Climate information services in Mali in the context of climate

December 2022

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INITIATIVE ON
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Executive Summary

The countries of the Sahel region are some of the most vulnerable to the impacts of climate change. The region's existing vulnerabilities are associated with environmental degradation, poverty, food insecurity, rapid population growth, gender inequality, political instability and conflict that are increasingly exacerbated with changing climate. Given their lack of readiness to improve resilience, the combined effects of climate change and of increasing vulnerability present unprecedented challenges to society in the Sahel countries. Given these challenges, we urgently need to develop and implement solutions from research and innovation that support systems transformation in order to contribute to restore land; enhance nutrition, health and food security; improve climate resilience and create green jobs. The focus should be on immediate climate risks, adapt to a much warmer world, limit GHG emissions from food systems, and put in place land-use systems that remove carbon from the atmosphere through improved livestock practices, trees, forests and soil organic matter.

One approach to achieve these goals would be to improve the understanding of climate, climate predictions, and the use of climate information services to serve the region's citizens' needs. The idea is to enable society to better manage the risks arising from climate variability and change, especially for those who are most vulnerable to climate-related hazards. This can only be achieved through developing and incorporating science-based climate information and prediction into planning, policy and practice at every level.

The purpose of this report is to develop a proposal for climate information services in Mali in the context of climate change to help develop effective risk management and adaptation strategies in the agricultural sector. While the concept of climate information services in Mali is not new and there are a number of successful examples of such services in the country, the idea here is to contextualize climate services for risk management under an increasingly volatile climate. For example, an existing service may forecast average seasonal total rainfall for the upcoming growing season, individual rain events (or lack thereof) may occur more intensively, thanks to climate change. How would farmers respond to such information? In this report we make the case for two efforts. First, national meteorological services must engage in further transforming information from an increasingly volatile climate into targeted, user-specific, and easy-to-digest products and advisory services that have been shown to offer a greater value to individuals and the society at large. Second, Mali and the Sahelian countries in general must foster participation from the private sector for effective and sustainable production of climate information, customization of sector-specific information and dissemination. These efforts can facilitate climate-smart decisions that will reduce the impact of climate-related disasters, improve food security and health outcomes, empower farmers to fine tune their planting and marketing strategies and enhance their resource management.

1. Introduction

The countries of the Sahel region (Figure 1) are some of the most vulnerable to the impacts of climate change. The region's existing vulnerabilities are associated with environmental degradation, poverty, food insecurity, rapid population growth, gender inequality, political instability and conflict that are increasingly exacerbated with changing climate. Given their lack of readiness to improve resilience to the effects of climate change, the combined effects of climate change and of increasing vulnerability present unprecedented challenges to society in the Sahel countries. Given these challenges, we urgently need to develop and implement solutions from research and innovation that support systems transformation in order to contribute to restore land; enhance nutrition, health and food security; improve climate resilience and create green jobs. The focus should be on immediate climate risks, adapt to a much warmer world, limit GHG emissions from food systems, and put in place land-use systems that remove carbon from the atmosphere through improved livestock practices, trees, forests and soil organic matter.

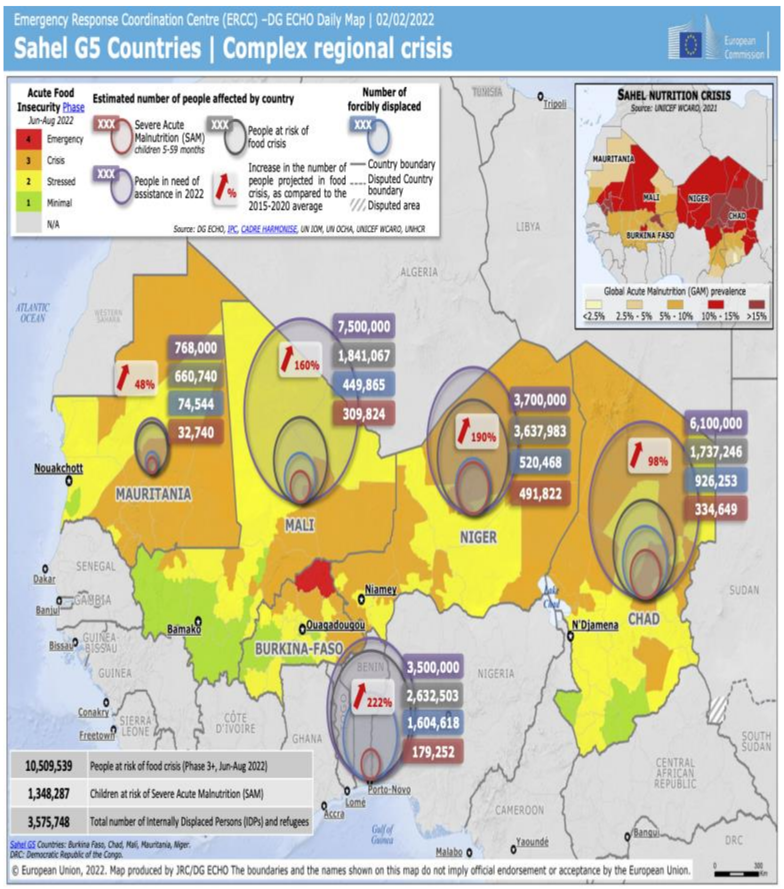

Figure 1*: Countries of the Sahel as defined by the EU Emergency Response Coordination Center. The map depicts existing emergencies (as of February 2022) and general vulnerabilities associated with food production and climate change. Source: EU-ECHO.*

Ironically, most of the Sahel countries have signed and ratified the Paris Agreement on climate change and have submitted their Nationally Determined Contributions. These commitments also

include identification of priority areas such as climate-smart agriculture, sustainable land management, water management and increasing access to renewable energy that form the basis for climate adaptation and mitigation in countries' respective economic development plans (IPCC, 2022). However, despite a wide range of national climate change commitments, implementing climate change policies and plans are still lacking at both the national and local government levels. The gap is often filled by relatively strong regional institutions, transboundary approaches and local actors that provide capacity for action. To this end, what is urgently needed is to prioritize climate change adaptation and mitigation as sectoral interventions, particularly in the agricultural sector.

One approach to achieve this goal would be to improve the understanding of climate, climate predictions, and the use of climate information services to serve the region's citizens' needs. The idea is to enable society to better manage the risks arising from climate variability and change, especially for those who are most vulnerable to climate-related hazards. This can only be achieved through developing and incorporating science-based climate information and prediction into planning, policy and practice at every level.

Climate information services are activities related to the generation and delivery of climate information to a range of users, from individuals to governments, to support climate-resilient development and to inform climate-related decision-making and climate-smart policy and planning. They include the collection, processing, packaging and delivery of weather and climate variables such as temperature, precipitation, wind, soil moisture, and extreme weather indicators (Kadi et al., 2011). They can describe historical, current and future weather and climate conditions and may entail future predictions on daily, monthly, seasonal or decadal timescales and projections at multidecadal and centennial scales (WMO, 2014). While these attributes alone are useful, their transformation into targeted, user-specific, and easy-to-digest products such as forecasts, trends, economic analysis, alerts, and advisory services has been shown to offer a greater value to individuals and the society at large (Vaughan and Dessai, 2014). These effective services and products can facilitate climate-smart decisions that will reduce the impact of climate-related disasters, improve food security and health outcomes, empower farmers to fine tune their planting and marketing strategies and enhance water resource management, to name a few.

There are numerous efforts to develop climate information service capabilities in the Sahel (Kadi et al., 2011), although many operate in isolation and with varying degrees of success with respect to improved management of risks arising from climate change. While many of the foundational capabilities and infrastructure for climate services already exist or are being established, coordination among numerous programs, projects and institutes that have addressed individual aspects of climate service are generally weak. The primary challenges include:

- Lack of coordination and communication between the supply side (providers) and demand side (users) of climate information services;
- Inability to act by users on available information regardless of the quality;
- Wide range of availability and quality of climate data;
- Lack of easily interpretable and user-specific information for the decision-making process; and

- Continued limitations on access to climate services.

With these issues in mind, the purpose of this report is to provide a framework for effective climate information services in Mali with a view towards improved climate risk management in multiple sectors, and in particular agriculture and food security. The report is presented in four sections. In the first part, existing climate information services and how they are being used for decision making in the agricultural sector in the country are reviewed. In the second part, these services are compared to climate services in other countries in the region or elsewhere with successful agricultural outcomes. In the third part, existing and projected climate change and their impacts are presented to set the stage for effective climate information services in the context of climate change, using inputs from gridded climate data, CMIP6 climate change data, and other observations. In the last section, a framework for how a successful climate information system can be developed in Mali with a view towards managing risks from climate change is outlined.

2. Existing climate information services in Mali

As with other Sahelian nations, Mali has had a fair share of developments in the climate information services sector in the last 50 years. Most of these services involve multinational organizations, with or without a western research organization, targeting all or some of the countries in the Sahel, including Mali (Figure 2), and are mostly funded by international aid organizations (Hellmuth et al., 2010; Vaughan and Dessai, 2014; Mwangi et al., 2019; Vaughan et al., 2019). The following sections describe a set of institutions that provide climate services in Mali and the Sahel countries in general, with particular attention to their history, mandate, focus areas, and the types of climatic information they aim to provide. Note that there are other organizations that provide Africa-wide climate services, of which Mali is a part but these cases are described in Part 3 within other complementary examples of climate information service providers.

Agro-meteorological information services provided by the National meteorological organization

Mali's national meteorological organization, the Direction Nationale de la Météorologie (DNM), now known as National Meteorological Agency (or MALI-METEO) <https://malimeteo.ml/> was established in 2012 but its origins go back at least 50 years. The mission of the organization is the observation and study of the weather, climate and atmospheric constituents with a view towards ensuring the safety of persons and property and contributing to the economic and social development of Mali through the provision of information and services appropriate for all users. It has been a member of the World Meteorological Organization (WMO) for over 50 years.

While the agency is considered to be a traditional national meteorological organization, it has been a flag carrier for successful agro-meteorological climate information services for farming communities in Mali since the early 1980s and thus fits squarely within the context of this report. DNM's considerable experience with providing climate services to small-scale farmers has its origins in the early 1980s as an emergency response to recurrent droughts through the previous decade (Hellmuth et al., 2010). Focused on five common crops - millet, sorghum, peanuts, cotton, and maize - the program's broad aim was to assist rural farmers in making informed agricultural

decisions to improve production and alleviate drought-related food insecurity (USAID, 2014). In addition to receiving rain gauges and associated training to guide decisions such as planting dates and variety selections, farmers were provided with weather (mostly rain) forecasts, which included agricultural advice in different parts of the country to help rural communities manage the risk associated with a variable climate (Hellmuth et al., 2010). The program received technical assistance from the Regional Centre for Training and Application in Agrometeorology and Hydrology (AGRHYMET), the World Meteorological Organization (WMO), and funding from the Swiss Agency for Development and Cooperation (SDC). One of the groundbreaking attributes of these services was the translation of climate data into practical advice for farmers by representatives from several government agricultural service agencies, who regularly formulated agro-meteorological opinions, warnings and advice and disseminated through various networks (USAID, 2014). Over the intervening years, the program has trained over 2,500 farmers and there is evidence to suggest significant yield gains for major crops for farmers using agrometeorological information to make management decisions compared with national averages (Hellmuth et al., 2010).

