Assessing the potential of rainwater harvesting as an adaptation strategy to climate change in Africa

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The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

1. **Lebel, S.**, Fleskens, L., Forster, P.M., Jackson, L., Lorenz, S., Assessing the potential of rainwater harvesting as an adaptation strategy to climate change for African agriculture. *(In review 2014).*

S. Lebel, P.M.F., and L.F. all contributed to the development of the original research idea. L.S.J. wrote the code for the pre-processing and regridding of the CMIP5 data, which was then adapted and used for the purpose of this analysis by S. Lebel and S.Lorenz. P.M.F. sourced the CMIP5 data. S. Lebel developed the methodology and conducted the calculations. The manuscript was written by S. Lebel with inputs from L.F. and P.M.F.

This publication was under review at the time of submitting this thesis, and has not yet been accepted for publication. It forms the main body of Chapter 3, entitled “Evaluation of *in situ* rainwater harvesting as an adaptation strategy to climate change for crop production in rainfed Africa”. Chapter 3 comprises supplementary analyses for millet and sorghum crops, in addition to the maize crop described in the publication manuscript. Part of the introduction from the manuscript is used in Chapter 1: Introduction.

2. **Lebel, S.**, Bekaert, D.P.S., Horton, D.E., Forster, P.M., Fleskens, L., Characterization of seasonal dry spell projections for climate change adaptation in agriculture. *(In preparation).*

S. L. developed of the original research idea and methodology, with some input from P.M.F. D.E.H. sourced, regridded, and bias corrected the CMIP5 daily precipitation data. D.P.S.B. and S.L. processed the bias corrected data. S. L. mapped the processed data and conducted the data analysis. The manuscript was written by S. L. with inputs from L.F. and P.M.F. This publication was under preparation at the time of submitting this thesis, and has not yet been accepted for publication. It forms part of Chapter 4, entitled “Characterizing growing season dry spells from CMIP5 climate change projections”.

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Abstract

Stabilizing smallholder crop yields under changing climatic conditions in Africa will require adequate adaptation strategies focused on soil and water management. In some regions, rainwater harvesting (RWH) is used already to decrease the susceptibility of crops to frequent dry spells. Findings from this thesis show that Africa is likely to see significant changes in rainfall patterns during crop growing seasons, including higher intensity rainfall and more frequent very long dry spells. It is shown that RWH is a valuable adaptation strategy to climate change in Africa for maize, millet, and sorghum for a number of reasons. RWH could bridge ~30% of the yield gaps attributable to water deficits in the 2050s, thereby reducing future irrigation requirements. However, yield increases from improved water availability remain marginal (e.g. ~5-6% for millet and sorghum), unless combined with improved fertility measures (doubling of yields possible). Key benefits, potentially of greater importance than increased water availability from RWH, include protecting seeds, concentrating nutrients, and reducing long-term soil degradation. While RWH strategies show great biophysical potential as adaptation strategies, there remain a number of locally specific barriers to their adoption which need to be addressed to ensure their successful implementation at larger scales. As humans normally respond to perceived risks brought on by certain situations, it was hypothesized that climate change perceptions may be key in promoting the adoption of adaptation strategies such as RWH at the field level. In Burkina Faso, farmers had skewed perceptions of climate change (e.g. perceived decrease in precipitation when there are observed and projected increases), and thought of RWH as a central adaptation strategy despite not addressing projected impacts directly. Widespread RWH adoption across three field sites (Burkina Faso, Ethiopia, and Tunisia) rather depended heavily on government and NGO intervention. Overall, RWH could be an integral part of “adaptation packages” aimed at smallholder farmers, but should not be promoted as an independent solution to climate change in rainfed Africa.

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List of Abbreviations

AOGCM	Atmosphere-Ocean General Circulation Model
AR5	Fifth Assessment Report
AWC	Available Water Capacity
C:CA	Catchment to Cultivated Area ratio
CDF	Cumulative distribution function
CF	Change Factor calibration method
CMIP5	Coupled Model Intercomparison Project, Stage 5
CN	Curve Number (see SCS-CN)
CWP	Crop Water Productivity
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El-Niño-Southern Oscillation
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Model
GPCP	Global Precipitation Climatology Project
HRU	Hydrologic Response Unit
INERA	Institut d’études et de recherches agricoles (Burkina Faso)
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
MUSLE	Modified Universal Soil Loss Equation
RCP	Representative Concentration Pathway
RWH	Rainwater harvesting
SCS-CN	Soil Conservation Service Curve Number
SWAT	Soil and Water Assessment Tool
UNAF	United Nations Adaptation Fund
USLE	Universal Soil Loss Equation
WAHARA	Water Harvesting for Rainfed Africa

Chapter 1
Introduction

1.1 Research motivation

Agricultural systems are suffering important pressures from population growth, anthropogenic land and water degradation, and climate change. This impedes on their ability to produce sufficient food, especially in areas where cropping conditions are already unfavourable. Rainfed agriculture, which primarily uses green water resources (i.e. infiltrated rainfall which forms soil moisture in the root zone) to grow crops (Rockström et al., 2010), is predominant in dryland areas of sub-Saharan Africa. With a changing climate, dryland African farmers who subsist from rainfed agricultural systems will have to cope with increased risk arising from more frequent extreme events and poor intra-seasonal rainfall distribution (Barros et al., 2014). Since rainfall patterns are the main factor steering crop productivity in Africa (Muller et al., 2011), these changes have the potential to be detrimental to food production by causing severe declines in crop yields (Blignaut et al., 2009, Cline, 2007).

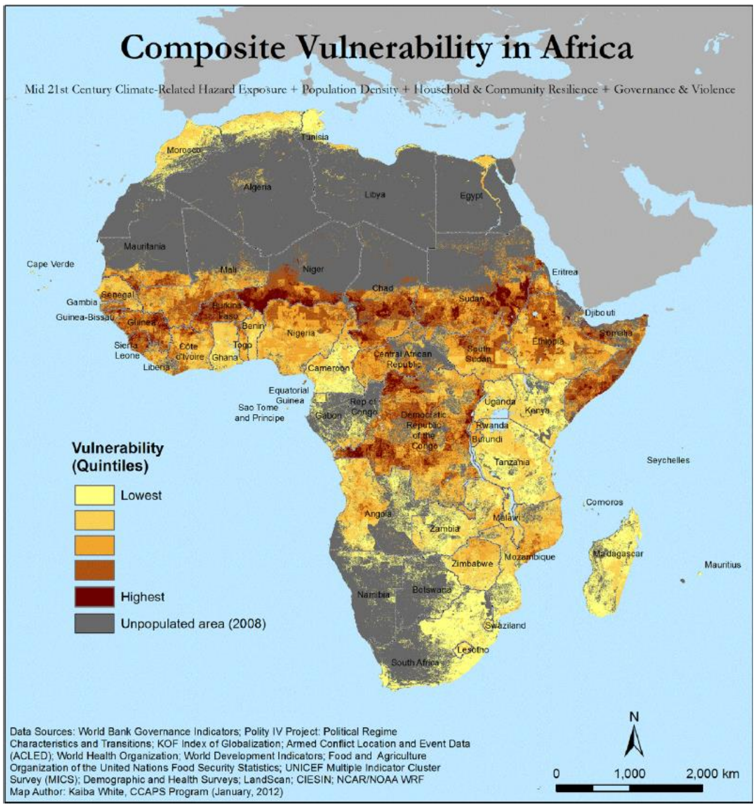
Harsh environmental conditions, along with social, institutional, and economic constraints, lead to important yield gaps in subsistence crop production (Wani et al., 2009). Specifically, yield gaps refer to the difference between potential yields under ideal management conditions, and the actual yields obtained by farmers for specified crops, particularly in rainfed agricultural systems (Singh et al., 2009). Despite this large number of constraints on production systems, these yield gaps could at least partially be bridged through the implementation of adequate rainwater harvesting and management strategies (RWH). When effectively carried out, these techniques can significantly reduce the susceptibility of crops to the adverse effects of frequent dry spell events.

This thesis was undertaken in collaboration with the EU-funded WAter HArvesting for Rainfed Africa (WAHARA) project, which studies RWH strategies used across four field sites (Burkina Faso, Ethiopia, Tunisia, and Zambia). My work builds on the WAHARA project by addressing the issue of climate change adaptation, which was initially not one of their stated objectives.

1.2 Background

1.2.1 Vulnerability and uncertainty in changing African climates

Busby et al. (2014) identified Burkina Faso and large parts of the Sahel as the most vulnerable to climate change by the 2050s, based on a composite index encompassing climate hazards (e.g. high precipitation intensity and number of dry days), population density, household and community resilience, and governance (Figure 1.1). The exposure to climate-related risk is likely the most important factor in assessing vulnerability, and therefore areas of focus for adaptation planning.



Data Sources: World Bank Governance Indicators; Polity IV Project: Political Regime Characteristics and Transitions; KOF Index of Globalization; Armed Conflict Location and Event Data (ACLED); World Health Organization; World Development Indicators; Food and Agriculture Organization of the United Nations Food Security Statistics; UNICEF Multiple Indicator Cluster Survey (MICS); Demographic and Health Surveys; LandScan; CIESIN; NCAR/NOAA WRF
Map Author: Kaiba White, CCAPS Program (January, 2012)

Figure 1.1 | Climate change vulnerability index across Africa (Busby et al., 2014).

In Africa, there is still a lack of information on the characterization of intra-seasonal rainfall patterns which could inform agricultural adaptation planning. The temporal and spatial scales of climate projections from General Circulation Models (GCMs) are often inadequate to meet those needs, and require intensive transformations (e.g. regridding, bias correction, downscaling) to be of use for informing regional or national-level agricultural policy-making. Analyses of climate extremes such as maximum consecutive number of dry days and days with intense precipitation are usually limited to annual means, and provide little information for crop production impacts in rainfed areas. Furthermore, the uncertainties associated with climate change projections (either from models, internal variability, or socio-economic scenarios), can render decision-making more challenging. Strategies to characterize, quantify, and address these uncertainties need to be clearly presented in impacts and adaptation studies, in order to lead to robust decision-making (Dessai and Hulme, 2007).

1.2.2 Adaptation to climate change

The term adaptation, used in the context of climate change, is rapidly evolving (c.f. Chapter 7). Originally, the term adaptation as it is used in the global change literature arose from evolutionary biology (Smit and Wandel, 2006), and was therefore not necessarily associated with human systems. The Intergovernmental Panel on Climate Change (IPCC) defined adaptation, as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2014b). This definition lacks the depth of other definitions: natural and human systems are seemingly disconnected, and the possibility of maladaptation is assumed to be inexistent. In the context of this thesis, the definition of adaptation suggested by Moser and Ekstrom (2010) was deemed most appropriate. They suggest that "[a]daptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting nonclimatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities" (Moser and Ekstrom, 2010: 22026). The key concepts used in this definition which contributed to its selection were: a) the term "social-ecological systems", which entails the interaction between humans and their environment, b) the range of adaptation strategies from short-term coping to deeper transformations, whereby we are not limiting adaptation to technical options and represents a range of temporal scales, and c) the idea that adaptation strategies may not always be successful in mitigating the negative impacts of climate change.

1.2.3 The role of rainwater harvesting in water resources management

The sustainable intensification of agricultural production in Africa, to help feed a growing population under changing climatic conditions, will require local solutions that are economically viable and socially acceptable. Several adaptation measures are being promoted to cope with a changing climate, such as the use of different crops or crop varieties, soil conservation, changing planting dates, and irrigation (Bryan et al., 2009). While all of these options offer benefits for agricultural production, they may not all be viable choices for smallholder farming either due to their high costs, technical restrictions, or even cultural limitations (Adger et al., 2012).

New pieces of evidence point to the African continent as having extensive groundwater reserves which could potentially be used to increase the small-scale irrigated area for food production (MacDonald et al., 2012). However, these are far from being sufficient or fully accessible to sustain large-scale irrigation schemes at the continental scale and will need to be managed carefully to avoid rapid depletion. In this context, better management of surface water resources to complement groundwater usage for agricultural production will be essential, and may start with rainwater harvesting. In areas such as the Sahel, where it is estimated that only 10-15% of rainwater is used productively for plant growth (Breman et al., 2001), RWH could help mitigate the impacts of climate change on crop production. *In situ* RWH strategies, such as planting pits or stone bunds implemented at the field level, act to shift a fraction of surface runoff water to productive purposes by storing water in the form of soil moisture (Rockström et al., 2002). This entails that the water is directly made available to the crops in the fields, and does not require being re-routed using pumps. This type of RWH strategies is not aimed at directly improving water use efficiency, but rather at reducing the variability in potential and actual crop yields (Fox and Rockström, 2000). By increasing the water holding capacity of often highly degraded soils, RWH can also reduce the susceptibility of crops to events such as localized flooding of lowlands and further erosion.

