tomato and rice). The overall transpiration response to elevated [CO_2] is relatively small but significant.

When running a simulation for future climatic conditions, the effect of increased [CO_2] is considered by adjusting the crop biomass WP in the simulations run in AquaCrop (See Table 13). The adjustment considers the atmospheric composition for that year and the crop's responsiveness with reference to the baseline period (1986-2005). Because biomass production and crop yield is proportional to WP, the total effect of CO_2 fertilization on crop production is positive as long as soil fertility does not limit the extra production of biomass (See Table 14).

Table 13. | Adjustment of the biomass water productivity (WP) for various emission scenarios (RCP) and future time periods, considering the atmospheric composition for that year and crop type, with reference to the baseline period (1986 – 2005)

Emission scenario	Baseline	RCP4.5	RCP4.5	RCP8.5	RCP8.5
20-year period	1986 – 2005	Horizon 2030 2021 – 2040	Horizon 2050 2041 – 2060	Horizon 2030 2021 – 2040	Horizon 2050 2041 – 2060
Projected [CO_2]	362.55 ppm	436.65 ppm	487.20 ppm	451.85 ppm	545.40 ppm
Adjustment of WP in percentage (*)					
C3 crops: Tomato, Rice	reference	+ 16.2%	+ 22.5%	+ 18.4%	+ 25%
C4 crops: Maize, Sorghum	reference	+ 5.1%	+ 7.2%	+ 6.0%	+ 7.8%

(*) The performance under elevated CO_2 concentration is selected according to the results of the FACE experiments, which correspond with a sink term of 0 percent in AquaCrop.

Simulations of future crop yields also consider changes in the climate, which are triggered by a rise in [CO_2]. The expected increase in global air surface temperature during thetwenty-first century is likely to expand the evaporating power of the atmosphere (i.e. the reference evapotranspiration). The amount and patterns of rainfall are also likely to be altered, together with a probable increase in frequency and intensity of extreme weather events. It is expected that greater water stress will occur in several regions as a result of higher air temperatures and ETo and of altered rainfall patterns. Hence, the effect of changes under altered weather conditions (i.e. air temperature, rainfall and ETo) on crop production is expected to be negative (See Table 14).

Table 14. | Effect of climate change on crop production

Climatic parameter	Effect on crop production
Increase of atmospheric CO_2 concentration	positive effect (due to CO_2 fertilization)
	If soil fertility and water are not limiting factors
Altered weather conditions: increase in air temperature increase in evapotranspiration altered and less predictable rainfall patterns and more extreme weather events (droughts and floods)	most likely negative effect (due to more water stress)
The combined effect of CO_2 fertilization and altered weather conditions	positive or negative depends largely on the irrigation and soil fertility management
	Studied with AquaCrop

The combined effect of CO_2 fertilization and altered weather conditions should be considered when studying the impact of climate change on crop production. This is typically done with the help of crop models such as AquaCrop. Whether the impact of climate change on crop production is positive or negative largely depends on irrigation and soil fertility management (See Table 14).

2.3.2 Simulations with unchanged soil fertility

In AquaCrop, soil fertility stress is expressed as a function of $B_{rel,}$ which is the relative biomass production (with reference to the maximum biomass production) that can be achieved given the soil fertility and in the absence of any other stress (percent change).

B_{rel} values calibrated for current climatic conditions are expressed with reference to the maximum biomass production (Bmax) of the baseline period (1986-2005). For future climatic conditions with unchanged soil fertility, the B_{rel} values decrease to account for the increase in the reference (Bmax) resulting from heightened water productivity (WP) due to CO_2 fertilization (See Figure 19). This means that under future climate conditions, B_{rel} decreases (the soil fertility stress increases) with higher CO_2 concentration if soil fertility is not adjusted.

For the simulation of actual crop production (limited by soil fertility) under current climate conditions, crop responsiveness to field management was calibrated, considering current field management strategies. The calibration consisted in reducing the soil fertility level from optimal to near optimal (80 percent B_{rel}), moderate (60 percent B_{rel}) or even poor (40 percent B_{rel}), depending on the local situation (See Table 11).

The reduction of B_{rel} for various increases in WP is presented in Figure 20. In the field management files, B_{rel} was further adjusted to consider the simulated gradual decrease in crop transpiration to maximum 5 percent at a [CO_2] of 550 ppm. An additional adjustment to consider the potential initial increase in photosynthetic nitrogen use efficiency (PNUE) was not implemented, since this is relatively small and is expected to fade out as a result of acclimatization to future atmospheric CO_2. Moreover, this increase in efficiency is valid for nitrogen, but differs for other nutrients.

Figure 19. | Maximum (Bmax) and relative (B_{rel}) biomass production for moderate soil fertility (Brel = 60 percent of Bmax) under current and future climatic conditions, and the required adjustment for B_{rel} for unchanged soil fertility (illustrated for a Bmax of 10 tonnes/ha under current climate conditions.

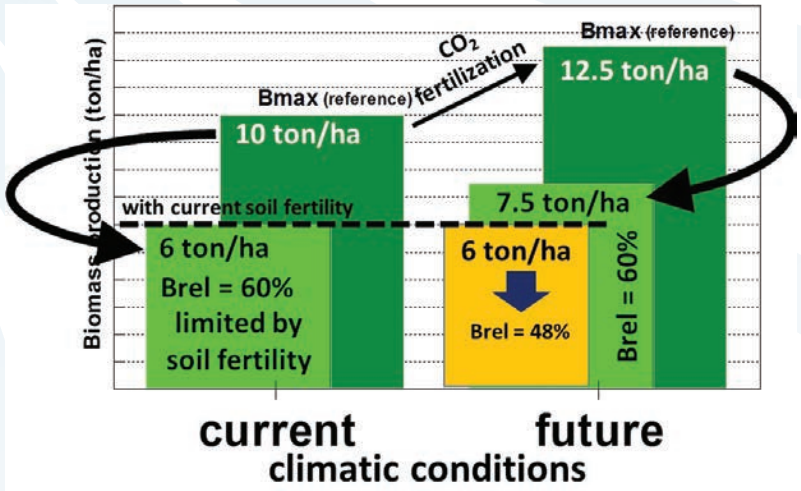
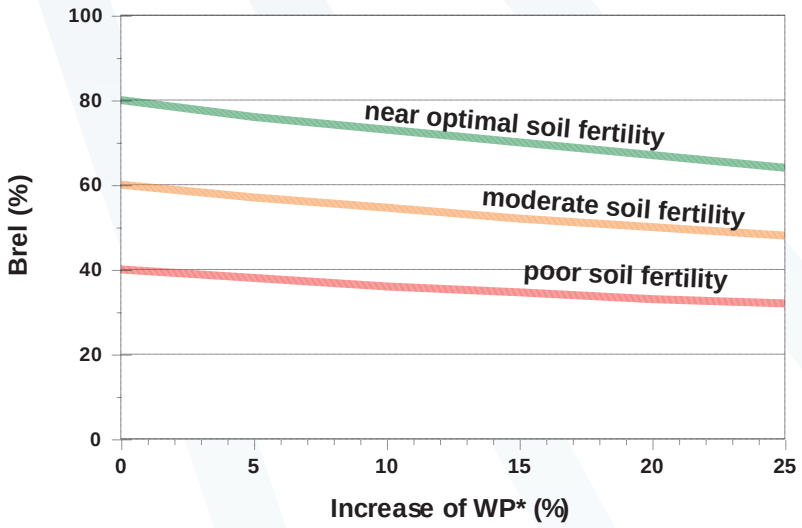


Figure 20. | Drop in relative maximum biomass production (B_{rel}) as a result of CO_2 fertilization under unchanged soil fertility management regimes for various increases of biomass WP



2.3.3 Study of the effect of adaptation strategies

Limited soil fertility and insufficient rain in the absence of irrigation are major factors affecting crop yield. To lessen the negative effects of climate change, the impact of adaptation strategies addressing these two major constraints have also been studied.

2.3.3.1 Improved soil fertility

In the absence of water stresses, CO_2 fertilization will increase WP under future climatic conditions (See Table 13) and biomass production and crop yield will improve. However, the increase in production can only be realized if soil fertility increases.

The effect of improved fertilizer management was studied through simulations using relative biomass production (B_{rel}) calibrated for the current climatic conditions (See Table 11). B_{rel} is expressed as a percentage of the maximum biomass production (B_{max}) that can be obtained without water stresses. Since B_{max} is increasing under future climatic conditions as a result of CO_2 fertilization, the crop yield will also increase when simulated with current B_{rel} values calibrated for current climatic conditions (See Figure 19). To keep crop production at the current relative level (B_{rel}), soil fertility needs to increase (See Table 15). The required increase in soil fertility for future climatic conditions was obtained by considering the increase in WP (See Table 13) and the decrease in crop transpiration under elevated [CO_2].

Table 15. | Required increase in soil fertility to match the CO_2 fertilization in future climates, for various emission scenarios (RCP) and future time periods, considering the atmospheric composition for that year and crop type, with reference to the baseline period (1986-2005)

Emission scenario	Baseline	RCP4.5	RCP4.5	RCP8.5	RCP8.5
20-year period	1986 – 2005	Horizon 2030 2021 – 2040	Horizon 2050 2041 – 2060	Horizon 2030 2021 – 2040	Horizon 2050 2041 – 2060
Projected [CO_2]	362.55 ppm	436.65 ppm	487.20 ppm	451.85 ppm	545.40 ppm
Required increase of soil fertility to match the CO_2 fertilization					
C3 crops: Tomato, Rice	reference	+ 14.0%	+ 18.5%	+ 15.7%	+ 18.9%
C4 crops: Maize, Sorghum	reference	+ 3.2%	+ 3.7%	+ 3.6%	+ 2.6%

(*) The performance under elevated CO_2 concentration is selected according to the results of the FACE experiments, which correspond with a sink term of 0 percent in AquaCrop.

2.3.3.2 Complementary irrigation for rainfed crops

In this section, we examine the effect of irrigation applications during the flowering stage for rainfed crops.

Rainfed rice and maize: An analysis of the simulation results under current climatic conditions showed that the main reason for low crop yields is not explained by water stress but by limited soil fertility (See Figures A6.7, A6.8 and A6.9 in Annex 6). The current simulated yield with limited soil fertility is almost identical for the whole simulation period, and is independent of the amount and distribution of rainfall. Simulations using future climatic conditions (2021-2060) revealed that yields could be improved in a very few years with complementary irrigation. Therefore, irrigation for rainfed rice and maize cannot be considered as the main adaptation strategy, as long as the constraints related to limited soil fertility are not addressed.

Rainfed sorghum: The analysis of the simulation results for current climatic conditions showed that, in more than half of the years, the major constraint to achieving higher crop yields was water stress (See Figure A6.10 in Annex 6). Sorghum yields can only be increased if supplementary irrigation[12] is applied over an entire season, since complementary irrigation with 1 or 2 applications is insufficient to increase production. Moreover, given the low value of the crop, even when water is available, farmers are likely to give irrigation preference to higher value crops. Therefore, although the production of sorghum will significantly benefit from irrigation, this is not likely to succeed as an adaptation strategy since farmers in WCA do not tend to irrigate sorghum.

[12] Supplementary irrigation is the process of providing additional water to stabilize or increase yields under site conditions where a crop can normally be grown under direct rainfall, the additional water being insufficient to produce a crop. The concept consists in making up rainfall deficits during critical stages of the crops in order to increase yields.

2.4 Simulations for future climatic conditions

2.4.1 Climatic data input

In each climate station, climatic data were generated using the three best regional climate models (See Table 16). Using the resulting data, simulations were run for different timeframes divided in 20-year periods as follows:

i. the generated control period (1986-2005),

ii. the generated future climatic conditions for the horizon 2030 (2021-2040); and

iii. the generated future climatic conditions for the horizon 2050 (2041-2060).

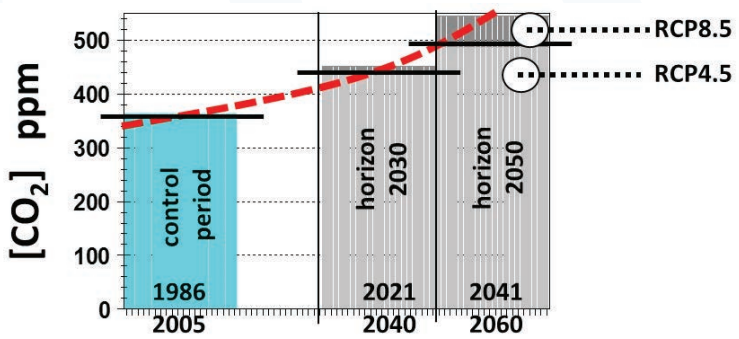
For the two future scenarios, simulations were run with climatic data that were generated by considering both a moderate scenario (RCP4.5) and a pessimistic scenario (RCP8.5).

Table 16. | Selected regional climate models for each climatic station

Climatic station	Regional climate model	Code	Nr
Zinder (Niger)	CNRM-CERFACS-CNRM-CM5	CNRM	M2
Tahoua (Niger)	MOHC-HadGEM2-ES	MOHC	M7
	MPI-M-MPI-ESM-LR	MPI	M8
Maradi (Niger)	CCCma-CanESM2	CCCma	M1
Kita (Mali)	CNRM-CERFACS-CNRM-CM5	CNRM	M2
	MPI-M-MPI-ESM-LR	MPI	M8
Yakro (Côte d'Ivoire)	CCCma-CanESM2	CCCma	M1
	CNRM-CERFACS-CNRM-CM5	CNRM	M2
	IPSL-IPSL-CM5A-MR	IPSL	M5
Sapu (Gambia)	CNRM-CERFACS-CNRM-CM5	CNRM	M2
Kerewan (Gambia)	MIROC-MIROC5	MIROC	M6
	MPI-M-MPI-ESM-LR	MPI	M8

Each of the 20-year simulation periods used a constant average CO_2 concentration to eliminate the effect of variations in [CO_2] throughout the 20-year periods under study (See Figure 21). To study the effect of altered weather conditions in future climates without CO_2 fertilization, simulations were also run with the average constant [CO_2] of the control period (362.55 ppm).

Figure 21. | Considered average CO_2 concentrations in the various time periods for the two scenarios



2.4.2 The simulation period and initial conditions

The simulation period for irrigated crops is linked to the crop cycle. The simulation started each year at the fixed planting date (See Table 7) and ended at crop maturity. A pre-wetted top soil resulting from pre-irrigation and/or rainfall was assumed at the start of the simulation period (See Figure 11).

Since the planting/sowing date for rainfed crops varies from year to year, the dates were based on rainfall at the onset of the wet season according to a rainfall criterion (See Table 8). As presented in Figure 11, since the soil water content is unknown at the time of planting/sowing, the simulation started well before the crop cycle on 1 April during the hot dry season, when it was known that the soil profile was at permanent wilting point.

2.4.3 Overview of the simulation runs

a) Current management conditions

The yield obtained with the current irrigation and field management conditions was simulated in the first set of runs (See Figure 22). Simulations for irrigated crops were run with the actual irrigation schedule as outlined in Table 10. For rainfed crops, rainfed conditions were considered. Simulations were run with the adjusted B_{rel} to consider the current fertilizer management approach in future climates (See Figure 20).

b) Improved soil fertility (adaptation strategy)

A second set of runs simulated the yield that is obtained under improved field management (See Figure 22). The increase in soil fertility needed to keep crop production at the current relative level (B_{rel}) is presented in Table 15.

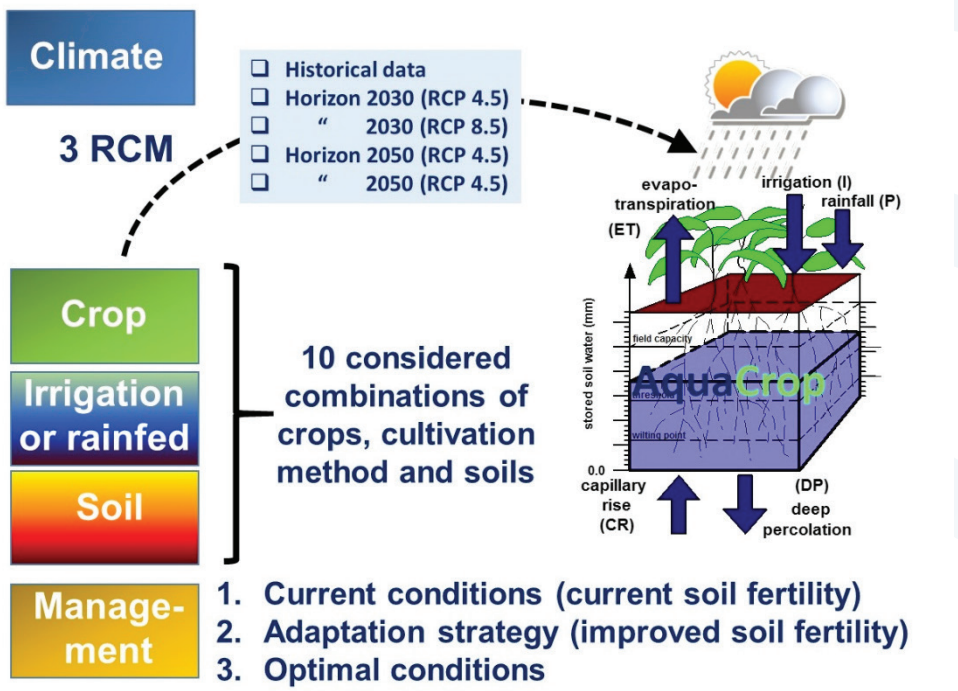
c) Optimal management conditions

A third set of runs simulated the maximum yield that can be obtained under future climatic conditions (See Figure 22). Optimal field management was assumed (unlimited soil fertility and no weed infestation). In addition, the net irrigation requirement for the irrigated crops was calculated based on the amount of water that would keep the root zone well-watered. The crop yield resulting from these simulations provides information on the maximum yield that can be expected in the region in the absence of soil water and soil fertility stress for irrigated crops, and in the absence of soil fertility stress for rainfed crops.

d) Number of simulation runs

For each of the ten combinations of crops, cultivation methods and soil types under study, simulations were run with climatic data under 3 different regional models (See Table 16) and for the different time horizons and scenarios (requiring 9 different CO_2 concentrations) under current, improved and optimal management conditions. For each of the 6 sites sown to irrigated crops (3 for tomatoes, 2 for rice and 1 for maize), and the 4 sites sown to rainfed crops (1 for rice, 2 for maize and 1 for sorghum), 81 simulations were run. Each simulation runs for a 20-year period.

Figure 22. | Overview of the simulation runs for future climatic conditions



2.4.4 Simulation results for future climatic conditions

a) Relative change in crop yield

- **Results and discussion**

Crop yields were simulated with the climatic data generated by each of three selected regional climate models (RCM) in the two-time horizons (2030 and 2050) and for two climate change scenarios (RCP4.5: moderate, and RCP8.5: pessimistic). The results were presented in boxplots as relative changes in crop yield with reference to the crop yield under the current management conditions simulated with the generated climatic data for the control period (1986-2005). Each of the three selected RCM has its own boxplot and reference[13].

The production of sorghum was already low under current climatic conditions. A yield of more than 1 tonne/ha could only be reached in under half of the years simulated (See Figure A7.10 in Annex 7). The future climatic conditions seemed to only make things worse as simulations indicated that the cultivation of sorghum in the research site (Sahelian zone) might be no longer feasible.

Differences between the moderate (RCP4.5) and the pessimistic (RCP8.5) scenarios in both horizons are small, because both scenarios experience a similar increase in [CO_2] by 2050 (See Figure 21). The relative yield change is somewhat more pronounced for time horizon 2050 than for 2030, but the same trends are observed (See Figure 23).

In this study, performance under an elevated CO_2 concentration was simulated according to the results of the FACE experiments. This was a conservative selection, since the increase in biomass production as a result of the CO_2 fertilization effect is about half of what can be theoretically expected.

[13] A selection of boxplots is presented in Annex 6. The averages (medians of the boxplots) of the three models for each management condition and for the two scenarios under study are summarized in Figure 23 for time horizons 2030 and 2050.

The relative yield change under current management conditions without considering the CO_2 fertilization effect (-CO_2), has no physical meaning. Nevertheless, the results are presented to highlight the beneficial effect of the CO_2 fertilization (+CO_2) which softens the negative effect of the increase in air temperate and ETo, and creates a possible altered rainfall pattern (See Table 14). For C3 crops, the relative yield decline without CO_2 fertilization is more than double the decline when the effect is considered. In the case of maize (a C4 crop), the effect is about 50 percent larger.

By not altering the current field management scenario (current +CO_2), the yield is expected to decline from 5 to 20 percent (See Figure 23) as a result of a decrease in soil fertility. In a future scenario with climate change, soil fertility needs to increase in order for the crops to benefit from CO_2 fertilization. By improving soil fertility in the fields of C3 crops (tomato and rice) from 15 to 20 percent (See Table 15), the relative yield might increase by about 8 percent (See Figure 23). Since C4 crops (maize and sorghum) hardly profit from the CO_2 fertilization effect, the need for increased soil fertility is greatly reduced (less than 5 percent). However, the benefits obtained under this scenario are rather small, as the yield remains nearly 2 percent below the current level.

The important difference (up to 100 percent and more) in relative yield change between improved and the optimal field management practices (See Table 17) highlights a strong opportunity for improvement. For irrigated crops, actions to improve soil fertility should go hand in hand with irrigation management improvement (See Figure 24). For rainfed crops, supplementary irrigation, which requires only 30 to 50 percent of the irrigation requirement, is recommended when soil fertility improves. As such, the crops can fully benefit from CO_2 fertilization under future climatic conditions.

Figure 23. | Average of the two scenarios (RCP) in terms of relative change in crop yield for the actual (red bars) and improved (green bars) management conditions, for time horizon 2030 (light colours) and 2050 (dark colours) in all sites for irrigated tomatoes, rice and maize, and for rainfed rice and maize

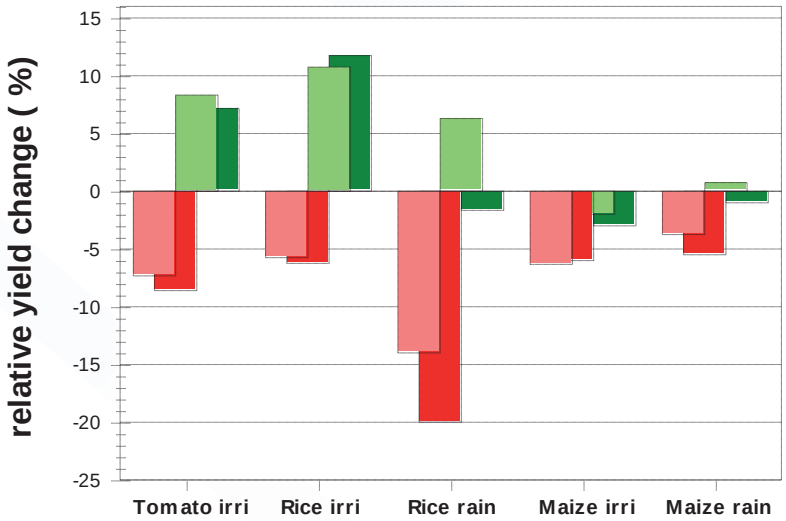
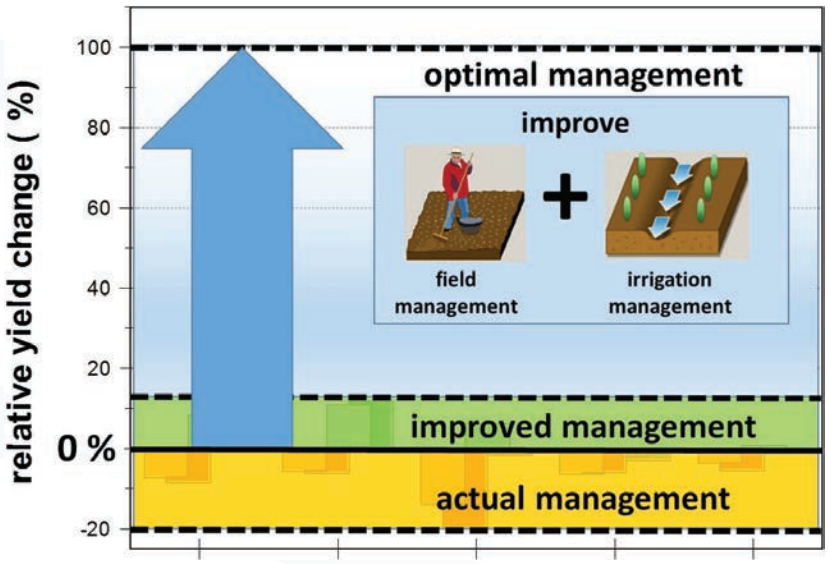


Table 17. | Average relative yield change (as a percentage) with reference to the control period (1986 – 2005) under various management conditions: current management conditions (without (-CO_2) and with (+CO_2) the CO_2 fertilization), Improved soil fertility and optimal management conditions for the two scenarios (RCP4.5 and 8.5)

Station	Management condition							
	Without adaptation		Improved	Optimal	Without adaptation		Improved	Optimal
	-CO_2	+CO_2			-CO_2	+CO_2		
	Moderate scenario (RCP4.5)				Pessimistic scenario (RCP8.5)			
Time horizon 2030 (period 2021 – 2040)								
Irrigated tomato								
Zinder	(- 21)	- 9	+ 7	+ 83	(- 22)	- 10	+ 7	+ 84
Kita	(- 15)	- 4	+ 9	+ 139	(- 14)	0	+ 11	+ 143
Yakro	(- 21)	- 10	+ 8	+ 85	(- 23)	- 11	+ 8	+ 85
Irrigated rice								
Yakro	(- 18)	- 7	+ 9	+ 90	(- 19)	- 6	+ 11	+ 92
Sapu	(- 17)	- 5	+ 11	+ 45	(- 17)	- 5	+ 12	+ 47
Irrigated maize								
Maradi	(- 10)	- 6	- 2	+ 142	(- 8)	- 6	- 3	+ 140
Rainfed rice								
Kita	(- 25)	- 14	+ 6	+ 182	(- 31)	- 20	- 2	+ 170
Rainfed maize								
Kita	(- 6)	- 3	+ 1	+ 70	(- 5)	- 5	+ 2	+ 72
Kerewan	(- 7)	- 4	0	+ 198	(- 6)	- 3	0	+ 195
Rainfed sorghum								
Tahoua	(- 74)	- 78	- 70	- 59	(-62)	- 57	- 22	- 2
Time horizon 2050 (period 2041 – 2060)								
Irrigated tomato								
Zinder	(- 25)	- 11	+ 8	+ 86	(- 27)	- 13	+ 5	+ 79
Kita	(- 17)	+ 4	+ 14	+ 148	(- 20)	- 2	+ 11	+ 140
Yakro	(- 23)	- 9	+ 10	+ 89	(- 26)	- 13	+ 6	+ 80
Irrigated rice								
Yakro	(- 22)	- 7	+ 13	+ 95	(- 23)	- 7	+ 10	+ 92
Sapu	(- 20)	+ 13	+ 13	+ 48	(- 22)	- 6	+ 11	+ 46
Irrigated maize								
Maradi	(- 12)	- 8	- 3	+ 139	(- 12)	- 10	- 8	+ 126
Rainfed rice								
Kita	(- 26)	- 12	+ 10	+ 192	(- 29)	- 14	+ 10	+ 165
Rainfed maize								
Kita	(- 8)	- 5	0	+ 65	(- 7)	- 4	- 1	+ 65
Kerewan	(- 10)	- 7	0	+ 195	(- 7)	- 6	- 3	+ 185
Rainfed sorghum								
Tahoua	(- 73)	- 62	- 53	- 45	(- 78)	- 73	- 65	- 63

Figure 24. | Requirements for increase of crop production in future climatic conditions



- **Limitations of the yield analysis**

The relative change in crop yield, as simulated by AquaCrop, focuses on the effect of irrigation and field management conditions. However, there are a number of aspects that have not been simulated due to insufficient knowledge and/or available data:

i. AquaCrop does not simulate losses due to pest and diseases, losses linked with particular harvesting methods, transportation and storage. Losses due to pest and diseases might increase under future climatic conditions, and thus, increase the relative change in crop yield.

ii. AquaCrop considers only the effect of heat stress on pollination. Other responses to heat stress are not considered in AquaCrop.

iii. As a result of the increased occurrence of extreme rain events and long dry spells, land degradation due to surface run-off of excess rain and wind erosion might become more pronounced in the future. In addition, extreme rain events might severely damage crops, resulting in a strong decline or complete loss of crop yield. These aspects were not considered in the simulations.

iv. The increased demographics pressure in West Africa might also result in an overexploitation of land for agriculture, fostering land degradation.

v. Simulations were done using available information on current cultivars. Other cultivars (e.g. that differ in terms of crop cycle length, stress tolerance, HI) or other crops might be more suited.

vi. Acclimatization, in which the current cultivars adjust to the changes in the climate conditions, are not considered.