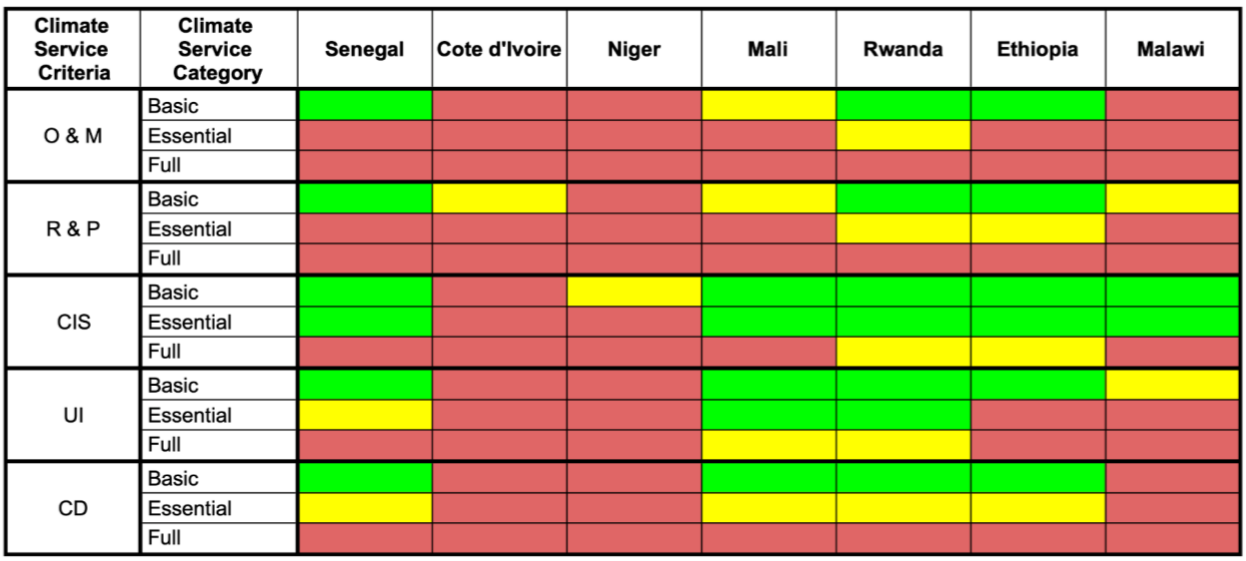

***Figure 2**: Rating of seven national meteorological services using three WMO categories (Basic Climate Services, Essential Climate Services, and Full Climate Services) across five service criterias (O & M - Observations and Monitoring; R & P - Research, Modeling and Prediction; CIS - Climate Service Information system; UI - User Interface Platform; and CD - Capacity Development). Green color indicates the criteria is fully satisfied, the yellow color indicates the criteria is partially satisfied, and the red color indicates that the criteria have not been satisfied. Adapted from USAID (2018).*

Data underpinning the program include diverse sources including meteorological observations at various types (i.e. synoptic, agro-meteo, rain gauge) of ground stations as part of MALI-METEO's network, rain gauge observations from participating farmers as well as short term (1-10 days) and seasonal forecasts from the meteorological agency and from the African Center of Meteorological Application for Development (ACMAD). These climate data are processed by the multidisciplinary working group and disseminated to farmers in the form of bulletins containing basic information

and agronomic advice and to national policy makers on the food security status of the country (Hellmuth et al., 2010).

Over the years, the program became popular among many farmers and expanded to include a wide range of information, from short-term weather forecasts to crop health conditions to targeted, actionable agrometeorological advice and alerts across several phases (Figure 3). Today, the program is on solid grounds given its own budget and its place as an institution within the Malian government, even though the donor funding ended in 2005 (USAID, 2014).

In 2014, a comprehensive review of the program highlighted numerous benefits but also identified key weaknesses that must be addressed to produce more effective climate information services that could be adopted by other countries in the Sahel (USAID, 2014). More specifically, the review presents the following findings.

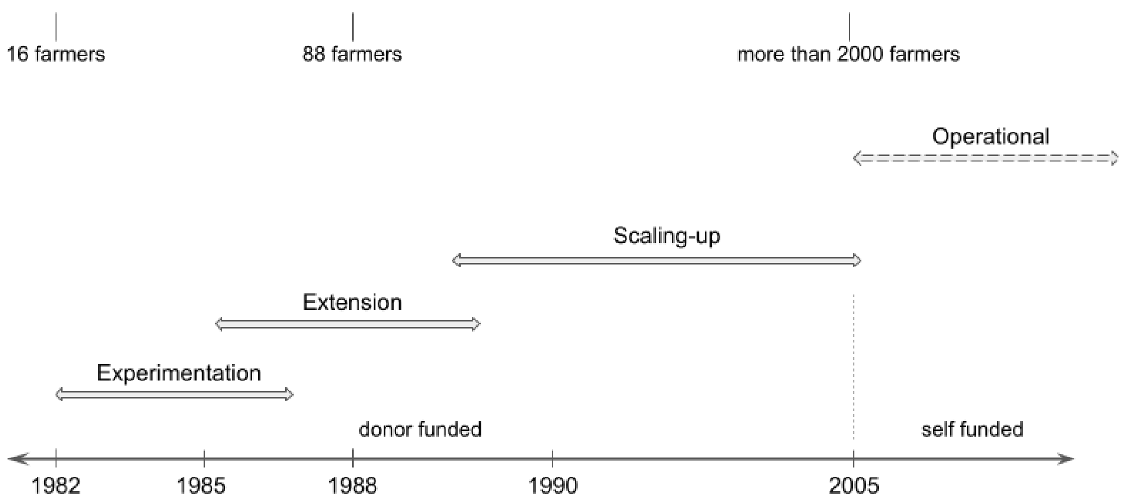

Figure 3*: Evolution of the agro-meteorological information and advisory services in Mali as part of the national meteorological agency. Adapted from USAID (2014).*

First, the use of agrometeorological advisories by farmers were generally low (often less than 20% in surveyed villages) and there were strong gendered differences, particularly in the south with Malian women's rate of use of the advisories was lower than that of men or simply non-existing. Second, the primary reason for low rates appears to be related to farmers' ability to use the advisories, rather than their trust in the quality of advisories. On this point, the assessment also found that those farmers who are able to use the advisories followed them closely with regard to variety selection and timing of planting, suggesting that at least for those the advisories are seen as useful. Third, the advisories currently do not include uncertainties surrounding forecasts, primarily because of the inherent assumption that the farmers are unable to understand them. Unfortunately, this creates a false sense of certainty in communicating inherently uncertain information that could undermine the trust in delivered information, and worse, select incorrect planting times or varieties. Finally, there is an important gap in evaluating the performance of forecasting methods. The MALI-METEO's forecasting methods date back to the establishment

of PRESAO (French acronym for Synthesis and evaluation of seasonal forecasts in West Africa) from the mid 1990s, which is based on the statistical relationship between historical sea surface temperatures in the Atlantic and rainfall quantities (Hamatan et al., 2004). Unfortunately, emergence of new trends associated with climate change challenge strong assumptions of stationarity and diminish our ability to forecast the future from past experience. To this end, there is an urgent need for a dynamical synthesis of our understanding of the West African climate system in the context of climate change (USAID, 2014).

AGRHYMET Regional Center in West Africa (AGRHYMET)

The AGRHYMET Regional Center (based in Niamey, Niger) was established in 1974 as a response to catastrophic droughts of the period in the form of a technical institute within the Permanent Interstate Committee for Drought Control in the Sahel (CILSS), which is composed of nine member States (Burkina Faso, Cape Verde, Chad, Gambia, Guinea Bissau, Mali, Mauritania, Niger, Senegal). The activities of the center including collecting, analyzing, synthesizing, and disseminating regional agro-meteorological and hydrological data, developing regional databases on agricultural statistics and natural ecosystems, generating knowledge on crop protection, environmental monitoring, desertification, and natural resource management as well as maintenance of meteorological instruments and electronic equipment and training officers from Sahelian countries and elsewhere (Seydou et al., 2014). In existence for nearly five decades, the AGRHYMET Center is considered to be a respected regional institution with the scientific and technical capacity to assist the CILSS member States achieve food security and increased agricultural production as well as improved natural resources management in the Sahelian region under an ever changing climate.

The primary climatic information service activities of the AGRHYMET Center in Malian context are rooted in West Africa seasonal climate outlook forums (PRESAO) that issue seasonal forecasts of cumulative rainfall for West Africa for informed decision making in the agricultural and water management sectors. Originally statistical in nature, these forecasts are increasingly based on outputs of coupled atmosphere–ocean dynamic models that are locally implemented and tested (Seydou et al., 2014). More recently, seasonal forecasts made by AGRHYMET include other characteristics of the rainy season that are more relevant for rainfed agriculture such as the inception and termination dates of the season as well the potential length of the dry periods during the critical growth stages of the major cereal crops (Seydou et al., 2014). Mali also benefits from extensive crop simulation experiments, results of which are used to map the onset dates of the crop growing season, the water requirements satisfaction indices and the potential yields in the country that are considered to be important agro-climatic services (Dingkuhn et al., 2003).

Emergence of climate extremes in the Sahel region, and Mali in particular, brings renewed focus on AGRHYMET capabilities. Of particular note are activities surrounding the assessment of climate change impacts on crop production and water resources. While the link between these activities and its role as an essential climate information service provider is not yet clear, the AGRHYMET Center is uniquely positioned to address many climate hazards and food security issues in the region.

Participatory Integrated Climate Services for Agriculture (PICSA)

Smallholder farming is vital for the food security and livelihoods of millions of people across the Sahel region. However, these farmers often don't have access to information on highly variable climatic factors such as the amount of rain that falls, extreme temperatures, the timing of seasonal changes, as well as the occurrence of extreme conditions like dry spells and floods that affect critical farming decisions (Dorward et al., 2015). Even when available, the top-down and generic nature of this information makes it difficult for effective use by individual farmers with a wide range of backgrounds, agricultural practices, wealth, and social status. Participatory Integrated Climate Services for Agriculture (PICSA) was developed to overcome these challenges. Developed in 2011 by researchers at the University of Reading, PICSA uses the process (Figure 4) of participatory approach for climate services and agricultural extension by combining historical climate data and forecasts with farmers' knowledge of what works in their own context, and then uses participatory planning methods to help them make informed decisions about their agricultural practices (Clarkson et al., 2022). The key to its success is the ability to combine accurate and hyper-local historical climate as well as seasonal and short-term weather forecasts with crop, livestock, and livelihood options at the level of individual farmers with the help of participatory decision-making tools that assist farmers to make informed decisions when planning their activities (Clarkson et al., 2022). As a result, PICSA is now being implemented in more than 20 countries and reaching tens of thousands of farmers worldwide (Dorward et al., 2015).