1.3 Research aims and objectives

This PhD project aims to assess the potential of rainwater harvesting (RWH) techniques as agricultural adaptation strategies to climate change across rainfed Africa. A biophysical modelling approach, in conjunction with climate data analysis and a socio-economic investigation, will contribute to a more comprehensive understanding of the processes that will affect climate change adaptation in rainfed agricultural systems. While it is generally accepted that RWH strategies for agricultural production can contribute to the development of small farming communities, their performance under varying climatic conditions is still poorly understood. Taking a modelling approach can help us understand underlying biophysical processes, where long-term observations of the climate and soil/water processes are scarce, such as in Africa. It is hoped that the findings from this research project will be used in decision-making for future planning and implementation of RWH systems, and allow policy makers to evaluate trade-offs. The lessons learnt will further contribute to the generation of a broader framework for the implementation of RWH technologies as adaptation strategies to climate change across rainfed Africa.

In this context, the specific objectives of this thesis will be to:

i. Characterize current and future projected crop growing season rainfall patterns over rainfed agricultural land based on model output from the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5).

ii. Evaluate current and future rainwater harvesting potential across Africa (continental-scale) under climate change conditions, through the development of an original method based on monthly surface runoff potential and crop water requirements.

iii. Evaluate agricultural management and climatic characteristics affecting RWH performance through integrated hydrological and crop modelling.

iv. Assess the social barriers to climate change adaptation through RWH at field site locations through the analysis of qualitative field data (i.e. focus group activities, key informant interviews, and socio-economic questionnaires).

1.4 Thesis outline

This thesis comprises eight chapters, including the introduction. The second chapter provides a literature review of the key concepts, methodologies, and datasets used to frame this research. Chapter 3 provides an overview of the potential for RWH across Africa, using an original methodology aimed at providing a quick assessment of impacts on crops, based on crop water requirements and surface runoff (obtained from GCMs) at a 0.5°x0.5° spatial resolution.

Chapter 4 provides a thorough discussion of the uncertainties associated with daily climate change projections, particularly within the CMIP5 datasets. How to address and characterize these uncertainties is discussed. Results from bias correction of daily climate variables are presented. In addition, changes in intra-seasonal dry spell patterns are characterized and implications for the selection of adaptation strategies in agriculture are discussed.

Chapter 5 identifies social barriers to adaptation, through an investigation of environmental risk perceptions and other factors affecting RWH adoption at three field sites across Africa (Burkina Faso, Ethiopia, and Tunisia). Farmers' perceptions of climate change are compared with long-term climate observations in Burkina Faso.

Chapter 6 investigates the impacts of different management options (e.g. RWH and cropping calendars) on soil water balance and crop yields at the watershed level for a field site located in Northern Burkina Faso. This work further complements Chapter 5 by assessing other factors which could be related to reported climate change perceptions.

Chapter 7 is a synthesis and critique of the approach to the work undertaken, through a comparison with an analysis of the climate change adaptation conceptualizations in the agricultural literature. Finally, Chapter 8 presents the main conclusions of the thesis, and suggestions for future research are put forward.

Chapter 2

Literature review

2.1 Introduction

This literature review aims to clarify key concepts and ideas used to frame this research, and identify current research gaps which could be addressed through this thesis. First, the current state of climate change projections from the Coupled Models Intercomparison Project (CMIP) is described, along with the concept of Representative Concentration Pathways (RCP) and the uncertainties associated with the CMIP5 ensemble. Projected impacts of climate change on African agriculture are described, as well as an attribution of causes. Then, rainwater harvesting is described as a potential adaptation strategy to some of the impacts presented. A range of existing hydrological models which could be used to test this potential are compared, and details are given for the selected Soil and Water Assessment Tool (SWAT). Finally, social barriers to the adoption of RWH are presented, with a particular focus on climate change perceptions as a key driver for decision-making at the farm level.

2.2 Climate change projections

General circulation models (GCMs) are global-scale models at a relatively coarse resolution (i.e. hundreds of kilometres) which use the laws of thermodynamics to represent the climate system, particularly atmospheric processes. An increasing number of these numerical models (i.e. as AOGCMs or Earth System Models) also couple the atmosphere with oceans, land, and/or the cryosphere. They represent the most complete representations of the climate system which are available to the research community at this time. They are particularly useful in evaluating the complex relationships with, and the long-term impacts of, anthropogenic forcings (e.g. greenhouse gas emissions) on our climate.

2.2.1 CMIP5

As of 2011, the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) began releasing General Circulation Model (GCM) climate change data encompassing simulations from over 20 research groups and 50 models. Of interest to this thesis are the long-term experiments (century timescale) in CMIP5, which look at responses of climate to various forcing factors (Taylor et al., 2011). CMIP aims to promote exchanges within the climate science community, and thereby improve models. In addition, the comparison of models allows for a better understanding of the limitations of climate models. For instance, the Inter Tropical Convergence Zone (ITCZ), the El-Niño-Southern Oscillation (ENSO), and the West African Monsoon are all known to play a central role in African climate (Collier et al., 2008), but many climate models poorly represent these key processes (Hulme et al., 2001).

This poor representation of natural internal climate variability can produce a highly uncertain representation of climate change on the continent. For example, the MIROC-ESM-CHEM model (an earth system model, the latest and most comprehensive type of model used in CMIP5 also known as coupled climate model with biogeochemical components) has shown consistent biases in terms of temperature and precipitation for the CMIP5 historical simulations. It tends to have a warm bias for the northern mid- and high latitudes, as well as a dry bias in the tropical lower troposphere, and has other shortcomings similar to the ones found in the earlier version of the model in terms of precipitation (Watanabe et al., 2011). While acknowledging the limitations of the different models is important, it does not necessarily mean that the models are not good. Using a range of models for the purpose of analysis has the potential to provide a less biased picture of future projections (IPCC, 2013a).

2.2.2 Representative Concentration Pathways

A set of four Representative Concentration Pathways (RCPs) have further been developed for CMIP5 based on an extensive review of climate modelling literature, and allow for broader considerations of global climate projections (van Vuuren et al., 2011a). Four pathways were developed for the modelling community, with 2.6[$W \cdot m^{-2}$] being the low emissions, 4.5[$W \cdot m^{-2}$] and 6.0[$W \cdot m^{-2}$] being the intermediate emissions, and 8.5[$W \cdot m^{-2}$] representing the high emissions scenario (van Vuuren et al., 2011a). These four pathways are named after the projected levels of radiative forcing in the year 2100, where emissions were converted into atmospheric composition and radiative forcing by a simple aggregate representation of the atmosphere and carbon cycle (Masui et al., 2011). They were developed following the SRES scenarios used in the IPCC AR4 to meet the demand for more detailed inputs for new climate and integrated assessment models, as well as to explicitly address the impact of climate policies on climate change, and related adaptation strategies. In AR4, the emissions scenarios had focused on stabilizing radiative forcings at 4.5[$W \cdot m^{-2}$] (Fisher, 2007). RCPs contain emissions, concentration and land-use trajectories; they are internally consistent sets of projections of the components of radiative forcing that are used in subsequent phases of modelling, but do not represent a final, complete set of socio-economic, emissions, and climate projections (van Vuuren et al., 2011a). The RCPs are also the first scenarios to include land use projections in addition to future emissions pathways (Thomson et al., 2011). The range of forcing levels available through the RCPs is expected to allow a broader study of possible climate futures. It is important to point out that all RCPs are developed from different models and have different baseline scenarios. Theoretically, a very large number of stabilization scenarios could be developed to lead to the same radiative forcing value for the end of the 21st century. Since the models used to establish the RCP scenarios used different climate models, two models with the same level of anthropogenic CO_2 emissions may reach different atmospheric CO_2 concentrations (Thomson et al., 2011).

More specifically, RCP2.6 (van Vuuren et al., 2011b) is a peak and decline scenario, peaking at 3[$W \cdot m^{-2}$] mid-century, and is representative of limiting the global temperature increase to 2°C through the mitigation measures. This RCP was developed from a baseline scenario assuming a medium development scenario, with historical trends continuing in the future. It would require more than 95% of emissions reductions by 2100, with CO_2 emissions reduced by more than 100%. Climate policies would lead to an increase in deforestation for biofuel production, and hence CO_2 emissions associated with land use are slightly higher than in the baseline. There is a greater uptake of CO_2 by the oceans and biosphere than the anthropogenic emissions by the end of the century (i.e. net decrease in CO_2 concentrations). In terms of abatement costs, carbon prices would rise from about 25USD/tC today to 600USD/tC by 2050, and from 700 to 900USD/tC for the rest of the century.

RCP4.5 is a cost-minimizing stabilization pathway, where stabilization occurs in 2080 with carbon prices reaching a constant value of \$85/tCO_2, but where radiative forcing does not peak previously such as in RCP2.6 (Thomson et al., 2011). The CO_2 concentration by the end of the century is about 650ppm CO_2-equivalent. It assumes that climate policies such as the introduction of a set of global greenhouse gas emissions prices limit emissions and therefore radiative forcing. Electric power generation shifts from the largest emitter to net negative emissions (Thomson et al., 2011).

RCP6.0 is similar to RCP4.5: a stabilization pathway where the 6.0[$W \cdot m^{-2}$] radiative forcing is not exceeded before 2100. Using the AIM/Impact [Policy] model, the final consumption from the discounted total global utility is maximized up to a maximal radiative forcing of 6.0[$W \cdot m^{-2}$], thereby forming a policy intervention scenario (Masui et al., 2011). The optimal emissions path obtained from that modelling phase is then used as a constraint to the AIM/CGE [Global] model, where regional differences are taken into account (e.g. rapid economic growth in Asia leading to the greatest CO_2 emissions). Carbon prices reach \$US180/tC (2001 constant \$US) by 2080 after which they stabilize. Energy intensity is expected to decline faster than in the reference scenario, down to -1.5%/year between 2060-2100 as opposed to -0.9%/year in RCP8.5 (Masui et al., 2011).

RCP8.5 does not include any specific climate mitigation target and policies, and is a continuously rising emissions scenario (Riahi et al., 2011). The main storyline around RCP8.5 assumes a global population of over 12 billion people by 2100. In addition, slow economic growth and little improvements in per capita income lead to poor progress in terms of technology and energy efficiency. Land use changes remain important with significant increases in cultivated land (16% until 2080 above 2000 levels), in order to increase agricultural production by 135% by 2080. About 75% of the predicted increase in greenhouse gas emissions by 2100 is due to rising CO_2 emissions from the energy sector. Since air pollution legislation is already in place in large regions of the world, there will be a clear decoupling of CO_2 emissions from pollutants (e.g. SO_2 emissions are reduced but CO_2 emissions continue to grow in the energy sector) (Riahi et al., 2011).

Overall, while there are significant advantages to using the RCPs, there remain a wide range of uncertainties and limitations that will require further investigation. A number of these limitations to the RCPs were identified in van Vuuren et al. (2011a), and are summarized as follow:

1. They are not forecasts and should not be seen as policy prescriptive.
2. The underlying socio-economic scenarios are not a consistent set and results should not be interpreted as a result of climate policy or particular socio-economic developments, but rather focus on the radiative forcing projections.
3. There is not a unique socio-economic scenario for each RCP.
4. It is important to consider the fact that each RCP comes from individual models runs in the interpretation of the results.
5. There are “unknown/unidentified” sources of uncertainties associated with the translation of emissions to concentrations and radiative forcing.

Table 2.1 │Summary of the characteristics of the four RCPs

Parameter	Parameter reference	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Radiative forcing [W·m^{-2}] in 2100	(Moss et al., 2010)	Peak at ~3 before 2100 then decline	~4.5	~6.0	>8.5
Pathway	(Moss et al., 2010)	Peak and decline	Stabilization without overshoot	Stabilization without over-shoot	Rising
Model providing RCP	(Moss et al., 2010)	IMAGE	GCAM	AIM	MESSAGE
Agricultural area	(van Vuuren et al., 2011a)	Medium for cropland and pasture	Very low for both cropland and pasture	Medium for cropland but very low for pasture (total low)	Medium for cropland and pasture
Air pollution	(van Vuuren et al., 2011a)	Medium-low	Medium	Medium	Medium-high
CO_2[1] concentration in 2100 [ppm] and (2000)	(Meinshausen et al., 2011)	421 (369)	538 (369)	670 (369)	936 (369)
CH_4 concentration in 2100 [ppb] and (2000)	(Meinshausen et al., 2011)	1,254 (1,751)	1,576 (1,751)	1,649 (1,751)	3,751 (1,751)
N_2O concentration in 2100 [ppb] and (2000)	(Meinshausen et al., 2011)	344 (316)	372 (316)	406 (316)	435 (316)
Multi-gas concentration level [ppmv CO_2-eq]	(Masui et al., 2011)	445-490	590-710	710-855	n.a.
Likely range of global mean temperature increase above pre-industrial levels at equilibrium (°C)	(Masui et al., 2011)	1.4-3.6	2.2-6.1	2.7-7.3	n.a.
Peaking year for CO_2 emissions	(Masui et al., 2011)	2000-2015	2020-2060	2050-2080	n.a.
Change in global emissions in 2050 (% of 2000 emissions)	(Masui et al., 2011)	-85 to -50	+10 to +60	+25 to +85	n.a.