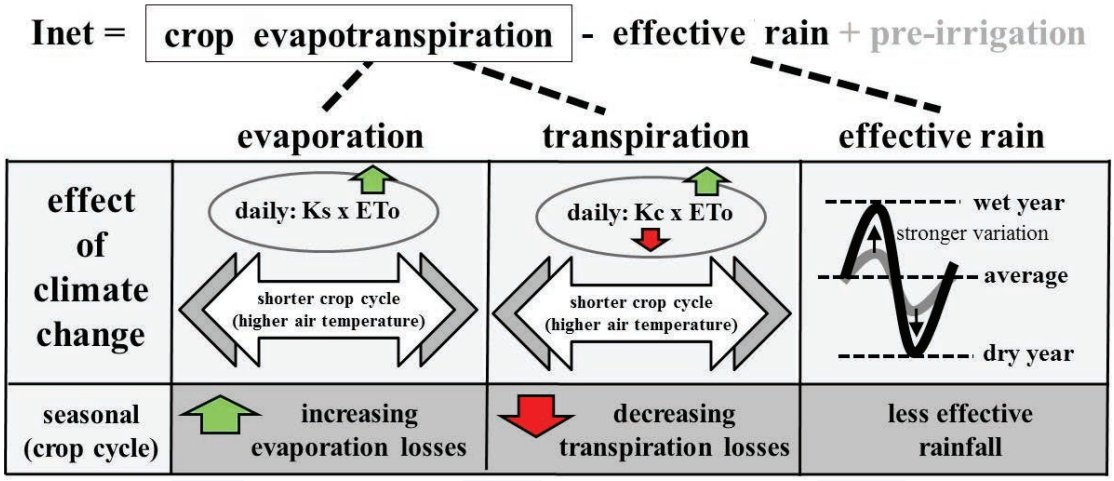
vii. Mixed cropping/intercropping has not been simulated. Yields in mixed cropping systems might be affected by the presence of the other crops (e.g. through effects on evapotranspiration, soil fertility).

b) Relative change in net irrigation requirement

Given unlimited soil fertility, irrigated crops will fully benefit from increased CO_2 concentration in future climate conditions due to the rise in biomass WP. The CO_2 fertilization results in higher crop yields (particularly for C3 crops) when optimal management conditions can be achieved. A rise in crop production, however, does not require a rise in net irrigation requirement (Inet), since Inet is determined by the difference between the outgoing (crop evapotranspiration) and incoming (effective rain) water fluxes at the boundary of the root zone.

To determine the net irrigation requirement, an optimal field management scenario (unlimited soil fertility and no weed infestation) was assumed for this study. Although the ETo increases in future climates, the daily crop transpiration will hardly differ from presently, since the crop coefficient (Kc) decreases as a result of a partial closure of the stomata when [CO_2] increases. Since the crop cycle of the current cultivars is expected to shorten slightly, the seasonal crop transpiration (Tr) will also decline, since in future climates, fewer calendar days are required to reach crop maturity with the required growing degree days (See Figure 25).

Figure 25. | The effect of climate change on the reference evapotranspiration (ETo), crop coefficient (Kc), length of the crop cycle, and seasonal evaporation, transpiration and effective rain



When crops are irrigated during the dry season, evaporation losses are small and rainfall is negligible. The future net irrigation requirement (Inet) will slightly decline, corresponding with a minor decline in seasonal crop transpiration (See Figure 25). This was found to be the case for irrigated tomato and maize, which are cultivated in the cold dry season in the Niger, Mali, Côte d'Ivoire and the Gambia. The simulations revealed that Inet calculated for optimal management conditions in the time horizons 2030 and 2050 are indeed smaller than Inet calculated for the control period (See Figure 26).

When crops are irrigated during the wet season (as is the case for rice in this study), changes in the total amount and distribution of rainfall set into motion changes in Inet. Although the relative changes in seasonal rainfall with reference to the control period are rather small in the two selected sites (See Table 18), the relative change in monthly rainfall during the irrigation season is much more important (ranging from 5 percent to 10 percent). The Inet is likely to increase in future climates as a result of less effective rainfall, since a drop in rainfall during one part of the season often has a greater effect on Inet than a similar increase

in rainfall during another part of the season (most likely resulting in more surface runoff and/or deep percolation). Hence, due to the stronger variation in rainfall in future climates, the average seasonal rainfall will likely become less effective and contributes less to a reduction of Inet (See Figure 25).

Figure 26. | Average for the two scenarios (RCP) of the relative change in the net irrigation requirement (Inet) for tomato (light green), maize (dark green) and for rice in Yakro (light blue) in the two-time horizons

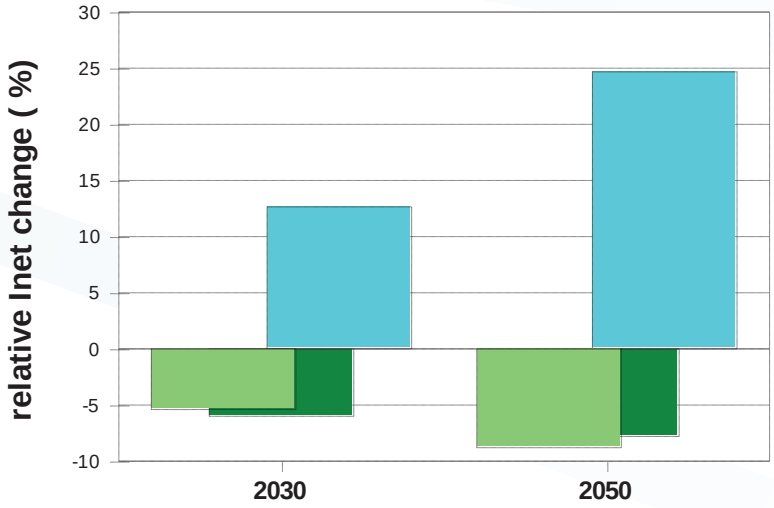


Table 18. | The average (of the three regional climate models) in terms of relative change (%) in the length of the crop cycle, the seasonal reference evapotranspiration (ETo), crop transpiration (Tr), crop evapotranspiration (ETc), rainfall, and significant net irrigation requirement (Inet) for irrigated rice for the two scenarios (RCP) and during the two time horizons with reference to the control period (1986-2005)

Station	Time horizon 2030 (period 2021 – 2040)											
	Moderate scenario (RCP4.5)						Pessimistic scenario (RCP8.5)					
	Cycle	ETo	Tr	ETc	Rain	Inet	Cycle	ETo	Tr	ETc	Rain	Inet
Yakro	-3.9	3.6	-2.7	8.0	-1.2	12.0	-5.6	4.8	-4.5	9.0	1.9	13.3
Sapu	-2.9	3.3	-0.8	0.9	-1.7	-	-4.6	5.7	-1.9	1.6	0.4	-
	Time horizon 2050 (period 2041 – 2060)											
Yakro	-4.4	4.0	-2.7	8.5	0.9	23.0	-7.2	6.6	-6.4	10.2	-0.4	26.3
Sapu	-3.6	3.8	-1.3	-0.1	-2.3	-	-6.2	5.9	-4.6	1.5	3.1	-

Inet*: Relative change only calculated for significant Inet (Inet > 10 mm/year). For Sapu, no relative change for Inet could be computed, since Inet is too small in most of the years.

The contribution of soil evaporation to the determination of crop evapotranspiration (ETc) and Inet increases with rainfall. When crops are irrigated during the wet season, the seasonal crop transpiration (Tr) will decline in future climate scenarios, but the soil evaporation from the soil surface wetted by rainfall will increase due to the rise in ETo (See Figure 25). Since evaporation losses from standing water layers in basins are very important in flooded rice fields, the seasonal ETc does not decline and even increases in the selected sites under most scenarios (See Table 18).

The combined effect of increased ET_C and less effective rainfall, will cause the net irrigation requirement for rice to increase in the future climate scenarios (See Figure 26). Although the relative change of Inet is

significant during the wet season, the absolute amount of required irrigation water remains small, especially when compared to the net irrigation requirement in the dry season.

c) Relative change in planting/sowing dates for rainfed crops

The selected rainfall criteria for generating a planting/sowing date (See Table 8) are not suited to deriving appropriate planting/sowing dates for rainfed crops when using climatic data sets that have been derived from regional climatic models. Although the selected RCM are able to capture the seasonal rainfall cycle for the control period, the daily distribution within that cycle is not adequately precise for the computation of planting/sowing dates. Therefore, an eventual shifting of future planting/sowing dates, generated by a rainfall based criterion, cannot be ascertained.

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3. Climate resilience assessment of smallholder farmers

FAO's Self-evaluation and Holistic Assessment of climate Resilience for farmers and Pastoralists (SHARP) tool was selected for the study because it enables the collection of objective information from smallholders in a participatory manner, allowing the description of the prevailing socioeconomic and environmental conditions in rural households. Moreover, the tool also addresses the need to better understand and incorporate the concerns and interests of farmers related to climate resilience. The SHARP surveys help to assess the climate resilience levels of smallholders, as well as the practices currently used to respond and adapt to climate change. The tool also assists in the identification of community needs that could serve to foster implementation strategies and interventions to address such needs (For further information, see www.fao.org/in-action/sharp/en/).

This chapter presents the main results of the survey in the four pilot countries, clustered by the different categories of indicators and intervention areas.[15]

3.1 Findings

3.1.1 Socioeconomic characteristics

The baseline assessment covered a population of 691 households in 21 irrigation sites in Côte d'Ivoire, the Gambia, Mali and the Niger. The majority of respondents (83 percent) identified themselves as

[15] In-depth information can be found in the individual country reports available on the project website.

agropastoralists, i.e. possessing a mixed system of crops and animals. Agriculture is the main livelihood of 87 percent of the respondents and 30 percent of crops are produced on irrigated land.[16]

The purposes of production are oriented toward on-farm consumption (94 percent) and markets (67 percent). The main crops are grains (e.g. rice and maize), horticultural plants (e.g. onions, cabbage, tomato), and legumes and pulses (e.g. beans, chickpeas, peanuts). Irrigated crops are mostly produced for the purpose of sales.

Nineteen percent of the surveyed households were headed by women and 81 percent by men. Education levels remain low: only 12 percent of household members have completed primary school. At least one member of the 53 percent of households sampled has migrated in the past ten years (either seasonally or permanently). The combination of the education and migration variables clearly influences the level of human capital available in the household.

3.1.2 Access to local markets and financial resources

Smallholders in WCA have access to local markets, though it is intermittent. Farmers bring their agricultural produce to local markets either on foot (55 percent), by car or truck (51 percent), by animal (34 percent) or on bicycles (32 percent).

Family (25 percent), remittances (10 percent) and friends (10 percent) constitute the main sources of financial support that farmers have relied upon to cover unexpected expenses over the past five years. Microfinance institutions (4 percent), banks (1 percent) and cooperatives (6 percent) provide access to a minor share of financial resources. People usually save by purchasing livestock (32 percent) and keeping cash at home (28 percent); only 21 percent use financial institutions such as banks and saving structures (11 percent and 10 percent respectively).

These numbers suggest that people depend heavily on social networks to cope with unexpected financial shocks. Moreover, there appears to be scope to further develop the microfinance sector to lend and assist smallholders, not only during shocks but also to expand investment and saving options.

3.1.3 Water and irrigation

3.1.3.1 Access to water (households and agriculture) and water management

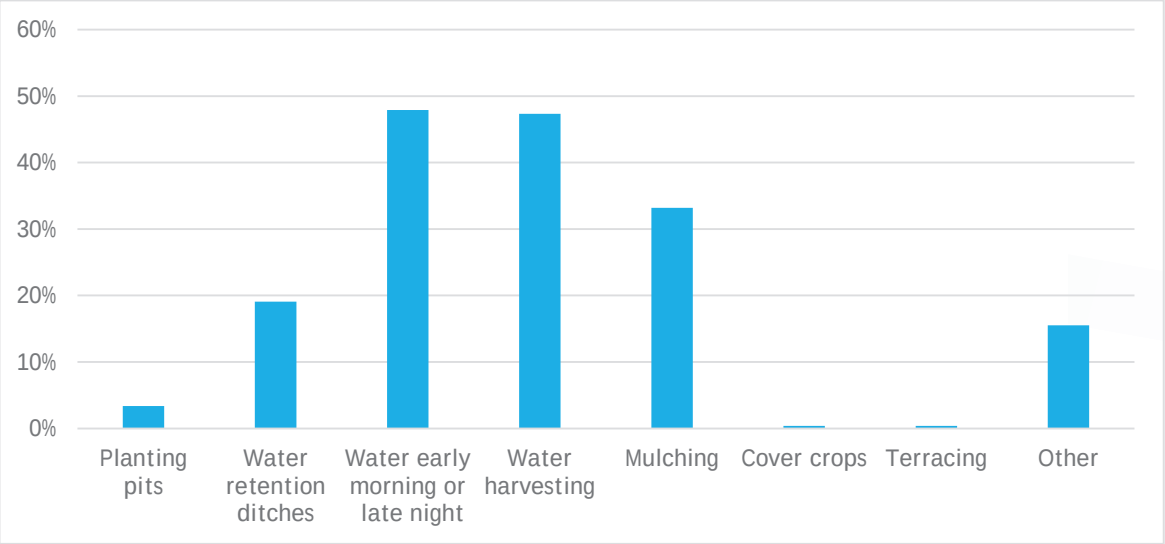
About 70 percent of the producers that were interviewed consider access and management of water to be very important for their household food security and income.

The main sources of water for irrigation are dams (26 percent), streams (20 percent) and runoff water (15 percent), however water supply is considered insufficient by 45 percent of households. Most of the respondents (67 percent) stated that there have been changes in water availability for crops over the past ten years as a result of variation in rainfall and/or temperature and 55 percent of respondents have taken adaptation actions at the field level to cope with these changes.

These adaptation actions include a number of management practices used by producers to conserve the quantity and quality of water such as watering in the early morning or late at night (48 percent), collecting water (47 percent), mulching (33 percent) and using water retention ditches (19 percent).

[16] The high percentage of people producing in under irrigated land is explained by the fact that project sites are irrigation zones.

Figure 27. | Water management practices used by WCA producers



Producers believe that the use of water management practices helps to improve crop production, however 43 percent do not consider their own practices to be adequate.

Most of the farmers mentioned that the quality of the water they have access is good for both human consumption and household needs (83 percent) and agriculture (i.e. 91 percent for animal consumption and 87 percent for irrigation).

3.1.3.2 Irrigation infrastructure

The majority of producers (84 percent) confirmed having an irrigation system in place. Inland valley bottoms (19 percent) and horticultural gardens (20 percent) are the most commonly-used systems. Tidal irrigation is also an important system in 32 percent of households, however it is only used in the Gambia.

Most of the irrigation systems are surface irrigation[16] is (57 percent), using buckets (69 percent), or basins (27 percent). The Californian systems[17] represent 35 percent of the irrigation systems used.

Groundwater extraction is mainly through traditional wells (54 percent), shallow modern wells (28 percent) and shallow and deep boreholes (28 percent and 25 percent respectively). Water intake takes place directly without infrastructure in 17 percent of the cases, especially for surface water. Various types of pumps are used to lift water: motor pumps are used by 39 percent of smallholders, solar pumps by 22 percent and manual pumps by 11 percent of producers. Water rotation is practiced by 15 percent of farmers, 84 percent of whom are satisfied with approach its operation. Only 19 percent of producers pay for irrigation water and/or to maintain an irrigation system.

In the last ten years, 54 percent of producers have changed their irrigation practices as result of climate change, but these have not been major changes. At the same time, 76 percent of farmers have either made large or complete changes to their irrigation infrastructure as a result of variation in rainfall and temperature.

[16] Surface irrigation systems are based on the principle of moving water over the land by simple gravity in order to moisten the soil.
[17] The Californian system consists in a network of PVC pipelines buried in the soil to deliver water from the source to the fields. These systems can reduce losses from infiltration and supply fields that are far from the pumping source or that have an irregular topography.

According to almost 70 percent of smallholders, irrigation contributes entirely to the income and food security of their households.

3.1.4 Soil quality and fertility management

Over the past five years, soil/land degradation has been observed by farmers in WCA. This includes soil fertility decline (53 percent), water and wind erosion (48 percent and 45 percent respectively), deforestation (43 percent) and the reduction of vegetative cover (43 percent).

The soil fertility in irrigated fields is not held to be suitable for growing crops by 73 percent of the surveyed farmers. In fact, only 29 percent of smallholders consider their land to be rich in organic matter. Farmers believe that soil and land fertility have an important impact on household food security and income.

A number of Practices and techniques are commonly used by 91 percent of smallholder farmers to prevent and/or reverse degradation while increasing the productivity of their crop lands. These include the incorporation of manure (74 percent) and crop rotation (57 percent) are the practices most commonly used by the respondents. Other land management practices are intercropping (37 percent), mulching and fallowing (both 31 percent), and minimum or zero tillage (21 percent).

Almost 60 percent of farmers used natural/organic fertilizers – mainly compost/ plant-based fertilizers (92 percent) and animal manure (99 percent) – during the last cropping season. At the same time, synthetic/ inorganic fertilizers were widely used by 77 percent of farmers, 83 percent of which examined the soil and plants first to see whether such fertilizers are needed.

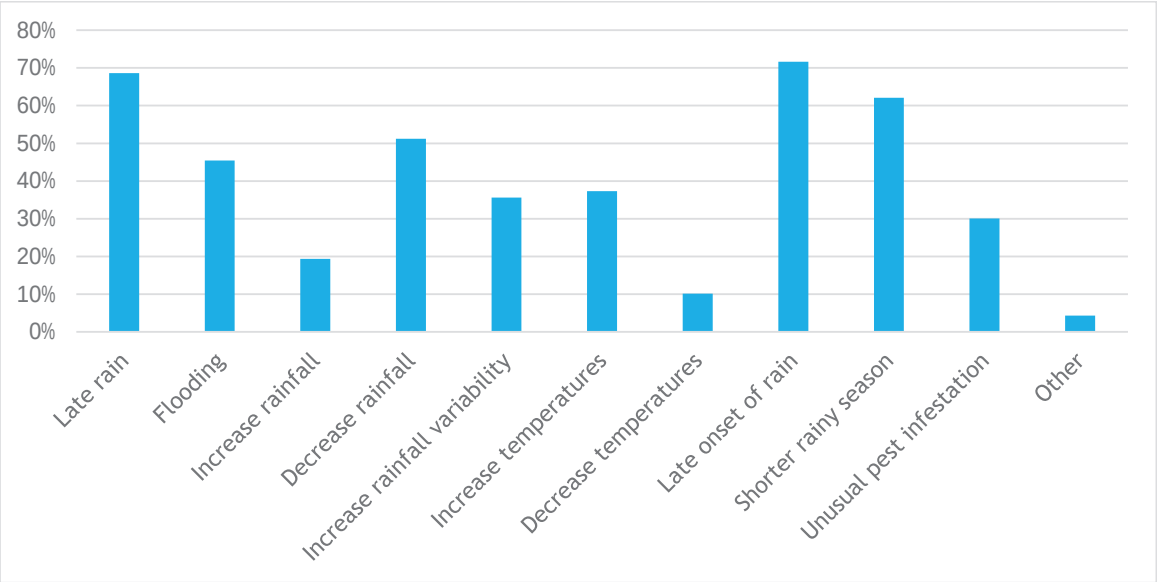
Organic and synthetic fertilizers are mostly sourced from shops or markets (52 percent), individual sellers (20 percent), extension services/agents (15 percent) and other sources (20 percent). On-farm production of organic fertilizers is rarely done by the assessed farmers (6 percent).

3.1.5 Climate variability, shocks and effects

Over the past last ten years, changes in climate have impacted agriculture and rural livelihoods in a significant way. Respondents noted that the late onset of rains (72 percent of interviewees), shorter rainy seasons (62 percent) and decrease in the amount of rainfall (51 percent) are noticeable effects of climate change. Floods (45 percent), increased temperatures (37 percent) and increased rainfall variability (36 percent) are other climate-related changes that have impacted smallholder farmers in the last decade.

As a result of climate variability and weather shocks, about 83 percent of respondents have faced crop failure, and thus a reduction in their farm incomes (77 percent of interviewees). Other impacts have been an increase in migration and participation in off-farm activities (22 percent), reduction in water availability for irrigation, drop in fodder yields, and larger expenditures on agricultural inputs (20 percent in each of the three scenarios).

Figure 28. | Main climate trends observed



3.1.6 Access to information on weather and cropping practices

About 80 percent of farmers use traditional knowledge, which enables them to predict weather events (e.g. traditional forecasters), while 61 percent have access to weather forecast services. Seventy-two percent of farmers have access to information on cropping practices, especially through radio (69 percent), extension agents (49 percent), other farmers (26 percent), field schools (21 percent) and television (20 percent). Other channels, such as newspapers and the internet, are rarely used to access information (by fewer than 10 percent of the farmers).

3.2 Resilience assessment

The resilience of farming communities was assessed using the SHARP tool.[18] This tool has four assessment areas: production, environment, social, and economic. Each assessment area is composed of a number of modules including questions that farmers can use to identify and assess their resilience. A specific module on irrigation was developed by the project to characterize the irrigation systems in the project sites and assess the importance of irrigation in the resilience of farmer communities. The four assessments areas are described in more detail below.

- Production: household, production types, crops, use of new varieties, crop losses, record-keeping and access to information on weather and cropping practices.
- Environment: water access, water conservation techniques and practices, water quality, irrigation infrastructure, field irrigation practices, land access, soil quality and land degradation, land management practices, farm equipment, energy sources, fertilizers and fertility management.
- Social: disturbances, group membership, trust and cooperation.

[18] For more details on the methodology, refer to the SHARP background document: www.fao.org/documents/card/en/c/a78ba721-9e03-4cfc-b04b-c89d1a332e54/

- Economic: access to markets, local farm inputs, financial support, information and communication technologies (ICT), main expenditures, income sources, non-farm income generating activities, and savings.

In each of the modules, resilience levels were classified on a scale from 0 to 20 points:

- Low resilience (from 0 to 7 points): Households/farm systems do not have the capacity to absorb shocks, and therefore they are not able to bounce back to their main characteristics and functions (e.g. productive capacity).
- Moderate resilience (from 8 to 12 points): Households/farm systems are able to absorb some shocks, however there is a need to further strengthen their capacity (e.g. through better practices, improved access to resources) to cope with climate-related effects.
- High resilience (from 13 to 20 points): Households/farm systems are able to absorb climatic and non-climatic shocks, cope with them and reorganize, keeping their main characteristics and functions.

Based on these classifications, the assessment determined that the average level of climate resilience among smallholders in the 21 irrigation sites was moderate at around 10.76 points (See Table 19). Interestingly, male-led households presented slightly higher resilience than households led by women. Male-headed households seem to have better access to information on cropping practices and weather forecasts, to ICTs and to local farm inputs. At the same time, female -headed households scored higher in areas related to the involvement of household members in farming activities as well as the use of fertility management practices.

Table 19. | Resilience levels by country and household head

Country	Respondents		Average Resilience (Academic + Adequacy)		
	Total	Weighted*	Total	Male-headed HH	Female-headed HH
Côte d'Ivoire	142	557	10.62	10.72	10.08
Gambia	271	467	10.87	10.92	10.72
Mali	90	178	10.70	10.64	10.80
Niger	188	950	10.83	10.90	9.91
Average	691	2 152	10.76	10.80	10.38

At the country level, the Gambia presents the highest climate resilience level at 10.87. Côte d'Ivoire - with 10.62 points – has the lowest resilience level. However, all four countries fall into the moderate category, and thus have need of resilience building activities and investment.

3.3 Sources of weaknesses and strength

The common areas in which weak resilience levels can be seen across the different irrigation sites in the four countries are as follows (See also Figure 29 and Table 20):

- Limited knowledge around field irrigation practices and rudimentary infrastructure. Almost 60 percent of farmers irrigate at the surface level and 69 percent still use cans and buckets for irrigation. Water intake is carried out directly without infrastructure in 28 percent of the cases; groundwater is mostly accessed through traditional wells (54 percent). Irrigation water supply is considered inadequate by almost half of producers (45 percent).

- Insufficient adaption of water management practices. Although 73 percent of farms use at least one agricultural water management practice, 67 percent consider these to be inadequate for improving crop production.
- Lack of non-farm income generating activities. Nearly half of farmers (44 percent) do not work outside of the farm, while only 19 percent have year-round sources of income beyond agriculture. Thirty-six percent of farmers have IGAs on an occasional or seasonal basis.
- Degradation of land and soil and extensive use of synthetic fertilizers. More than 70 percent of farmers believe that their soils and land are poor in organic content and that fertility is inadequate. All farmers have observed degradation processes due to wind or water erosion, deforestation and reduction of vegetative cover. Most farmers have taken action to improve soil fertility (e.g. 74 percent use manure and 57 percent rotate crops), however 77 percent still use synthetic fertilizers to add nutrients to the soil and only 6 percent produce their own organic soil amendments.

Figure 29. | Average resilience levels by country

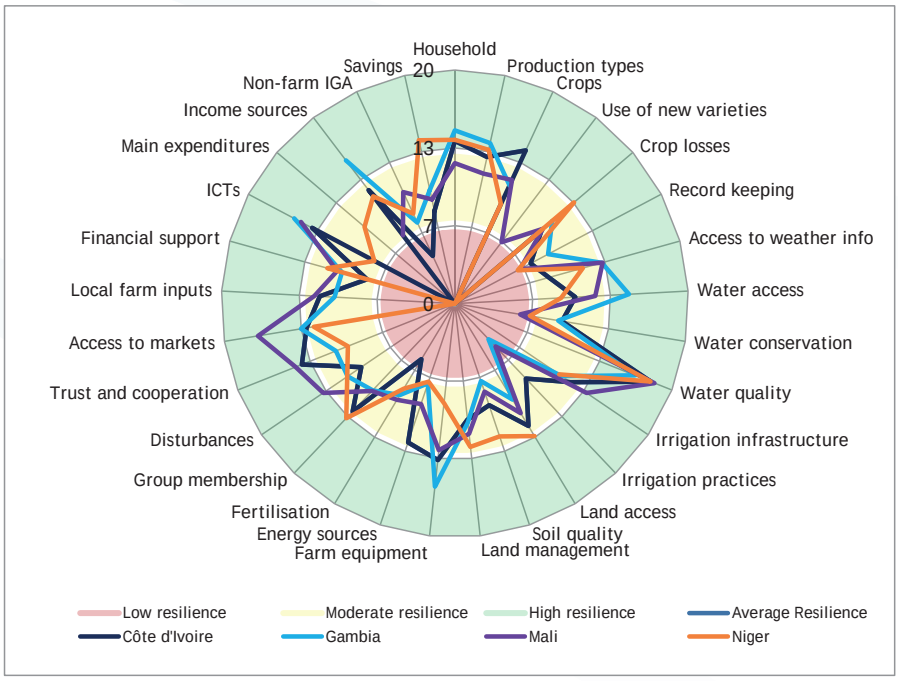


Table 20. | Low-resilience and high resilience modules

Country	Weaknesses (low resilience scores)	Strengths (high resilience scores)
Côte d'Ivoire	▪ Non-farm IGAs (4.52 points) ▪ Fertility management (5.55 points) ▪ Record-keeping (7.34 points) ▪ Field irrigation practices (7.50 points) ▪ Financial support (7.75 points)	▪ Crop production (14.46 points) ▪ Trust and cooperation (14.10 points) ▪ Household composition (13.94 points) ▪ Access to ICTs (13.84 points) ▪ Farm equipment (13.47 points)
Gambia	▪ Field irrigation practices (4.20 points) ▪ Soil quality (6.99 points) ▪ Energy sources (7.21 points) ▪ Non-farm IGAs (7.65 points)	▪ Farm equipment (15.76 points) ▪ Access to ICTs (15.57 points) ▪ Income sources (15.44) ▪ Water access (14.93 points) ▪ Household composition (14.83)
Mali	▪ Field irrigation practices (5.06 points) ▪ Water conservation practices (5.67 points) ▪ Record-keeping (6.31 points) ▪ Income sources (7.35 points) ▪ Soil quality (7.95 points)	▪ Access to local markets (17.09 points) ▪ Access to ICTs (14.92 points) ▪ Trust and cooperation (14.68 points) ▪ Irrigation infrastructure (16.63 points) ▪ Disturbances (13.62 points)
Niger	▪ Record keeping (6.13 points) ▪ Water conservation practices (6.79 points) ▪ Energy sources (6.96 points) ▪ Non-farm IGAs (7.77 points)	▪ Trust and cooperation (14.23 points) ▪ Household composition (14.06 points) ▪ Access to local markets (13.37 points) ▪ Production types (13.55 points) ▪ Land access (13.45 points)

Key factors enabling people to cope, adapt and overcome climate-related disturbances include:

- good access to ICTs, such as radios, from which they can obtain information on cropping practices and weather forecasts;
- use of farm equipment, allowing smallholders to reduce the burden and time spent on farming activities;
- strong social cohesion reflected in trust and cooperation between family and community members, community collaboration and high-functioning customary mechanisms for problem solving.

The interviewees gave priority to:

- improving the number and quality of water access sources;
- strengthening access to local and regional markets;
- preserving locally-sourced farm inputs; and
- practices that increase soil fertility improving household food security and revenues.

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4. Adaptation strategies

As discussed in Chapter 2, climate change is expected to have a negative impact on crop production in the countries under review, limiting the capacity of agriculture-reliant households to produce food and have adequate revenues from agricultural production. Efforts to develop, plan and implement adaptation strategies, in particular for agricultural water management, are needed to face the threats related to climate variability and change.

Based on expected climate-related impacts and after extensive consultations, the four countries under review identified their general adaptation needs as follows:

- a better response to changes in water availability;
- enhanced coping strategies in response to the increase in the incidence of extreme events (floods and droughts);
- improved response to the deterioration of water quality;
- diversification of production systems.

The countries identified investments in water harvesting-related practices and soil conservation techniques as important responses to climate change. The introduction of pest and drought-resistant crop varieties, as well as increased information on pest management practices were also considered to be key elements for climate change adaptation.