A hallmark of the PICSA approach is the work agricultural extension does with groups of farmers long before the start of the agricultural season. Following the analysis and review of historical climate information, farmers and extension agents develop crop plans and livestock options best suited to individual farmers' circumstances with the help of participatory tools. These meetings continue into the growing season to review and consider the practical implications of seasonal and short-term forecasts on the plans farmers have made and revise them if necessary. The University of Reading team is working out novel scaling approaches to support smallholder farmers in several countries.

Implementation of PICSA in two sites in Mali and Senegal in 2016 received strongly favorable views and profound benefits to participating farmers by making strategic plans long before the season, based on their improved knowledge of local climate features (Dayamba et al., 2018). The approach also enabled participating farmers to consider additional interventions such as changing sowing dates, selecting crop varieties, and fertilizer management within their own context and resources. The study also demonstrated the potential of farmer-to-farmer extension in scaling up the approach, which is of great interest especially in the current context of limited extension services in the West African region (Clarkson et al., 2022).

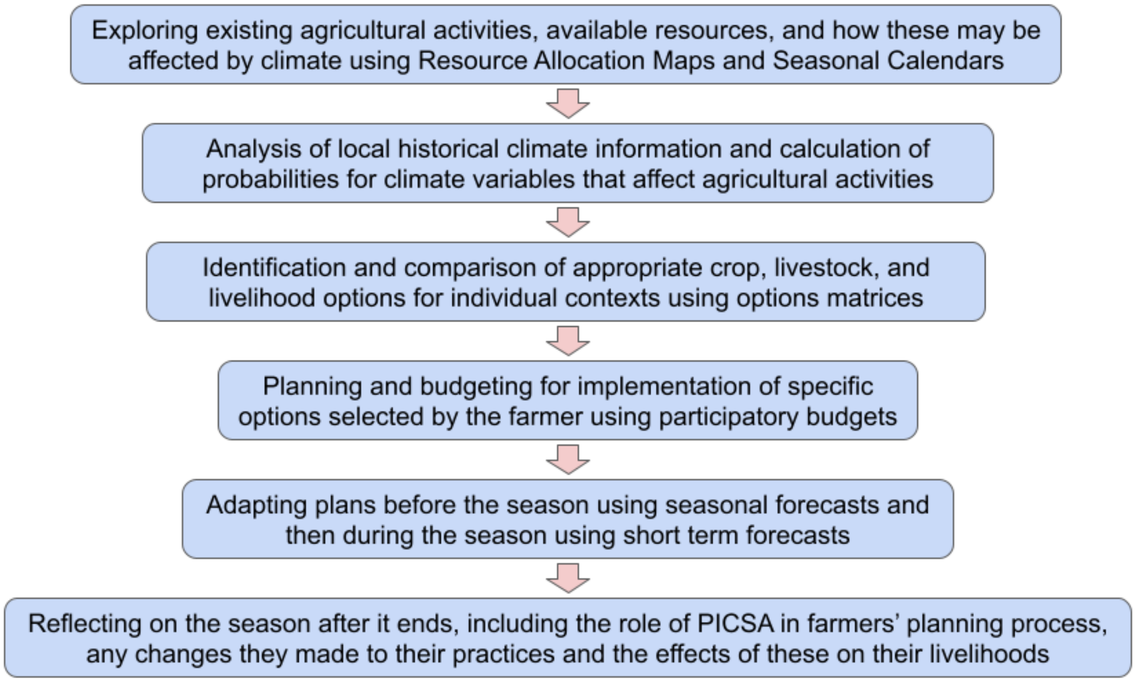

Figure 4*: The PICSA workflow. Adapted from Clarkson et al (2022).*

Summary of climate information services in Malian context

As detailed in the list above, Malian farmers have been exposed to a wide variety of climate information services for some time. These services appear to be generally beneficial but not all farmers benefit equally, nor can they all act on the information they receive. The METEO-MALI approach with fortnightly bulletins is a strong player in generating and disseminating agriculturally-relevant climate information but it is often seen as too top-down without considering the actual needs and livelihood circumstances of farmers. While a more farmer-centric approach is beginning to take shape, climate change is challenging the forecast approaches that rely on historical information and analog climate years. On the other hand, the test phase of the PICSA approach in Mali was hugely successful, thanks to a new way of doing extension and communicating with farmers to help them make their own decisions that suit their conditions and improve their livelihoods with local climate information. The Mali work also suggests that the scalability issue - the current bottleneck - can be overcome by farmer-to-farmer extension of PICSA and reach a large number of farmers in Mali and beyond.

3. Comparison of climate information services to others in the Sahel

The purpose of this section is to compare Mali's existing climate information services to other services in the region. As described above, Mali benefits from being part of other Africa-wide climate information services so the description of some of the services provided below is somewhat repetitive. Nevertheless, the services described below, regardless of Mali being a part, provide important reference points. As with existing services in Mali, the emphasis of the services described below is mostly on agro-meteorological services and often does not include climate change and associated risk, an important focus of this report.

It is important here to review here some data sharing activities and protocols that are in place that provide the framework of climate information services in Africa. In general, regional data-sharing policies are implemented at the country level by national meteorological and hydrological services. For example, the Intergovernmental Authority on Development (IGAD) Climate Prediction and Application Centre (ICPAC), based in Nairobi, Kenya, implements a data-sharing policy with the services of countries in the Greater Horn of Africa; the AGRometeorology, HYdrology, METeorology (AGRHYMET) regional center in Niamey, the Niger, implements a data-sharing policy with national services in countries in West Africa; and the Southern African Development Community – Climate Service Centre (SADC-CSC) implements a data-sharing policy with national services in countries in Southern Africa.

African Centre of Meteorological Application for Development (ACMAD)

ACMAD was created in 1985 as a result of the Conference of Ministers of the United Nations Economic Commission for Africa on behalf of the member States of the United Nations Economic Commission for Africa. By design, it is supported by and operated within the member States of the United Nations Economic Commission for Africa and of the World Meteorological Organisation. The purpose of ACMAD is to improve the understanding of atmospheric and climatic processes over Africa; collecting, analyzing and disseminating meteorological and hydrological information; providing a meteorological watch and early warning system over Africa and; promoting the training of African scientists and technicians in the application of meteorology for development. ACMAD data and services can help alleviate the effects of drought, atmospheric phenomena, and tropical cyclones by applying methodologies based on a thorough knowledge of the impact of meteorological factors on food production, on the availability of water resources and on efficient use of renewable sources of energy. ACMAD is based in Niamey, Niger.

The Weather and Climate Information Services for Africa (WISER)

The Weather and Climate Information Services for Africa (WISER) was conceived by the UK Department for International Development (DfID, which has now been replaced by the Foreign, Commonwealth & Development Office or FCDO) in 2015 to stimulate the uptake of climate information by policy makers and vulnerable groups including the youth and women. The initiative is the fruit of collaboration between the African Climate Policy Centre (ACPC) and the United Kingdom Met Office. The WISER program is aimed at helping to address climate information gaps and ensure accelerated uptake of climate information services for development planning and practice. The program is essential to weather-sensitive business and economic activities such as transport, aviation, construction, and agriculture, agriculture being the dominant source of employment and highly sensitive to weather and climate. In implementing this programme, the ACPC has noted the limited contribution of the private sector in the production and uptake of climate information services (see below). The WISER program is composed of two components: The East Africa component is implemented by the UK Met-Office and the Pan-Africa component, of which Mali is a part, is led by ACPC.

The Enhancing National Climate Services (ENACTS)

The Enhancing National Climate Services (ENACTS) initiative is an ambitious effort to simultaneously improve the availability, access and use of climate information in Africa. The main thrust behind ENACTS is to assist national Meteorological and Hydrological Services (NMHS) in Africa to develop high-resolution, spatially and temporally complete gridded historical meteorological datasets; produce suites of derived climate information products; and disseminate them through a web-based platform (Dinku et al., 2018). ENACTS enables the NMHS to provide enhanced services by overcoming the challenges of data quality, availability and access – while at the same time fostering stakeholder engagement and use. The new data products allow for characterization of climate risks at a local scale and offer opportunities to support applications and research. ENACTS has so far been implemented in 10 countries at the national level and at regional levels in East Africa and the West African Sahel (Figure 5).

ENACTS initiative is led by Columbia University's International Research Institute for Climate and Society (IRI). Currently, the primary source of climate data is observation by ground-based weather stations across the continent. However, given the declining quantity and quality of these stations, ENACTS increasing relies on generating gridded and quality controlled climate datasets to achieve the following objectives (Dinku et al., 2018): 1) Improve the availability and quality of climate data and information products at the local, national, and regional levels; 2) Enhance access to climate data, information products, and services relevant to the needs of the public, national, and local practitioners in climate-sensitive sectors, as well as policy makers, those in the private sector, and researchers; and 3) Promote the widespread use of climate information and services by pursuing effective stakeholder engagement and tapping into existing demand for climate information. In doing so, the ENACTS approach has been shown to be an effective means of transforming decision-making surrounding vulnerabilities and risks at multiple scales, through implementation in over a dozen countries at national level as well as at the regional levels in both East and West Africa. Through the ENACTS approach, challenges to availability of climate data are alleviated by combining quality-controlled station observations with global proxies to generate spatially and temporally complete climate datasets. Access to climate information is enhanced by developing an online mapping service that provides a user-friendly interface for analyzing and visualizing climate information products. Use of the generated climate data and the derived information products is promoted through raising awareness in relevant communities, training users, and co-production processes.

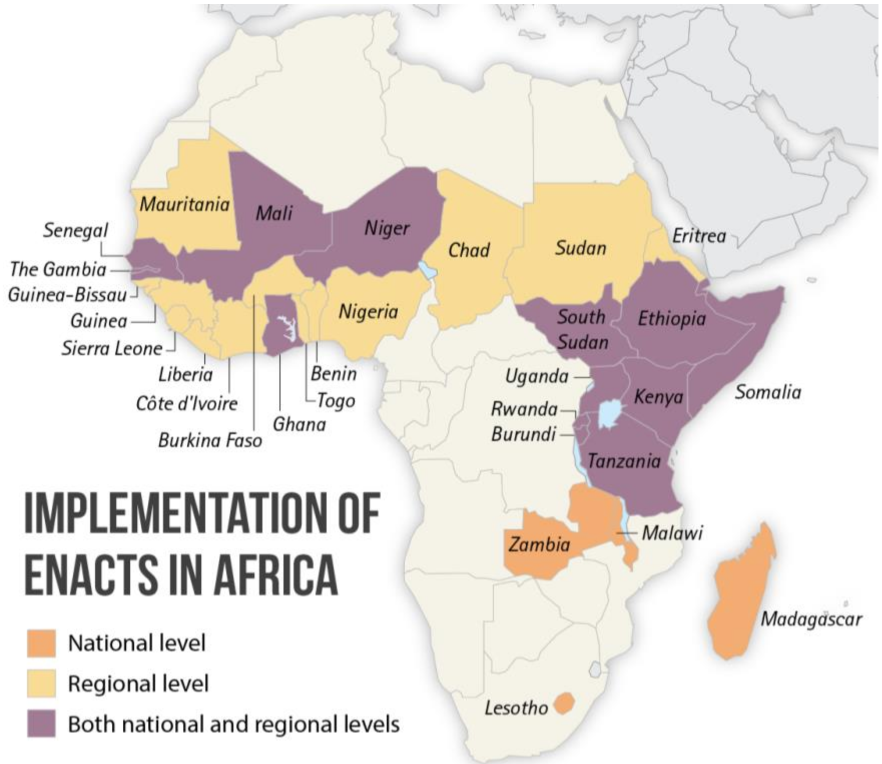

Figure 5*: Map showing the countries participating in the ENACTS Program. The map was downloaded from the ENACTS website on December 1, 2022.*

4. Climate change impacts on the agricultural sector in Mali

It is widely accepted that projected climate changes associated with increasing atmospheric concentrations of greenhouse gasses will fundamentally alter the magnitude and the seasonal variations of temperature and precipitation patterns in many parts of the globe (IPCC, 2022). What is less known, however, are the impacts these changes will have on social and economic sectors that are important to human well-being, such as agricultural production, water availability, and public health (Rosenzweig and Parry, 1994; Tubiello and Ewert, 2002; Tubiello et al., 2007). In particular, climate change impacts on agricultural productivity, defined as the amount of food/fiber production over a unit of land area, are critically important as global population increase coincides with diminishing productive land area and water resources.