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[1] For all the RCPs, harmonization of the historical predictions was done to start the simulations (MEINSHAUSEN, M., SMITH, S., CALVIN, K., DANIEL, J., KAINUMA, M., LAMARQUE, J. F., MATSUMOTO, K., MONTZKA, S., RAPER, S., RIAHI, K., THOMSON, A., VELDERS, G. & VAN VUUREN, D. P. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change,* 109**,** 213-241.)

2.2.3 Uncertainties in climate change projections

In the context of climate change adaptation, two approaches can generally be taken to guide decision-making. First, a projection-based approach which relies heavily on climate models and projections, with the aim of providing information relevant for decision-makers can be taken. In the second case, projections are not of prime importance. Rather, the second approach focuses on current and past vulnerability to climatic factors, with the decisions to be made at the centre of the agenda (Challinor et al., 2013, Vermeulen et al., 2013, Dessai and Hulme, 2004). Up to this day, the adaptation literature has focused heavily on the first approach[2], while real-life decisions might tend to take more of the second approach (Dessai et al., 2009). This is likely due to the large range of uncertainties associated with the impacts focused approach. Indeed, uncertainties are an inherent part of climate change projections, having repercussions on decision-making in both the mitigation and adaptation policy realms. These uncertainties from the climate projections percolate down to the adaptation response level, accumulating throughout the process (Wilby and Dessai, 2010).

2.2.3.1 Sources of uncertainties in climate models

In general, three main sources of uncertainties can be identified in climate change projections arising from GCMs (Hawkins and Sutton, 2011), not all of which can equally be quantified or have the same weight in total projections uncertainties. First, there is model uncertainty, whereby different climate models project a range of future changes under the same radiative forcing and initial conditions. In most cases, the average of all models will be considered as the “best estimate” of future climate realization. In fact, a model’s ability to reproduce historical climates cannot be considered as a strong indicator of its ability to represent future climates. In second place is scenario uncertainty, or our inability to predict human behaviour with regards to greenhouse gas emissions and mitigation policy into the future (c.f. Section 2.2.2). We are therefore unsure of what the future anthropogenic radiative forcings are likely to be. Finally, there exists random, somewhat chaotic, internal variability of the climate system. This internal variability has the potential to mask, or enhance, over the medium-term the signal from changes in anthropogenic forcings (Hawkins and Sutton, 2011).

Results from an analysis conducted by Hawkins and Sutton (2011) shows that model uncertainty is the dominant contributor to uncertainties throughout the 21st century, but as we move forward in time, scenario uncertainty becomes prevalent as human behaviour with

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[2] While a review of the climate change adaptation literature is not presented in this Chapter, a thorough meta-analysis of the agricultural adaptation body of literature published between 1992 and mid-2013 is available in Chapter 7.

respect to greenhouse gas emissions mitigation is highly uncertain. In fact, climate projections really begin to diverge towards the middle of the century. The proportion of internal variability contribution to the total uncertainties is highest at the beginning of the 21st century. Recently, Mora et al. (2013) showed that by the 2050s, global climate could have departed from its current range of natural variability under an increasing emissions scenario (RCP8.5).

2.2.3.2 Characterizing the uncertainty range in CMIP5

To characterize and quantify these uncertainties, different methods have been developed. For example, one could compute the signal to noise ratio to explore whether the uncertainties are larger than the expected change in the projections. More and more, impacts modellers take an ensembles approach, comparing multiple model simulations to be able to quantify uncertainties arising from models themselves. These approaches would allow determining how valuable the information might be for decision-makers, and support robust decisions.

Several ways to reduce uncertainties in climate projections have also been sought in CMIP5. The first approach was to change the way in which scenarios of change from anthropogenic action are conceptualized. That is, instead of using emissions scenarios as in CMIP3, the new Climate Model Intercomparison Project uses RCPs which allow an indefinite number of socio-economic scenarios to lead to pre-defined future forcings (c.f. Section 2.2.2). This approach allows to isolate uncertainties associated with scenarios from those linked to climate system response (Challinor et al., 2013). Improving climate change projections has been thought to be another way towards reducing uncertainties. Therefore, the improvements of projections in CMIP5, including precipitation in the tropics (e.g. over Africa) compared to earlier projections were thought to be positive. However, initial analyses of the robustness and uncertainties in CMIP5 seem to show that there is little improvement in reducing uncertainties associated with climate change projections (Knutti and Sedlacek, 2012).

2.3 Impacts of climate variability and change on African agriculture

2.3.1 Climate change projections over Africa

The latest Intergovernmental Panel on Climate Change (IPCC) assessment report published late 2013 shows projections of temperature increases over most of Africa ranging between 2°C and 3°C under RCP8.5 by the 2050s, with respect to the 1990s. On the other hand, projected changes in precipitation vary across the continent, with Southern Africa becoming dryer while the majority of other regions see a slight increase in precipitation (IPCC, 2013b). Overall, there are no projected continent-wide effects of climate change for Africa. Some of the most significant changes, with the potential to affect agricultural production, occur over Southern Africa and Eastern Africa. In Southern Africa, it is very likely that the onset of precipitations at the beginning of the rainy season will occur later, and may lead to decreases in agricultural yields (Shongwe et al., 2009). In contrast, Eastern Africa should experience general increases in both quantity and intensity of rainfall for the short and long rains alike (Shongwe et al., 2010). Furthermore, important declines in precipitation have already been observed over the past 30 years during the growing seasons in Southern Africa, which can be attributed to a warming of the Indian Ocean, and it is expected that this trend should continue with expected climate change (Funk et al., 2008).

In addition to changes in temperature and precipitation, increased atmospheric CO_2 concentrations will affect crop productivity. From a concentration of 369ppm in 2000 (IPCC, 2007a), atmospheric CO_2 could reach highs anywhere between 421ppm (RCP2.6) and 936ppm (RCP8.5) by the end of the century (Meinshausen et al., 2011). Several crops are expected to benefit from such increases by responding with higher water use efficiencies (Aggarwal, 2009), but this does not take into account other constraints to crop yields such as decreases in soil productivity, water scarcity, and pest proliferation amplified by climate change.

2.3.2 Projected impacts on crop production

Sub-Saharan Africa is widely affected by climate variability, and is expected to suffer harshly from projected climate change, as rainfed agriculture constitutes the main form of agricultural production. Climate change projections, despite their high uncertainties, suggest that all of Africa is at risk of some crop yield reductions. Yields decreases could reach as much as −100% according to some econometric assessments (Muller et al., 2011). On the other hand, Schlenker and Lobell (2010) found that for maize, millet, and sorghum, yields could decrease by 22%, 17%, and 17% respectively across sub-Saharan Africa by the mid-century.

Portmann et al. (2010) estimated that only about 21% of the total cropland harvested area is irrigated in Southern Africa, and 1% is irrigated in Western Africa, meaning that a majority of agricultural land is relying on rainfed production systems. However, the erratic rainfall patterns found in semi-arid tropical areas of Sub-Saharan Africa lead to very high risks of meteorological droughts (i.e. a prolonged period of precipitation amounts below a “normal” threshold) and intra-seasonal dry spells (Rockström et al., 2002). Thornton et al. (2006) identified a number of “hotspots”, using a vulnerability mapping approach, where climate change is likely to have the most severe impacts, including the mixed arid and semi-arid systems in the Sahel, arid and semi-arid rangelands in Eastern Africa, and Southern Africa’s drylands. While these represent the most severe cases, almost all areas of sub-Saharan Africa show high levels of vulnerability. As agriculture represents 60% of employment on average across Africa (Collier et al., 2008), it is very likely that climate change will have significant impacts on the economy.

Estimating risks for African agriculture due to climate change bears a great deal of uncertainty arising from the array of climate change projections themselves, downscaling, and the level of aggregation, amongst others (Muller et al., 2011). In Eastern Africa, Thornton et al. (2009) have looked at the potential impacts of climate change on maize and bean yields, and have found important spatial and temporal heterogeneity in the results, but that future average temperature can be a good predictor of the directionality of changes in crop yields. While rainfall patterns are generally acknowledged to be the main factor steering crop productivity in Africa (Muller et al., 2011), an expected increase in seasonal average temperatures in the tropics and sub-tropics could cause important yield losses where food insecurity is already high (Battisti and Naylor, 2009). A review done by Luo and Zhang (2009) identified extreme temperatures as being highly detrimental to crop production, especially during sensitive crop reproductive phases, while soil moisture deficits were also found to have negative impacts on yields at those stages (Oweis and Hachum, 2006, Doorenbos and Kassam, 1979). Schlenker and Lobell (2010) also effectively point out that the marginal impact of temperature change on crop yields is greater than that of rainfall for one standard deviation difference, and that predicted climate change in Africa show a more significant increase in temperature than changes in precipitation across CMIP3 climate models. However, this does not mean that the effects of changes in rainfall patterns are trivial. Through the use of historical weather data for South Africa, Blignaut et al. (2009) estimate the sensitivity of maize and wheat crops to changes in climate with respect to 1970, and use the observed drying and warming trend to extrapolate the relationships between possible future climates and crop productivity. They estimate that every 1% decrease in rainfall could potentially decrease maize yields by 1.16% and wheat yields by 0.5%, thereby significantly affecting food security in the region. Finally, agricultural production in the Sahel countries is likely to be more adversely affected than other regions of Africa in the face of future climate change. Already high temperatures are expected to increase, and there exist few novel climate analogs (none in the case of Burkina Faso) within the continent in terms of available genetic resources which could help bridge the widening yield gap (Burke et al., 2009).

2.3.3 Addressing adaptation needs for rainfed agriculture

Africa has been found to be a vulnerability “hotspot” when it comes to climate change, with severe negative impacts expected on crop yields in areas where the latter are already suboptimal. Key changes to the climate, such as increased temperature leading to heat stress or higher intra-seasonal rainfall variability, have been identified as factors affecting crop production. However, further research is required into key climatic processes such as intra-seasonal dry spells and resulting water stress to understand which adaptation strategies may be required. Which adaptation strategies can we implement today for impacts in the future? Can we address some impacts with short-term coping strategies to be implemented at a later stage?

2.4 Rainwater harvesting

2.4.1 Defining RWH

While new pieces of evidence point to the African continent as having extensive groundwater reserves which could potentially be used to increase the small-scale irrigated area for food production (MacDonald et al., 2012), these are far from being sufficient to sustain large-scale irrigation schemes at the continental scale and will need to be managed carefully to avoid their rapid depletion. In this context, better management of surface water resources to complement groundwater usage for agricultural production will be essential, and may start with rainwater harvesting.

Rainwater harvesting consists in the concentration and storage of surface runoff for productive purposes (Rockström et al., 2002, Oweis and Hachum, 2006). In general, rainwater harvesting strategies can be subdivided into either *in situ* or *ex situ* strategies, based on the method of water storage (SEI, 2009). In the former case, water is stored in the form of soil moisture, whereas in the case of *ex situ* strategies, rainwater is harvested from large catchment areas into various types of structures. In a comprehensive review of rainwater harvesting strategies in sub-Saharan Africa, Biazin et al. (2011) identified the most common micro-catchment (*in situ*) strategies used as: pitting, contouring, terracing, and micro-basins. In terms of macro-catchment (*ex situ*) strategies, traditional open ponds, cisterns, earthen dams, sand dams, and ephemeral stream diversion were noted as widely used across sub-Saharan Africa (Biazin et al., 2011). Other *in situ* conservation techniques include, amongst others: field bunds, furrows, intercropping, working across the slope, water conservation ditches, and land levelling (GOI, 2007, de Fraiture et al., 2009), and further *ex situ* methods include subsurface tanks and sunken pits (de Fraiture et al., 2009, GOI, 2007, APRLP, 2004a, APRLP, 2004b).

2.4.2 RWH advantages and limitations

Rainwater harvesting strategies (RWH) are thought to have several advantages, including the increase in water availability, the prevention of severe declines in water table levels, being environmentally friendly, the improvement of groundwater quality, and the prevention of soil erosion and flooding (Kumar et al., 2005). They are also thought to be effective under a range of climatic condition, starting at annual precipitations as low as 50-80mm (Hamdy et al., 2003). Hence, RWH has the potential of being particularly useful in dryland areas to increase agricultural productivity. In semi-arid drylands, RWH should focus on maximizing soil water storage during the fallow period, and on maximizing water available for transpiration during the growing season (Bennie and Hensley, 2001). Rainwater harvesting structures also have the potential to increase groundwater recharge (Glendenning et al., 2012). This water can then be used for supplemental irrigation during periods of water scarcity at the most critical stages of the crop growing stages. Some terracing techniques, in addition to promoting soil and water conservation, increase nutrient retention through the deposition of small sediment particles onto the cropping area (Makurira et al., 2009).