In Chapter 2, two adaptation strategies (increased soil fertility and application of complementary irrigation) were assessed using climatic and crop modelling. In order to identify the priority adaptation strategies in the four countries, a consultation was held with national stakeholders after the impact and resilience assessments had taken place. Following the approach used in the *Regional Stocktaking Report*, a number of

different adaptation strategies were classified using criteria summarized in Table 21. The list of selected country adaptation strategies – summarized in Tables 22-25 – is not exhaustive. The proposed adaptation strategies consider both supply side and demand side solutions.

It is important to note that implementing the adaptation strategies will depend on local conditions, including socioeconomic capacity.

Table 21. | Criteria for selecting adaptation strategies

Attributes	Evaluation	Criteria
Level	F (farm)	The action is local and the strategy can be implemented by the farmer.
	P (public)	The action extends to more than a single farm and is implemented by the government.
Category	AG (agronomic)	Research and innovation in agricultural practices and technologies
	MA (management)	Development of institutional and organizational skills
	IN (infrastructure)	Construction works and physical facilities
Technical difficulty	L (low)	Available at present time but no technical skill or training needed
	M (medium)	Available in present time but requires training
	H (high)	Requires new technological and managerial developments not available in the present time (i.e. research needed)
Potential cost	L	Cost can be supported by individuals or administrations and no additional financing is required, the farmer can implement the strategy with their own resources at a cost of less than 5 years of production.
	M	Cost is assumed by local institutions through standard short and medium- term financing (less than 10 years) or by standard cost recovery actions (i.e., financed by implementing a canon or tax); cost to farmers is between 5 and 20 years of production.
	H	Cost is assumed by national or international institutions and requires long-term financing commitment (more than 10 years) from international policy or lenders.
Potential benefits	L	Potential benefits are mainly directed to the farmers that implement the strategy.
	M	Scope transcends the farmer level, with benefits mostly affecting the agricultural sector; the positive externalities are regional.
	H	Global scope, with potential benefits at the regional level; positive externalities could benefit other sectors.

4.1 Côte d'Ivoire

Table 22. | Assessment of selected adaptation strategies in Côte d'Ivoire

Adaptation strategy	Level	Category	Technical difficulty	Potential cost	Potential benefit
IMPROVING RESILIENCE AND ADAPTIVE CAPACITY					
Increase access and training for households in the use of climate and weather information	P	MA	M	M	H
Train households on the reasonable use of fertilizers	P	AG	M	M	H
Increase access and training for farmers on appropriate agricultural techniques or practices (e.g. mulching, agroforestry, zero tillage)	P	AG	M	M	H
Awareness raising and training for households on keeping farm records	P	MA	L	L	H
Awareness, information and incentives to diversify sources of income beyond agriculture	P	MA	L	L	H
Information and awareness on the use of clean and cheap energy sources for irrigation water pumping	P	MA, AG	M	M	H
Strengthen household capacity for early detection and monitoring of crop diseases, and implementation of biological or physical control measures	P	MA, AG	M	M	H
Information and awareness of households on new crop varieties with high yield potential introduced by research	P	MA	M	M	M
Regular consultation with agricultural extension and meteorological services	F	MA	L	L	L
Reduce additional fertilizer inputs during the growing season.	F	AG	L	L	H
Promote the exploitation of lowlands	F	AG, IN	M	M	M
Promote agroforestry and set up reforestation operations	P	AG	M	M	M
Promote medium-cycle varieties of food and cash crops	F	AG	M	M	M
Grow adapted varieties (maize, sorghum, etc.) on the plateau and floating rice and/or vegetable in the lowlands	F	AG	L	M	M
Adopt sustainable cultivation techniques to prevent soil erosion (intercropping, crop rotation, zero/minimum tillage)	F	AG	L	M	H
Recover and enhance runoff water	F	AG	M	M	H
Build water collection basins	F	IN	M	H	H
RESPONDING TO CHANGES IN WATER AVAILABILITY					
Select small-scale irrigation systems, focusing on water-saving irrigation techniques	P	MA, AG, IN	M	H	H
Encourage supplementary irrigation (water collection basins and others)	F	AG, IN	M	M	H
Promote the implementation of sustainable groundwater mobilization development as an alternative to low surface water availability	F	AG, IN	M	H	H
RESPONDING TO FLOODS AND DROUGHTS					
Promote the cultivation of crop varieties that are resistant to drought, thermal rise and/or short cycle	F	AG	H	M	M
Implement measures to prevent flood risks and limit the use of floodplains	P	MA, IN	H	H	H
RESPONDING TO INCREASED IRRIGATION REQUIREMENTS					
Avoid the use of water-intensive crop varieties	F	AG	M	H	H
Prioritize farming techniques that promote soil and water conservation (partitioned ridges, mulching, etc.)	F	AG, IN	M	M	H
IMPROVING FOOD SECURITY & LIVELIHOODS					
Strengthen the monitoring of waterborne diseases linked to abundant rainfall (e.g. malaria, cholera)	P	AG	M	M	M

4.2 The Gambia

Table 23. | Assessment of selected adaptation strategies in Gambia

Adaptation strategy	Level	Category	Technical difficulty	Potential cost	Potential benefit
IMPROVING RESILIENCE AND ADAPTIVE CAPACITY					
Strengthen crop evaluation and suitable crop variety dissemination capacities of the National Agricultural Research Institute	P	AG	H	H	H
Develop and disseminate soil suitability classification maps and fertility requirement maps per crop	P	AG	H	M	H
Enhance availability and access to production inputs and services	P	AG	M	M	M
Support development of appropriate production curricula and tools on climate-smart agriculture and community training on climate change	P	AG	M	M	H
Create affordable loan facilities for acquiring equipment and machinery for production services	P	MA	M	M	M
Improve water-use efficiency of crops through soil fertility and on farm water management: use of mulching, drip irrigation system and appropriate watering periods	F	AG	L	L	L
Pilot and upscale small-scale mobile solar powered low-lift pumping units in tidal areas to enhance irrigation/drainage of high/low areas	P	AG, IN	M	M	M
IMPROVING FOOD SECURITY & LIVELIHOODS					
Establish seed banks at strategic locations to enhance production diversification and stocking mechanisms at family and community levels	P	IN	M	M	M
Establish mechanisms for training and linking various value chain actors and consumers to enhance marketing	P	MA	L	M	M
Establish/reactivate and strengthen water user associations (WUA) in rice irrigation schemes, including marketing and input provision services to members	P, F	AG	L	L	M
IMPROVING THE QUALITY OF RESOURCES (LAND, SOIL AND WATER)					
Promote good agricultural practices, including varietal selection and integrated pest management	P	AG	L	L	L
Crop diversification and rotation as a means of minimizing amount of harvest loss and effect of diseases/pests	F	AG	L	L	L
Construct series of water retention structures (contour bund) in the uplands to reduce run-off quantity and rate	P	IN, AG	M	M	M
Support upland conservation and erosion control measures to reduce runoff quantity and flow rate, and increase groundwater recharge	P,F	AG	L	L	L
Promote agroforestry through planting of hedgerows and/or tree crop on marginal land with a view to reducing consequences of wind during the dry season	F	AG	L	L	L

4.3 Mali

Table 24. | Assessment of selected adaptation strategies in Mali

Adaptation strategy	Level	Category	Technical difficulty	Potential cost	Potential benefit
IMPROVING RESILIENCE AND ADAPTIVE CAPACITY					
Promote the diversification of agriculture-based livelihoods (i.e. presence of mixed systems: livestock, aquaculture and crops)	F	AG	L	L	L
Develop and revise technical manuals for hydro-agricultural infrastructure design and management related to climate change	P	AG	H	M	M
Mobilize and monitor rainwater, surface water and groundwater	P	AG	M	M	M
Use environmentally friendly drilling technologies (e.g. solar or wind pumps)	F	AG	M	M	L
Prevent and manage risks and natural disasters by strengthening early warning systems to prevent damage in flood-prone areas	P	AG	M	M	M
Establish an information system on the risks of crop diseases stemming from climate change, particularly related to water	P	AG	M	M	M
Develop research on irrigation and solar nexus	P	AG	H	M	H
Train beneficiaries on agricultural adaptation practices (technology packages).	P	AG	L	L	L
Improve access to information and communication technologies around the use of good agricultural practices and water management	P	AG	M	L	M
Develop maps on potential irrigation areas	P	AG	M	L	M
IMPROVING THE QUALITY OF RESOURCES (LAND, SOIL AND WATER)					
Use climate-smart agricultural practices and development of practices promoting water and soil conservation	F	AG	L	L	L
Restore, maintain and/or improve the level of soil fertility	F	AG	L	L	L
Use mulching-based systems	F	AG	L	L	L
IMPROVING THE GOVERNANCE					
Operationalize the National Policy on Agricultural Water Management	P	MA	M	M	H
Ensure access to land to rural population, especially for women and youth	P	MA	H	M	H

4.4 The Niger

Table 25. | Assessment of selected adaptation strategies in Niger

Adaptation strategy	Level	Category	Technical difficulty	Potential cost	Potential benefit
IMPROVING RESILIENCE AND ADAPTIVE CAPACITY					
Construct water-spreading weirs to promote the retention of solid elements	P	IN	M	H	H
Develop water and soil conservation works, soil protection and restoration (e.g. construction of stone barriers)	P	IN	M	H	H
Train producers in the application of supplementary irrigation	P	AG, IN	M	L	L
Disseminate meteorological information (e.g. through community radio stations)	P	MA, AG	M	L	H
Select crop varieties (sorghum, maize and tomato) that are more resistant to pests and diseases, tolerant to drought and with a similar yield as the local varieties	P	AG	M, H	H	H
Establish a fund for the purchase of approved phytosanitary products	P	MA	L	M	H
RESPONDING TO CHANGES IN WATER AVAILABILITY					
Strengthen existing solar pumping systems and install solar batteries to extend pumping time	P	MA, AG	M	M	H
Improve water management through the construction of irrigation canals	P	MA, IN	M	H	H
Build farmer capacity in the management of irrigation infrastructure and equipment	P	AG, MA	L	L	L

5. Financial and economic analysis of adaptation strategies at crop production level

5.1 Methodology

Cost-benefit analysis (CBA) is a tool that facilitates decision-making around investment projects from economic and social points of view. The broad purpose of CBA is to ensure the efficient allocation of resources, demonstrating the greater effectiveness of a particular project or programme compared to the alternatives. Financial and economic analyses are used to assess the feasibility of different investment options.

The financial analysis uses a project's cash flow forecasts to calculate suitable net return indicators. A particular emphasis is placed on two financial indicators: the Financial Net Present Value (FNPV), which is the present value of an investment's expected cash inflows minus the costs of acquiring the investment; and the Financial Internal Rate of Return (FIRR), which measures the profitability of potential investments.

The calculation of the FNPV and the FRR is based on the following steps:

i. Calculate costs (C_t) and benefits (B_t) of production for the main crops. Only cash inflows and outflows are considered.

ii. Integrate investment costs in irrigation and adaptation strategies (i.e. soil fertility management).

iii. Define the time horizon of the investment (T).

iv. Determine the discount rate (r) of the investment. The analysis adopts a financial discount rate of 5 percent to calculate the present value of future cash flows.[19]

v. The calculation of FNPV for a production system and adaptation strategy is defined as follows:

$$FNPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1-r)^t}$$

vi. Calculation of the CBA ratio:

$$CBA = \sum_{t=0}^{T} \frac{C_t}{B_t}$$

The economic analysis requires a study of a project's net impact on economic welfare. This is done by integrating a monetary value of the social welfare that the prospective investment will provide through the FNPV and FRR. The integration is carried out by discounting costs and benefits with a 3.5 percent discount rate (instead of 5 percent) and calculating standard conversion factors (SCF), e.g. border prices for specific tradable goods like agricultural products and technology, computed for each country. The SCF help address price distortions of inputs and outputs of traded items (e.g. technology) and reflect opportunity costs of the investment in adaptation strategies.[20] The SCF were calculated based on macroeconomic data: exports (X), imports (M), taxes (T_X) and tariffs (T_M), and at the sector level (primary and secondary technology transfer) as follows:

$$SCF = \frac{X + M}{(X + T_X) + (M + T_M)}$$

The methodology used to conduct financial and economic analyses follows the following assumptions:

- Only cash inflows and outflows are considered (reserves and other accounting items that do not correspond to actual flows are ignored).
- The determination of project cash flows is based on the incremental approach, i.e. the differences in the costs and benefits between the scenario that includes the project (do-something alternative) and the counterfactual scenario that does not (business-as-usual scenario -BAU).

The financial and economic analyses consider three scenarios:

- the current scenario (BAU), where there is no change in production practices;
- the improved scenario, where improved fertilization practices and supplementary irrigation are used;
- the optimal scenario, where full fertilization and irrigation are used.

Irrigation systems, such as tidal irrigation, (semi) Californian systems and gully plugs, were analysed in Côte d'Ivoire, the Gambia, Mali and the Niger. The analysis covered the main irrigated and rainfed crops in the WCA region, which were calibrated using the AquaCrop model, namely: rice (rainfed and irrigated), maize

[19] The European Commission and the African Development Bank suggest a benchmark real discount rate of 5%.
[20] Prices on world markets represent the country's actual trading opportunities and, as such, they are an appropriate measure of opportunity costs.

(rainfed and irrigated), sorghum (rainfed) and tomato (irrigated). To simulate the different analyses, the moderate scenario was considered (RCP4.5) and the variation in the crop yields was integrated based on the predicted yields specific to the irrigation site and crop type (See Table 17 in Chapter 2).

The costs and benefits were calculated on the basis of cultivated hectares.[21] The off-farm costs of irrigation investments (e.g. swamp or dam development) were divided by the total number of users on the irrigation site studied.[22] The SCF described in Table 26 were calculated for each country project.

Table 26. | Conversion factors for the economic analysis

Country	Conversion factors (benefits) – primary sector/ agriculture	Conversion factors (costs) – secondary sectors/ technology
Côte d'Ivoire	0.99	0.92
Gambia	0.86	0.88
Mali	0.71	0.91
Niger	0.81	0.73

Once the FNPV and FRR values are computed for each of the selected crops and irrigation technologies in the different scenarios, we recommend implementing the option in which the FNPV has a positive value. In the case where multiple options are available and only one can be financed, we suggest selecting the measure with the highest FNPV. This approach is recommended because the FNPV allows the correct selection and ranking of the project, especially when mutually exclusive options are present. This section presents the results of the FNPV, internal rate of return or the benefit-cost ratio.

It is important to note that other adaptation strategies identified through the resilience assessment (e.g. practicing crop rotation and intercropping, including non-farm income generating activities, access to markets and knowledge) were not analysed in this section given the lack of quantitative data for modeling and/or because they were beyond the scope of the project.

5.2 Results

a) Côte d'Ivoire

The cost-benefit analysis for the production of irrigated rice and tomato in semi-Californian irrigation systems (See Table 27) was conducted in sites in M'bé and Kpato respectively.

Rice production using controlled submersion is financially unprofitable, since farm expenses exceed revenues, resulting in a negative return on investment over a 10-year timeframe and a CBA ratio below 1. The investment in this system, including operation and maintenance (O&M) represents the largest share of farm expenses. Rehabilitating dams and canals for rice production represent 54 percent of the total costs of production.

[21] Prices were converted to USD using the official exchange rate on February 11th, 2019 as follows: 1 USD = 0.0017 CFCA for Côte d'Ivoire, Mali and the Niger, and 1 USD = 0.000291 GMD for the Gambia.

[22] Information obtained from the questionnaire distributed to the irrigation managers.

Table 27. | Cost-benefit analysis in Côte d'Ivoire

	Financial analysis			Economic analysis		
Controlled submersion	Without adaptation	Improved	Optimal	Without adaptation	Improved	Optimal
Rice						
FNPV	USD (7 195)	USD (6 298)	USD (1 077)	USD (1 250)	USD (362)	USD 5 021
IRR	-21%	-15%	3%	3%	6%	20%
CBA	0.68	0.72	0.95	0.92	0.98	1.29
Semi-Californian						
Tomato (horticulture)						
FNPV	USD 15 852	USD 17 978	USD 30 909	USD 17 116	USD 19 221	USD 32 062
IRR	40%	41%	48%	42%	43%	50%
CBA	1.78	1.88	2.48	1.91	2.03	2.67

Note: Numbers within brackets indicate a negative value, i.e. losses in the investments in a 10-year timeframe.

When incorporating price accounting for the social benefits derived from an investment, rice production still appears unprofitable for farmers. The use of soil improvement fertilization practices at a moderate level does not bring adequate revenue to smallholders despite a predicted 9 percent yield increase. The use of optimal fertilization,[23] however, is economically suitable as this generates a positive return on investment of 20 percent and a positive CBA ratio. Therefore, an investment in optimal practices has the potential to bring social and economic benefits to rural populations.

An investment in semi-Californian irrigation systems to produce tomatoes (or applied to horticultural crops in general) is both financially and economically feasible. Although the investment costs associated with the system (e.g. purchase of motor pumps and pipes, fuel and O&M) accounts for 46 percent of total production costs, the financial return rate is always positive and exceeds 40 percent. The use of soil fertility improving practices increases the FNPV by 7 percent with respect to current management conditions. The incorporation of full fertilization practices and irrigation improves the FNPV by 84 percent (from USD 16 826 to USD 30 909).

Although farmers already use technologies and practices, such as irrigation, to adapt to climate change, climate variability is still a threat to crop production. Crop yields are projected to decrease with changing climate patterns and more frequent and extreme weather events. Under current management conditions, irrigated rice is expected to have a reduced yield of 6 percent, and irrigated tomato of 7 percent by 2030. Figure 30 and Figure 31 depict the FNPVs for irrigated rice and tomato in Côte d'Ivoire over a 10-year period.

[23] Optimal fertilization consists of the application of 200 kg of NPK and 50 kg of urea.

Figure 30. | FNPV - irrigated rice (Côte d'Ivoire)

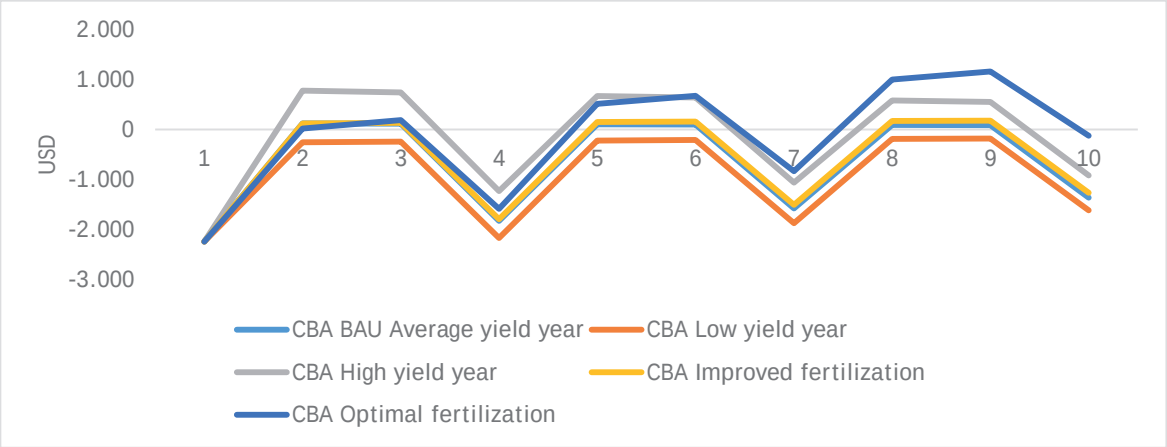
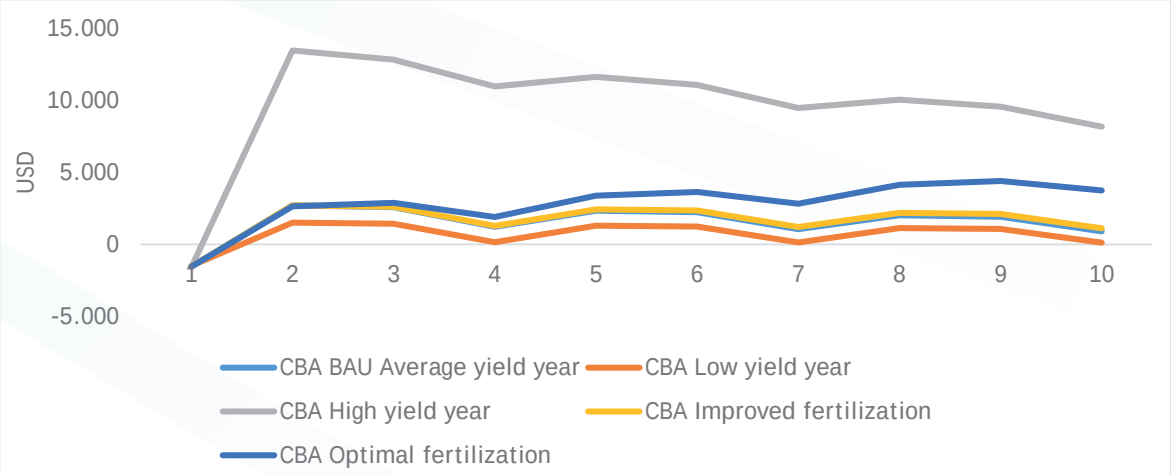


Figure 31. | FNPV - irrigated tomato (Côte d'Ivoire)



The FNPVs were calculated for an average yielding year in the BAU scenario, low yield year (BAU), high yield year (BAU), and with improved fertilization and optimal fertilization. The figures reflect that not investing in improved irrigation infrastructures and water management practices, as well as technologies for land and soil improvement would make agriculture fully or nearly unprofitable in all cases when climate shocks are experienced. This will increase the vulnerability of farmers to climate change, especially when agriculture is the main source of their livelihoods.

b) The Gambia

Rainfed maize, and rice production using tidal irrigation were analysed in the irrigation sites of Jahaly, Pacharr and Salikenni. The financial analysis shows that investment in practices to improve soil fertility and water management for the two crops is financially and economically feasible and profitable in the long term (See Table 28).

Table 28. | Cost-benefit analysis in Gambia

	Financial analysis			Economic analysis		
Tidal irrigation	Without adaptation	Improved	Optimal	Without adaptation	Improved	Optimal
Rice - wet season	Average yield year			Average yield year		
FNPV	USD 68	USD 73	USD 131	USD 62	USD 67	USD 122
FRR	56%	57%	66%	55%	56%	65%
CBA	2.52	2.48	3.48	2.46	2.42	3.43
Rice - dry season						
FNPV	USD 81	USD 88	USD 110	USD 75	USD 80	USD 101
FRR	60%	61%	64%	59%	60%	63%
CBA	2.75	2.73	3.03	2.70	2.65	2.97
Rainfed						
Maize						
FNPV	USD 6	USD 8	USD 48	USD 5	USD 7	USD 45
FRR	22%	24%	42%	21%	23%	41%
CBA	1.26	1.32	2.55	1.14	1.19	2.30

Note: Numbers within brackets indicate a negative value, i.e. losses in the investments in a 10-year timeframe.

The use of fertilization management practices involves a cost of USD 0.87 per ha for improved[24] fertilization and USD 1.31 per hectare for optimal[25] fertilization. The implementation of these practices increases rice yields by 11 percent (improved) and 35 percent (optimal), enhancing the return on investment by more than 50 percent.

The use of tidal irrigation systems in the production of rice is costlier than producing rice under rainfed systems because it involves significant expenses to develop swamps (more than 30 percent of total farm costs). However, the return on investment is more than double that of rainfed production in an average yield year and without improved fertilization practices (return on investment is 22 percent under rainfed and an average of 56 percent using tidal irrigation).

Using optimal management conditions in rainfed maize systems increases financial and economic investment returns by almost double that of current conditions. The FNPV value is substantially higher when incorporating optimal soil management practices into the crop production system, going from USD 6 in a BAU scenario to USD 48. This means that investing in such practices would certainly benefit smallholders' living conditions since they will see crop yields and revenues increased, with minor capital disbursements.

Maintaining current management conditions of soil and water, the production of irrigated rice is expected to have reduced yields of 6 percent, while yields for rainfed maize will decrease by 3 percent by 2030. As illustrated in Figure 32 and Figure 33, the optimal fertilization scenario increases the FNPV of the project during the whole period and overtakes the values of the high yield scenario after Year Four. These results show that an optimized management of the system is more adapted to future climate conditions and can even increase the FNPV over time. Figure 33 shows a large difference between the optimal fertilization conditions and the low yield scenario (BAU). These results strengthen the finding that optimizing management conditions is crucial for the future of rainfed maize in the Gambia.

[24] Improved fertilization consists of the application of half the recommended doze that is of 100 kg NPK and 50 kg of urea at a government price of GMD 15/kg.
[25] Optimal fertilization consists on the application of a recommended rate of 200 kg NPK and 100 kg of urea at a government price of GMD 15/kg

Figure 32. | FNPV - irrigated rice, wet season (Gambia)

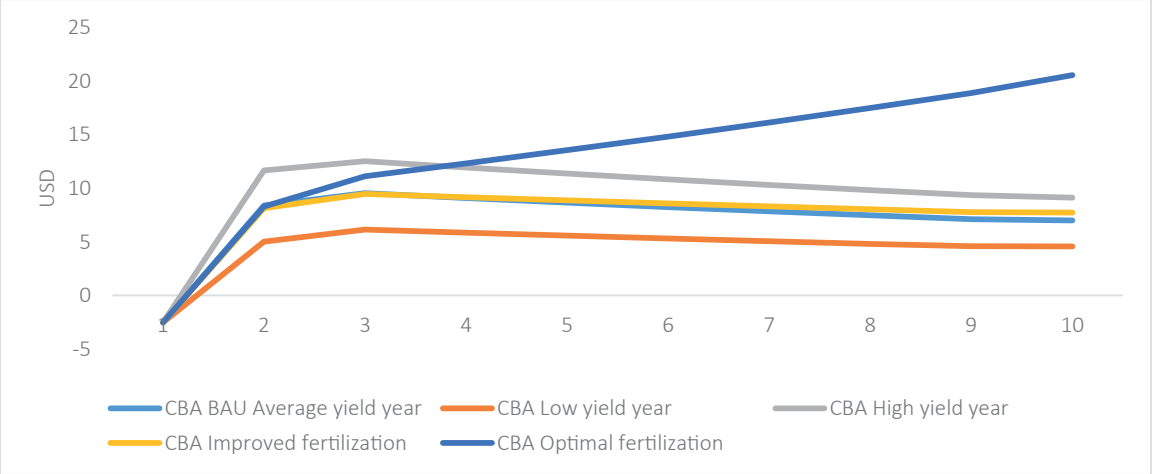


Figure 33. | FNPV - irrigated rice, dry season (Gambia)

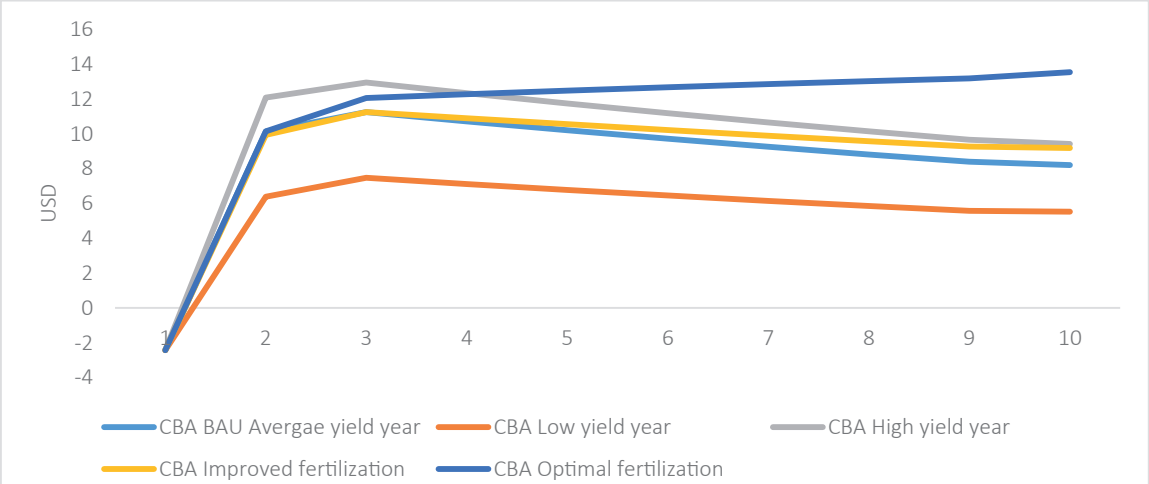
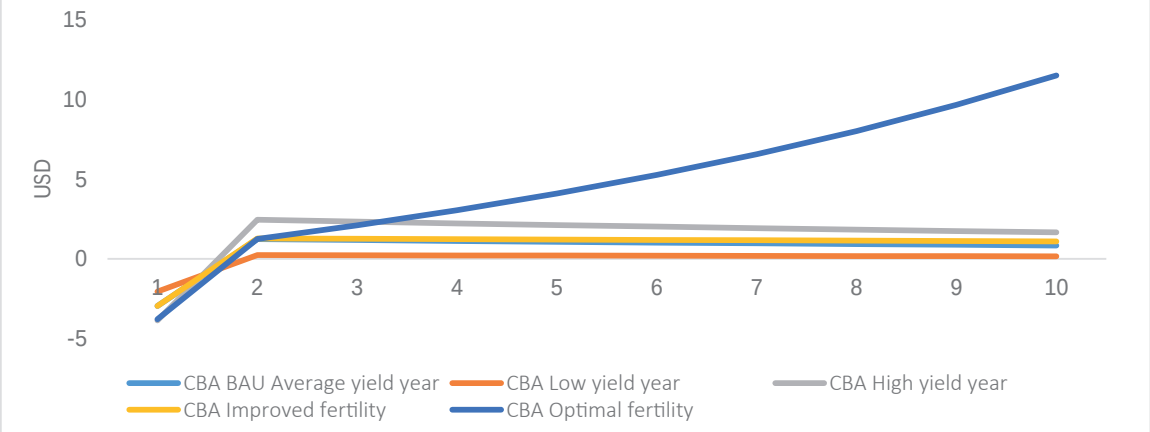


Figure 34. | FNPV – rainfed maize (Gambia)



c) Mali

Cost-benefit data related to the production of three crops – irrigated tomato (Californian systems), irrigated lowland rice (using gully plugs called *seuils d'épandage*) and rainfed maize – were collected in the irrigation site of Founia/Kita. Information about the three crops was gathered on a daily basis in the presence of at least ten members of the management committee). The results are presented in Table 29.