While a vast amount of research in recent decades has focused on crop productivity under changing climates, a great deal is still unknown about many regions, particularly in the Sahel and Western Africa (Trisos et al., 2022). There is evidence to suggest that climate change is already negatively impacting crop production and slowing productivity growth in Africa (Ray et al., 2019; Sultan et al., 2019; Ortiz-Bobea et al., 2021). These effects are largely dependent on current climatic and soil conditions, the direction of change, and the adaptation strategies used to cope with these changes. For example, in sub-Saharan Africa, climate change has already reduced maize and wheat yields by 5.8% and 2.3%, on average, respectively in the period 1974–2008 (Ray et al., 2019).

With these issues in mind, the purpose of this section is to quantify climate change impacts on the agricultural sector in Mali. We first start the section by exploring recent trends in climate across Africa with a focus on western Africa. We then describe projected changes in temperature and precipitation patterns under two emission scenarios across three time periods. In the last

part of this section, we explore the impacts of these projected changes on the agricultural sector, with particular attention to crop production, crop disease, and water use for agriculture. Our goal is to set the stage for developing a framework for climate information services for Mali in the context of climate change (the last chapter).

Observed changes in climatic variables in the Sahel and Mali

Observed mean annual and seasonal temperatures have increased 1–3°C since the mid-1970s across Africa with the highest increases in the Sahara and Sahel (Gutiérrez et al., 2021; Ranasinghe et al., 2021) and positive trends in mean annual maximum and minimum of 0.16°C and 0.28°C per decade, respectively (Barry et al., 2018) (Figures 6 and 7). The frequency of very hot days (defined as maximum temperature > 35°C) and warm nights has increased by 1–9 days and 4–13 nights per decade between 1961–2014 (Moron et al 2016), and cold nights have become less frequent (Barry et al., 2018). In the 21st century, heatwaves have become hotter, longer and more extended compared to the last two decades of the 20th century (Barbier et al., 2018).

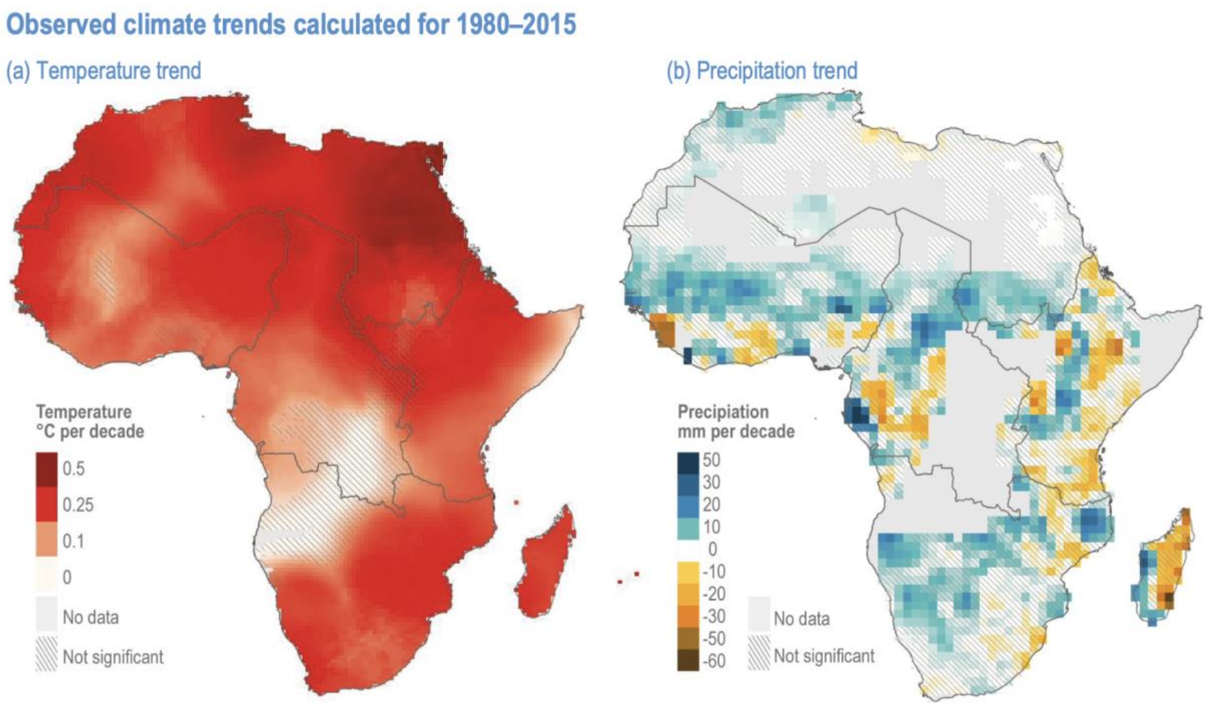

***Figure 6**: Changes in temperature (a) and precipitation (b) patterns due to human-caused climate change across Africa for 1980–2015. Trends were calculated with respect to the climatological mean over 1980–2015. The Climate Research Unit Time Series data (CRU TS) are used to compute temperature trends using 2-m temperature and the Global Precipitation Climatology Centre data (GPCC) precipitation trends. Regions with no cross-hatching indicate statistically significant trends over this period and regions in gray indicate insufficient data. The figures are derived from Gutiérrez et al (2021).*

Negative trends in rainfall accompanied by increased rainfall variability were observed between 1960s–1980s over west Africa (Thomas and Nigam, 2018), caused by a combination of anthropogenic aerosols and GHGs emitted between the 1950s and 1980s (Douville et al., 2021) (Figure 6). A shift to a later onset and end of the west African monsoon is also reported in west Africa and Sahel but this observation has low confidence (Ranasinghe et al., 2021). Between 1981–2014 the Gulf of Guinea and the Sahel have experienced more intense precipitation events and the frequency of mesoscale storms has tripled (Panthou et al., 2018). Extreme heavy precipitation indices show increasing trends from 1981–2010 (Barry et al., 2018), increasing high flow events in large Sahelian rivers as well as small to mesoscale catchments leading to pluvial and riverine flooding (Douville et al., 2021). Meteorological, agricultural and hydrological drought in the region has also shown signs of increased frequency since the 1950s (e.g. Seneviratne et al., 2021).

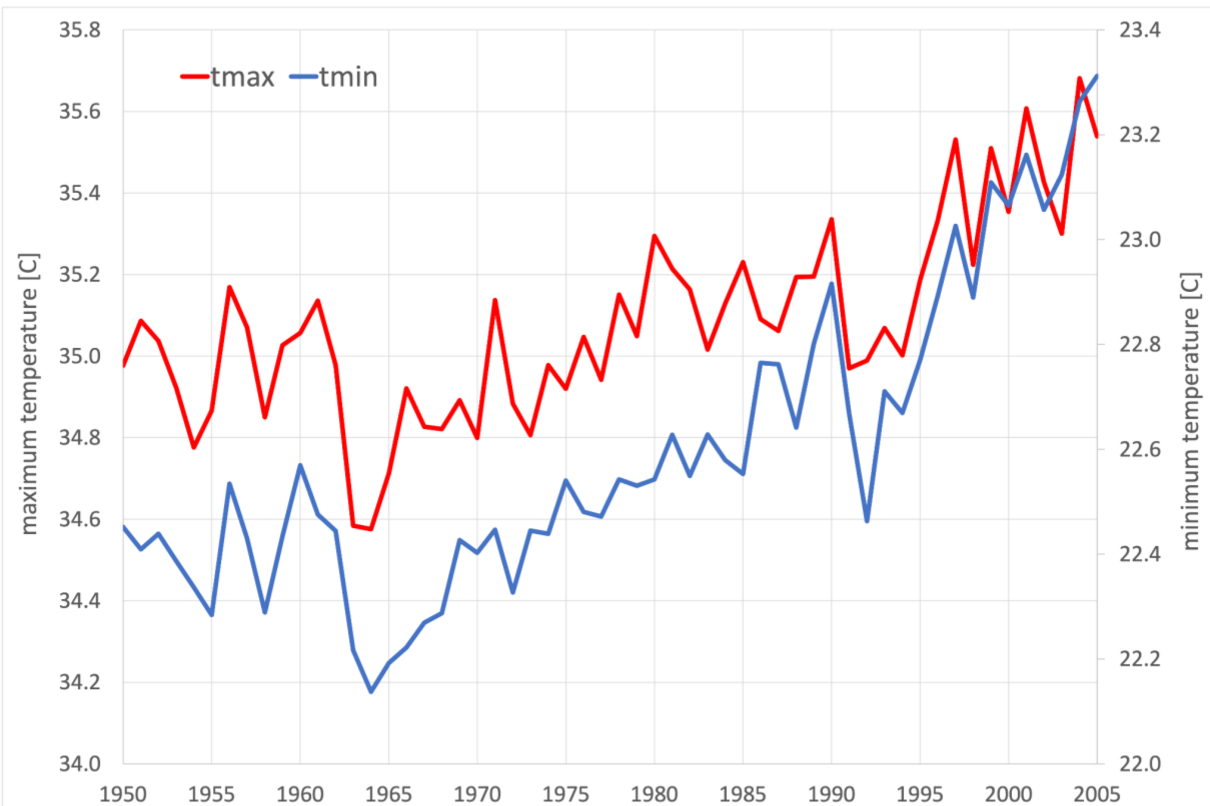

Figure 7: *Minimum and maximum temperature trends in Mali between 1950 and 2005 obtained from ERA5. As can be clearly observed, both temperatures show strong positive trends, starting from the second half of the 20th century that continues today. Note the changes in scale across the left (maximum temperature) and right (minimum temperature) vertical axes.*

Projected changes in climatic variables in the Sahel and Mali

Mean annual temperatures in west Africa are projected to increase between 0.6°C and 2.1°C when compared to the 1994-2005 average period, depending on the emission scenario and

location. Under mid- and high-emission scenarios, temperatures could increase by 2°C and 5°C, respectively (Dosio, 2017; IPCC, 2022) (Figure 8). Associated with these changes will be the projected increases in hot days at all global warming levels (GWL) with larger increases at higher warming levels. For example, by 2060 the frequency of hot nights is projected to be almost double the 1981–2010 average at GWL 2°C (Ranasinghe et al., 2021), with potentially devastating effects for maize production (Fitzpatrick et al., 2020).