While RWH is often praised for its capacity to increase agricultural productivity, a review of literature by Vohland and Barry (2009) found that these strategies do not lead to increased yields in all conditions. First of all, RWH strategies provide some leeway during the growing season to mitigate the effects of dry spells, but they might not provide any benefits in the case of prolonged droughts (Glendenning, 2009). Biazin et al. (2011) further emphasised the close linkages between the economic performance of rainwater harvesting systems and nutrient inputs in sub-Saharan Africa. Nutrient availability is often cited as a leading cause of poor agricultural productivity, sometimes before water availability (Rockström et al., 2009). In fact, nutrient availability has been identified as the most important factor affecting crop productivity in Sahelian agriculture, and its improvement could increase water use efficiency by three to five-folds (Breman et al., 2001). Furthermore, Andersson et al. (2011) recently observed a median change of 0% in modelled maize yields in South Africa with the implementation of *in situ* rainwater harvesting strategies. However, when fertilization was combined with the water harvesting, yields were found to have a median increase of 30%. Overall, they found that additional water availability coming from rainwater harvesting could reduce the spatial variation of crop yields within a basin, whereas increased soil fertility would essentially improve yield magnitudes. Fox and Rockström (2000) also stated that RWH is not aimed directly at improving water use efficiency, but rather at reducing the variability in potential and actual crop yields. Furthermore, rainwater harvesting can have significant hydrological impacts and the implementation of macro-catchment strategies should be considered carefully. Impacts on hydrological catchments can be particularly significant in areas with high rainfall variability such as arid environments or monsoonal areas (Glendenning et al., 2012). In the case of no-till practices, these can be recommended to increase water infiltration under some conditions. However, in semi-arid areas, where soils often lack organic matter, no-till practices can cause higher surface runoff and soil erosion than conventional tillage practices, resulting in lower crop yields (Bennie et al., 1994, Rockström et al., 2009). Finally, most RWH have important limitations, and should be considered carefully before implemented.

2.4.3 Where should RWH implementation be prioritized?

The example of no-till practices shows that the selection of RWH strategies which are appropriate for local biophysical conditions is very important. Numerous studies have investigated the siting of rainwater harvesting systems at the watershed level under current climatic conditions (Kadam et al., 2012, Mbilinyi et al., 2007, Sekar and Randhir, 2007). While several of these studies acknowledge the importance of RWH to abate the negative impacts of climate change on crop production, most fail to assess the performance of these systems under changing climatic conditions at a larger spatial scale. Moreover, prior studies often provide data intensive, site-specific, and crop independent analyses, which can be inadequate to inform national-level policy making. While we know that RWH can bring benefits to rainfed agricultural systems today, it is still unclear which regions could increasingly benefit from RWH under changing climatic conditions. This specific question will be investigated in Chapter 3.

2.5 Biophysical modelling of rainwater harvesting

2.5.1 Hydrological models

Modelling is an interesting tool for looking at complex systems where data is scarce. The use of a biophysical model with improved agricultural management options allows for the analysis of the effectiveness of different soil and water management practices. Through the development of a range of scenarios including crop diversification, technological improvements (e.g. use of RWH), and intra-seasonal rainfall variability associated with climate change, one can assess the impacts of each of these factors on crop production and agricultural production systems viability.

2.5.1.1 Hydrological models for agricultural applications

The characteristics of a number of hydrological models were reviewed in Lebel (2011), of which summary Table 2.2 is a reproduction and is expanded to include the PESERA model. Key processes of interest for modelling included here are the soil water balance, but also soil erosion processes. As mentioned in Section 2.4.2, *in situ* RWH not only has the potential to increase soil water availability, but also reduce soil erosion. Hence, understanding the long-term impacts of reduced soil erosion on crop production can also be valuable.

Table 2.2 | Summary of model characteristics, modified from Lebel (2011)

Model	Modules	Water balance	Erosion calculations	Scale
APSIM	Growth of crops, soil water, soil N, erosion	Numerical solution of Richards equation (mechanistic approach)	Modified USLE (Littleboy et al., 1992)	Field to small watershed scales
SWAP	Crop growth, soil water flow, drainage, solute transport, surface water management, heat flow	Numerical solution of Richards equation (mechanistic approach)	Physically-based mathematical relationships (De Roo et al., 1996)	Field scale (Top soils only)
EPIC	Weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, tillage, economic budgets	Empirical calculations	MUSLE (MUST and MUSS) and RUSLE	Field scale
APEX	Same as EPIC, plus routing pollutant flows and manure management between subareas	Empirical calculations	MUSLE (MUST and MUSS) and RUSLE	Field and small watershed scales
SWAT	Water movement, sediment movement (erosion), crop growth, nutrient cycling, pesticide transport, management	Empirical calculations	MUSLE	Meso- to large-scale watershed
PESERA	Runoff and soil erosion	Empirical calculations	Process-based model; bucket model for runoff estimates (Kirkby et al., 2008)	1km resolution grid-based (used for large-scale, e.g. Europe)

2.5.1.2 The Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) was selected for the biophysical modelling component of the research. SWAT is a widely used hydrological model, with a range of applications. It has several advantages, including having built-in databases, being open-source, representing daily processes for meso-scale watersheds, and having been thoroughly tested and documented. Furthermore, it comprises an integrated crop model (a simplified version of the EPIC crop growth model developed by Williams et al. (1983). SWAT also allows the user to incorporate climate change scenarios into their analysis either through adjustment factors for precipitation (%) and temperature (ΔT°) values for each sub-basin, or by modifying the climatic inputs directly using time series (Neitsch et al., 2005). However, as discussed in Section 2.2, the use of daily time-series was preferred here to represent changes in daily variability in the climate as well as mean monthly changes. In addition, SWAT allows the user to integrate changes in CO_2 concentrations, which directly impact plant growth. The Penman-Monteith evapotranspiration equation (Monteith, 1965) must be used in the simulations, as a modification has been introduced in the canopy resistance variable calculation to account for these changes, assuming a baseline CO_2 concentration of 330ppm. Glendenning et al. (2012) identified SWAT as the most promising model for assessing the potential of rainwater harvesting, although the routing routines and conceptual description of the groundwater-surface water interaction still require more testing. Indeed, as of early 2012, only one case study was found where SWAT was used to assess the impacts of soil and water conservation measures on groundwater resources, as the model is lacking a strong groundwater module. Despite the latter issue, Rao and Yang (2010) were able to show that water harvesting strategies had a significant impact on the changes in groundwater levels in the long-term. Similar findings for a small agricultural watershed in India were presented by Lebel (2011).

2.5.1.3 Model calibration, validation, and evaluation

Models are only aimed at producing a representation of reality, based on our understanding of the biophysical processes involved. For this reason, the calibration, validation, and evaluation of a model’s performance under various conditions is generally recommended. For instance, while the SWAT model comprises integrated databases of crop characteristics, these were developed for the United States biophysical conditions, and may not be applicable to the semi-arid conditions of Burkina Faso. Hence, the calibration of the SWAT model is required to capture local crop, soil, and management (i.e. RWH) characteristics through the parameterization of the different model input variables. Where data is available over longer time periods, the validation of the selected parameter values through simulations spanning different time periods from the calibration simulations are recommended. However, due to a significant lack of data, validation of SWAT in Burkina Faso is not possible. Rather, a comparison with different datasets and published studies in the area of interest can be useful in assessing the performance of the model after calibration.

2.5.1.4 Conceptualizing RWH in SWAT

As mentioned in the previous section, the parameterization of the SWAT model to represent local soil and water management practices is an integral part of the calibration process. More importantly, correctly conceptualizing the processes involved in the use of RWH strategies should be the first step in the calibration process. In fact, several studies have taken different approaches to the representation of RWH in SWAT.

In order to model rainwater harvesting strategies in SWAT, a number of parameters can be adjusted. First, since *in situ* water harvesting systems are specifically aimed at increasing soil water storage, it can be appropriate to increase the Available Water Capacity (AWC) parameter value (which affects both hydrology and crop growth) to represent increased soil water retention in SWAT (Masih et al., 2011). Faramarzi et al. (2010) suggested a seemingly arbitrary increase of 20% in the AWC value due to improved soil water management practices, and evaluated these impacts on water consumption in Iran. On the other hand, Andersson et al. (2011) used the definitions of blue and green water to justify their use of the Soil Conservation Service Curve Number (SCS-CN) (SCS, 1972) to simulate *in situ* rainwater harvesting in SWAT. They argue that by altering the parameter which controls the partitioning of surface runoff and infiltration water, they can replicate the field scale impacts of *in situ* rainwater harvesting. However, their overall method was found to be ineffective at correctly representing RWH, due to a lack of consideration for water storage in the soil profile. Furthermore, as presented earlier in Table 2.2, SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to estimate runoff and sediment losses. Within this equation, the support practice factor (USLE P) is used to estimate the effects of practices such as terracing or contour cropping on soil erosion and runoff (Neitsch et al., 2005). In a study by Mishra et al. (2007), the USLE P and slope length (LS) are identified as the most appropriate parameters to represent strategies such as bunding and terracing. Other soil water management options such as cover crops, residue management, or field borders can be represented through the modification of different parameters in SWAT, but they do not have an explicit management option function in the model (Arabi et al., 2008).

In a few studies using SWAT, sensitivity analyses were conducted and it was found that the SCS-CN was the most sensitive parameter for stream flow simulation (Arabi et al., 2008, Ullrich and Volk, 2009). Other studies, including one by Kadam et al. (2012), use the

SCS-CN as an indicator to site rainwater harvesting strategies at the macro-catchment level, even though they state that the curve number was developed for watersheds smaller than 15km^2.

Ex situ water management practices such as check dams can also be modelled by SWAT. The SWAT reservoirs are appropriate to represent on-stream structures, as they are conceptualized as impoundments on the main channel network (Neitsch et al., 2005). Another interesting study in arid environments by Ouessar et al. (2009) adapted the SWAT model to allow for the collection of rainwater within the hydrologic response units (HRUs), by using the irrigation-from-reach option and fractioning the amount of runoff collected using the FLOWFR parameter (i.e. fraction of the flow that is allowed to be applied to the HRU).

2.5.2 Summary of hydrological modelling needs and advantages

The SWAT model is used in this thesis to test a range of hypotheses with regards to the potential of short-term coping and long-term adaptation strategies to climate change. This applies primarily to RWH, but also extends to include changes in cropping calendars and improved soil fertility. In a context of complex biophysical and social changes, crop/hydrological models such as SWAT can provide important insight into erosion, water balance, and crop growth processes which can impact the long-term sustainability of strategies such as RWH and inform adaptation investments.

2.6 Social barriers to rainwater harvesting adoption

2.6.1 General factors affecting RWH adoption

In order to assess the sustainability of RWH, one has to ensure that the technologies are adequate for the local biophysical, but also for socio-economic conditions. Too often, development projects tend to promote a system before comprehensive scientific evidence about its effectiveness is available (Pannell, 1999), contributing to low adoption rates of the technologies.

Technology adoption is highly dependent on a wide variety of biophysical and socio-economic factors. In order to promote technology adoption, the said technologies have to be adapted to local conditions. As Zida (2011) states it, “[a] technology can only be considered a successful ‘innovation’ that is likely to spread spontaneously when it is or can be fully embedded within the local social, economic and cultural context”. Hence, unless a technology such as rainwater harvesting is widely adopted, it can be argued that it is not sustainable.

A rich body of literature exists where researchers have attempted to identify the factors affecting technology adoption in developing countries (Adesina and Zinnah, 1993, Chomba, 2004, Dreschel et al., 2005, Feder et al., 1985, He et al., 2007, Kassie et al., 2009, Knowler and Bradshaw, 2007, Pannell, 1999, Shiferaw et al., 2009).

Here, some examples of studies looking into rainwater harvesting technology adoption only are presented. First, He et al. (2007) used an econometric analysis to identify the various aspects affecting the adoption of rainwater harvesting and supplemental irrigation, and concluded that in order to target the right areas for investments, agronomic conditions need to be considered together with farmer socio-economic conditions to increase adoption rates of the technologies. In some cases, socio-economic factors relative to RWH seem to have more importance than biophysical factors in terms of constraining adoption rates with farmers from sub-Saharan Africa. Several socio-economic factors have been identified by Dreschel et al. (2005) and include, amongst others, low returns on investments (real or perceived), poor credit and capital availability, restricted labour availability, land tenure, risks and uncertainties, and policy support. In Zambia, rainfall amounts, fertilizer access, seed prices, distance to town/markets and roads, and land tenure were identified as the most significant factors affecting adoption rates of some soil and water management strategies, through the use of a binary logit analysis (Chomba, 2004).

Using a frequency analysis, Knowler and Bradshaw (2007) identified 46 variables from 31 studies regarding factors affecting conservation agriculture adoption, and found that there were important discrepancies between studies. Overall, the only two variables that showed consistency in terms of significance and sign across studies were: (a) awareness of environmental threats (positive sign, 4 studies) and (b) high productivity soils (negative sign, 3 studies).