Table 29. | Cost-benefit analysis in Mali

	Financial analysis			Economic analysis		
Seuils d'épandage	Without adaptation	Improved	Optimal	Without adaptation	Improved	Optimal
Rice	Average yield year					
FNPV	USD 856	USD (871)	USD (771)	USD 286	USD (1 328)	USD (1 365)
FRR	31%	-100%	-13%	14%	-100%	-100%
CBA	1.81	0.72	0.80	1.22	0.57	0.63
Californian systems						
Tomato						
FNPV	USD 7 433	USD 4 668	USD 16 977	USD 4 247	USD 1 316	USD 10 811
FRR	34%	28%	44%	27%	16%	37%
CBA	2.07	1.42	2.37	1.60	1.12	1.89
Rainfed						
Maize						
FNPV	USD (1 366)	USD (2 638)	USD (2 634)	USD (1 704)	USD (2 969)	USD (3 083)
FRR	-100%	-100%	-100%	-100%	-100%	-100%
CBA	0.57	0.42	0.49	0.45	0.33	0.39

Note: Numbers within brackets indicate a negative value, i.e. losses in the investments in a 10-year timeframe.

The production of lowland irrigated rice appears to be financially adequate under current conditions, since the inclusion of soil fertilization would significantly increase the costs for producers. The cost of introducing soil fertility management techniques for rice production is equivalent to USD 272 and USD 352 per ha for improved[26] and optimal[27] fertilization respectively. The inclusion of these costs in the analysis produces a negative return on investment and a negative discounted net cash flow (FNPV) during the 10-year timeframe. This implies that producing would become unprofitable for small-scale farmers, even with a projected increase in the crop yield, due to high cost of fertilizers.

The production of tomato under the Californian systems is the most expensive investment that was assessed in Mali, largely due to the need to purchase pumps. The benefits of tomato production are significant, producing a revenue of USD 744 per ha in a low-yield year (approx. 2.5 tonnes/ha) and up to USD 2 975 per ha during a year with high yields (approx. 10 tonnes/ha). The cost of improving soil fertility is USD 833 per ha, while optimal fertilization implies a cost of USD 1025 per ha. Considering these costs in the financial and economic analyses, the FNPV, IRR and the CBA ratio are positive and above 1 in all cases. The improvement of fertilization practices does not seem to bring important financial and economic benefits when compared with either current production practices or optimal soil fertilization techniques.

Finally, rainfed maize production appears to not be financially feasible since the cost of production exceed the revenues obtained from crop sales in all scenarios. Similar to rice, the costs of improved fertilization

[26] Improved fertilization consists of the application of 250 kg of NPK fertilizer and 10 000 kg of manure.
[27] Optimal fertilization consists of the application of 300 kg of NPK fertilizer and 15 000 kg of manure.

are USD 272 and USD 352 for optimal fertilization. However, although the increase in yield is 70 percent in the optimal scenario, costs still surpass the benefits, making the investment unprofitable. The analysis also suggests that the economic benefits derived from the production of maize without irrigation is unprofitable.

Figure 35. | FNPV – irrigated rice (Mali)

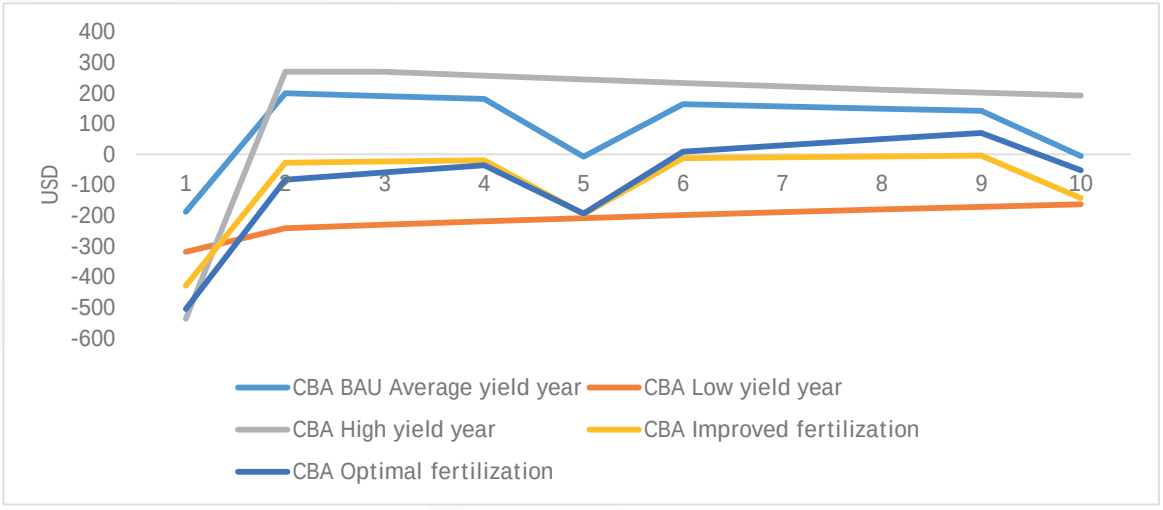


Figure 36. | FNPV – irrigated tomato (Mali)

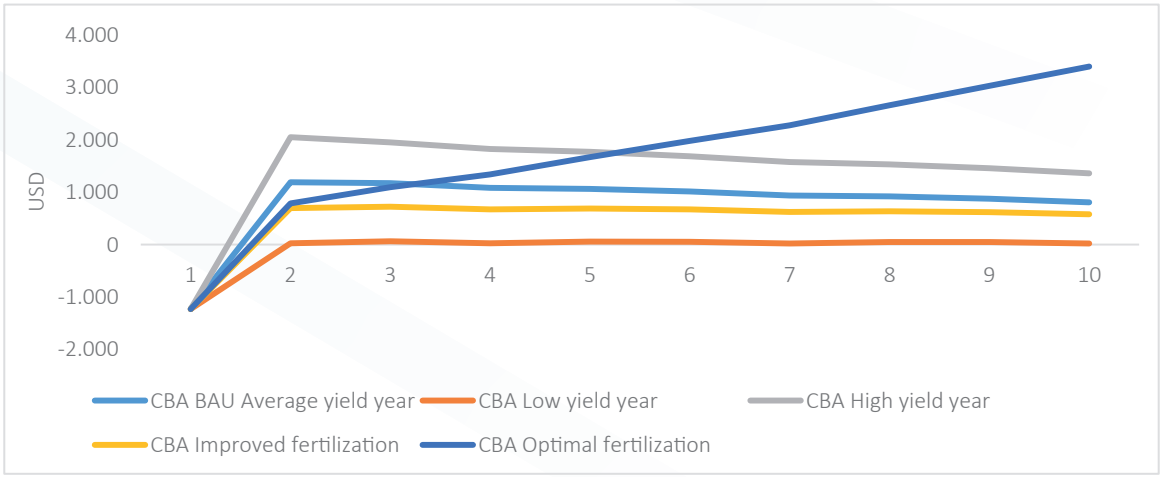
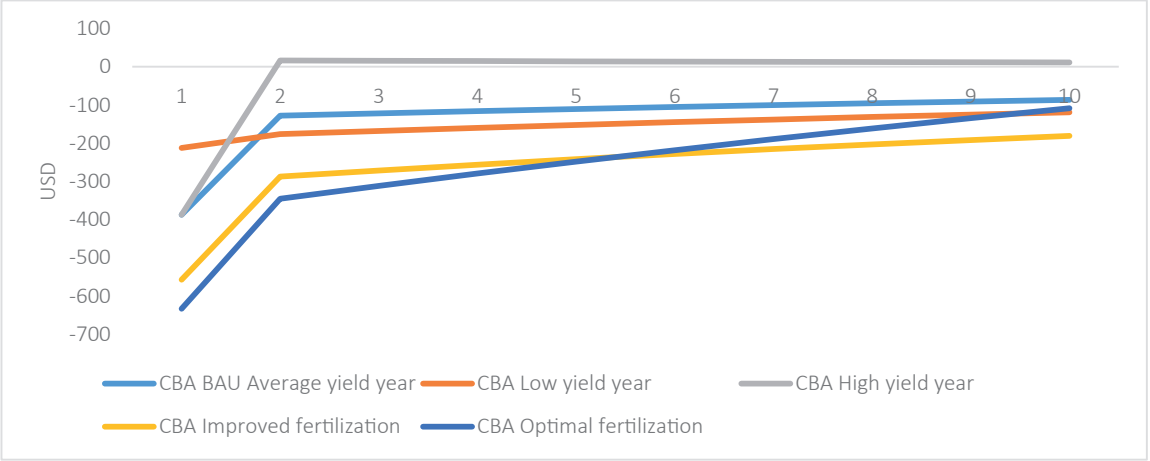


Figure 37. | FNPV – rainfed maize (Mali)



Finally, considering a scenario with low crop yields – expected to be more frequent due to changes in climate and unexpected shocks, the production of irrigated rice and tomato, and rainfed maize will be unprofitable for famers by 2030 (See Figure 35, Figure 36 and Figure 37).

The production of irrigated rice and rainfed maize appear to suffer the most the most if no adaptation measures are taken, or if the measures already existing are not improved, especially for the case of irrigation. Nonetheless, due to the extra costs of adaptation and O&M, the FNPV of the investments for most scenarios (except high yield) is at or below zero. Hence, the revenue margin for irrigated rice projects in this site is very narrow. On the other hand, Figure 36 reflects that, with exception of the low yield year scenario, the FNPVs for every year are positive. The optimal fertilization scenario has the highest and constantly increasing values over the -year period.

d) The Niger

Irrigated tomato and maize and rainfed sorghum were analysed in the irrigation sites of Falki, Soumarana and Fachi respectively (See Table 30).

The table shows that investments in surface irrigation systems (*seuils d'epandage* and lined canals) bring financial profits to smallholders as the average return on investment is 15 percent under a BAU scenario. Moreover, when including the economic benefits – i.e. the social surplus of the investments – the FRR increases by 20 percent. Financial and economic benefits are both achieved, even when important investments are needed to reach improved and optimal fertility and irrigation conditions. In the case of irrigated tomato, optimal fertilization would cost around USD 1 200 per ha,[28] while an improved management of soil fertility would cost about USD 622 per ha. The construction of five gully plugs and a protection dyke in the irrigation site would involve a cost of about USD 385 885.

Table 30. | Cost-benefit analysis in Niger

	Financial analysis			Economic analysis		
Seuils d'épandage	Without adaptation	Improved	Optimal	Without adaptation	Improved	Optimal
Tomato						
FNPV	USD 5 661	USD 3 427	USD 9 147	USD 5 806	USD 4 274	USD 9 224
FRR	18%	14%	21%	20%	18%	24%
CBA	1.36	1.18	1.39	1.50	1.30	1.53
Lined canals						
Maize						
FNPV	USD 444	USD 1 183	USD 6 182	USD 720	USD 1 269	USD 5 340
FRR	11%	16%	30%	15%	18%	32%
CBA	1.10	1.29	2.40	1.21	1.43	2.65
Rainfed						
Sorghum						
FNPV	(USD 50)	(USD 4 689)	(USD 4 230)	(USD 3 018)	(USD 3 218)	(USD 2 875)
FRR	7%	-24%	-18%	-16%	-19%	-14%
CBA	0.98	0.36	0.40	0.41	0.40	0.44

Note: Numbers within brackets indicate a negative value, i.e. losses in the investments in a 10-year timeframe.

[28] Optimal fertilization (rainfed tomato): 400 kg/ha NPK + 80 voyages/ha organic manure and 800 kg/ha of urea. Improved fertilization (rainfed tomato): 200 kg/ha NPK + 40 voyages/ha organic manure and 400 kg/ha of urea.

The use of full fertilization and irrigation in irrigated maize would increase the investment by more than ten times in comparison to a BAU scenario (from USD 558 to USD 6 182 in the FNPV). The cost of fertilizers needed reach optimal fertilization would be equivalent to USD 110 per ha of cultivated maize.[29] The off-farm irrigation costs related to the irrigation equipment (four boreholes, basins, irrigation channels, solar pump) and the gully plugs would require about USD 629 639 at the level of the irrigation site.

In line with the results of the simulations using the AquaCrop model, both the financial and the economic analyses show that the production of sorghum will not be longer profitable for smallholders by 2030. With the exception of the BAU scenario, the results show that producing the crop will be unprofitable since the FNPV is always negative during the simulated 10-year period. Similar outcomes are obtained with the use of improved and optimal fertilization practices and supplementary irrigation. The projected decreasing rate in crop yields (-70 percent and -59 percent using improved and optimal fertilization respectively by 2030 - See section 3) is the main reason for the poor economic sustainability of the investment.

Figure 38. | FNPV - irrigated tomato (Niger)

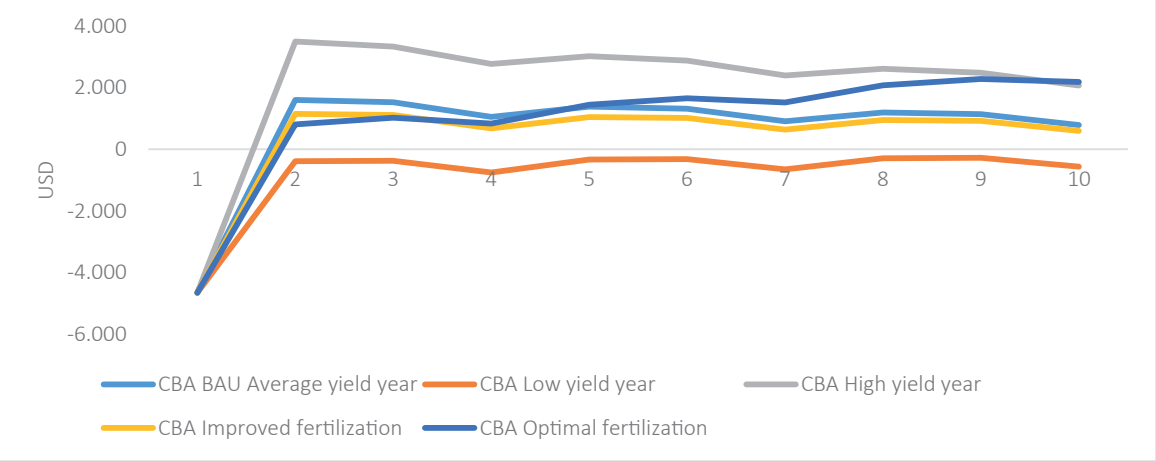
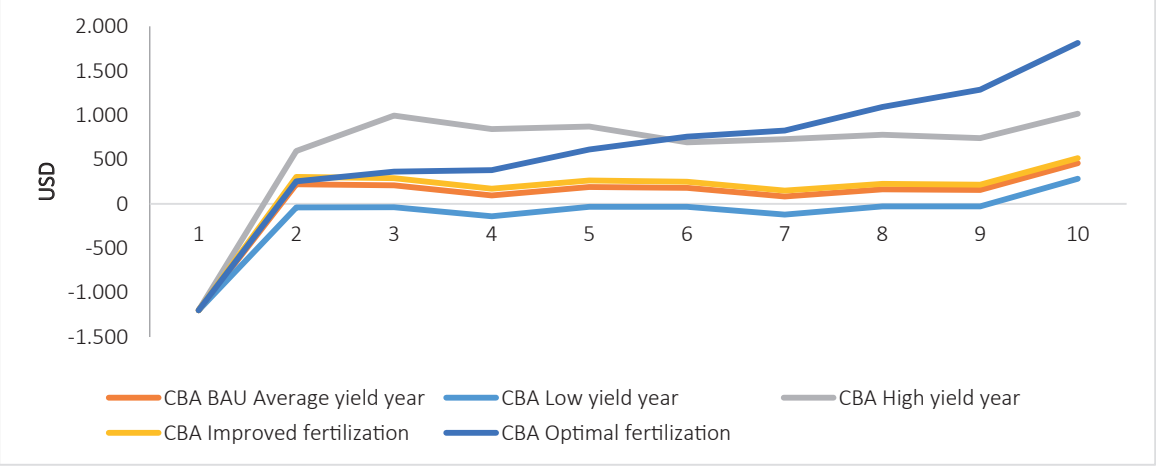


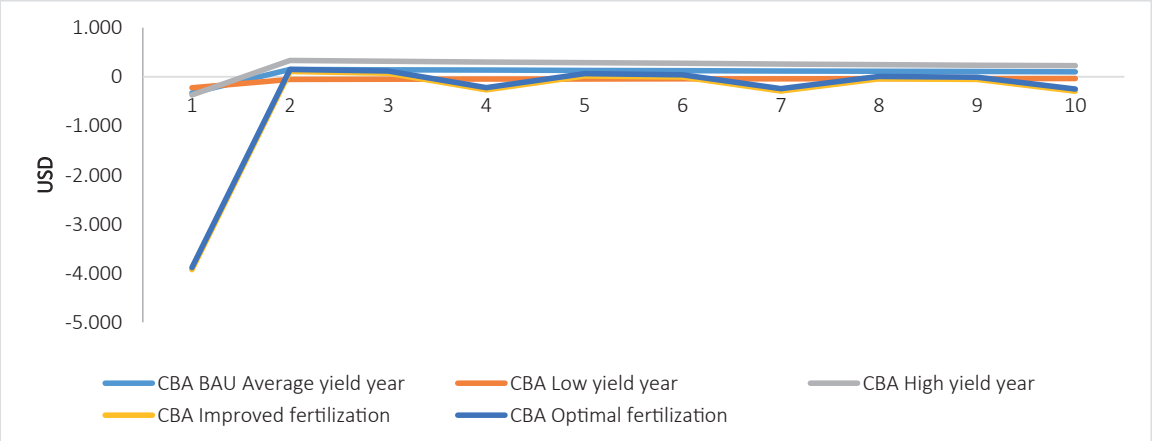
Figure 39. | FNPV - irrigated maize (Niger)



[29] Optimal fertilization (rainfed maize): 160 kg/ha NPK and 80 kg/ha of urea.

Finally, when considering a year with low-yield as reference for analysis, it can be noted that investing in improved irrigation infrastructure and soil and water practices are key to enhancing climate adaptation and farmers' resilience. Figures 38 to 40 indicate the importance of adaptation from a financial point of view.

Figure 40. | FNPV – rainfed sorghum (Niger)



5.3 Main findings of the economic and financial analyses of adaptation strategies

The use of adaptation practices and technologies to improve soil quality and water delivery to crops tends to have a positive impact on the financial and economic investment returns to family farmers. Producing under irrigated agriculture – using current irrigation practices – appears to be economically profitable for smallholder farmers in almost all cases, especially the use of Californian systems, tidal irrigation (rice), rainfed (maize - the Gambia), Semi-Californian (tomato), *seuils d'épandage* (tomato - the Niger), and line canals (maize).

Rainfed agriculture seems unprofitable for small-scale agricultural producers overall. Both financial and economic analysis indicate that investing in the production of maize (in Mali) under rainfed agriculture is not beneficial to smallholders. In line with the results of simulations of the AquaCrop model, both the financial and the economic analysis show that the production of sorghum will no longer be profitable for smallholders by 2030.

Financing the implementation of irrigation systems brings positive returns on the investment, however an important share of capital needs to be disbursed in order to put such systems into place. The implementation of swamps and dams, as well as expenses related to operation and maintenance, are among the largest costs borne by farmers. The high cost of fertilizers and infrastructure can limit the capacity of farmers to adapt to climate change, as costs surpass the benefits, making the investment unprofitable. This is especially true for the production of rice using *seuils d'épandage* (in Mali) and under controlled irrigation.

It is important to note that these analyses were conducted using a year with average crop yield as the reference. However, considering climate change and variability, it is projected that agricultural production will decrease, with a consequent fall in agricultural-based income. If no actions to adapt and mitigate

climate change are taken now, low agricultural yield can be seen as the new reference for assessing future investments.

Therefore, further access to affordable knowledge on sustainable soil and water management practices, inputs and resources is needed to enable farming families to overcome the negative effects that changes in climate and extreme weather events are expected to have.

5.4 Limitations

Data for this study was collected through interviews with local communities in the irrigation sites and the costs and benefits reported are specific to these communities. To draw conclusions at the regional level would require a more comprehensive assessment, including the revision of other secondary data, to truly reflect the costs and benefits derived from investments in irrigation and soil fertility management practices and technologies.

It is important to note that some production costs are likely underestimated, being based on the use of inputs produced at the farm level (e.g. organic fertilizers and seeds) and labour provided by family members. The reported costs do not consider external financial and technical support received from governments at different levels or from international agencies. Such support, including the financial expenses derived from them, needs to be accounted for when planning large-scale investments.

Likewise, environmental benefits, such as ecosystem services, were not included. In the calculation of benefits from investing in irrigation and soil fertility management. These need to be accounted for in future analyses to make sure the impact of the investment is accurately reflected.

Finally, a risk assessment is needed before proceeding with investment plans. Such an assessment requires studying the probability that a project will achieve a satisfactory performance (in terms of some threshold value of the FRR or the FNPV). This will enable investors to calculate the acceptable levels of risk presented by the project and the ways in which such risks can be mitigated.

6. Conclusions

West and Central Africa is particularly vulnerable to climate change due to its high exposure and low adaptive capacity. Climate projections show that temperatures are expected to increase from 0.7 °C to 3.2 °C with a higher increase for sites in the Sahel than for sites in Soudanian zones. Rainfall will become more unpredictable and variable, with more frequent and prolonged droughts and floods.

Smallholder farmers are likely to be hit the hardest by climate change. Climate change may increase existing vulnerabilities, including insufficient access to water for agriculture, and food insecurity. Small-scale irrigation is a promising solution that farming families can use to adapt to climate change and increase crop productivity and incomes.

The projected climate change and its impacts have consequences for the design of agricultural investment plans, including irrigation, and ignoring them may compromise the benefits and sustainability of the investments. Given that irrigation infrastructure has a long life cycle, the development of climate-resilient irrigation systems require integrating climate change concerns in the planning and design of investments in improving the performance of irrigation systems and the livelihoods of rural populations.

This report aims to provide evidence-based information and a methodological approach for governments, financing institutions and project managers to support decisions on how to integrate climate change adaptation needs into project and investment design. It has drawn on a number of studies, including climate projections, impact and vulnerability assessments, and the identification of adaptation needs.

In order to integrate climate change adaptation into investment planning, additional financing is needed for climate-related assessments. It is also necessary to engage with relevant stakeholders at local, national and regional levels as well as to promote collaboration across sectors. Decision-making around adaptation to climate change presents a complex challenge due to the uncertainties associated with climate projections, socio-economic trends and the lack of data. For this reason, it requires a practical and flexible approach to facilitate robust decision-making and minimize the potential for maladaptation.

7. References

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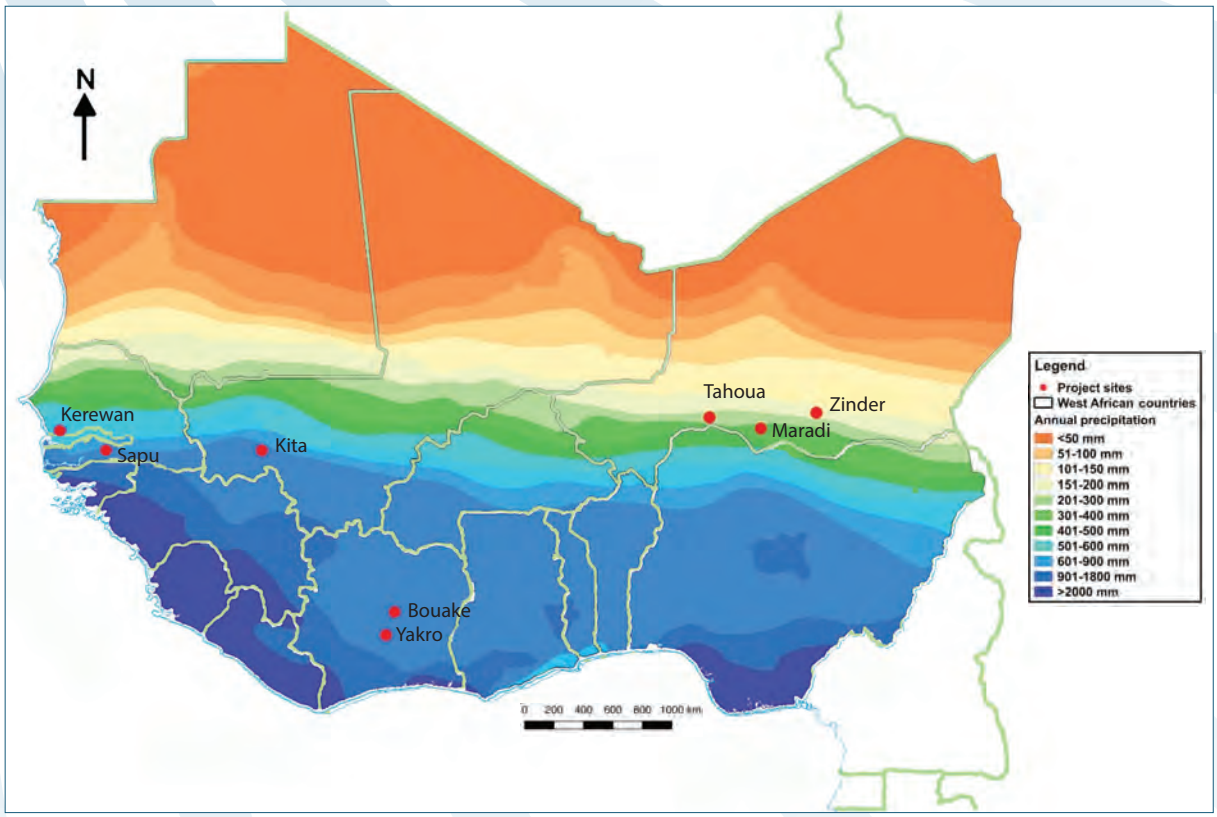
Annexes

Annex 1. List of project workshops

- **Country-phase inception workshop** – Bouaké, Côte d'Ivoire, 06/02/2017 - 08/02/2017
- **Training on the Self-evaluation and Holistic assessment of climate resilience of farmers and pastoralists (SHARP) tool** – Bouaké, Côte d'Ivoire, 09/02/2017 - 11/02/2017
- **National workshop on SHARP tool** – Banjul, the Gambia, 14/03/2017 - 17/03/2017
- **Regional workshop on the assessment of the impacts of climate change on crop yields with the AquaCrop tool** – Niamey, the Niger, 17/04/2018 - 21/04/2018
- **National validation workshop on the assessment of climate change impacts and resilience of rural communities in Niger** – Niamey, the Niger, 24/05/2018 - 24/05/2018
- **National validation workshop on the assessment of climate change impacts and resilience of rural communities in the ProDAF area in Mali** – Bamako, Mali, 25/05/2018 - 25/05/2018
- **Regional workshop on the calibration of the AquaCrop model** – Rome, Italy, 25/06/2018 - 27/06/2018
- **Regional validation workshop on the assessment of the impacts of climate change on crop yield with the AquaCrop model** – Abidjan, Côte d'Ivoire, 03/12/2018 - 07/12/2018

Annex 2. Observed climate trends in the project sites

Figure A2a. | Rainfall distribution across West Africa



Data source: AGRHYMET Regional Centre, 2018

The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers and boundaries.