West African rainfall projections show a gradient of precipitation decrease in the west, including Mali, and increase in the east with medium confidence (Ranasinghe et al., 2021) (Figure 9). This pattern is evident at 1.5°C of global warming and the magnitude of change increases at higher warming levels (Kumi and Abiodun, 2018). A reduction in length of the rainy season is projected over the western Sahel through delayed rainfall onset by 4–6 days at global warming levels of 1.5°C and 2°C (Kumi and Abiodun, 2018). Although there are uncertainties in rainfall projections over the Sahel, CMIP6 models project monsoon rainfall amounts to increase by approximately 3% per degree of warming (Jin et al., 2020).

At 2°C global warming, west Africa is projected to experience a drier, more drought-prone and arid climate, especially in the last decades of the 21st century (Klutse et al., 2018) (Figure 9). The duration of meteorological drought in the western parts of West Africa is projected to increase from approximately 2 months during 1950–2014 to approximately four months in the period 2050–2100 under RCP8.5 and SSP5-8.5 (Ukkola et al., 2020).

Impacts of climatic changes on the agricultural sector in Mali

Climate-related hazards in Mali's agriculture include droughts, floods, growing season changes, crop diseases and pests. These hazards are a natural occurrence in Mali, which nevertheless pose serious constraints on development and food security, and their intensity and frequency are likely to increase under a changing climate. Climatic changes are already a significant threat to the country's development and the nutrition and health of its inhabitants, due to erratic rainfall, increased crop pests, rainfall shortages, and breaks during critical growing periods, as well as desertification over the last 50 years. The most highly stressed regions of the country are in the south where agriculture is concentrated, including Sikasso, Mopti, and Segou. Not only are these regions critical to the country's continued food security, they also include regions with important ecosystem services which are deteriorating.

This section provides a summary of key climate hazards affecting agriculture in Mali. It allows quick evaluation of vulnerability, thereby identifying the magnitude and locations of exposure of cropping systems. The section is organized as types of risks associated with agriculture, particularly from the viewpoint of crop production (yield) losses, changes in growing periods that affect yield and crop selection, expected increases in crop diseases and increased use of water in irrigated areas.

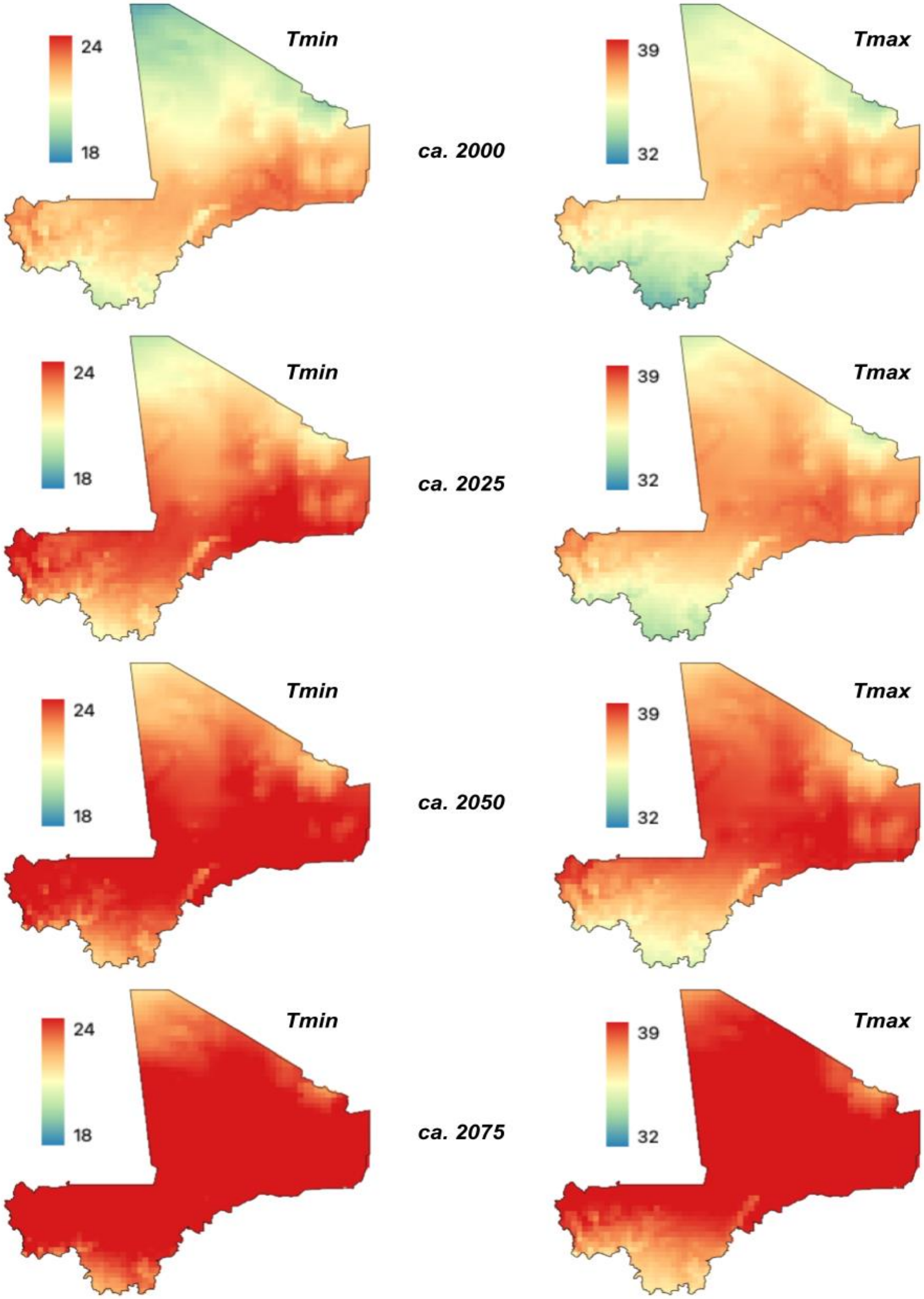

***Figure 8**: Projected changes in minimum (left panel) and maximum (right panel) annual mean temperatures in Mali under the rcp4.5 scenario across three time periods including the historical period (the top panel). Multi-model ensemble CMIP6 output downscaled by CORDEX.*

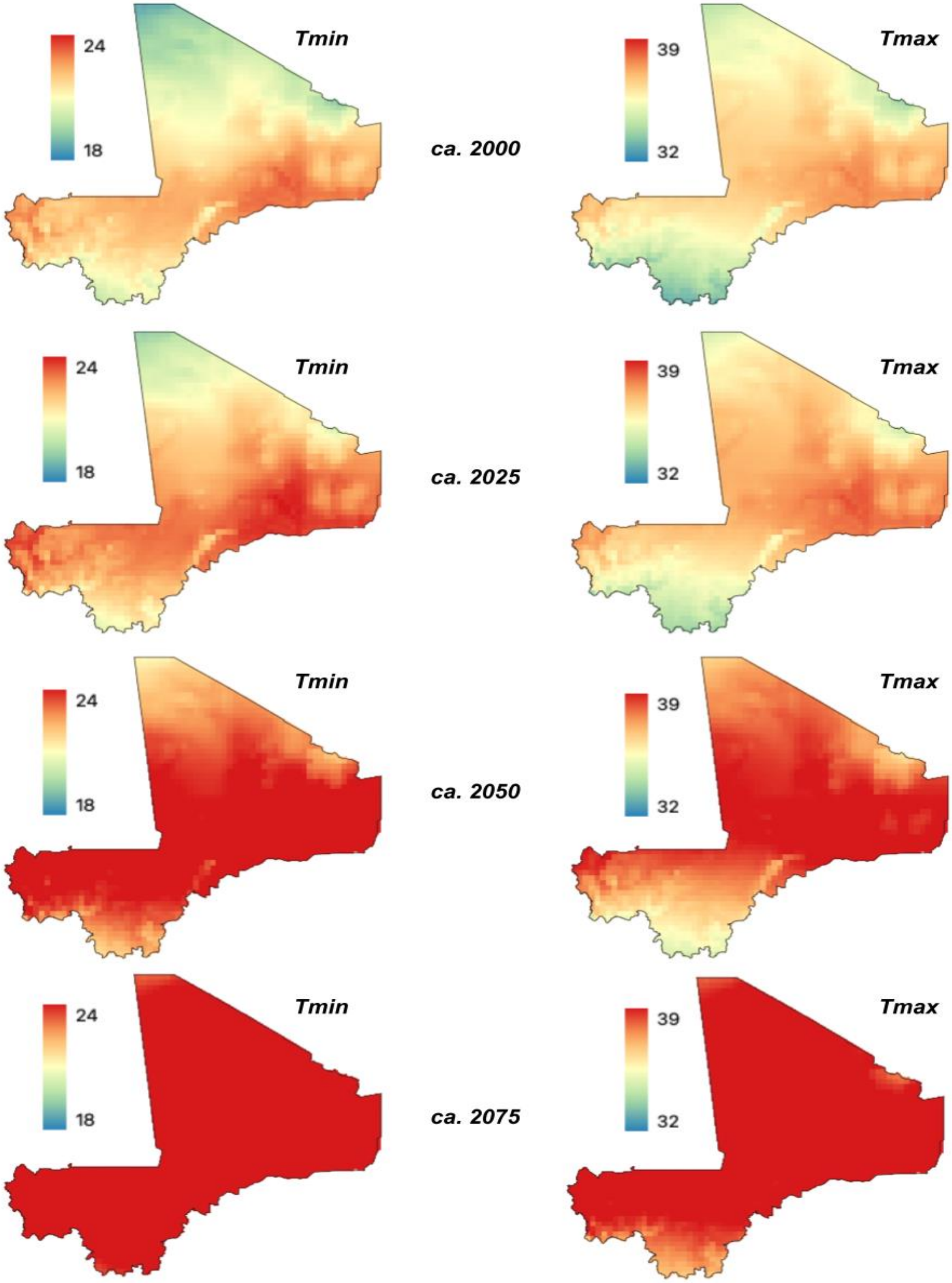

Figure 8 (continued)*: Projected changes in minimum (left panel) and maximum (right panel) annual mean temperatures in Mali under the rcp8.5 scenario across three time periods including the historical period (the top panel). Multi-model ensemble CMIP6 output downscaled by CORDEX.*