2.6.2 Climate variability and change perception as a factor affecting adaptation decision-making

Recently, technology adoption studies have begun focusing on farmers' perceptions of climate variability and change, to assess the extent to which this factor might affect decision-making. Thomas et al. (2007) found that up to 80% of respondents could relate changes in long-term trends to increased variability. Farmers in Ethiopia and South Africa were also found to be able to identify long-term trends in climate (Bryan et al., 2009). In contrast, Osbahr et al. (2011) pointed out that climate perceptions had low correlations with actual meteorological conditions because farmers tended to perceive greater changes where they saw significant impacts on their livelihoods. This means that, for example, independently of the frequency of dry spells, only the ones that were timed when crops would suffer most from the water stress were considered significant and reported. Furthermore, Osbahr et al. (2011) indicated that people tend to associate a “normal” year with what they consider the ideal weather for their livelihoods, and describe climate in a specific year as a deviation from that ideal.

Some studies have shown that despite being able to accurately perceive changes in climate, a large number of farmers did not implement adaptation strategies, mainly because of other constraints such as lack of credit or shortage of land (Bryan et al., 2009, Deressa et al., 2009). Mertz et al. (2009) also did not find climate to be an important factor driving change in farming communities of the Sahel region, and where climatic factors were mentioned they rarely were without associating economic factors. Another fundamental aspect is identified by Maddison (2007), when he says that “[i]t is unlikely that farmers know immediately the best response to climate change when such agricultural practices as it requires are outside the range of their experience”. Despite these facts, Thomas et al. (2007), argued that farmers were adequately responding to changes in their climatic environment in South Africa.

Interestingly, while some studies asked farmers directly about climate change perceptions (Bryan et al., 2009, Deressa et al., 2009), it was noted that very few respondents reported seasonal changes in rainfall patterns when asked open-ended questions about climate such as: ‘‘Have you noticed any long-term changes in the mean temperature/precipitation over the last 20 years?” (Bryan et al., 2009). Studies by Thomas et al. (2007) and Osbahr et al. (2011) underlined the importance of having questions not geared towards climate directly, but rather towards broader themes such as environmental risk, uncertainty, and food security. Climate issues in those studies were only addressed when raised by the respondents themselves, and questions were non-directional (i.e. interviewers do not guide the responses). Finally, farmers’ climate change perceptions are generally compared with measured meteorological information (Thomas et al., 2007).

Another interesting aspect which may influence reported perceptions of climate change are local environmental and social conditions. Gbetibouo (2008) found that farmers in South Africa cropping highly fertile land were very likely to perceive changes in rainfall patterns but not temperature, and factors such as years of experience and education had little impact on perceptions. Vedwan and Rhoades (2001) show, using rainfall and snowfall data, that climate change perception in rural communities of the western Himalayas of India are dependent on knowledge about crop-climate interactions and associated yields. Furthermore, cultural events associated with weather and crop cycles were found to provide fixed indicators from which perceptions of intra- and inter-annual abnormalities in climatic patterns could be identified in those communities (Vedwan, 2006).

In Burkina Faso, recent land degradation, caused in large part by an increasing population and intensifying agricultural activities, has been found to produce counterintuitive impacts on hydrological processes (Mahe et al., 2003). Surface runoff and river discharge has increased tremendously in response to reductions in soil water holding capacity, despite having years of severe meteorological droughts since the 1970s (Mahe et al., 2005). This illustrates well how environmental factors such as land degradation have the potential to influence farmers' perceptions of trends in rainfall.

2.6.3 Implications of RWH adoption factors for this thesis

The factors affecting the adoption of rainwater harvesting today could be key in determining their usage as an adaptation strategy to climate change. An investigation of the factors that affect RWH adoption in Burkina Faso will be presented in Chapters 5 and 6, with the methodological approach adapted to address some key themes identified in literature (e.g. non-directional approach, participatory, comparison with weather observations, soil water balance modelling). To understand climate change perceptions in a wider context of agricultural decision-making, household questionnaires addressed current cropping practices and foreseen changes in those practices in the future. Chapter 4 addresses changes in the timing of dry spells, as this could have an impact on future adoption. This could be true if in fact impacts on livelihoods (in this case crop production) are a main driver of climate change perceptions and technology adoption. Finally, other changes in the environment are investigated to determine probable sources of climate change perceptions in Burkina Faso. For instance, land degradation is addressed in the context of soil water balance (Chapter 6), while deforestation is discussed with regards to increased temperature (Chapter 5).

2.7 Summary

Several concepts have been explored in this Chapter, with the aim of building a strong theoretical basis for the methodological approach to the research problems. First, it was established that the use of a range of different GCMs would be required in the analysis to take into account model uncertainty and the range of possible climate realizations. However, due to time limitations, only RCP8.5, which is currently thought to be the most likely pathway to unfold based on public climate policies, was selected. Based on preliminary reports on the CMIP5 projections to the 2050s, changes in rainfall patterns and increased evapotranspiration were identified as key challenges for agricultural production, which could partially be addressed through rainwater harvesting. However, technical limitations to the RWH systems were also identified, which will be further explored in Chapters 3 and 6 (e.g. inability to bridge droughts). The SWAT model was selected to evaluate these challenges and limitations. Finally, different barriers were identified to the adoption of RWH. Chapter 5 will further explore if these barriers differ between a historical aim to improve crop yields, and a more complex future aim to adapt to climate change.

Chapter 3

Evaluation of *in situ* rainwater harvesting as an adaptation strategy to climate change for crop production in rainfed Africa

3.1 Introduction

Assessing the biophysical potential of rainwater harvesting as an adaptation strategy to climate change can be a complex task. Here an attempt to provide a quick overview of that potential over Africa is made, for three crops which are generally found in RWH systems: maize, millet, and sorghum. Chapter 3 aims to inform national-level decision-making with regards to the prioritization of certain regions for RWH implementation, while also underlining their spatial limitations. An original method is developed for this purpose, using readily-available global climate datasets and cropping calendars in regions which are otherwise data scarce.

In this Chapter the potential of RWH to reduce water deficits experienced by three different crops is estimated under present and future climate projections of the 2050s across Africa for increasing radiative forcings conditions (RCP8.5). Under this scenario, the 2050s would be the first period where climate would depart from its current variability, and therefore lead to unprecedented environmental conditions (Mora et al., 2013), to which farmers will need to adapt. Maize is the most widely grown crop in Africa, especially in Southern Africa where it represents 50% of the harvested area, while sorghum is harvested on 12% of the rainfed agricultural land across the continent, making it the second crop in importance. As for millet, it is most important in West Africa, where it is harvested on approximately 17% of the land (Portmann et al., 2010). It is expected that these crops will remain widely grown in the future. Using a grid-based empirical approach with the latest data from the Coupled Model Intercomparison Project Phase 5 (CMIP5, c.f. Appendix A), water deficits experienced by maize are established on a monthly basis. Then, the amount of water that can physically be harvested within each grid cell in Africa is evaluated. Our analysis takes into account local biophysical characteristics to evaluate RWH capacity, as opposed to assuming that a constant fraction of runoff can be harvested at any location (e.g. Rost et al., 2009). Finally, RWH benefits on crop yields under current and future climatic conditions are estimated. In the main text of this Chapter, results will be presented for maize only, and results for millet and sorghum can be found in Appendix B.

3.2 Materials and methods

3.2.1 Climate input data

Three General Circulation Models (GCMs) from the CMIP5 were selected based on the availability of model output at the time of beginning this study, and the model ability to reproduce realistic surface runoff. Indeed, at the time of beginning the analyses in this Chapter, not all CMIP5 experimental data had been released to the research community, and only a limited number of models had released all the climate variables necessary for this analysis under RCP8.5. Figure 3.1 shows the calculated surface runoff coefficient (c.f. Section 3.2.2.2) for the month of September from the selected models. The models selected represent three modelling research groups: BCC-CSM1-1, MIROC5, and NorESM1-M. While the MRI-CGCM3 model was also initially selected, it was deemed inappropriate for this study due to its poor representation of surface runoff. The selection of a range of models is important to get a better grasp of the uncertainties associated with the use of different climate models. As the performance of climate models in representing historical climate cannot always indicate their ability to represent future climate, each climate model simulation is considered to have an equal likelihood of realisation in the future. This is why, for instance, the use of multi-model means to analyse future climates is common. However, as we only had access to a limited number of models and to better visualize the model spread, the multi-model mean was not used here. The data was extracted for two experiments (Historical and RCP8.5 respectively), with a focus on the medium-term projections for the highest radiative forcings pathway RCP8.5 (2046-2065), and a 20-year historical time period (1986-2005). RCP8.5 is a rising pathway where 8.5[$W \cdot m^{-2}$] radiative forcing is likely to be exceeded after 2100, and CO_2 concentrations possibly tripling by the same date compared to the year 2000 (Meinshausen et al., 2011). All the CMIP5 data was regridded to a finer 0.5°x0.5° latitude/longitude spatial resolution to allow for inter-model comparison. Grid cell values were interpolated using area weighting when multiple lower resolution grid cells overlapped a single 0.5°x0.5° grid cell. Monthly means for the 20-year periods were calculated for temperature, precipitation, solar radiation, and surface runoff from all three GCMs. Bias correction was not conducted, as monthly means are generally well represented within climate models. Figure 3.2 provides a first glimpse into CMIP5 projections for annual precipitation and potential evapotranspiration. Potential evapotranspiration is shown to increase in all models, while changes in rainfall are less consistent. Hence, an increase in rainfall could not directly be associated with better crop yields, as crop water requirements are simultaneously increasing as well.

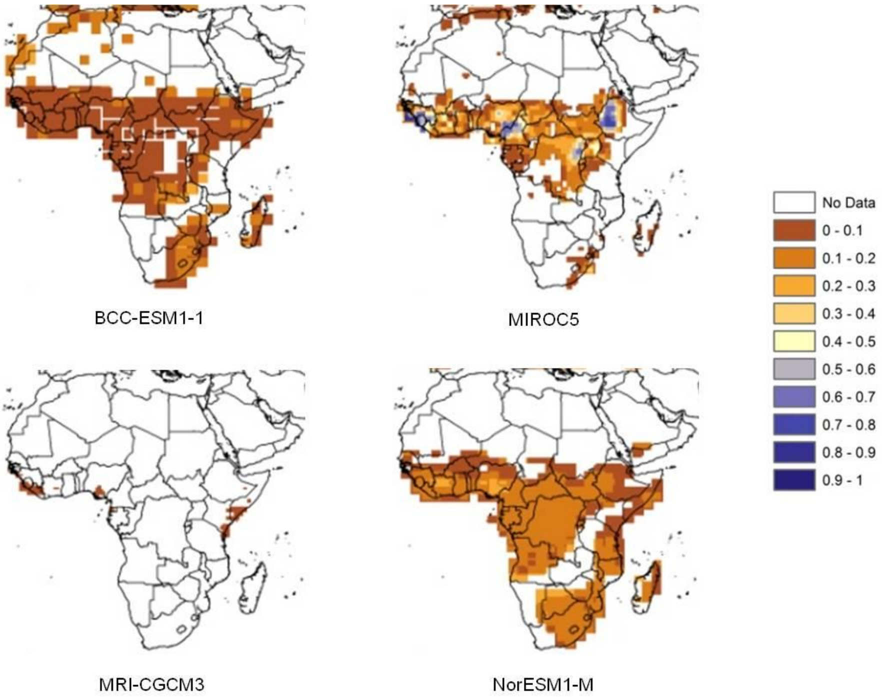


Figure 3.1 │Surface runoff to precipitation ratio for the month of September (1986-2005). September is a month where rainwater harvesting is particularly important in the Sahel, from four GCMs.

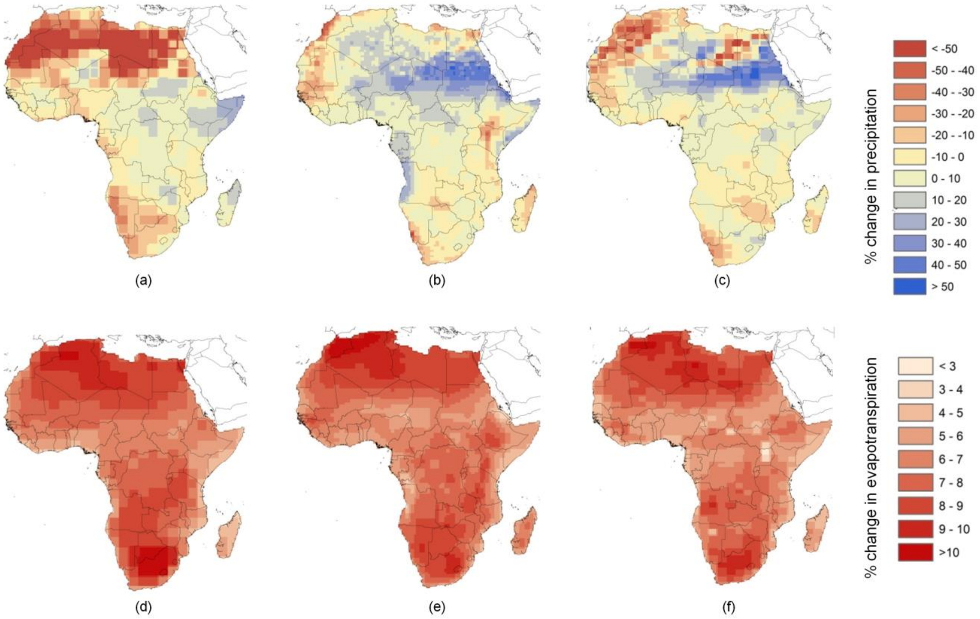


Figure 3.2 │Projected percentage changes in annual precipitation (a,b,c) and potential evapotranspiration (d,e,f) for BCC-CSM1-1 (a,d), MIROC5 (b,e), and NorESM1-M (d,f) between the 1986-2005 and 2046-2065 (RCP8.5) periods.