Figure A2b. | Precipitation and temperature intra-annual variability on the project sites

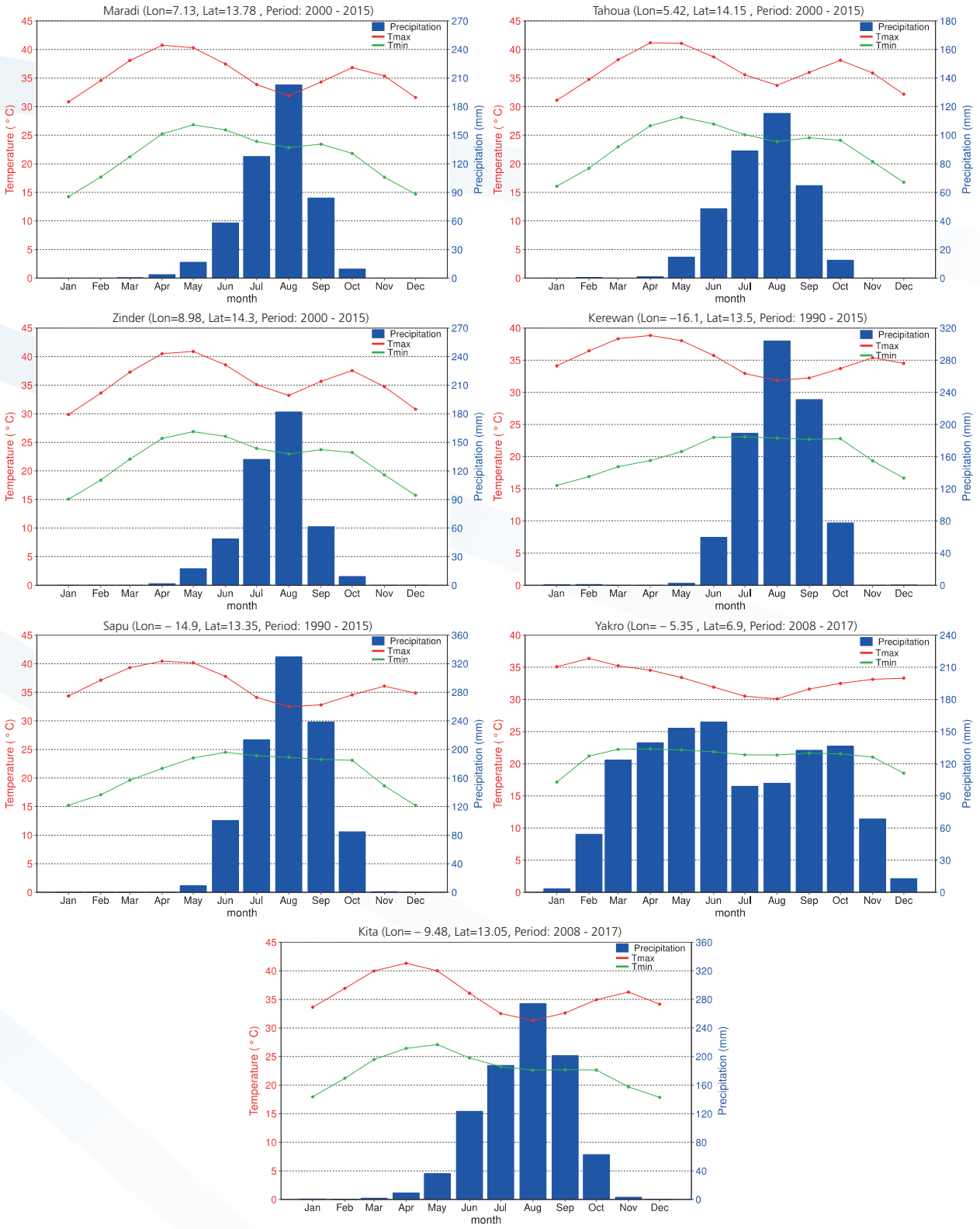


Figure A2c. | Annual precipitation trends on the project sites

Figure A2d. | Annual mean temperature trends on the project sites

Figure A2e. | ET (mm/day) intra-annual variability on the project sites

Annex 3. Comparison of climate trends from RCM control runs and observations

Figure A3a. | Annual precipitation cycle from RCM control runs and observations

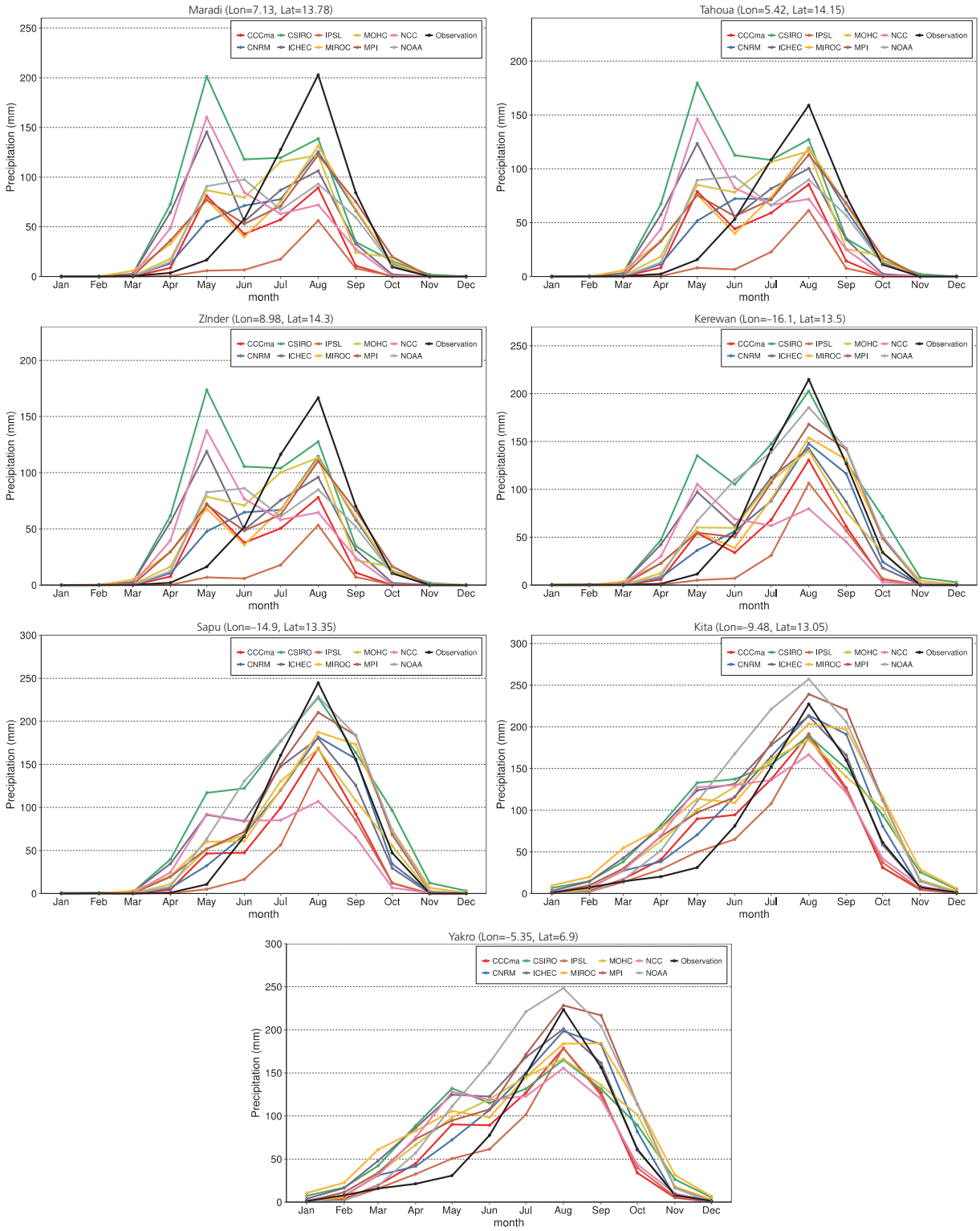


Figure A3b. | Annual mean temperature cycle from RCM control runs and observations

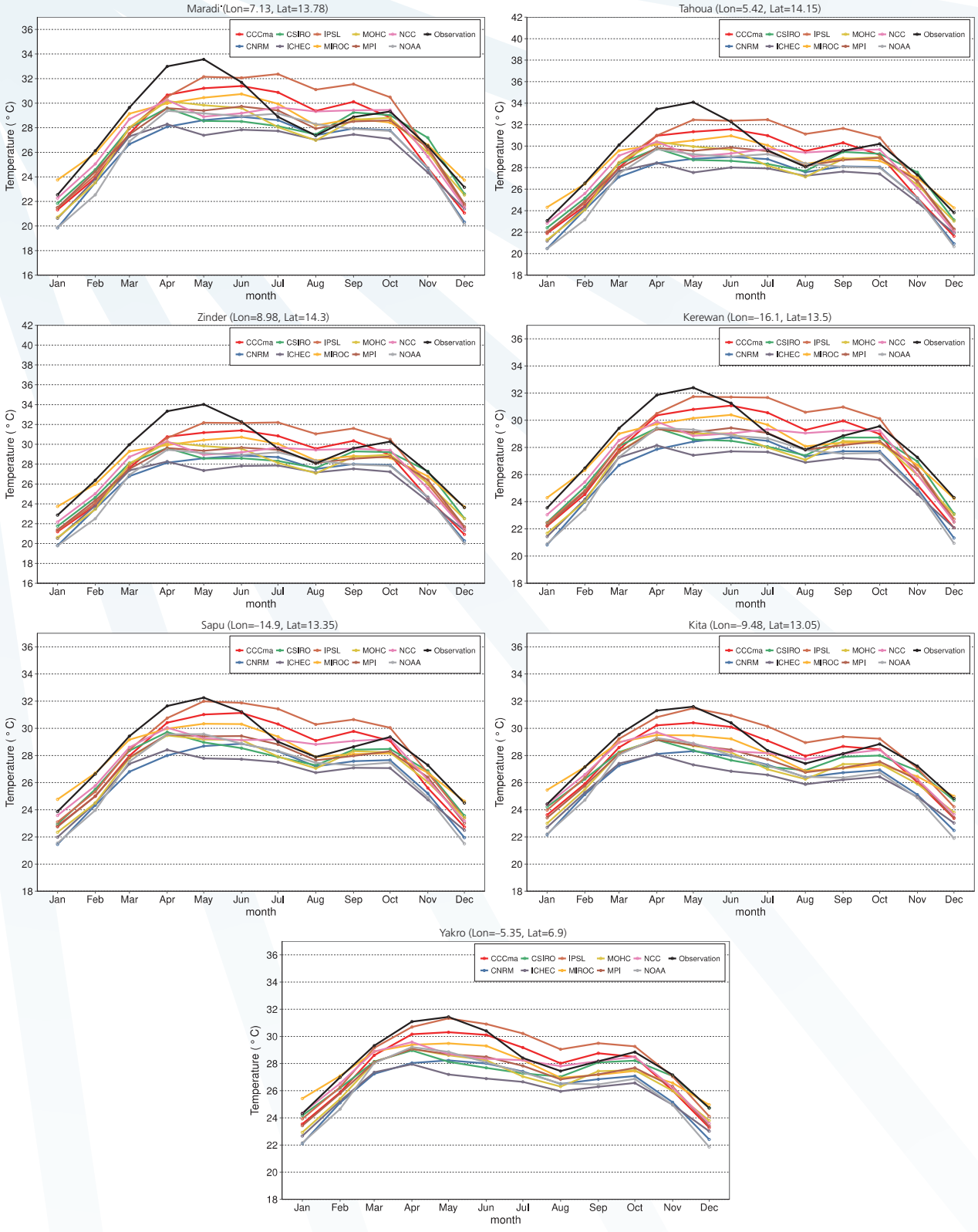
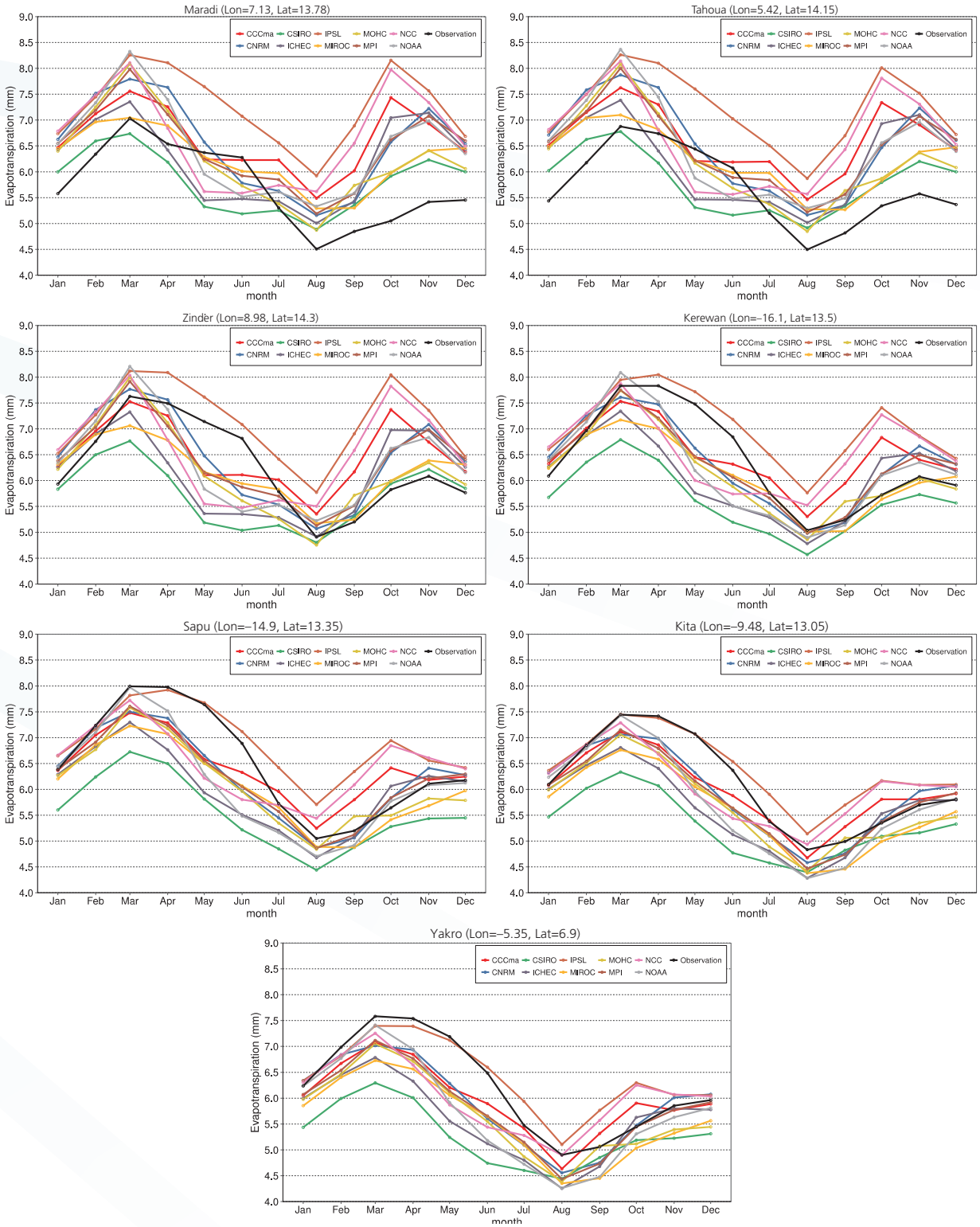
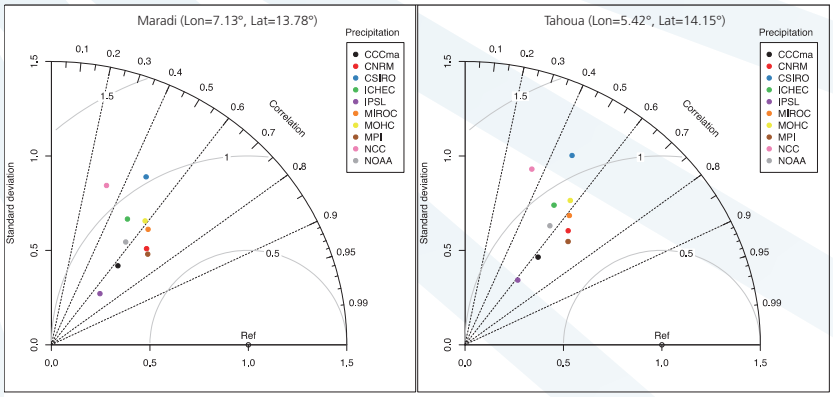


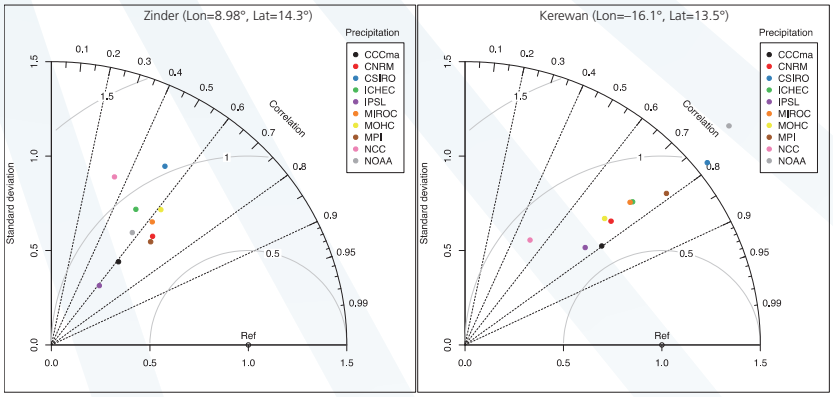
Figure A3c. | Annual ET (mm/day) cycle from RCMs control runs and observations

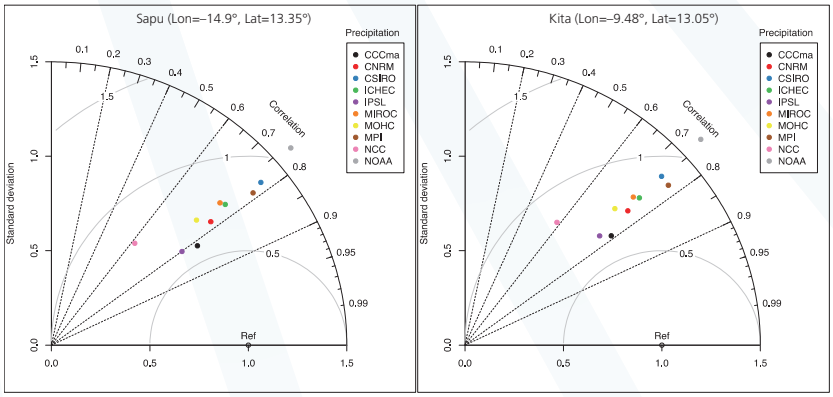


Annex 4. Taylor diagrams

Figure A4a. | Taylor diagrams of monthly precipitation (RCM vs observation)







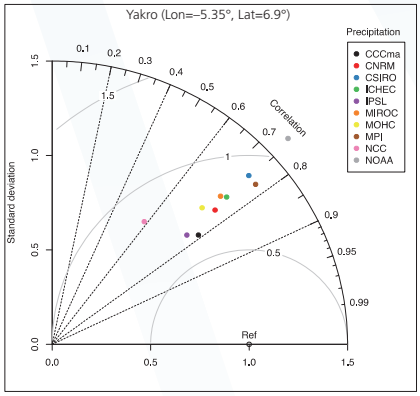


Figure A4b. | Taylor diagrams of monthly mean temperature (RCM vs observation)

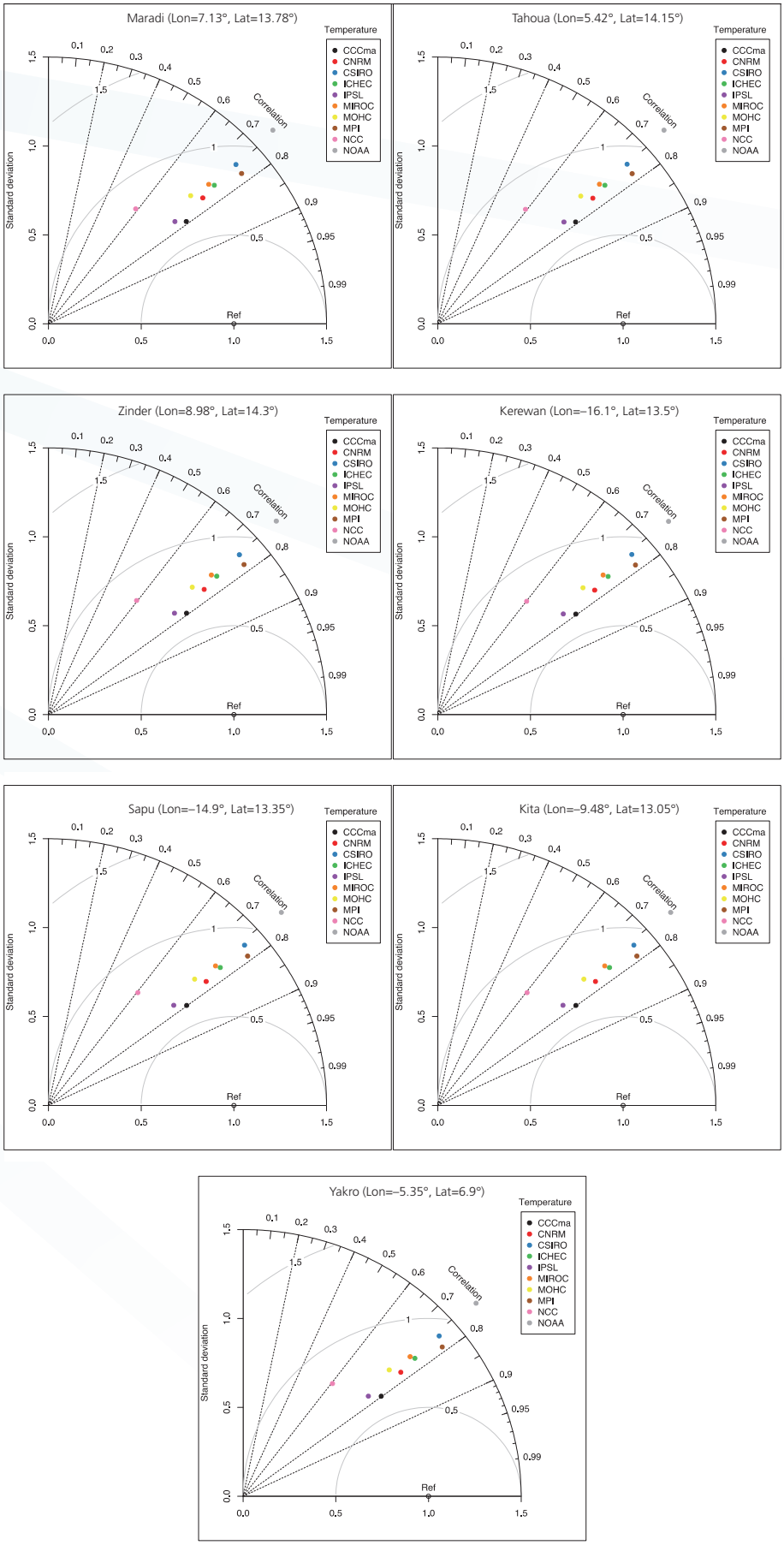
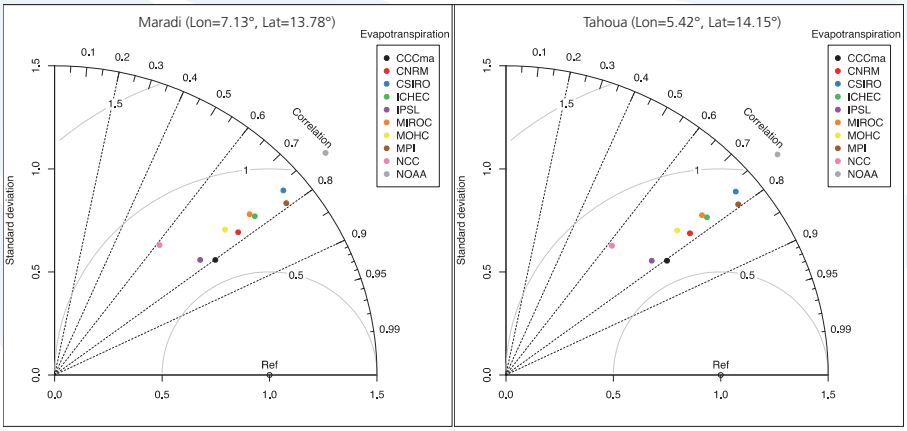
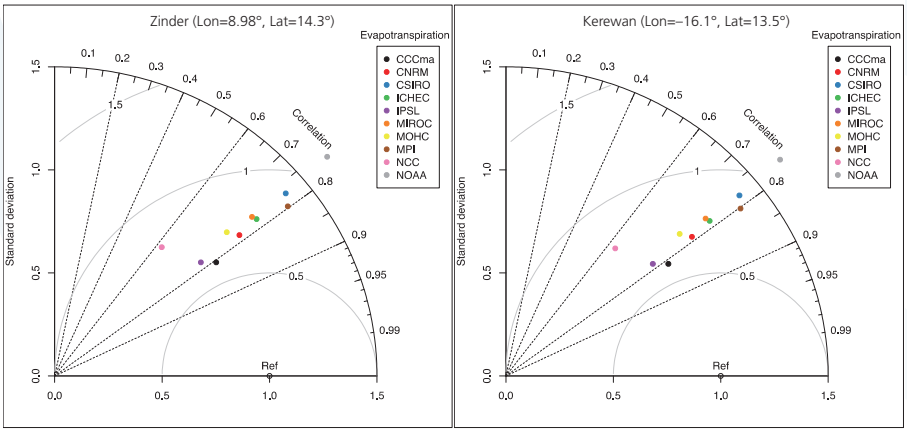
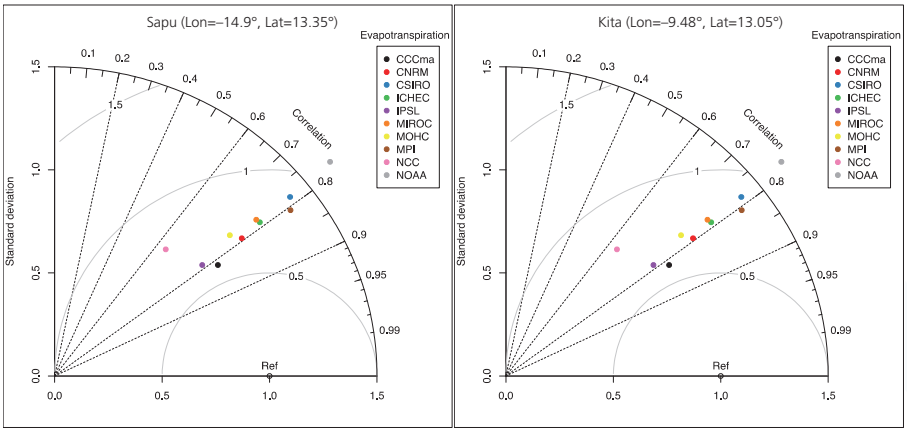
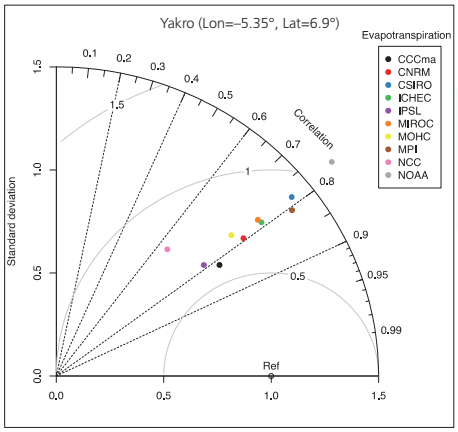


Figure A4c. | Taylor diagrams of monthly mean ET (RCM vs observation)









Annex 5. Crop files

- **Tomato (irrigated agriculture)**

Table A5.1. Selected sites and planting dates for irrigated tomatoes

Site	Country	Climatic station	Planting date
Falki	Niger	Zinder	1 October
Kita	Mali	Kita	15 October
Kpato	Côte d'Ivoire	Yakro	1 October

Table A5.2. Characteristics of the calibrated tomato crop

Characteristic	Value
Plant density	40 000 plants/ha or 4 plants/m² (initial canopy cover, CCo = 0.8%)
Maximum canopy cover (CCx)	70%
Calendar days from transplanting:	
▪ to recovered transplant	7 days
▪ to maximum canopy cover	60 days
▪ to maximum rooting depth	30 days
▪ to start of senescence	110 days
▪ to maturity	120 days
▪ to flowering	50 days
Length of flowering stage	50 days
Maximum effective rooting depth (Zrx)	0.50 m
Normalized biomass water productivity (WP*)	18 gram/m²
Reference harvest index (HIo)	63%
Performance under elevated CO_2 concentration	0%
Dry matter content of the fresh fruits	10%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	40%
▪ Reduction in canopy growth coefficient	24%
▪ Canopy cover decline from mid-season	0.08%/day
▪ Reduction in WP*	44%

To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 120 days was calculated for the three climatic sites for the period between 2008 and 2014. The required thermal times for the 120 days were: 1 945 for Zinder (the Niger), 1 985 for Kita (Mali) and 2 005 for Yakro (Côte d'Ivoire). A default base temperature for tomatoes of 7 °C and a default upper temperature of 30 °C were assigned. Given the small variation of the GDD in the region, a common value of 1 978 GDD was considered for all sites.

- **Rice (irrigated agriculture)**

Table A5.3. Selected sites and planting dates for irrigated rice

Site	Country	Climatic station	Planting date
Sapu	Gambia	Sapu	20 July
M'bé	Côte d'Ivoire	Yakro	1 June

Table A5.4. Characteristics of the calibrated irrigated rice crop

Characteristic	Value
Plant density	0.20 by 0.20 m 250 000 plants/ha or 25 plants/m²
	(initial canopy cover, CCo = 1.5%)
Maximum canopy cover (CCx)	90%
Calendar days from transplanting:	
▪ to recovered transplant	5 days
▪ to maximum canopy cover	45 days
▪ to maximum rooting depth	30 days
▪ to start of senescence	90 days
▪ to maturity	120 days
▪ to flowering	85 days
Length of flowering stage	7 days
Maximum effective rooting depth (Zrx)	0.50 m
Normalized biomass water productivity (WP*)	19 gram/m²
Reference harvest index (HIo)	43%
Performance under elevated CO_2 concentration	0%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	41%
▪ Reduction in canopy growth coefficient	25%
▪ Canopy cover decline from mid-season	0.07%/day
▪ Reduction in WP*	48%

To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 120 days was calculated for Sapu for the period between 2005 and 2015. The required thermal time for the 120 days was 2 218 GDD. A default base temperature of 8 °C and a default upper temperature of 30 °C for paddy rice were assigned.