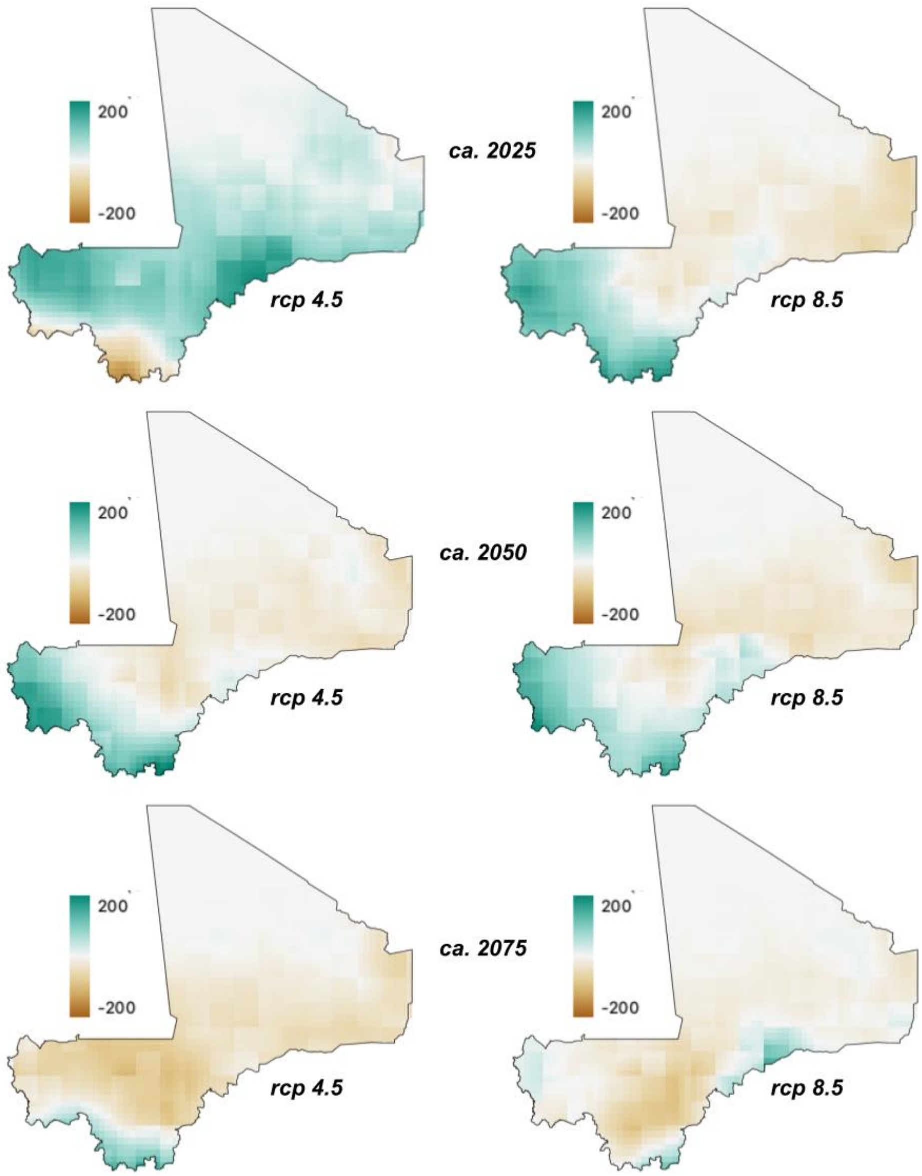

Figure 9*: Projected changes in growing season (May - December) precipitation in Mali across three time periods (ca. 2025, 2050, and 2075) and two emission scenarios (rcp4.5 and rcp 8.5). Multi-model ensemble CMIP6 output downscaled by CORDEX.*

Note that the methodology that is applied to estimate the magnitude of changes in these variables is a form of synthesis from existing studies, incorporating statistical analyses, crop modeling studies, and field observations (Knox et al., 2012). The reason for this approach is that these synthesized studies capture the in-depth changes in crop productivity in the Sahel beyond a single study. The included studies are provided in Table I.

Table I: *List of climate change impact studies focused on Mali and the Sahel. These studies are synthesized in this report to draw conclusions about climate change impacts on agricultural activities.*

Publication	**Countries**	**Crops**	**Changes captured**	**Approach**
Soumaoro (2021)	Mali	Maize	Yield	Panel regression
Abdoulaye et al (2021)	Mali	Maize	Yield	Regression
Sultan et al (2014)	West Africa	Sorghum	Yield	Crop modeling
Traoré et al (2013)	Mali	Cotton, Sorghum, Groundnut	Yield	Regression
Falconnier et al (2020)	SSA	Maize	Yield	Crop modeling
Carr et al (2022)	West Africa	Maize, Sorghum, Rice, Millet	Yield	Synthesis
Guan et al (2015)	West Africa	Sorghum	Yield	Crop modeling
Traoré et al (2017)	Mali	Maize, Millet	Yield	Crop modeling

Crop yields in Mali and the Sahel in general are especially vulnerable to future climate change in part because 90–95% of food production in the region is rainfed. Synthesis of a number of studies (Table I) suggests that maize, rice, sorghum and millet yields in the Sahel are projected to decrease around 5% per degree Celsius of global warming in a multi-model ensemble, particularly driven by projected rainfall changes (Figure 10). Without adaptation, substantial yield declines (in excess of 8%) are projected for staple crops in the region.

Note that these negative changes in yields of staple crops are expected to occur even when accounting for CO_2 increases and adaptation measures. For example, for maize in West Africa, compared to 2005 yield levels, median projected yields decrease 9% at 1.5°C global warming and 41% at 4°C, without adaptation (Figure 10). However, uncertainties in projected impacts across crops and regions are driven by uncertainties in crop responses to increasing CO_2 and adaptation response, especially for maize and sorghum in West Africa (Faye et al., 2018; Trisos et al., 2022).

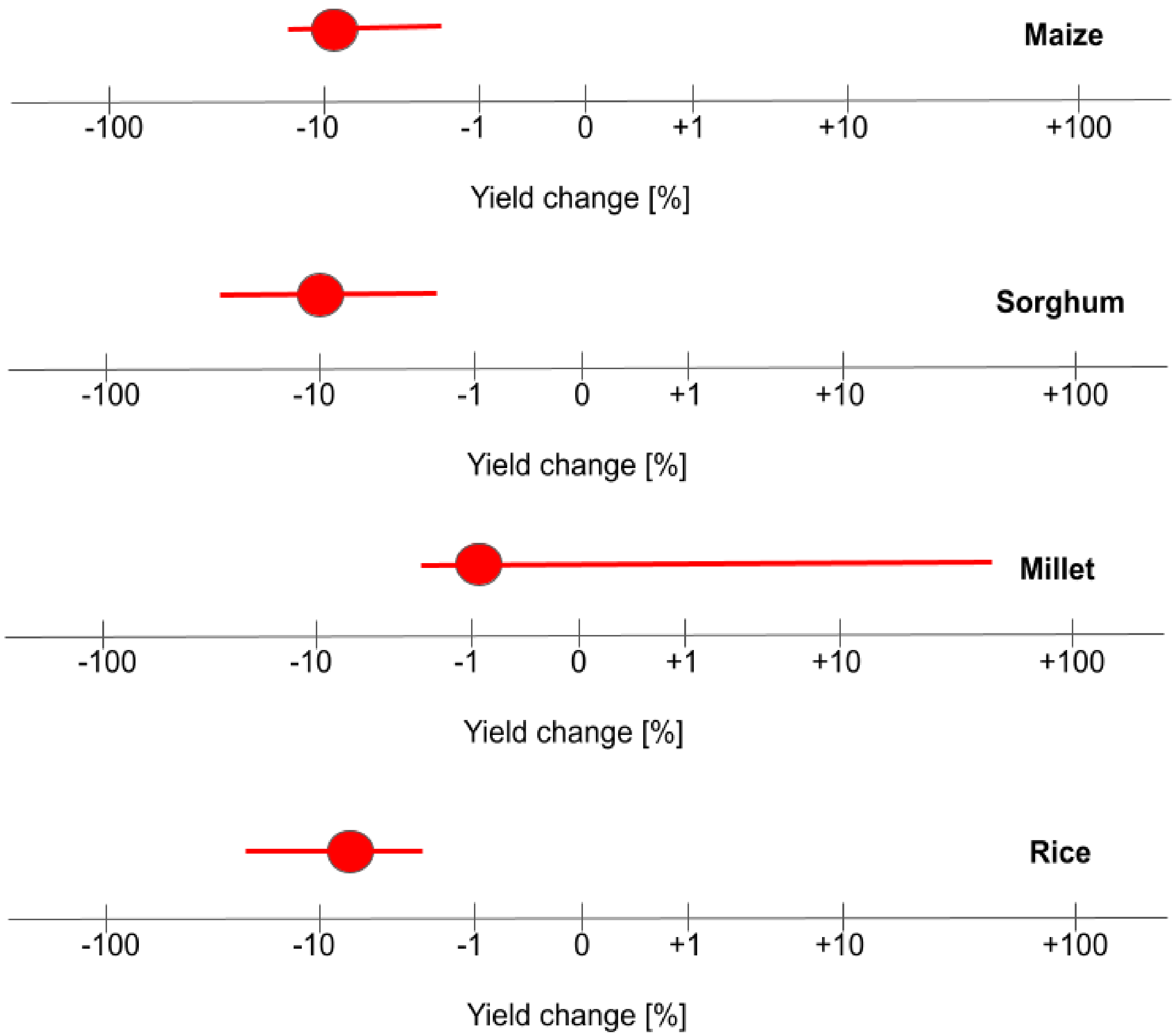

***Figure 10**: Projected changes in crop yields associated with global climate change for four major crops in the Sahel, and particularly in Mali. The results are developed from a review of the studies listed in Table I. The closed red circle indicates the median response across the studies and the horizontal red bar indicates the 25th and 75th percentiles of the responses across all studies. All values have been log-transformed for better visual comparison.*

Climate change impacts on irrigation water use

In the Sahel, many other economic sectors (especially the agriculture sector) rely on water resources for their activities. Consequently, climate impacts on the water sector have repercussions on the entire economies of the region's countries. Climate change has already increased pressure on water resources as a result of droughts and floods, thus endangering access to quality and quantity of water in the Sahel, especially in the Niger River Basin. Climate

change is expected to exacerbate this situation. Rising temperatures and expected reduction in precipitation amounts will increase demand for irrigation water in central irrigated parts of Mali while less water is expected to be available in the Niger river basin Abdoulaye et al (2021) (Figure 11).