3.2.2 Methodology

A simple empirical approach to the determination of RWH potential was developed based on widely available datasets. The aim was to provide a spatially-relevant overview of agricultural water management requirements for national-scale policy-making, in regions where higher-resolution data can be scarce. A schematic representation of the methodological process is presented in Figure 3.3.

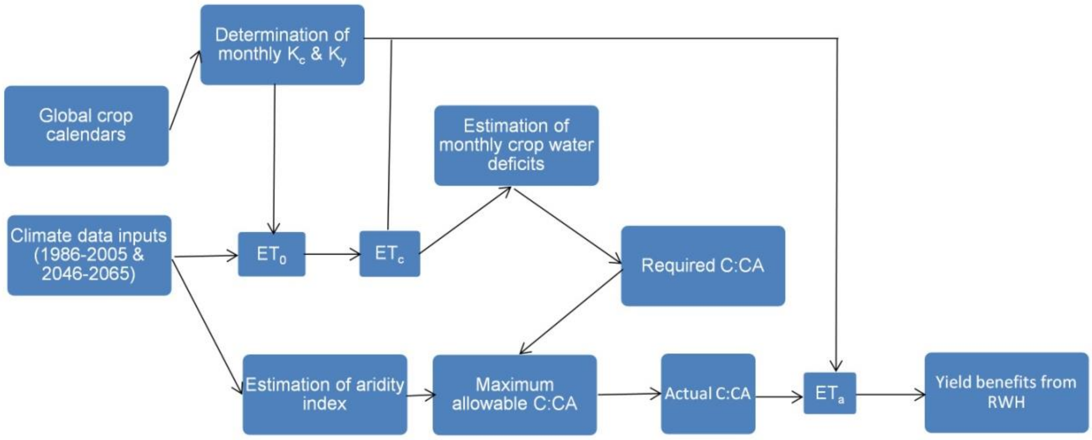


Figure 3.3 │Schematic representation of the methodological process followed to determine rainwater harvesting (RWH) benefits for crop yields.

3.2.2.1 Estimating crop water requirements

The water requirements of different crops vary both in quantity and in their temporal distribution. Crop water requirements were estimated for the 20-year historical and future monthly climatic averages from the three GCMs across Africa. Crop water requirements, equivalent to crop evapotranspiration here (ET_c), are defined by the empirical Equation 3.1 (Allen et al., 1998):

$$ET_c = K_c * ET_0 \qquad \textbf{(3.1)}$$

The reference evapotranspiration (ET_0) values were estimated using CMIP5 climatic data. While ET_0 remains an important variable in hydrological models, it is not always calculated directly in climate models. In order to estimate ET_0, most hydrological models use the data intensive and physically-based Penman-Monteith equation recommended by the FAO. Simpler equations have been shown to be as good, and sometimes better, at evaluating ET_0 compared to the Penman-Monteith equation (Kay and Davies, 2008). In this context, due to limited data availability within GCM outputs, and due to computational limitations, an alternative equation to calculate ET_0 was selected (Oudin et al., 2005).That is shown in Equation 3.2:

$$\boldsymbol{ET_0 = \frac{R_e}{\lambda\rho_w}\frac{T_a+5}{100}\ if\ (T_a+5) > 0} \qquad \textbf{(3.2)}$$

$$\boldsymbol{ET_0 = 0\ otherwise\ (negatives\ values\ are\ being\ reset\ to\ zero)}$$

Where R_e is the extraterrestrial radiation (J/m^2/s), λ is the latent heat flux (taken as $2.45\text{x}10^6$ J/kg), ρ_w is the density of water (1,000kg/m^3), and T_a is the mean monthly air temperature (°C).

Cropping calendars datasets based on typical national level and sometimes sub-national planting and harvest dates for the 1990s or early 2000s (Sacks et al., 2010) were used to produce weighed monthly crop evapotranspiration values based on the crop coefficient (K_c) values of the different crops at the four crop growth stages (initial, crop development, mid-season, late season). The cropping calendars were also used to estimate monthly values of the yield response factor (K_y), for yield impact evaluations. The yield response factor is widely used in irrigation planning, and is at the core of the FAO's crop water requirements models CropWat and AquaCrop. Each crop growth stage has differing sensitivities to environmental stresses (e.g. grain filling and flowering, which occur mid-season, are the most sensitive stages to water stress), which in turn affect the K_c and K_y (c.f. Equation 3.4) values. Standard K_c and K_y values for maize (Table 3.1) were obtained from the FAO (Allen et al., 1998).

Table 3.1 │Estimated Kc and Ky values for maize, millet, and sorghum from Allen et al. (1998).

Crop		**Initial stage**	**Crop development stage**	**Mid-season stage**	**Late season stage**
Maize	**K_c**	0.40	0.80	1.15	0.70
	K_y	0.40	1.50	0.50	0.20
Millet	**K_c**	0.35	0.70	1.10	0.65
	K_y	0.20	0.55	0.45	0.20
Sorghum	**K_c**	0.35	0.75	1.10	0.65
	K_y	0.20	0.55	0.45	0.20

Subsequently, the monthly water deficits were established from the difference between estimated monthly crop water requirements (ET_c) and the monthly rainfall amounts having a probability of occurrence of 67% (i.e. minimum rainfall expected two years out of three). The latter is what is termed "design rainfall" when determining the sizing of RWH systems, and is discussed further in the next section. The "design rainfall" is used to account for the significantly greater inter-annual variability present with rainfall, than with solar radiation or temperature used to estimate crop water requirements.

3.2.2.2 Estimating rainwater harvesting system design requirements

The design of RWH systems has been described in Critchley and Siegert (1991), yielding Equation 3.3 to evaluate the optimal design catchment to cultivated area ratio (C:CA):

$$\mathrm{C{:}CA} = \frac{(ET_c - Design\ Rainfall)}{(Design\ Rainfall * Runoff\ Coefficient * Efficiency)} \qquad \mathbf{(3.3)}$$

Here the runoff coefficient is simply defined as the fraction of surface runoff to precipitation. While it is acknowledged that not all models produce reliable surface runoff from their land surface component (e.g. MRI-CGCM3), the use of gridded runoff data generated through GCMs is selected as it has been argued that runoff data generated through GCMs can be a desirable replacement option for macro-scale studies as they guarantee a closed hydrological cycle (Weiland et al., 2012). It was found that for the three models selected, the runoff coefficient remained within reasonable bounds over Africa (i.e. between 0.05 and 0.3 over rain-fed agricultural land for a key month of the growing season, Figure 3.1). As only the fraction of rainfall which is converted to surface runoff is of interest, as opposed to actual surface runoff values, this approach was deemed appropriate.

Finally, a relatively conservative value for the efficiency of the *in situ* RWH systems was set to 0.6, where it can reasonably reach up to 0.75 for such short slope catchments (Critchley and Siegert, 1991). The efficiency factor takes into account the fact that not all harvested runoff can be used effectively by the crops, as there will be losses through deep percolation amongst others. The catchment to cultivated area ratios were calculated for each crop on a month-to-month basis, for both the historical and the future periods.

The maximum monthly value of the C:CA ratio required to fully bridge the crops water deficits was determined. Further consideration was given to the fact that RWH sometimes requires an excessively large catchment area to harvest a sufficient amount of surface runoff to fully bridge crop water deficits. However, in arid environments where this situation is more likely to occur, farmers already use very low cropping densities (e.g. Bationo et al., 1992), making the selected values here seem relatively conservative. In this study, the C:CA ratio (i.e. a calculated value used to optimize the design of RWH systems) is varied spatially to values which are suited to the aridity of the different regions. It integrates the reality whereby drier regions often have lower cropping densities, and hence the use of larger catchment areas in those conditions does not necessarily reduce the availability of arable land for agricultural production. The aridity indices determined using the De Martonne Aridity Index (which ranges from 0 for very dry to 100 for very humid environments) (de Martonne, 1927), were calculated for both the historical and future period, as the range of reasonable C:CA ratios vary with aridity (Table 3.2).

Table 3.2 │Assumed maximum allowable C:CA ratios by aridity zone

Aridity zone	Maximum allowable C:CA ratio
Arid	15:1
Semi-Arid	10:1
Dry sub-humid	5:1
Humid	3:1

If the C:CA value fell within a reasonable range as per Table 3.2 (e.g. positive value ≤ 15:1 for an arid zone), then that value was kept as such. Otherwise, it was assumed that RWH could only partially bridge the water deficit or was unnecessary. The gridded aridity indices were then used to re-assign the values of the C:CA ratio where only a partial bridging of the water deficit could be accomplished. The dryer areas were assigned higher ratios, and wettest areas the lowest ratio of 3:1.

The actual evapotranspiration (ET_a) of the different crops is equal to the design rainfall where there is no RWH. In the case where RWH is used, the C:CA ratios adjusted for aridity were used to estimate the amount of water actually harvested, which was then added to the design rainfall to obtain the total monthly ET_a values for each crop.

3.2.2.3 Estimating impacts on crop yields

The yield gap (or yield decrease from water deficits) expected in the cases with and without RWH was estimated on a monthly basis, using Equation 3.4 (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Y_a}{Y_p}\right)=K_y\left(\frac{ET_a}{ET_c}\right) \qquad (3.4)$$

Where Y_a is the actual yield and Y_p is the potential yield. The maximum value of the potential yield decrease caused by water deficits within a growing season was selected for the determination of potential for increasing crop yields through the bridging of that water deficit with the use of RWH. Due to the use of the 33rd percentile rainfall in the determination of the actual evapotranspiration, the monthly maximum potential yield decrease value effectively represents the minimum yield gap that will occur in one of three growing seasons. Finally, to evaluate the future performance of RWH systems with respect to their historical performance, Equation 3.5 was developed:

$$\boldsymbol{Y_{Index,t} = CA_t\left(1 - \frac{Y_{Gap,t}}{100}\right)\left(1 + \frac{Y_{Increase,t}}{100}\right)} \qquad \textbf{(3.5)}$$

Where $Y_{Index,t}$ is the yield index corrected for cropped area (CA_t), percentage yield gap caused by water deficits ($Y_{Gap,t}$), and percentage yield increase associated with the use of RWH ($Y_{Increase,t}$) for the time period *t* (1986-2005 or 2046-2065). When $Y_{Index,2046-2065} < Y_{Index,1986-2005}$, the performance of RWH in the future is less than during the historical period, and would point towards the need for different climate change adaptation strategies for the concerned regions.

3.2.3 Methodological limitations

As in any modelling study, the approach taken to evaluate RWH potential has inherent uncertainties. For instance, the selection of K_c and K_y can have a large impact on the estimation of crop water requirements. However, standard values were selected here as a coarse-scale assessment of those water requirements was conducted, both spatially and temporally. This approach allowed getting a quick overview of areas that might suffer from greater water deficits than others. However, part of the spatial variation associated with different choices of crop varieties and varying agro-climates was not taken into account. The use of cropping calendars at a coarse resolution in this study leads to some regional anomalies in the results, especially at the borders between countries due to national-scale input data and sometimes more than 30 days difference in planting dates across those borders. Notwithstanding, the greatest uncertainties in this study arise from the climate models, their coarse resolution, and their ability to reproduce surface runoff. While there are uncertainties associated with the use of the surface runoff variable from GCM outputs, it is thought that this choice is adding to the physical consistency of the analysis.

Furthermore, using an empirical approach has the disadvantage of ignoring a wide range of processes involved in crop production, such as the increased nutrient use efficiency associated with higher water availability. This can lead to a significant underestimation of the potential of RWH to increase crop yields. The coarse resolution of this approach ignores small-scale hydrological processes (e.g. crusting of soils in the Sahel), local socio-economic conditions, and most importantly the impact of intra-seasonal daily rainfall variability. For example, the potential to increase yields in the future under climate change seems reduced in the Sahel where there is a projected increase in total monthly precipitation, while in reality that potential might remain due to a change in the daily distribution of that rainfall.

Finally, the use of a field-scale equation to evaluate RWH potential with climate data at a much coarser resolution could lead to inaccuracies in the results. That is, as mentioned above, small-scale hydrological processes are not well represented and surface runoff can be underestimated in many arid and semi-arid locations. That being said, obtaining such data at a high resolution is impractical and currently impossible for a continental-scale assessment of RWH potential. The next section will also demonstrate that despite scale discrepancies, estimated C:CA from the coarse scale climate data is rather representative of the design requirements of reported local techniques.