- **Maize (irrigated agriculture)**

Table A5.5. Selected site and sowing date for irrigated maize

Site	Country	Climatic station	Sowing date
Soumarana	Niger	Maradi	1 October

Table A5.6. Characteristics of the calibrated irrigated maize crop

Characteristic	Value
Plant density	0.80 x 0.8 m 20 000 plants/ha or 2 plants/m²
	(initial canopy cover, CCo = 0.13%)
Maximum canopy cover (CCx)	75%
Calendar days from sowing:	
▪ to emergence	7 days
▪ to maximum canopy cover	45 days
▪ to maximum rooting depth	60 days
▪ to start of senescence	70 days
▪ to maturity	90 days
▪ to flowering	65 days
Length of flowering stage	10 days
Maximum effective rooting depth (Zrx)	0.80 m
Normalized biomass water productivity (WP*)	33.7 gram/m²
Reference harvest index (HIo)	35%
Performance under elevated CO_2 concentration	0%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	40%
▪ Reduction in canopy growth coefficient	24%
▪ Canopy cover decline from mid-season	0.18%/day
▪ Reduction in WP*	38%

To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 90 days was calculated for the period between 2000 and 2015. The required thermal time for the 90 days was 1 440 GDD. A default base temperature of 8 °C and a default upper temperature of 30 °C for maize were assigned.

- **Rice** (**rainfed agriculture**)

Table A5.7. Selected site and planting period for rainfed rice

Site	Country	Climatic station	Planting period
Kita	Mali	Kita	Between 1 June and 31 July: generated with a rainfall criterion of 40 mm in 5 days (second occurrence)

Table A5.8. Characteristics of the calibrated rainfed rice crop

Characteristic	Value
Plant density	0.20 by 0.20 m 250 000 plants/ha or 25 plants/m² (initial canopy cover, CCo = 1.5%)
Maximum canopy cover (CCx)	90%
Calendar days from transplanting:	
▪ to recovered transplant	7 days
▪ to maximum canopy cover	60 days
▪ to maximum rooting depth	32 days
▪ to start of senescence	105 days
▪ to maturity	135 days
▪ to flowering	80 days
Length of flowering stage	10 days
Maximum effective rooting depth (Zrx)	0.50 m
Normalized biomass water productivity (WP*)	19 gram/m²
Reference harvest index (HIo)	37%
Performance under elevated CO_2 concentration	0%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	40%
▪ Reduction in canopy growth coefficient	24%
▪ Canopy cover decline from mid-season	0.12%/day
▪ Reduction in WP*	47%

To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 135 days was calculated for the period between 2008 and 2017 by assuming that the crop was planted in 1 July. The required thermal time for the 135 days was 2 489 GDD. A default base temperature of 8 °C and A default upper temperature of 30 °C for paddy rice were assigned.

- **Maize (rainfed agriculture)**

Table A5.9. Selected sites and sowing period for rainfed maize

Site	Country	Climatic station	Sowing period
Kita	Mali	Kita	Between 1 May and 31 July – generated with a rainfall criterion of 20 mm in 2 days (2nd occurrence)
Kerewan	Gambia	Kerewan	

Table A5.10. Characteristics of the calibrated rainfed maize crop

Characteristic	Value
Plant density	0.80 x 0.8 m 20 000 plants/ha or 2 plants/m² (initial canopy cover, CCo = 0.13%)
Maximum canopy cover (CCx)	75%
Calendar days from sowing:	
▪ to emergence	7 days
▪ to maximum canopy cover	45 days
▪ to maximum rooting depth	60 days
▪ to start of senescence	70 days
▪ to maturity	90 days
▪ to flowering	65 days
Length of flowering stage	10 days
Maximum effective rooting depth (Zrx)	0.80 m
Normalized biomass water productivity (WP*)	33.7 gram/m²
Reference harvest index (Hlo)	35%
Performance under elevated CO_2 concentration	0%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	40%
▪ Reduction in canopy growth coefficient	24%
▪ Canopy cover decline from mid-season	0.18%/day
▪ Reduction in WP*	38%

To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 90 days was calculated by assuming sowing at 1 July for the common period between 2008 and 2015 for Kita (Mali) and Kerewan (the Gambia). The required thermal time was 1 647 GDD for Kita and 1 598 GDD for Kerewan. A default base temperature of 8 °C and A default upper temperature of 30 °C for maize were assigned. Given the small variation of the GDD in the region, a common value of 1 628 GDD was considered for both sites.

- **Sorghum** (**rainfed agriculture**)

Table A5.11. Selected site and sowing period for rainfed sorghum

Site	Country	Climatic station	Sowing period
Fachi	Niger	Tahoua	Between 1 May and 31 July: generated with a rainfall criterion of 20 mm in 2 days (second occurrence)

Table A5.12. Characteristics of the calibrated rainfed sorghum crop

Characteristic	Value
Plant density	40 000 plants/ha or 4 plants/m² (initial canopy cover, CCo = 0.12%)
Maximum canopy cover (CCx)	70%
Calendar days from sowing:	
▪ to emergence	7 days
▪ to maximum canopy cover	50 days
▪ to maximum rooting depth	60 days
▪ to start of senescence	80 days
▪ to maturity	90 days
▪ to flowering	55 days
Length of flowering stage	20 days
Maximum effective rooting depth (Zrx)	0.80 m
Normalized biomass water productivity (WP*)	33.7 gram/m²
Reference harvest index (HIo)	30%
Performance under elevated CO_2 concentration	0%
Calibration to soil fertility stress for a relative biomass production of 50%:	
▪ Reduction in maximum canopy cover	40%
▪ Reduction in canopy growth coefficient	24%
▪ Canopy cover decline from mid-season	0.14%/day
▪ Reduction in WP*	36%

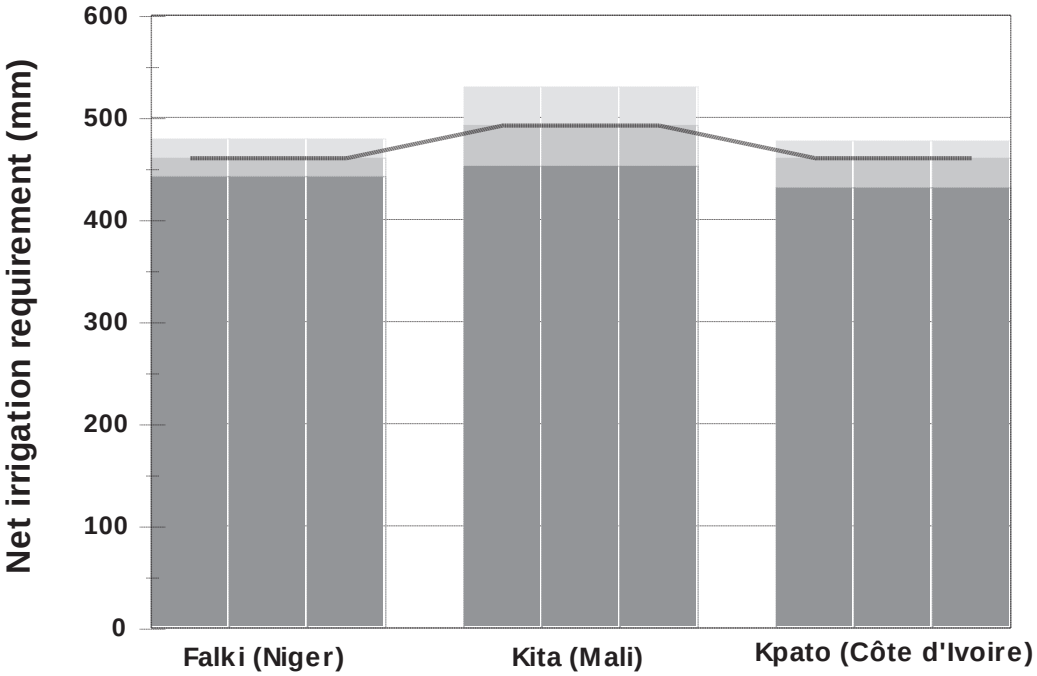
To convert the crop cycle, expressed in calendar days, to growing degree days (GDD), the mean required GDD to reach maturity in 90 days was calculated by assuming sowing at 1 July for the period between 2000 and 2015. The required thermal time is 1 728 GDD. A default base temperature of 8 °C and A default upper temperature of 30 °C for sorghum were assigned.

Annex 6. Simulation results for current climatic conditions

- **Net irrigation requirements under current management and climatic conditions for irrigated tomato, rice and maize**

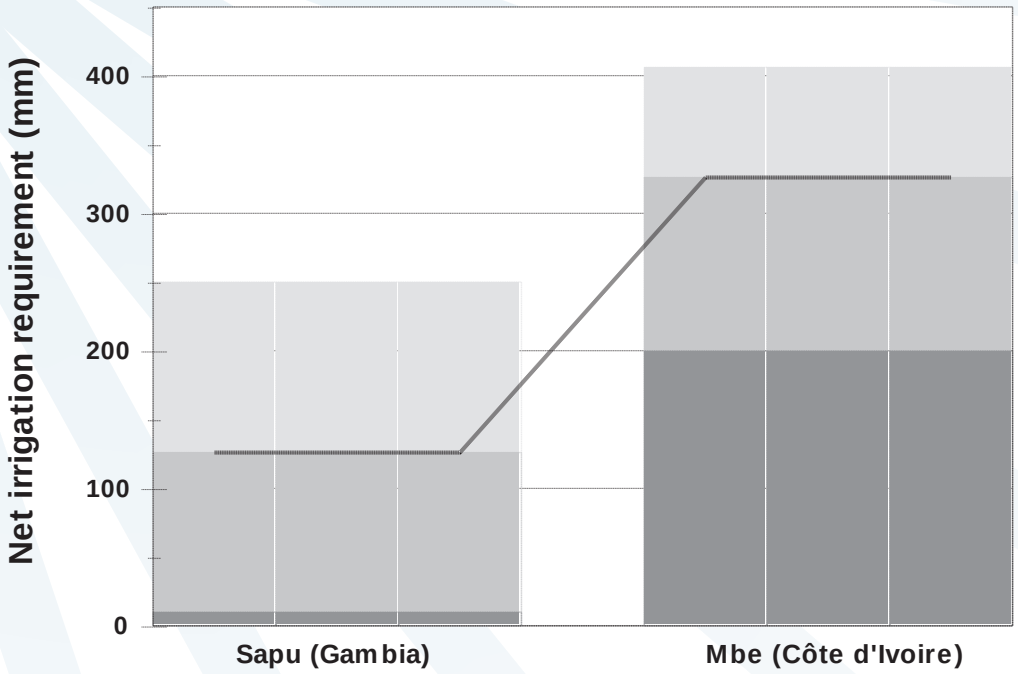
Irrigated tomato: The average net irrigation requirement (Inet) for tomato is 470 mm for the three sites. The variation of Inet over the years is small, since rainfall is minimal during the cold dry season in which the crop is cultivated (See Figure A6.1).

Figure A6.1. | Net irrigation requirement for tomato, with indication of low (dark bars), average (line) and high (light bars) requirements for the three sites



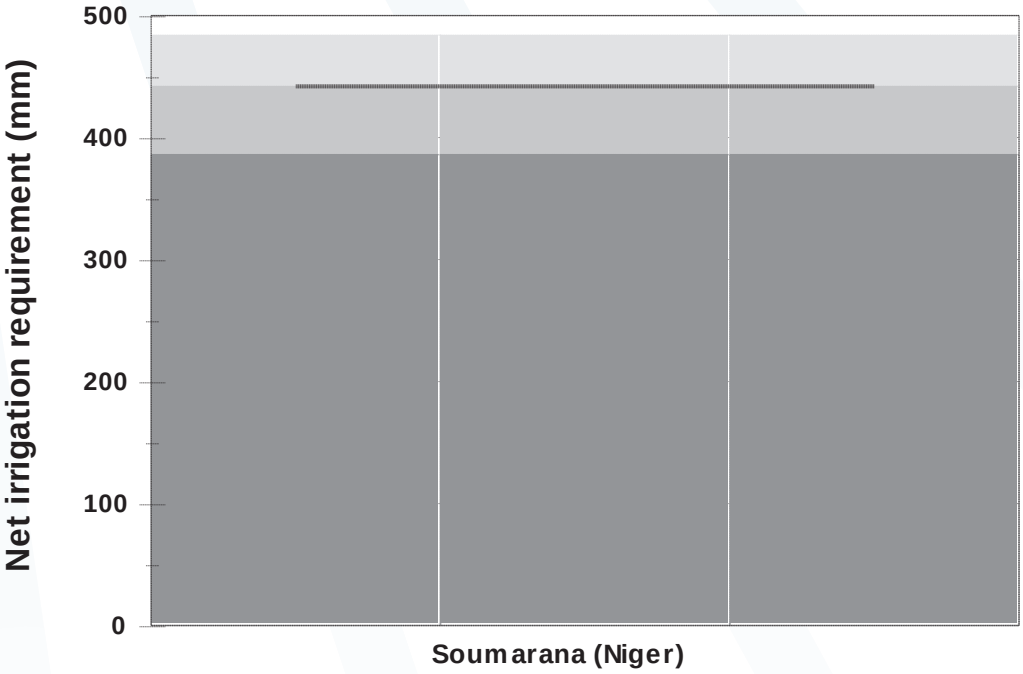
Irrigated rice: The average net irrigation requirement (Inet) for rice in both sites is linked to rainfall in the wet season in which the crop is cultivated. The average Inet is 126 mm for Sapu (the Gambia) and 326 mm for M'bé (Côte d'Ivoire). The variation of Inet over the years is important since rainfall varies substantially from year to another (See Figure A6.2).

Figure A6.2. | Net irrigation requirement for rice, with indication of low (dark bars), average (line) and high (light bars) requirements for the two sites



Irrigated maize: The average net irrigation requirement (Inet) for maize is 442 mm for Soumarana (the Niger). The variation of Inet over the years is slight, since rainfall is minimal during the cold dry season in which the crop is cultivated (See Figure A6.3).

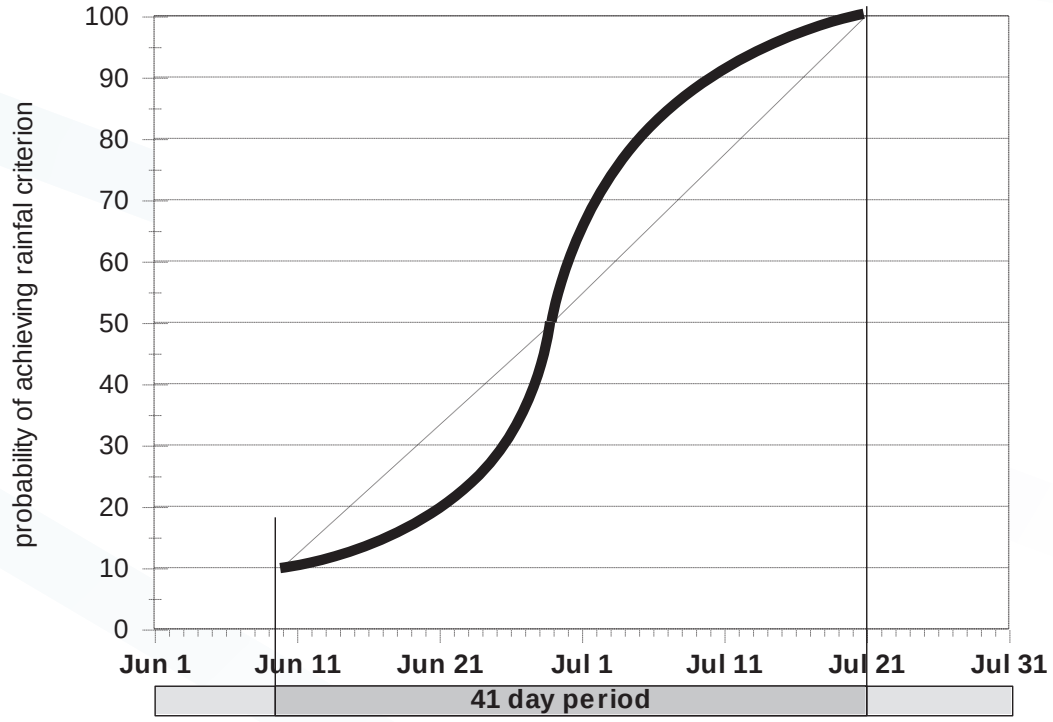
Figure A6.3. | Net irrigation requirement for maize with indication of low (dark bars), average (line) and high (light bars) requirements for the two sites



- Sowing or planting period under current climatic conditions for rainfed rice, maize and sorghum

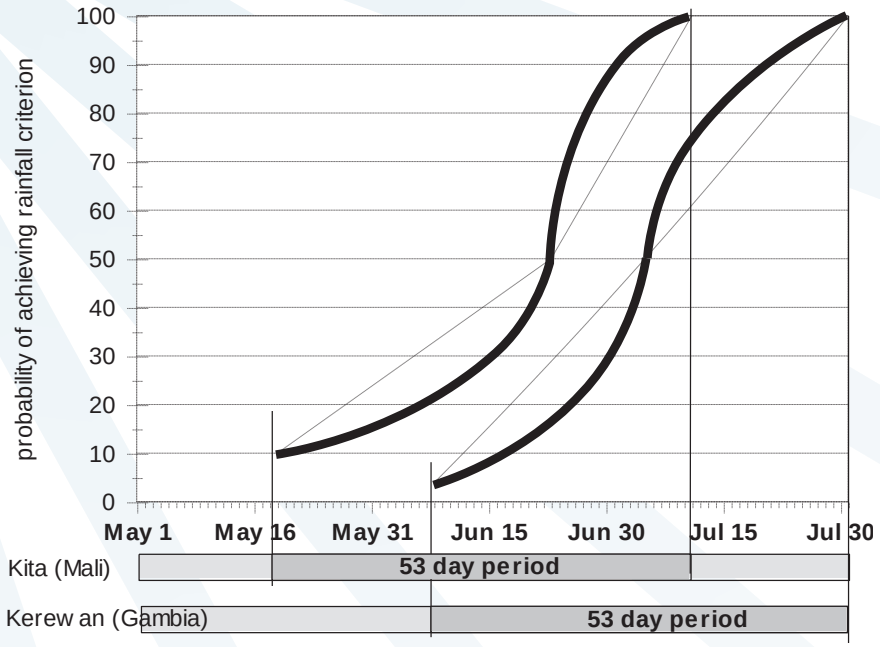
Rainfed rice: The selected rainfall criterion (second occurrence of 40 mm in 5 days) was easily met within the designated time window (1 June-31 July) for rainfed rice. In the 2008-2017 period, sufficient rainfall for planting occurred as early as 10 June. In each year, planting could take place before or at the latest on 21 July (See Figure A6.4).

Figure A6.4. | Probability of achieving rainfall criterion (second occurrence of 40 mm in 5 days) for planting rice within the time window (1 June-31 July) for Kita (2008-2017)



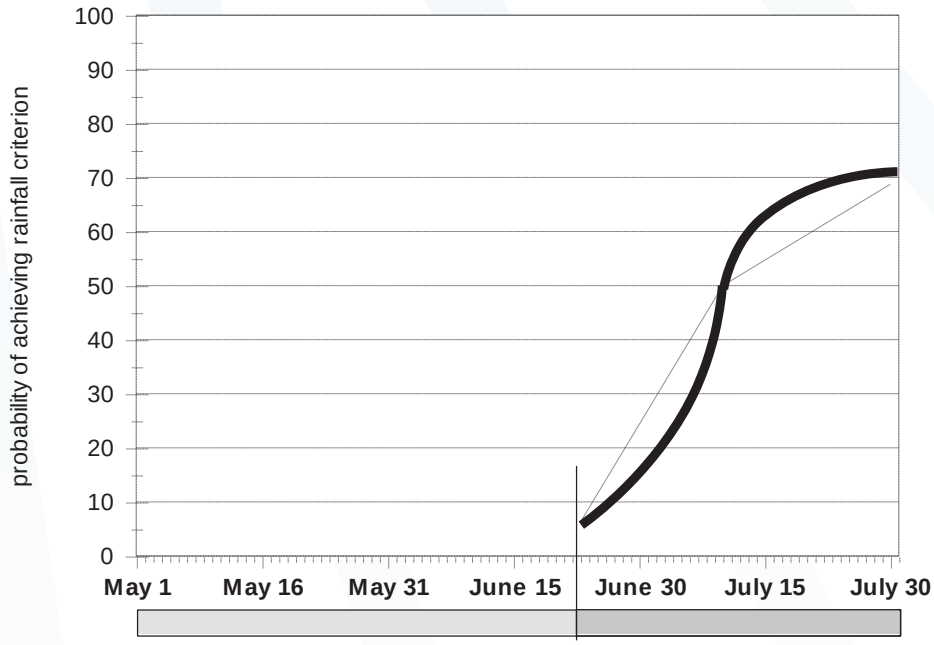
Rainfed maize: The selected rainfall criterion (second occurrence of 20 mm in 2 days) was met within the designated time window (1 May-31 July) for rainfed maize. In the 2008-2017 period, sowing in Kita started as early as 19 May and was finalized at or before 11 July. In Kerewan, the sowing period started 20 days later, at the earliest on 8 June and was finalized on or before 31 July (See Figure A6.5).

Figure A6.5. | Probability of achieving rainfall criterion (second occurrence of 20 mm in 2 days) for sowing maize within the time window (1 May-31 July) for Kita (2008-2017) and Kerewan (1990-2015)



Rainfed sorghum: The selected rainfall criterion (second occurrence of 20 mm in 2 days) could not always be met within the designated time window (1 May-31 July) for rainfed sorghum. In the 2000-2015 period, rainfall was sufficient to generate a sowing date at the earliest on 23 June. In five out of the 16 years (31 percent of occurrence), the rainfall criterion was not met before 31 July (See Figure A6.6).

Figure A6.6. | Probability of achieving rainfall criterion (second occurrence of 20 mm in 2 days) for sowing sorghum within the time window (1 May-31 July) for Fachi (2000-2015)



- **Recommendations for soil fertility management under current management and climatic conditions**

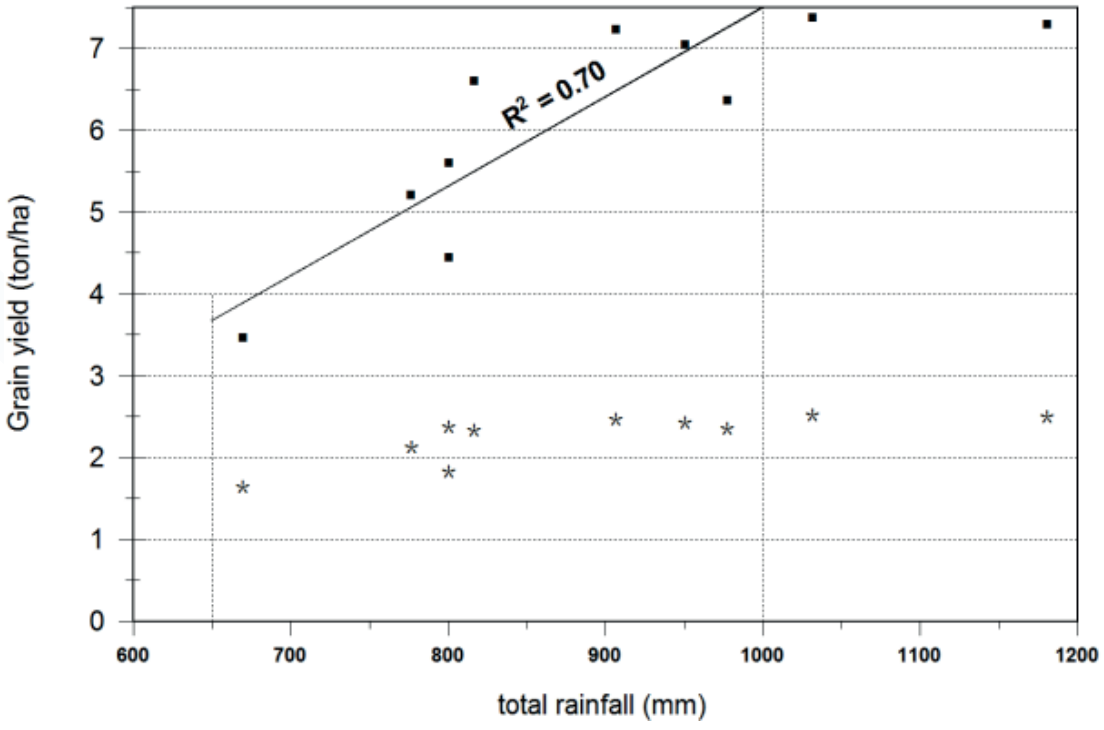
Irrigated tomato: In the absence of water stress in irrigated agriculture, it is soil fertility that severely limits the production of tomato. Given nearly optimal soil fertility, the fresh yield of irrigated tomatoes can rise to about 70 tonnes/ha (80 percent of the maximum yield), assuming that pests and diseases, harvest and post-harvest losses can be limited.

Irrigated rice: Good rice yields can be obtained in Sapu (the Gambia) with a near optimal fertilizer management. In the absence of water stress in irrigated agriculture, it is soil fertility that limits rice production in M'bé. Given nearly optimal soil fertility, the yield of the irrigated rice in Mbe can rise to about 6.5 tonnes/ha (80% of the maximum yield).

Irrigated maize: In the absence of water stress in irrigated agriculture, it is soil fertility that severely limits the production of maize. Given nearly optimal soil fertility, the yield of the irrigated maize can almost double to about 4.5 tonnes/ha (80 percent of the maximum yield), assuming that pests and diseases, harvest and post-harvest losses can be limited.

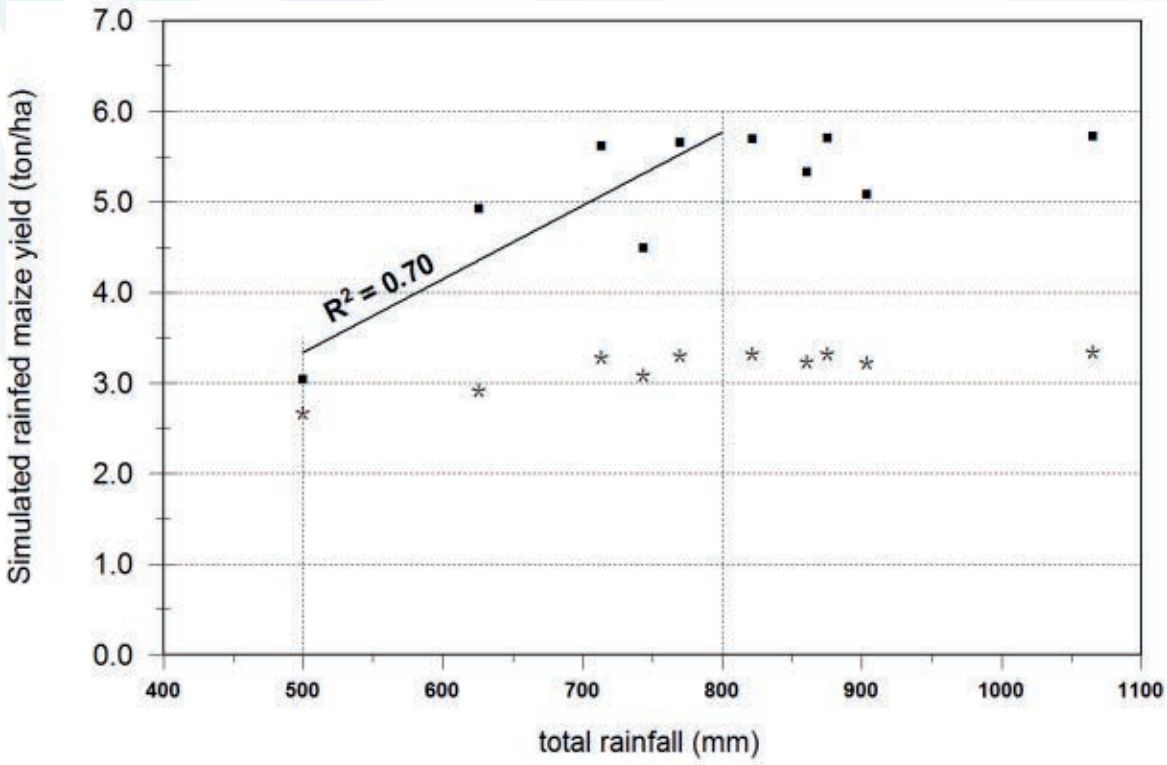
Rainfed rice: The difference between the simulated yield with optimal soil fertility (maximum yield) and the yield with poor soil fertility (calibrated yield) for rainfed rice is important, even in the driest year (See Figure A6.7). This indicates that field management practices are not well adapted to the area. Since rainfall is important for the region, a much greater yield could have been obtained with higher soil fertility, even in the driest year. Analysis of the simulation results in the various years indicate that yield might almost double each year with moderately improved soil fertility.