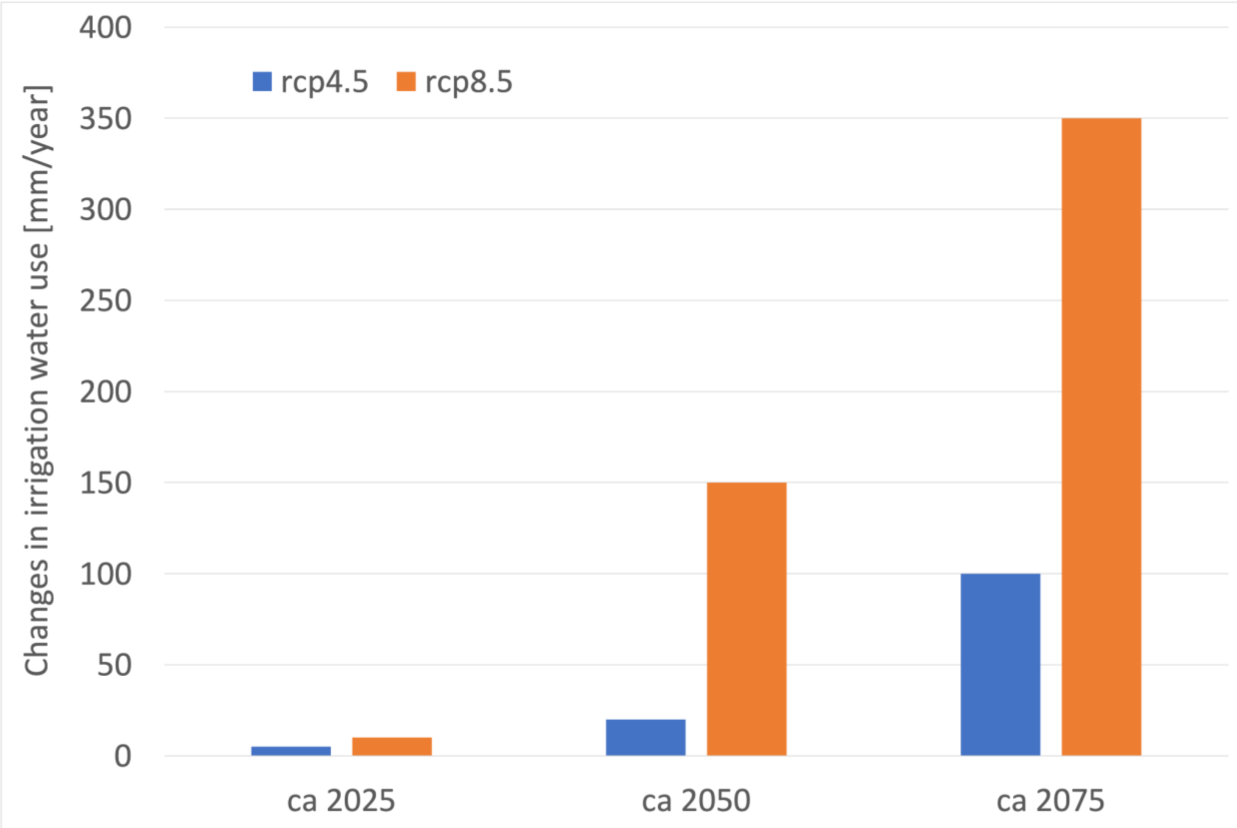

Figure 11. *Projected changes in irrigation water requirements for major crops in irrigated areas in central Mali across three time periods (ca. 2025, 2050, and 2075) and under two emission scenarios. The changes are computed using the FAO approach and account for the anticipated changes in rainfall patterns. The changes are in absolute units (mm/year) above existing irrigation water requirements.*

5. The role of climate information services on assessing and mitigating climate change risk in the agricultural sector

As established above, the countries of the Sahel, and Mali in particular are highly vulnerable to climate change and the importance of climate information services for planning adaptation and mitigation actions are ever more important. The purpose of this final section is to develop a proposal for effective climate information services in Mali with a view towards mitigating risks associated with climate change in the agricultural sector. Our goal is to first contextualize risk, and then establish common vocabulary. To this end, let's first define what these terms are.

Risk: Probability of an event occurring times its consequence (Figure 12). For example there is a high probability of reduction in sorghum yields in Mali under increasingly extreme temperatures and reduced rainfall and this decline has important economic and livelihood consequences for many farmers in the county, hence we can suggest that risk is high.

Adaptation: Adjustment of a system to moderate potential damages, to take advantage of opportunities, or to cope with consequences, associated with climate change (Figure 12). For example, using heat and drought tolerant sorghum varieties, Malian farmers can adapt to significant vulnerabilities associated with climate change.

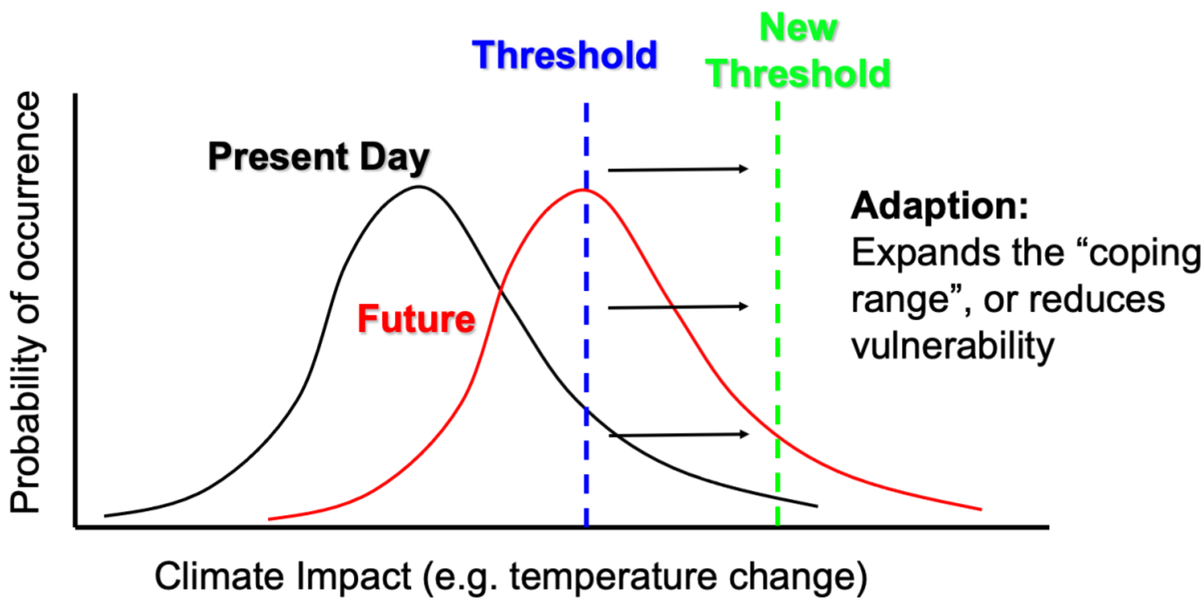

***Figure 12**: Demonstration of a hypothetical risk and adaptation scenario. Present day conditions for a risk imposing phenomena (e.g. probability of occurrence of extreme temperatures) is given with black solid line. With climate change, the probability of occurrence increases, shown in shifted red distribution. Moving the critical threshold from the original location (blue dashed vertical line) to the new location (green dashed vertical line) expands the coping range, thereby reducing the vulnerability through adaptation. Adapted from Corfee-Morlot and Agrawala (2004).*

When we consider the adaptation strategies in the Sahel we need to think about regional climate (and associated uncertainties as demonstrated in Figure 13) and its impacts. In the Sahel, these strategies will be highly dependent on each country's coping range, as well as zones of adaptive and mitigative capacity and residual risk. Particularly in Mali, some potential adaptation strategies include: Developing heat and drought tolerant crop varieties; Expansion of drip irrigation; Investment in indoor farming; Developing rainwater storage mechanisms; Raising public awareness; Reduce gender inequity; Implement agricultural insurance; and Strengthening hydrological infrastructure. Note that different parts of the Sahel will have their own adaptive capacities and mitigation strategy, depending on the culture, institutions, sector-specific impacts of climate change, and most importantly economics.

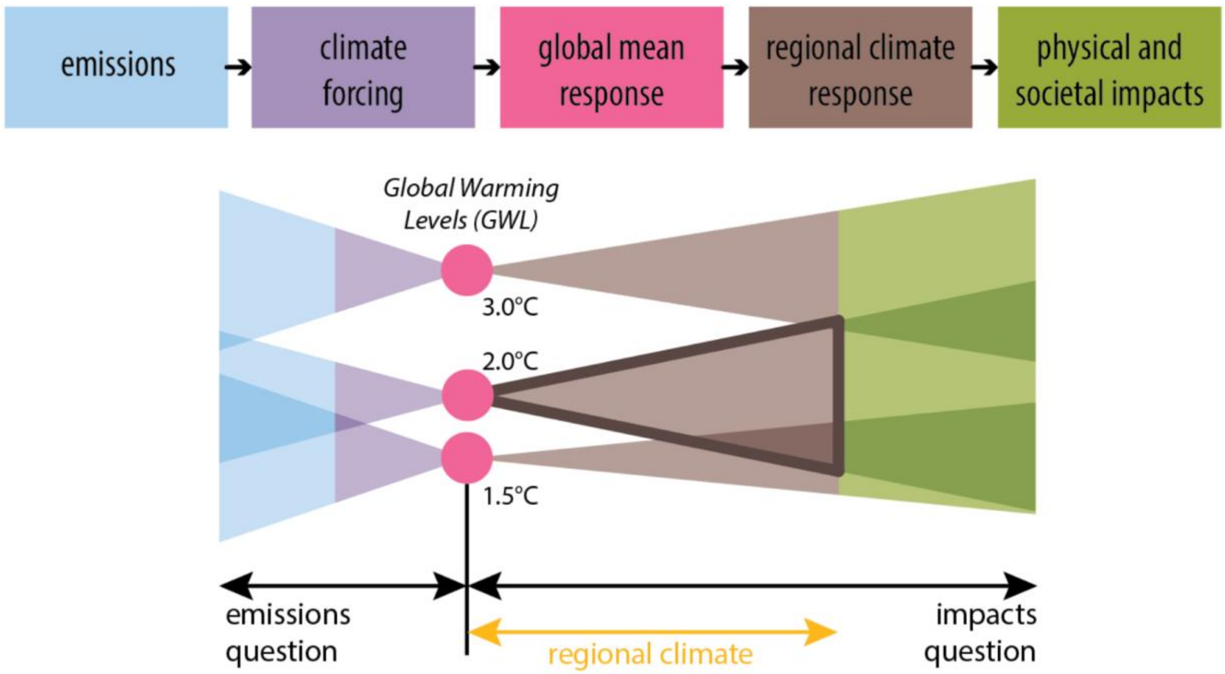

Figure 13: *Schematic representation of relationship between emission scenarios, global warming levels (GWLs), regional climate responses, and impacts. The illustration shows the implied uncertainty problem associated with differentiating between 1.5, 2°C, and other GWLs. Note that the width of the triangle is an indication of uncertainty. Adapted from IPCC (2022).*

Proposal to develop climate information services to reduce risks from climate change

The countries in the Sahel, and Mali in particular, have limited capacity to adapt to climate change, in part due to the poor quality and inaccessibility of climate information, low financing capacity and lack of political interest. The other issue in the Sahel (and Africa in general) is the lack of transformation of climate-related data and other relevant information into customized products such as projections, trends, economic analysis, counseling on best practices and the development and evaluation of solutions and any other service about climate that may be used for the benefit of the society at large.