3.3 Results

3.3.1 Rainwater harvesting design requirements

Here it was assumed that the C:CA ratio for RWH generally corresponds to local cropping densities, and that cropping densities will change in response to climate change, independently of RWH adoption. Presented in Figure 3.4 are the calculated C:CA ratios, based on biophysical requirements and limitations, as described in Section 3.2.2. Calculated values seem to correspond well with observed RWH systems in Africa, with more humid areas having ratios of 1:1 to 3:1 and drier regions such as the Sahel reaching maximum values between 5:1 and 10:1. Regions reaching the maximum allowable ratio of 15:1 are rare. Reported values for RWH C:CA ideally sit between 1:1 and 3:1, but some areas require greater ratios due to local biophysical conditions such as soil types and aridity (Critchley and Siegert, 1991). For example, a typical zaï pit density of 10,000 pits ha^{-1} in Northern Burkina Faso, with pits having a diameter of 30cm, would represent a cropped area of about 7%, or a C:CA of 13:1. This corresponds to 3 plants m^{-2} with typically three plants per pit, a value slightly lower than the typical value of 3.7 plants m^{-2} reported by Jones and Thornton (2003) for typical rainfed smallholder maize production systems in the tropics. Values as low as 2,000 zaï pits ha^{-1} have been reported for millet in Niger (Bationo et al., 1992). Indeed, in arid and semi-arid regions, farmers normally choose lower cropping densities. Higher cropping densities, up to 40,000 pits ha^{-1} for millet in Niger, were found to reduce crop yields due to increased water stress (Bationo et al., 1990).

The selected GCMs tend to agree on a limited number of areas with regards to the magnitude and direction of change in cropping densities and C:CA ratios by the 2050s. Southern Africa is likely to be the most adversely affected region, while the Sahel does not see significant changes in RWH design requirements despite some projected increases in precipitation (c.f. Figure 3.4). Areas of full agreement between models include greater C:CA ratios over Tanzania and Mozambique for instance, while two out of three models show the need for greater C:CA ratios over Zambia and Zimbabwe.

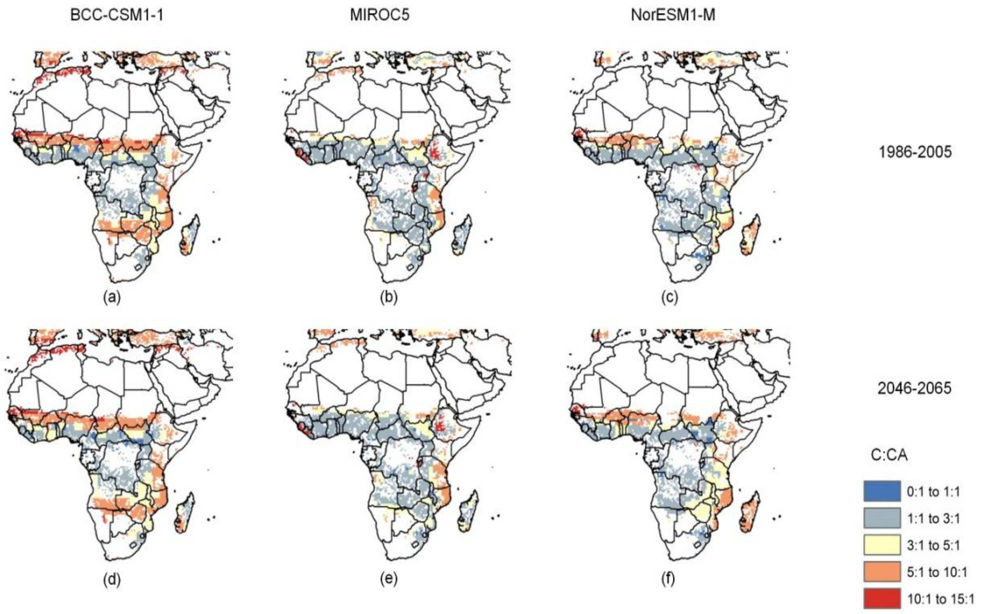


Figure 3.4 │Catchment area to cultivated area ratio (C:CA). Actual C:CA in consideration of optimal design requirements and maximum allowable ratio for the aridity of the region for the 1990s (a,b,c) and the 2050s under RCP8.5 (d,e,f). GCMs used for calculations were BCC-CSM1-1(a,d), MIROC5 (b,e), and NorESM1-M (c,f). White areas are where no rainfed agriculture is practiced.

3.3.2 Mapping crop water deficits over rainfed areas

Crop water deficits for maize for the month of the growing season where water stress is maximal are found to be already important during the historical period without the use of RWH. Our analysis shows that there are likely to be important changes in the peak monthly water deficit by the 2050s (see Figure 3.5 for maize, and Appendix B Figures A1.1 & A1.2 for sorghum and millet). The peak water deficits tend to increase under future climate change projections over most rainfed regions of Africa, except over the Sahel and parts of Southern Africa in the NorESM1-M model which seems to indicate a slight decrease in the crop water deficits. In comparison, changes in irrigation water demand estimated by Wada et al. (2013) shows increases in water requirements of 25% or more over most of Africa by the 2080s under RCP8.5. Despite their use of more complex modelling approaches and their focus on the 2080s, their results tend to complement the trend in changes in crop water deficits presented here for the 2050s, whereby those changes are comprised between 1 and 25% over most areas.

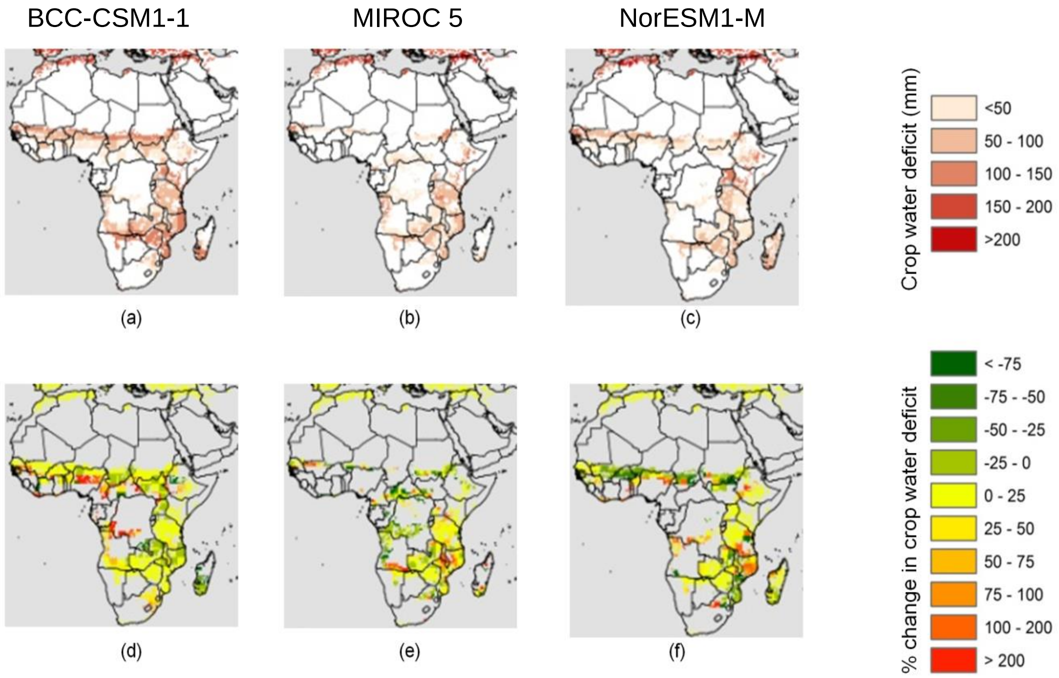


Figure 3.5 │Peak monthly water deficits for maize. The peak water deficits that a maize crop might experience for one month during the main growing season for the historical period (1986-2005) in mm (a,b,c), and the % change (d,e,f) between that period and the future period (2046-2065, RCP8.5), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

3.3.3 Stabilizing crop yields through rainwater harvesting

As described in section 3.2.2.3, yield gaps are the difference between a crop’s potential yields without any biophysical stress, and actual yields when taking into account water deficits. Brauman et al. (2013) identified areas of very low maize water productivity, which correspond well to the areas with the largest yield gaps in Figure 3.6. Due to the use of the design rainfall, or minimum rainfall obtained two of three years, the yield gaps presented in Figure 3.6 represent the minimum yield gaps one would expect once every three years. There is good agreement between the three GCMs regarding yield gaps caused by water deficits in Eastern Africa, which are some of the highest on the continent. While MIROC5 is underestimating the water deficits suffered by crops during the growing season in the Sahel (i.e. projected excess water in all months), the two other models show a reasonable gradient over the region. For example, Northern Burkina Faso sees minimum yield gaps of 30-50%, while the southernmost regions of the country are significantly less vulnerable. Over the

Sahel, where models disagreed on changes in precipitation, the model projecting the most drying (i.e. BCC-CSM1-1) is the only one to project a worsening of the yield gap in the 2050s. Despite the very large yield gaps identified, once the use of RWH is taken into account most regions see a significant decrease in those yield deficits (Figure 3.7).

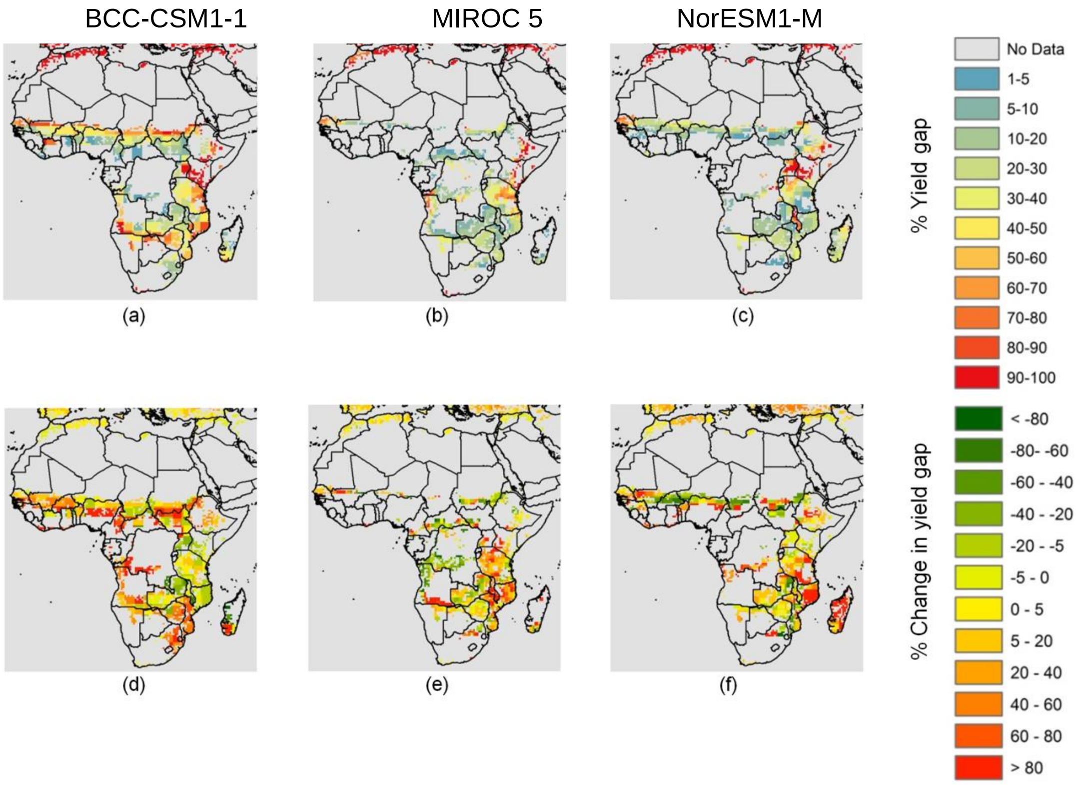


Figure 3.6 │Minimum yield gap attributable to water deficits for maize. The minimum percentage yield below potential (yield gap) that a maize crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and the percentage change with respect to the future period (2046-2065) (d,e,f), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

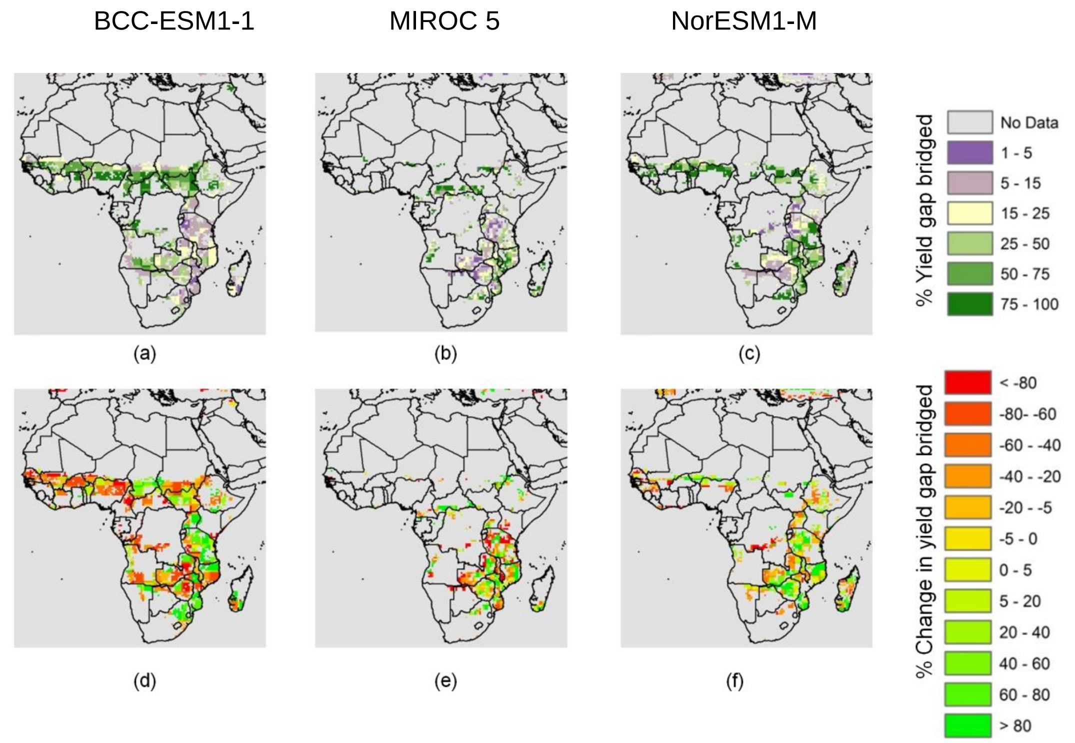


Figure 3.7 │Percentage of the minimum yield gap attributable to water deficits bridged through rainwater harvesting for maize. (a,b,c) represent the historical period (1986-2005) (a,b,c), and (d,e,f) show the change for the future period (2046-2065), estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]).