Figure A6.7. | The total rainfall (from 1 April to maturity) and the corresponding simulated maximum (square) and calibrated (asterisk) grain yield for rainfed rice for Kita (2008 - 2017), with indication of the trend line and R^2 for the maximum yield (range: 650-1 000 mm)



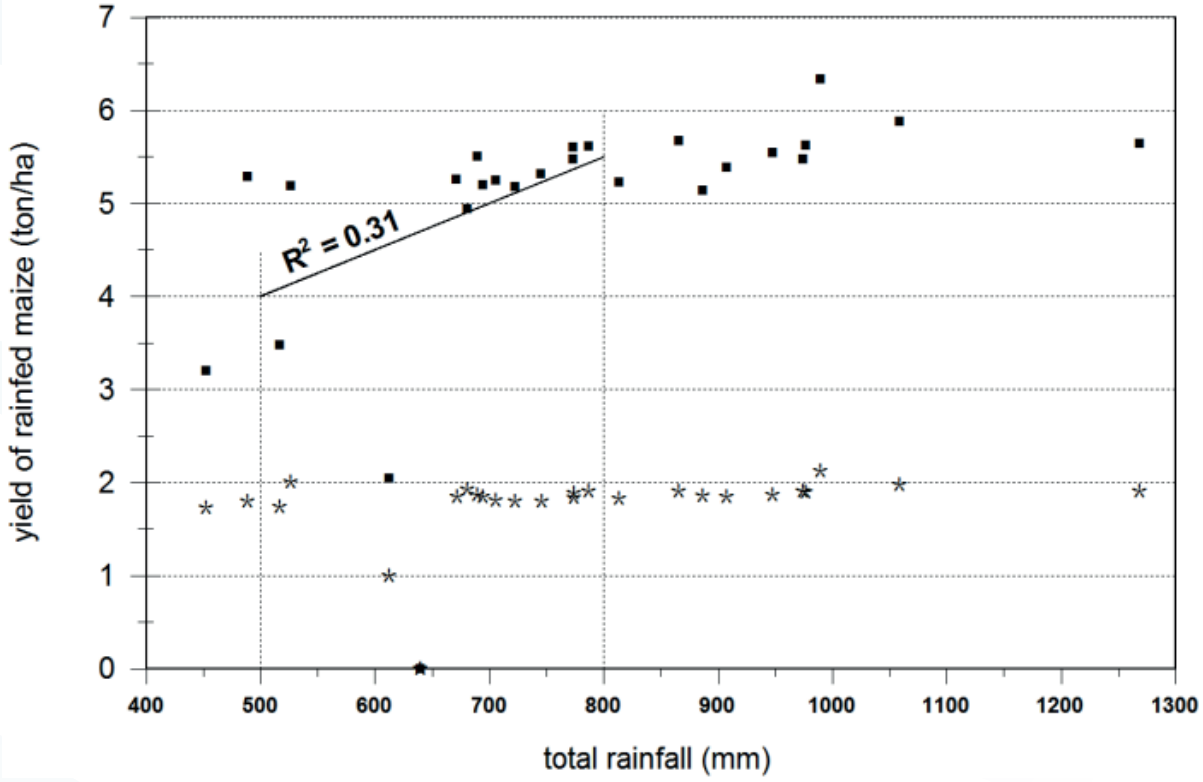
Rainfed maize: In Kita, the simulation indicated that a similar yield for rainfed maize could be obtained in the driest year with, on the one hand, unlimited and, on the other hand, moderate soil fertility (See Figure A6.8). This indicates that moderate soil fertility is a good (although conservative) field management strategy for the region.

Figure A6.8. | The total rainfall (from 1 April to maturity) and the corresponding simulated maximum (square) and calibrated (asterisk) grain yield for rainfed maize for Kita (Mali), with an indication of the trend line and R^2 for the maximum yield (range: 500-800 mm)



In Kerewan, the difference between simulated yield with unlimited soil fertility (maximum yield) for rainfed maize and yield with poor soil fertility is important, even in the driest year (See Figure A6.9). This indicates that field management practices are not well adapted to the region. Since rainfall is important for the region, much greater yield, could have been obtained with higher soil fertility, even in the driest year.

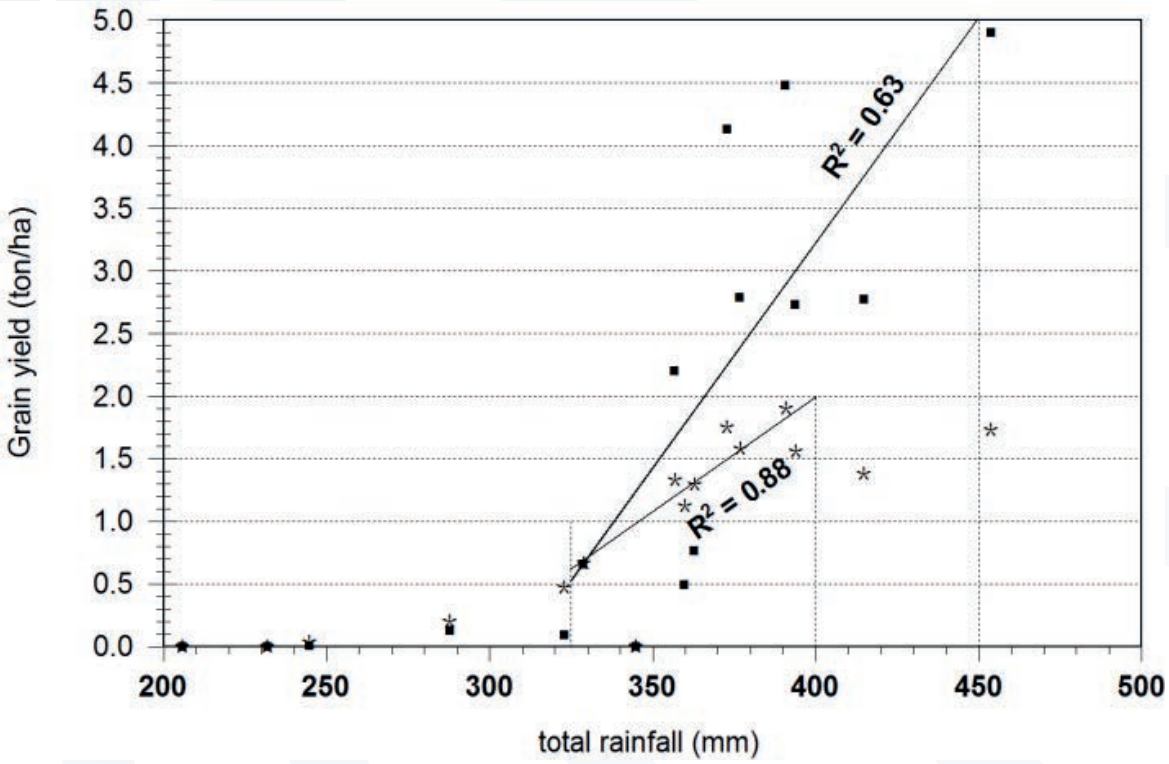
Figure A6.9. | The total rainfall (from 1 April to maturity) and the corresponding simulated maximum (square) and calibrated (asterisk) grain yield for rainfed maize for Kerewan (Gambia), with indication of the trend line and R^2 for the maximum yield (range: 500-800 mm)



Comparing results with Kita, the simulations indicate that by increasing soil fertility from poor to moderate, the average yield could increase by one third (from 2 to 3 tonnes/ha), assuming that pest and diseases, harvest and post-harvest losses can be limited.

Rainfed sorghum: The difference between the simulated yield with optimal soil fertility (maximum yield) and yield with poor soil fertility (calibrated yield) for rainfed sorghum is not significant in over half of the years (See Figure A6.10). This indicates that poor soil fertility is a good field management strategy for this region. The crop yield could have been doubled with a higher soil fertility in wet years only.

Figure A6.10. | The total rainfall (from 1 April to maturity) and the corresponding simulated maximum (square) and calibrated (asterisk) grain yield for rainfed sorghum (2000-2015) for Fachi (Niger) with indication of the trend lines and R^2 for the simulated maximum yield (range 325-450 mm) and for the calibrated yield (range 325-400 mm)



Annex 7. Simulation results for future climatic conditions

- **Box plots with relative yield change for two time horizons and two scenarios under current management conditions**

Figure A7.1. | Relative yield change for irrigated tomato in Zinder (Falki, Niger) for two time horizons (2030 and 2050, under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

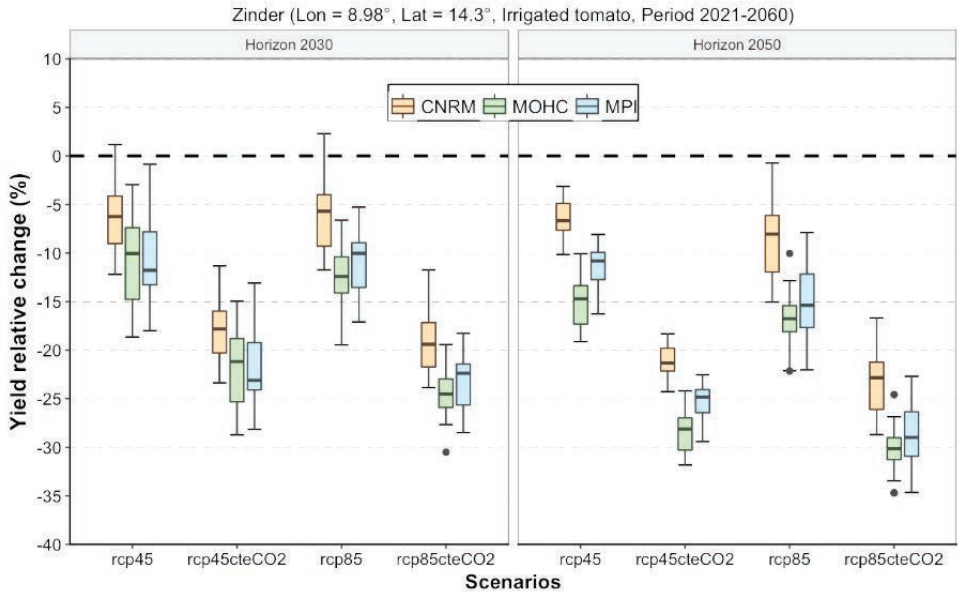


Figure A7.2. | Relative yield change for irrigated tomato in Kita (Kita, Mali) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

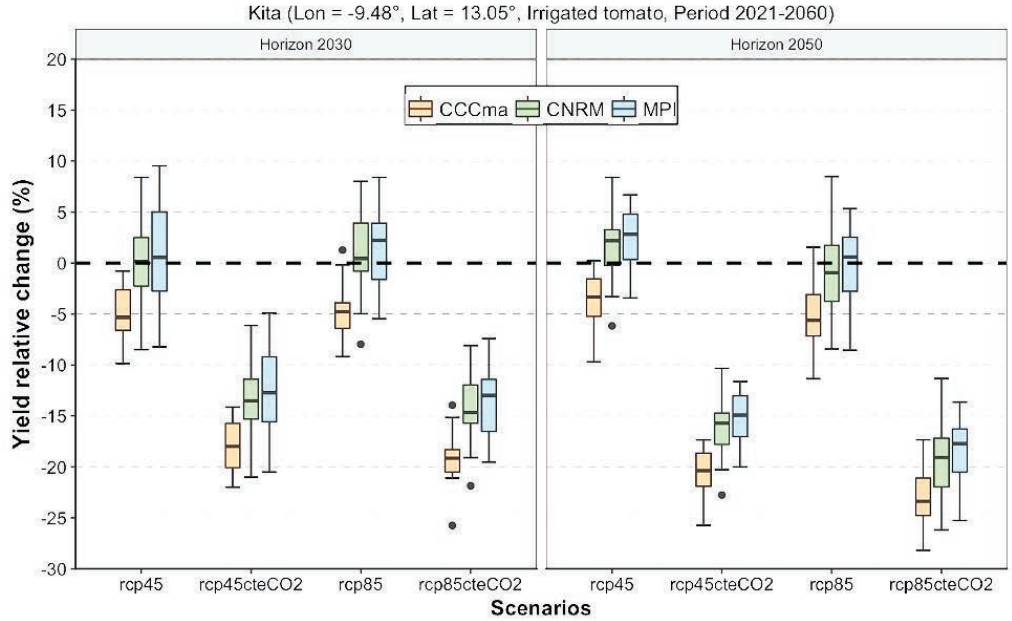


Figure A7.3. | Relative yield change for irrigated tomato in Yakro (Kpato, Côte d'Ivoire) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

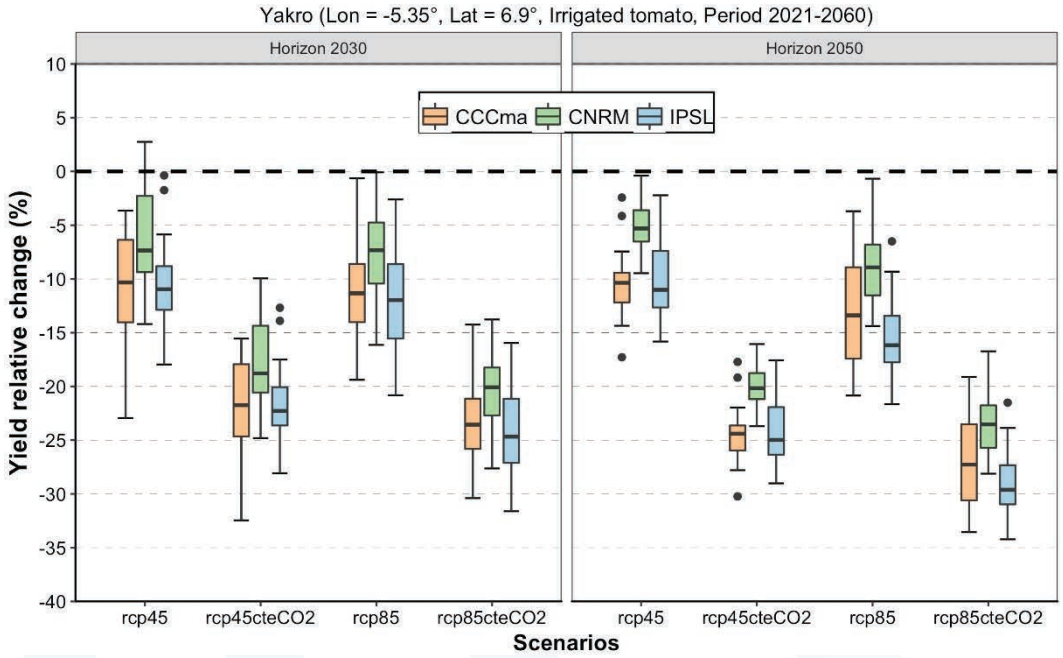


Figure A7.4. | Relative yield change for irrigated rice in Yakro (Mbe, Côte d'Ivoire) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

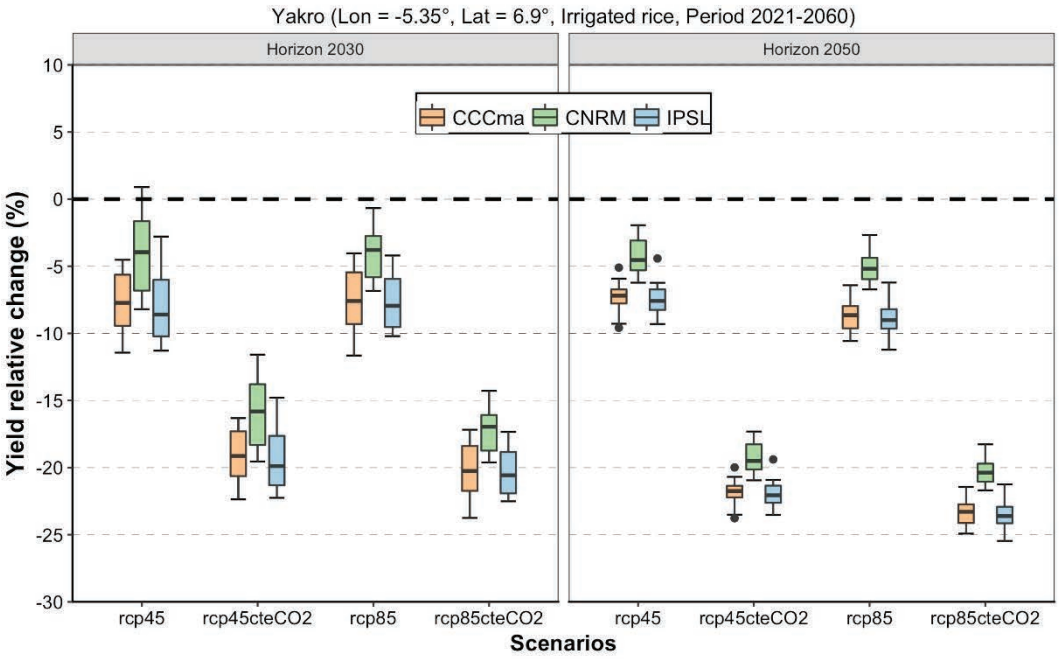


Figure A7.5. | Relative yield change for irrigated rice in Sapu (Sapu, Gambia) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

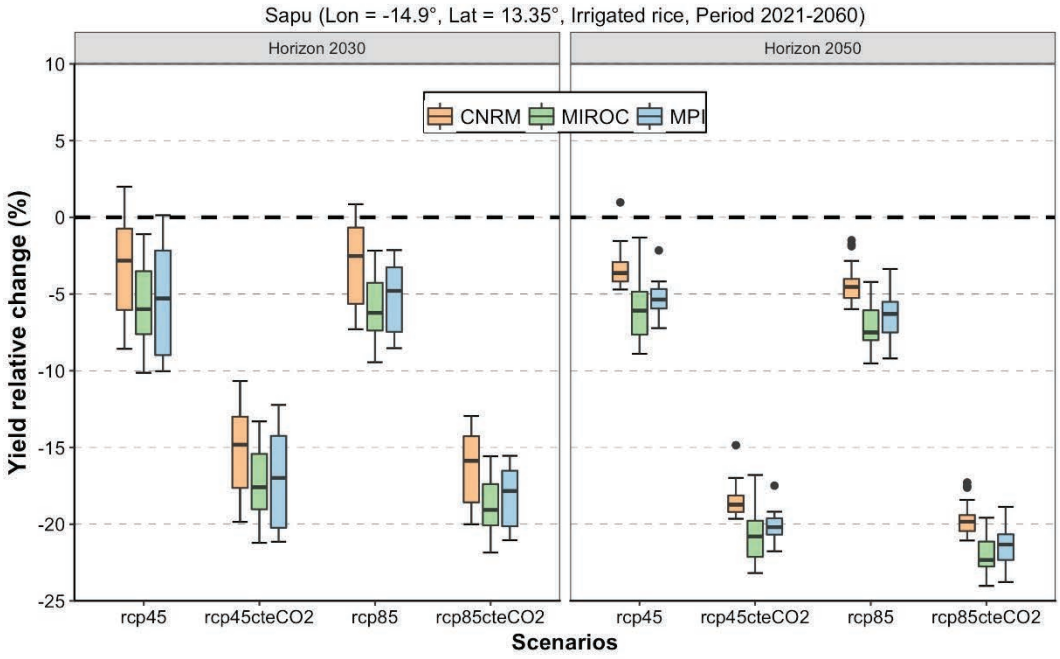


Figure A7.6. | Relative yield change for irrigated maize in Maradi (Soumarana, Niger) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

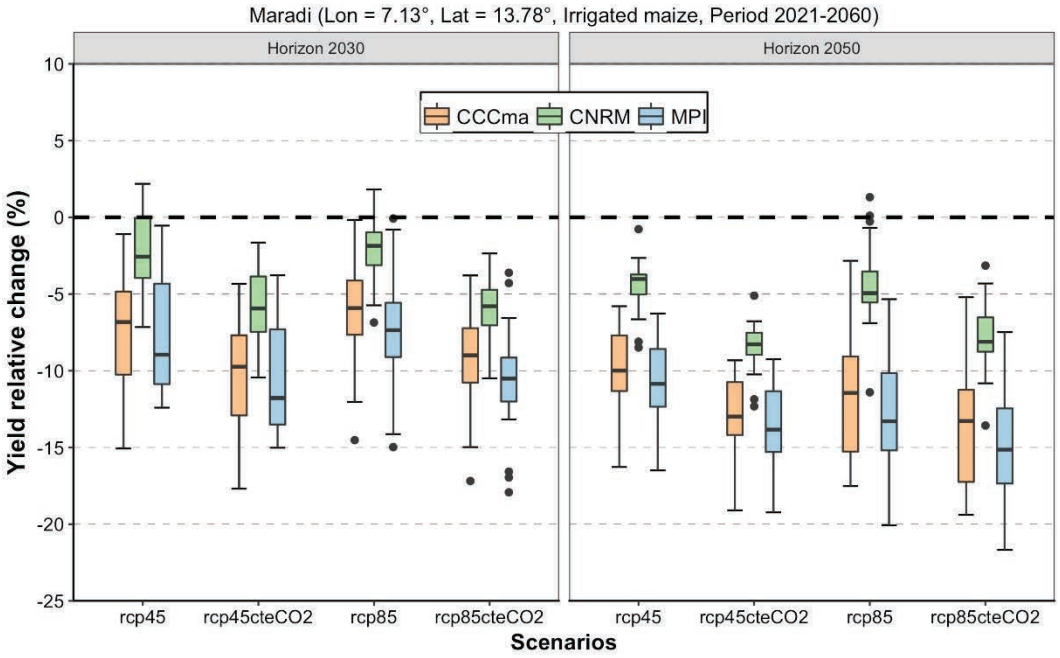


Figure A7.7. | Relative yield change for rainfed rice in Kita (Kita, Mali) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

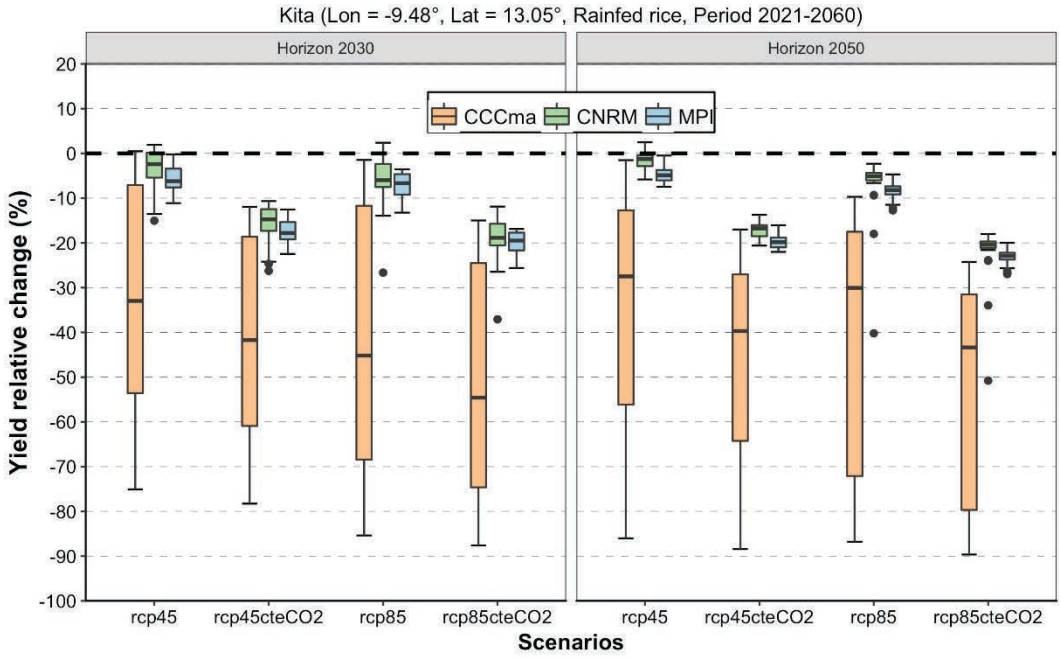


Figure A7.8. | Relative yield change for rainfed maize in Kita (Kita, Mali) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

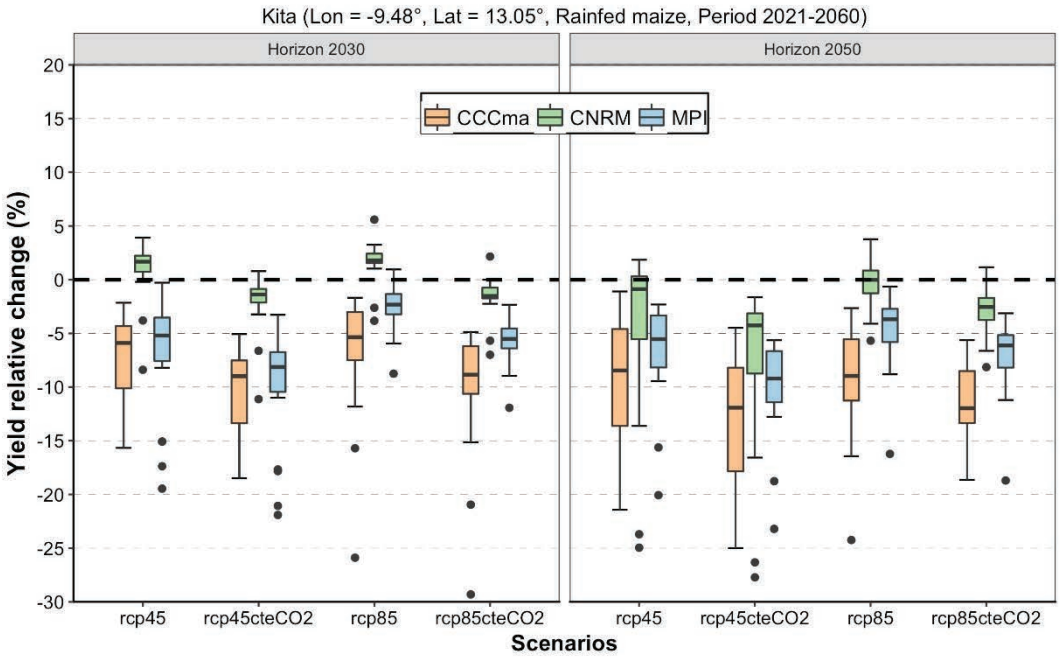


Figure A7.9. | Relative yield change for rainfed maize in Kerewan (Kerewan, Gambia) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization

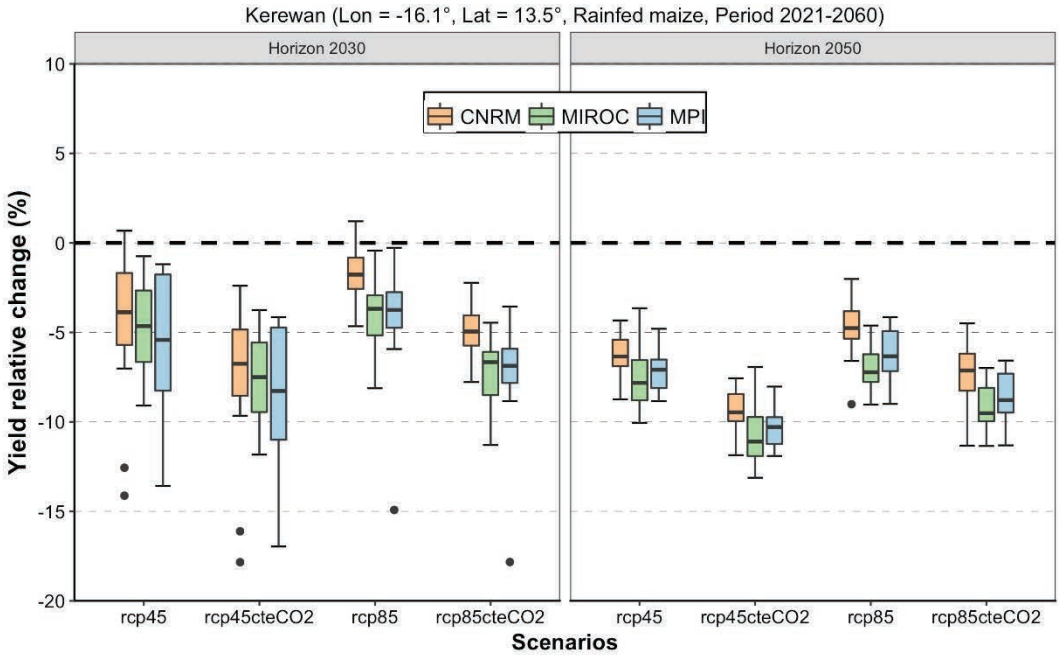
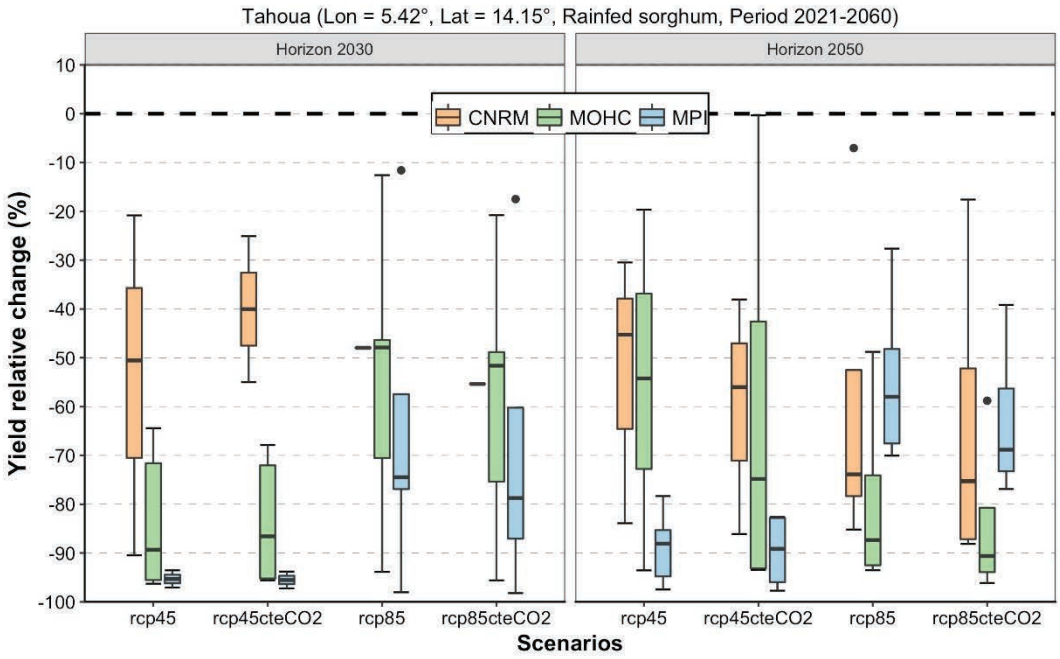