The purpose of this part is to develop a proposal for climate information services for effective adaptation and mitigation strategies in the agricultural sector. The proposal calls for two equally important efforts. First, national meteorological services must continue to push for generation and analysis of new forms of data that are directly related to understanding and mitigating risk within the context of farmers' livelihoods. Second, there should be an increasingly important role for the private sector to champion research on effective and sustainable production of climate information, customization of sector-specific information and dissemination. As climate change threatens development, the importance of private sector involvement cannot be exaggerated.

Effort 1: As summarized earlier, significant investments have been made to develop climate information services in Mali and research shows that availability and access to weather and climate information can help reduce negative impacts from climatic events through proper preparation and planning, thereby helping farmers increase their resilience to climate variability and change (Vogel et al., 2019). However, there remains a mismatch between the supply and uptake of climate information services in Mali. The reasons for the mismatch include inaccessibility, information afforded not being relevant to context or scale, or information being poorly communicated (Antwi-Agyei et al., 2021). One way to address these issues is to encourage national meteorological service agencies that have traditionally been the custodian of climate information services to venture into transdisciplinary co-production of climate information (Vogel et al., 2019; Carter et al., 2020). Co-production of climate information involves information producers, practitioners and stakeholders, and other knowledge holders participating in equitable partnerships and dialogues to collaboratively identify climate-based risk and develop scale-relevant climate information to address this risk (Carter et al., 2020) (Figure 14).

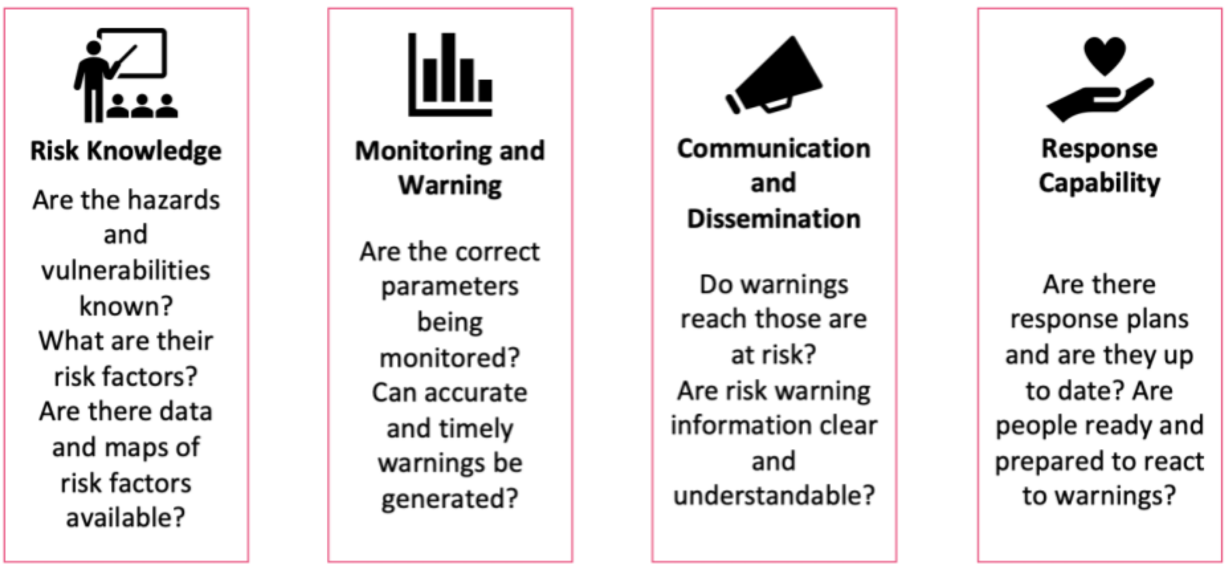

Figure 14: *Four tenets of successful risk management that should be included in the proposed climate information services framework in the context of climate change. Adapted from Neussner (2009).*

The second part of effective risk management involves perceptions of climate variability and change as these perceptions determine how individuals and institutions act, and thus contribute to the success or failure of adaptation policies related to weather and climate (Simpson et al., 2021). Together with perception, climate literacy and understanding the anthropogenic cause of climate change can affect the difference between coping responses and more informed and transformative adaptation (Figure 15) (Mutandwa et al., 2019). Combining co-generation of climate information services that are farmer centric, improved climate change literacy, enhanced institutional capacity building and strategic financial investment, there is a high probability that a new breed of climate information services can help Malian stakeholders adapt to projected climate risks (Figure 15).

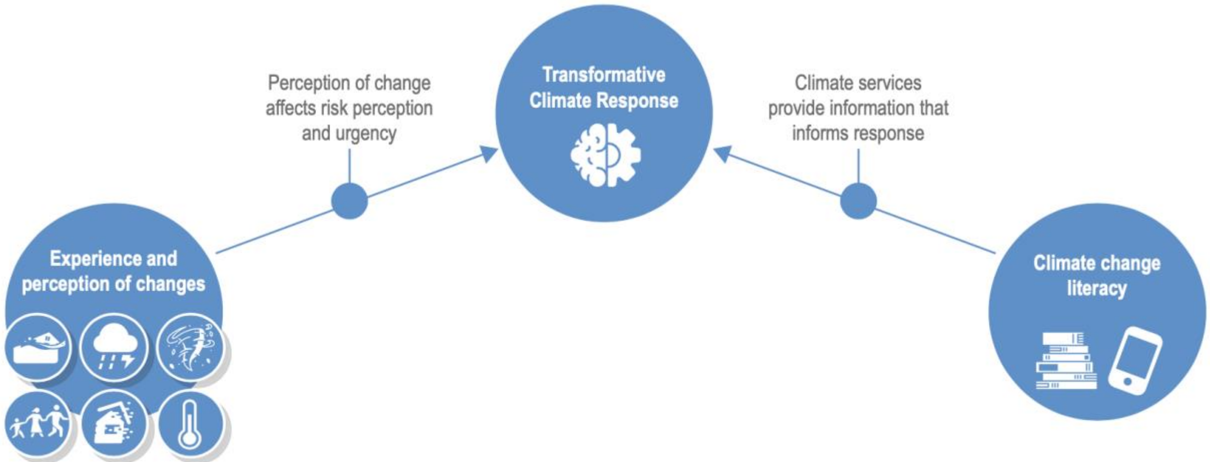

Figure 15: *Climate services and climate literacy are important for informing transformative responses to climate change, including adaptation and mitigation responses. While climate services promote climate resilient development by providing climate information for adaptation decision making, uptake of climate services relies partly on climate risk perception of users. Climate change literacy encompasses being aware of climate change and its anthropogenic causes and, together with climate services, can strengthen responses to climate change through better understanding of future risk (adapted from Simpson et al., 2021 and Trisos et al., 2022)*

Effort 2: The process of providing climate information services involves many levels, including but not limited to, data production through monitoring and processing, contextualizing of data including research, value-adding or customizing information to sector-specific and dissemination to end users. The need for climate information must be understood and organized for sector use. Governments alone cannot effectively manage all the elements along the value chain of climate information services, especially as the impacts of climate change are becoming more varied and rampant, and as the concerns for adaptation and mitigation are growing. Moreover, the increasing demand for accurate and timely climate information at different levels and in different sectors necessitates a collaborative approach. National meteorological and hydrological institutions struggle to meet the demands of the general public and the various sectors at the same time. To this end, the involvement of the private sector is the best option to relieve the operations of the national institutions to some extent. The private sector can take responsibility for the contextualization of information and knowledge derived from climate research for decision-making at all levels of society. In some countries, the private sector is involved in climate information services at all stages of the process and there is now a growing recognition that private service providers could offer the resources needed to fill key gaps in climate information across Africa.

It is important to note that at least two gaps must be filled before effective engagement of the private sector can succeed. First, the business model of climate information providers in African countries must be compatible with the needs and requirements of the private sector. National meteorological and hydrological services should take pragmatic steps to fully integrate private sector services. There should be a clear national policy and legal framework on collaboration with private actors, specifying the roles and responsibilities of each player, especially those of national

services and private actors. Second, in order to meet the demands of the private sector, cutting-edge technology must be deployed. This means that the current infrastructure, equipment and software of the national services needs to be upgraded. They need to improve their existing infrastructure to enable them to deliver high quality, high resolution, customized information in a timely manner. They need to build high-quality databases of clients and partners that will be used to create access to climate reports tailored to the needs of the private sector and development sectors.

6. Conclusions

It has been well established that the countries of the Sahel region are some of the most vulnerable to the impacts of climate change. However, implementing climate change policies has been difficult at both the national and local government levels and the gap is often filled by relatively strong regional institutions and local actors that provide capacity for action. To alleviate climate risks and adapt to negative effects of climate change, there is an urgent need to prioritize climate change adaptation and mitigation as sectoral interventions, particularly in the agricultural sector.

There is significant value in climate information services as a tool for reducing the impact of climate impacts and associated risks within the agricultural sector in the Sahel. These services also have the potential to increase the resilience of climate-sensitive sectors to climate shocks. If climate information services are effective, climate-sensitive economic sectors, particularly agriculture, will be better able to cope with high productivity and improved livelihoods across the region, even as climate variability increases.

In Mali, existing climate information services are primarily provided through national meteorological and hydrological institutions supported by regional NGOs, which are largely funded by governments and foreign donors. While there is dedicated funding for these activities, provision of climate services would benefit immensely from private sector partnerships to deliver information would help to alleviate the burden on those institutions and ensure more efficient services.

Malian farmers have been exposed to a wide variety of climate information services for some time. In general, these services are beneficial but there is evidence to suggest that not all farmers benefit equally, nor can they all act on the information they receive. While a more farmer-centric approach is beginning to take shape, climate change is challenging the forecast approaches that rely on historical information and analog climate years. There are new and improved ways to provide these services that include extension and communicating with farmers to help them make their own decisions that suit their conditions and improve their livelihoods with local climate information.

There is still a great deal of uncertainty about crop productivity under changing climates in the Sahel despite a vast amount of research in recent decades. There is evidence to suggest that climate change is already negatively impacting crop production and slowing productivity growth and vulnerability of crop production from future climate change is great. Even with adaptation

and potential beneficial effects of increased CO_2 concentrations, substantial yield declines (in excess of 5%) are projected for staple crops in the region.

In this report a proposal is developed for climate information services for effective adaptation and mitigation strategies in the agricultural sector. The proposal calls for two equally important efforts. First, national meteorological services must continue to push for generation and analysis of new forms of data that are directly related to understanding and mitigating risk within the context of farmers' livelihoods. Moreover, these institutions must be encouraged to participate in transdisciplinary co-production of climate information that involves information producers, practitioners and stakeholders, and other knowledge holders with a view towards collaboratively identifying climate-based risk and developing scale-relevant climate information to address this risk. Second, there should be an increasingly important role for the private sector to champion research on effective and sustainable production of climate information, customization of sector-specific information and dissemination. As climate change threatens development, the importance of private sector involvement cannot be exaggerated.

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