Figure A7.10. | Relative yield change for rainfed sorghum in Tahoua (Fachi, Niger) for two time horizons (2030 and 2050), under actual management conditions and based on two scenarios (RCP4.5 and RCP8.5): without (cteCO2) and with CO_2 fertilization



- **Box plots with relative yield change under improved and optimal management conditions, for two time horizons and scenario RCP8.5**

Figure A7.11. | Relative yield change for irrigated tomato in Zinder (Falki, Niger) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

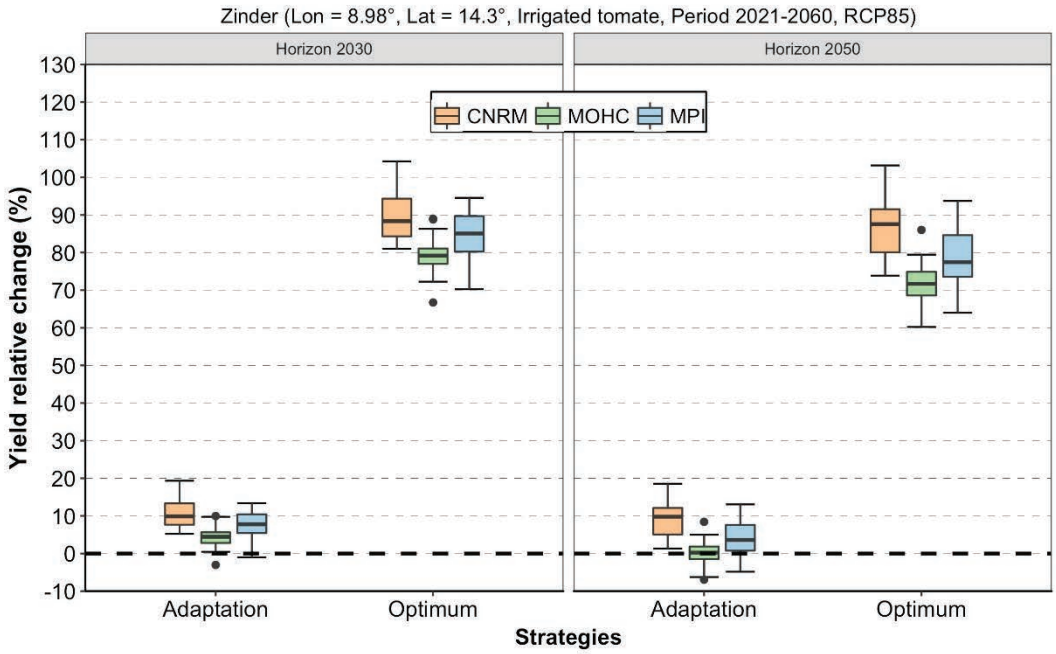


Figure A7.12. | Relative yield change for irrigated tomato in Kita (Kita, Mali) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

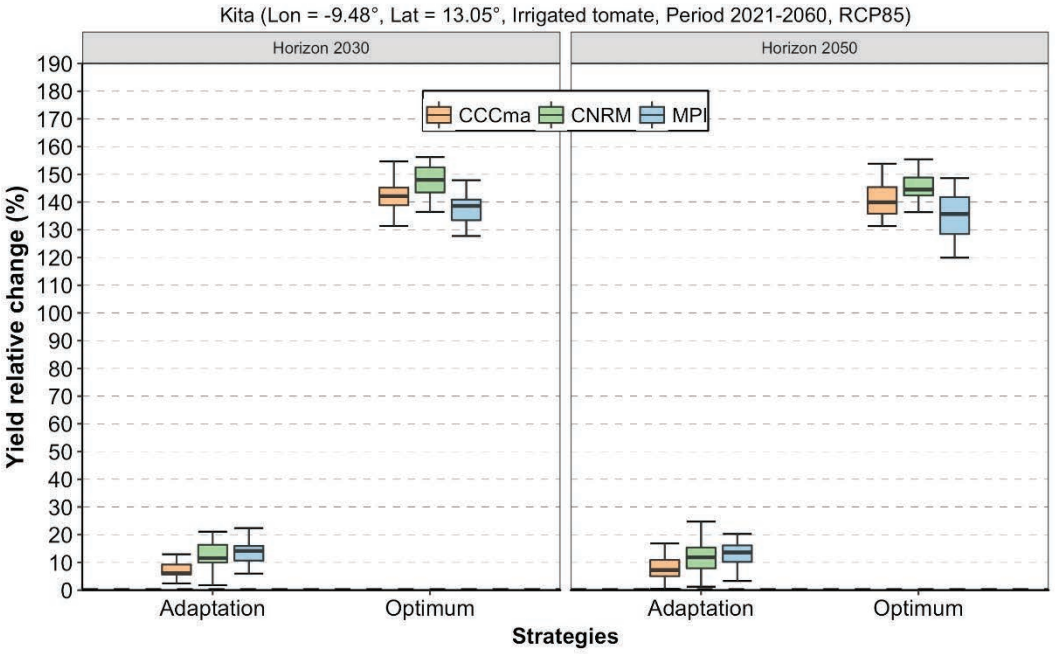


Figure A7.13. | Relative yield change for irrigated tomato in Yakro (Kpato, Côte d'Ivoire) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

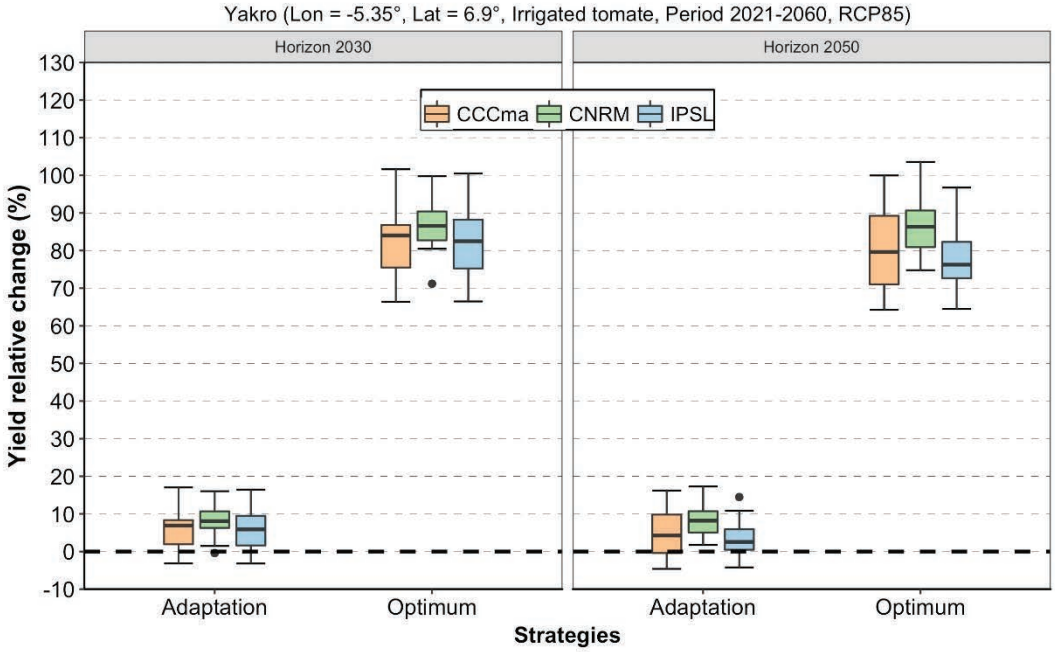


Figure A7.14. | Relative yield change for irrigated rice in Yakro (Mbe, Côte d'Ivoire) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

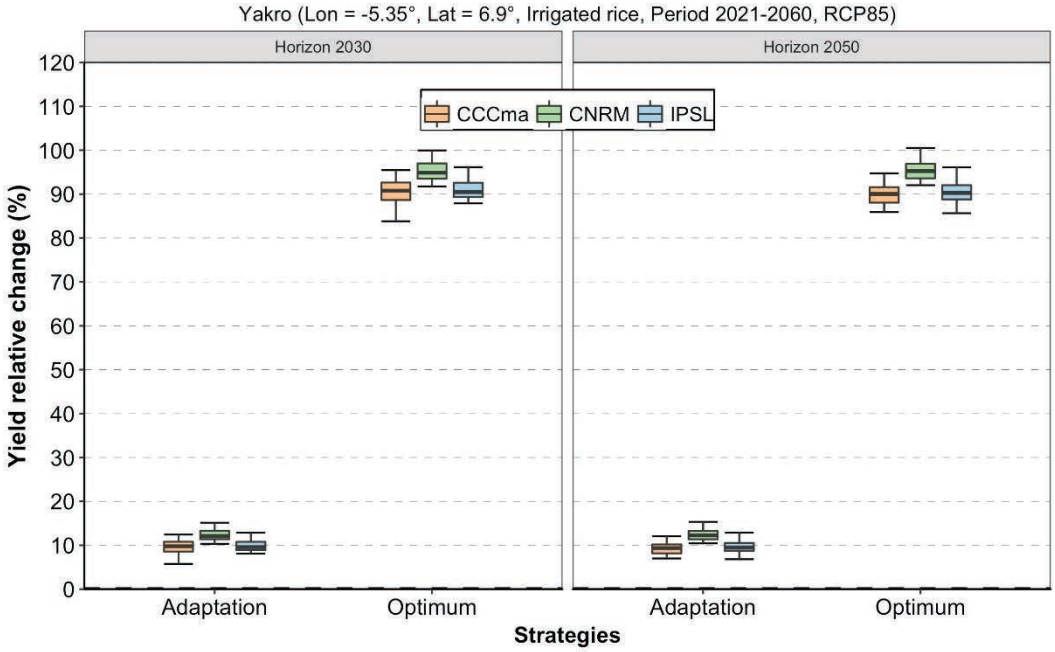


Figure A7.15. | Relative yield change for irrigated rice in Sapu (Sapu, Gambia) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

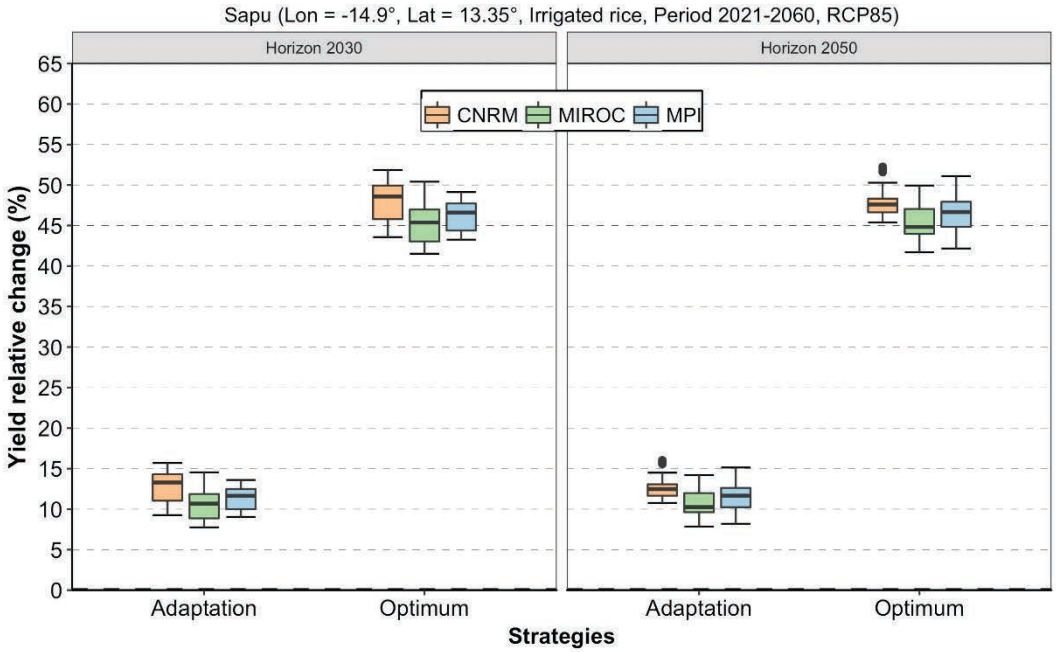


Figure A7.16. | Relative yield change for irrigated maize in Maradi (Soumarana, Niger) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

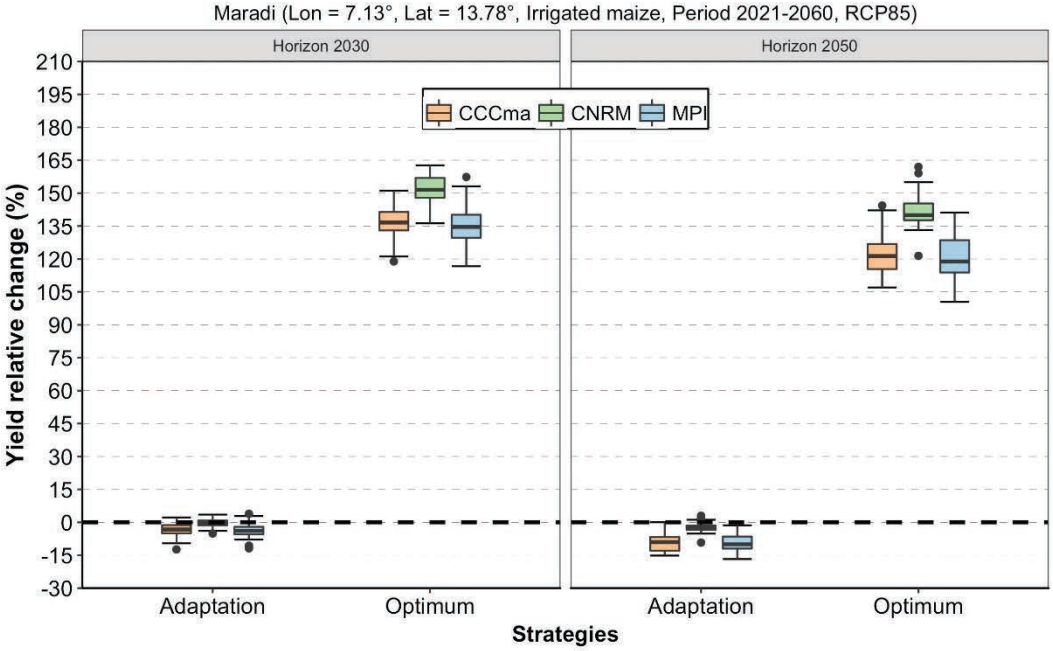


Figure A7.17. | Relative yield change for rainfed rice for Kita (Kita, Mali) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

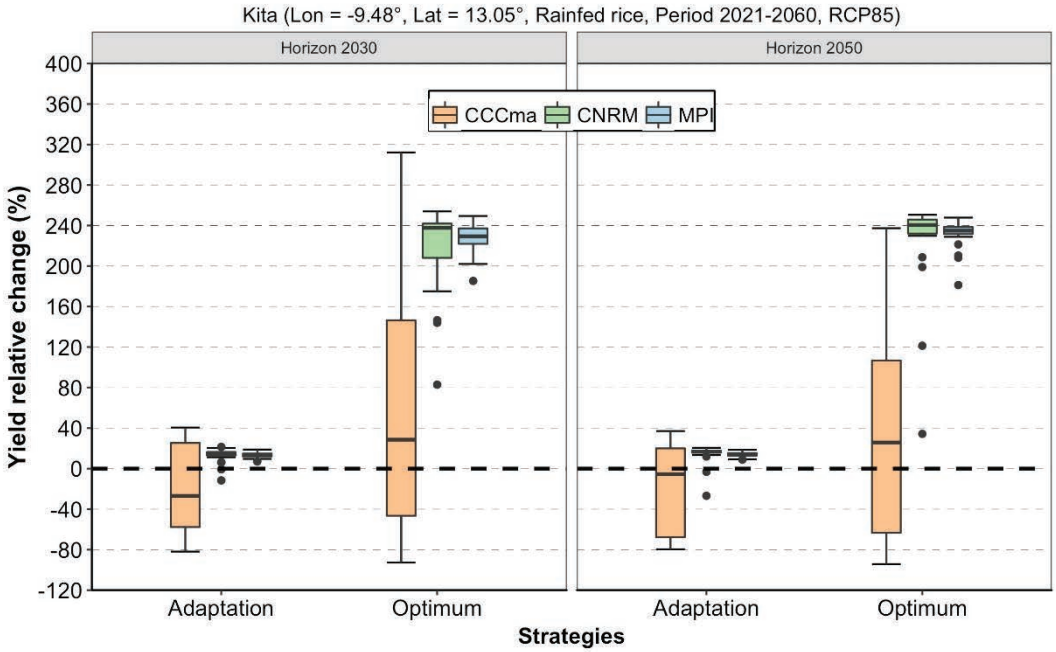


Figure A7.18. | Relative yield change for rainfed maize in Kita (Kita, Mali) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

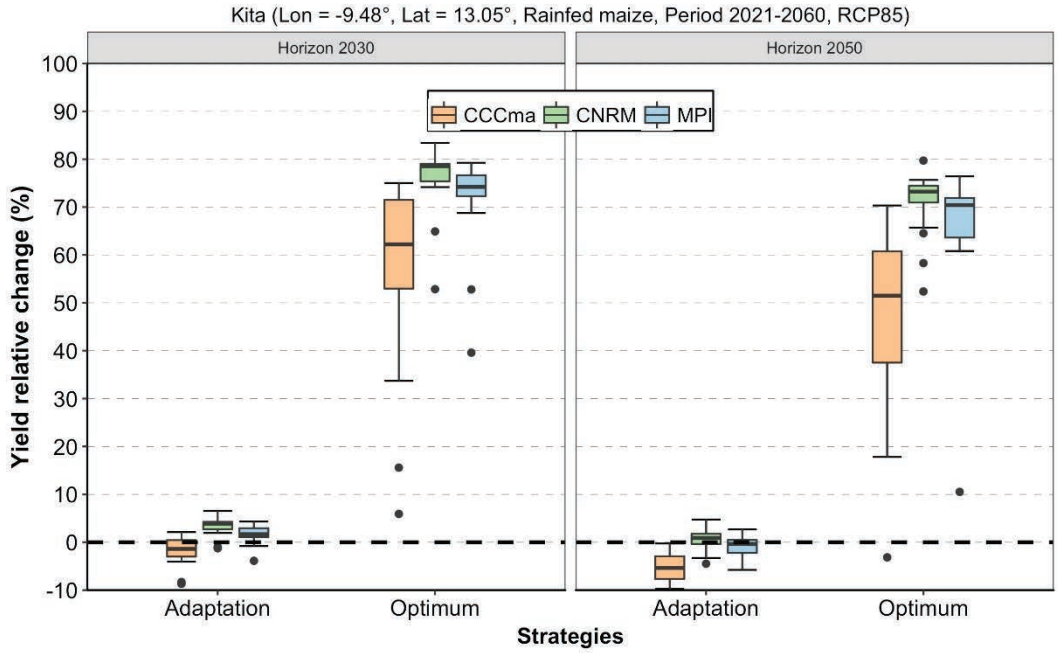


Figure A7.19. | Relative yield change for rainfed maize in Kerewan (Kerewan, Gambia) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario

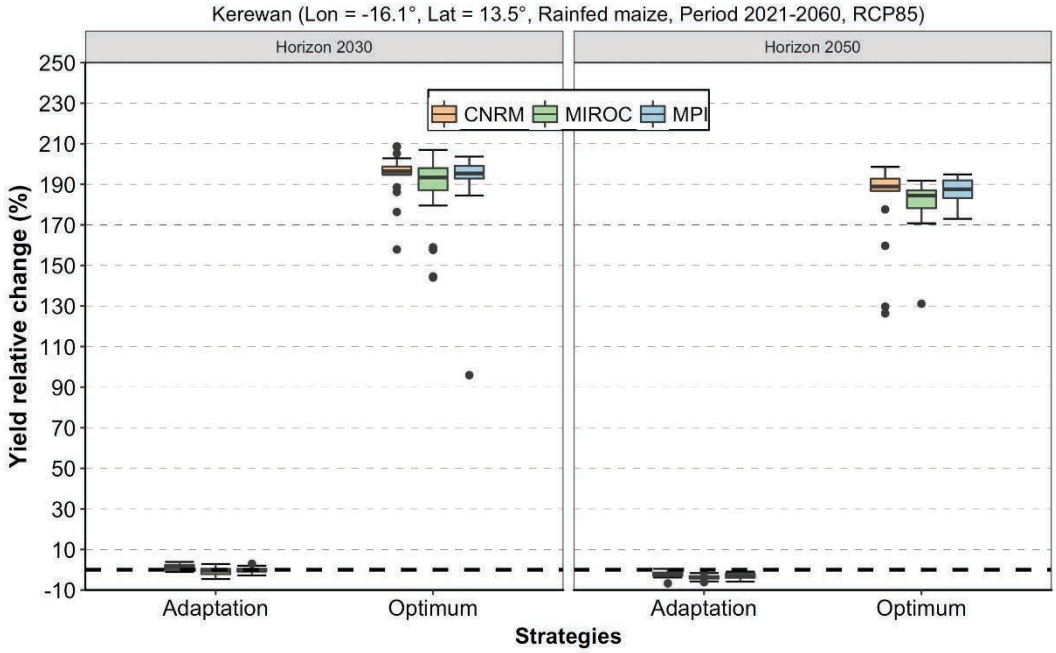
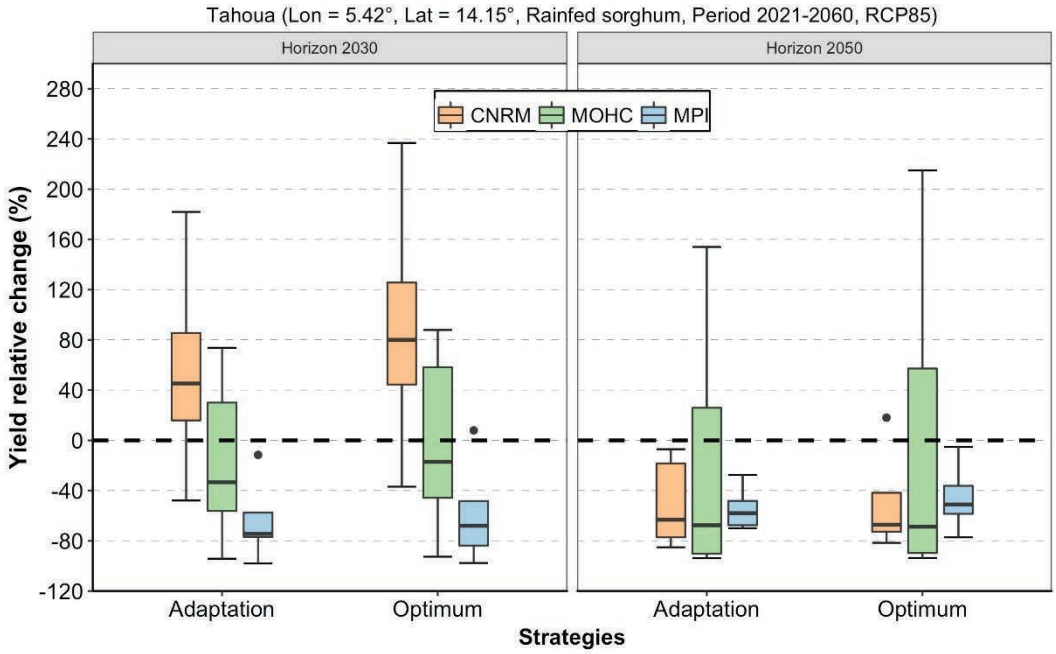


Figure A7.20. | Relative yield change for rainfed sorghum in Tahoua (Fachi, Niger) for two time horizons (2030 and 2050), under improved and optimal management conditions and based on the RCP8.5 scenario



Annex 8. The calculation scheme of AquaCrop

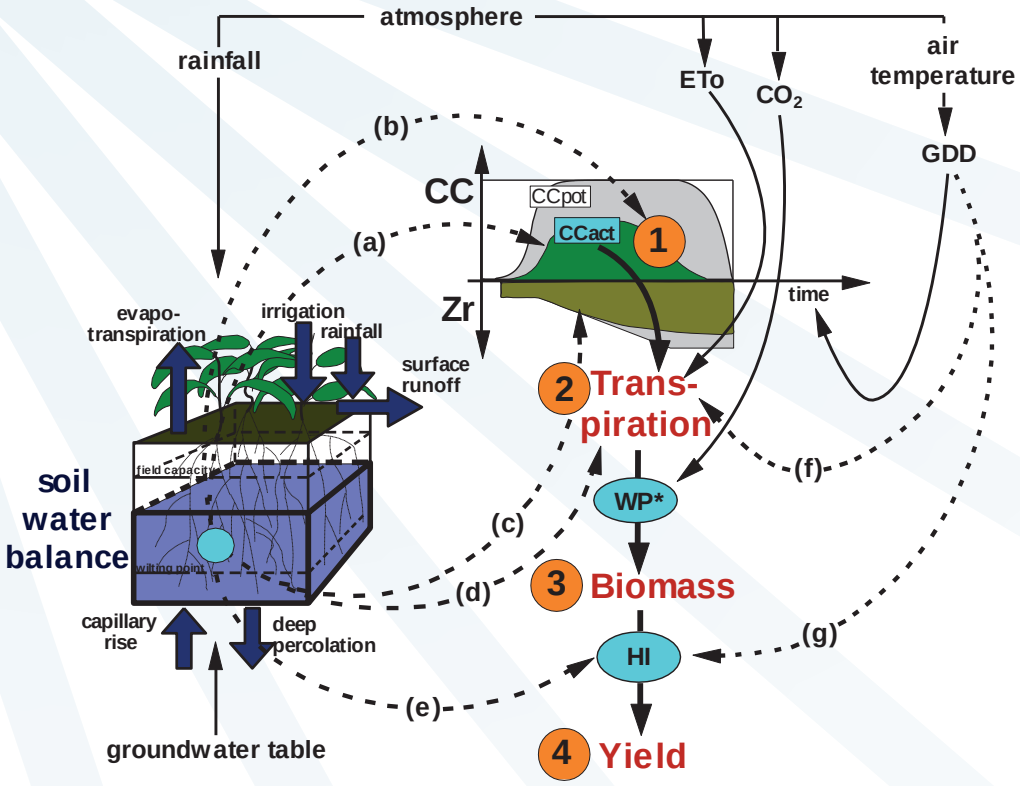
AquaCrop simulates final crop yield in four easy steps that make the modelling approach transparent (See Figure A8). The four steps include:

1. **Calculate development of green canopy cover** (**CC**): In AquaCrop, foliage development is expressed through green canopy cover rather than Leaf Area Index (LAI). The CC is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (i.e. when 0% of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached (i.e. when 100 percent of the soil surface covered by the canopy). By adjusting the water content in the soil profile on a daily basis, AquaCrop keeps track of the stresses that might develop in the root zone. Soil water stress can affect the leaf and hence canopy expansion, and, if severe, could trigger early canopy senescence;
2. **Calculate crop transpiration** (**Tr**)**:** Under well-watered conditions, Tr is calculated by multiplying the reference evapotranspiration (ETo) with a crop coefficient (Kc_{Tr}). The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop, corresponding with the simulated canopy cover. Water stress not only affects canopy development but might also induce stomata closure and hence affect crop transpiration;
3. **Calculate above-ground biomass** (**B**)**:** The above ground biomass of a crop is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity (WP). In AquaCrop, WP is normalized[30] for the effect of climatic conditions, which makes the normalized biomass water productivity (WP*) valid for diverse locations, seasons, and CO_2 concentrations;
4. **Calculate crop yield** (**Y**)**:** The simulated above ground biomass integrates all photosynthetic products assimilated by the crop during the season. By using a harvest index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B. The actual HI is obtained by adjusting, during simulation, the reference harvest index (HIo) with an adjustment factor for stress effects.

Temperature and water stresses directly affect one or more of the above processes (See Figure A8). AquaCrop also considers the effects of weed infestation, soil fertility and soil salinity stress on canopy development, crop transpiration and biomass production.

[30] Normalized water productivity (WP*) is the crop biomass water productivity (WP) normalized for ET_o and air CO_2 concentration (tome/ha of kg/m^2)

Figure A8. | Calculation of AquaCrop with indication of the four steps and the processes (dotted arrows) affected by water stress (a to e) and temperature stress (f to g)



CC is green canopy cover; Zr, rooting depth; ETo, reference evapotranspiration; WP*, normalized biomass water productivity; HI, harvest index; and GDD, growing degree day. Water stress: (a) slows canopy expansion, (b) accelerates canopy senescence, (c) decreases root deepening but only if severe, (d) reduces stomatal opening and transpiration, and (e) affects the harvest index. Cold temperature stress reduces crop transpiration (f). Hot or cold temperature stress inhibits pollination (g) and reduces HI.

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