Generally, the fraction of the yield gap caused by water deficits which can be bridged through RWH decreases by the 2050s, in regions where that yield gap increases. However, where aridity shifts to a higher aridity zone into the 2050s, the allowable catchment areas can be increased, leading to an increase in the benefits arising from the use of RWH. Overall, the maize yield gaps which could be bridged through RWH range on average across Africa from 37-47% for 1986-2005, and decrease to 28-36% for the 2050s (Figure 3.7). Local-scale analyses could allow for a closer evaluation of the trade-offs between the potential yield decreases associated with water deficits and the land area required to collect the extra rainfall required to fully supplement crops in water. Overall, it seems that RWH systems could maintain their ability to bridge a large part of water deficits in the future, which shows their ability to mitigate some of the negative impacts of climate change.

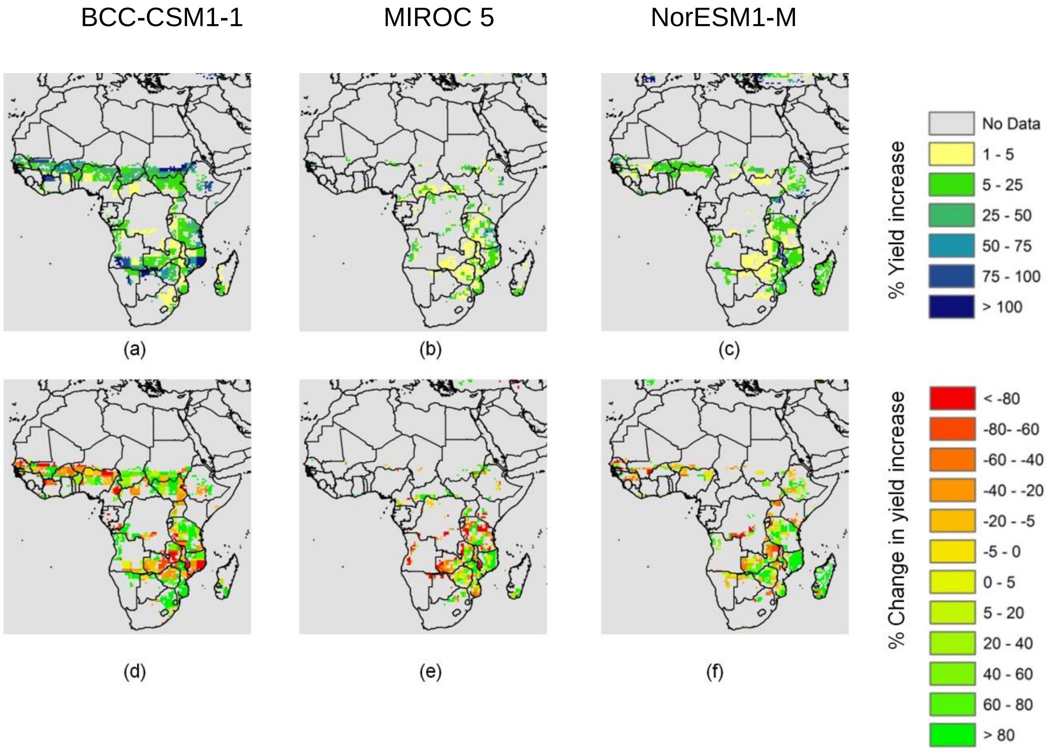


Figure 3.8 │Percentage yield increase attainable through rainwater harvesting. The minimum yield increase that a maize crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and change with respect to the future period (2046-2065) (d,e,f), were estimated using the calculated design C:CA ratios and maximum crop water requirements throughout the main growing season. Three GCMs were used: BCC-CSM1-1 (a,b), MIROC5 (c,d), and NorESM1-M (e,f).

Figure 3.8 shows that RWH is currently capable of stabilizing crop yields, and is likely to remain so in the future. In fact, in sub-Saharan Africa where RWH is found to be able to stabilize crop yields for 1986-2005, the mean potential yield increase associated with its use ranges between 9 and 39% (Figure 3.8). The mean yield increase over Africa due to the use of RWH for maize is projected to grow in the 2050s to 14-50%, depending on the model. The changes are less pronounced for sorghum and millet, as these crops are less sensitive to water stress. Yield increases remain largely unchanged at about 5% across models for millet, and grow from 5% to 6% for sorghum. In parts of Eastern Africa, such as Tanzania, yield gaps remain very large and RWH can only partially bridge those deficits, but maize yield improvements can easily reach 25-50%. Brauman et al. (2013) showed that improving water management, through RWH for example, has the potential of increasing calorie intake through maize yields by up to 60% in rainfed regions with very low productivity. In contrast, Elliott et al. (2014) mapped out the potential for maize yield increases over areas currently rainfed through the implementation of irrigation. The authors found that maize yields could increase by up to 10% over wetter areas, while drier areas could see increases over 50% under RCP8.5 by 2100.

3.3.4 Prioritizing areas for rainwater harvesting implementation

While RWH was shown to be able to partially bridge maize yield gaps to various degrees across Africa today, it is likely to bring decreased benefits in the future in several regions (Figure 3.9). Indeed, climate change will likely increase the vulnerability of maize crops to water stress in Southern Africa and particularly Zambia where all models agree to a decreasing of RWH performance based on the yield gaps, potential yield increase, and change in C:CA due to changes in aridity. Irrigation potential should be investigated in areas where RWH is unlikely to perform as well by the 2050s than under our current climate. On the other hand, RWH implementation for maize production should be prioritized in parts of Zimbabwe, Mozambique, Ethiopia, Tanzania, and a limited number of areas in the Sahel.

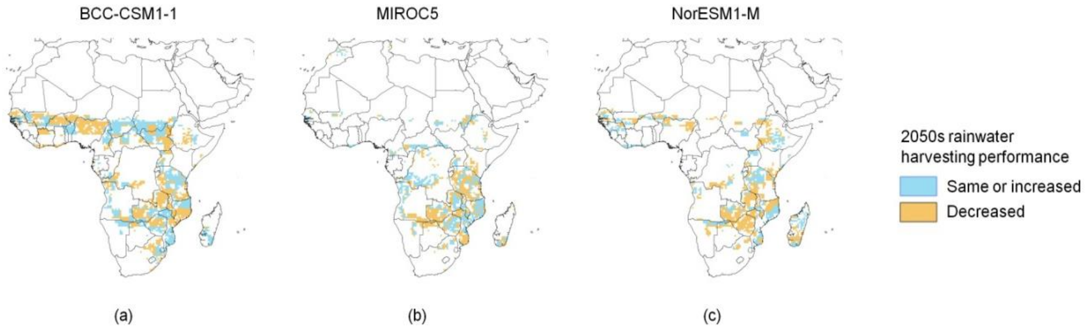


Figure 3.9 │Projected performance of rainwater harvesting (RWH) systems across Africa by the 2050s with respect to the 1990s, using three GCMs: BCC-CSM1-1 (a), MIROC5 (b), and NorESM1-M (c).

3.4 Discussion

Field-level experience has already shown the great potential of RWH to stabilize crop yields in otherwise harsh environmental conditions (Makurira et al., 2009, Sawadogo et al., 2008, Rockström et al., 2002). At a larger scale, it was found that the ability of RWH to bridge water deficits and to stabilize crop yields in Africa is projected to continue under the medium-term (2050s) and increasing radiative forcings (RCP8.5), despite a few regions becoming more vulnerable. Where RWH is projected to perform more poorly in the future, irrigation should be considered as an appropriate adaptation strategy to climate change. However, in regions where groundwater resources are also limited or inaccessible (MacDonald et al., 2012), RWH could still provide a readily accessible supplemental source of water for crop production by smallholder farmers. Otherwise, the production of drought resistant crops such as millet and sorghum instead of maize could be of interest.

In a number of regions, particularly in the semi-arid tropics and more arid environments, RWH has already played an important role in stabilizing crop yields for several decades by mitigating the negative impacts of high evapotranspiration. However, those regions are projected to experience a higher frequency of lethal high temperatures which will likely not be mitigated by RWH. Hence, areas where there is a decrease in the water deficit between the historical period and the 2050s should not always be interpreted as potentially benefiting from climate change. This is particularly true in the Sahel where already high temperatures are expected to increase, leading to increased evapotranspiration and lethal high temperature, and devastating effects on food production (Battisti and Naylor, 2009, Long and Ort, 2010).

While this study focused primarily on bridging water deficits, it is important to note that in several areas, RWH is also used in combination with nutrient management strategies (Zougmoré et al., 2003, Rockström et al., 2002). It has also been found to promote fertilizer utilization in areas of low fertilizer use (Wakeyo and Gardebroek, 2013). RWH systems allow for the retention of water, for the conservation of nutrients through a reduction in soil losses associated with water erosion, and an overall reduction in risk to crop production. Hence, the increases in yields that can be associated with RWH systems go far beyond the simple bridging of the yield gap caused by water deficits, and the estimates presented here are only a fraction of the true benefits RWH can have on increasing crop yields in African drylands. There is still a need for higher spatial and temporal resolution studies to capture intra-seasonal distribution of rainfall and use of fertilization on the efficiency of RWH systems, amongst other factors.

Where rainfall patterns have been reliable in the past, farmers have been more reluctant to adopt improved soil management practices or invest in irrigation systems (Deressa et al., 2009). In a context where we are unable to provide farmers reliable and consistent long-term inter- or intra-seasonal projections of changes in the climate, another possible benefit of RWH which was not explored here could be to help deal with precipitation variability by increasing the flexibility of cropping calendars. Specifically, RWH could extend the growing period by concentrating surface runoff associated with isolated rainfall events early or late during the season, and reduce the risk associated with the heavy reliance on those first few rains to determine when farmers are able to plant their crops.

Finally, one of the objectives of this study was to provide the “big picture” of the potential of RWH to stabilize crop yields, and reduce the dependence on groundwater resources. In a context where African agriculture needs to be more productive to be able to feed its own population, these benefits from RWH could be non-negligible. While agricultural development discourse has been heavily focused on the successes of the Green Revolution in Asia (and the expansion of irrigation), we still need to take into account the strikingly different situation of Africa today. If it is possible to bridge a minimum of 30-40% of yield gaps associated with crop water deficits simply with *in situ* RWH, the questions of energy requirements to access water, costs of implementation for wells or pumps, or overall low adaptive capacity, all become less of an issue for smallholder farmers.

3.5 Conclusions

Stabilizing smallholder crop yields under changing climatic conditions in sub-Saharan Africa will require adequate adaptation strategies focused on soil and water management. In some regions, rainwater harvesting has been used for several decades already to decrease the susceptibility of crops to frequent dry-spell events. While rainwater harvesting is bringing benefits to these systems today, regions which could increasingly benefit from rainwater harvesting under changing climatic conditions have been identified mainly in Southern and Eastern Africa, along with a limited number of areas in the Sahel . Rainwater harvesting is a valuable adaptation strategy to climate change in Africa for the three key staple crops studied here. Rainwater harvesting was found to bridge up to 40% of yield gaps attributable to water deficits under current conditions and 31% under future (2050s) climatic conditions during the main growing season for maize, hence providing an alternative to irrigation from scarce or inaccessible groundwater resources. On average, for the 2050s across Africa, bridging water deficits through rainwater harvesting could result in yield increases ranging from 14-50% for maize, and 5-6% for the less water sensitive millet and sorghum. While in-field rainwater harvesting strategies show great biophysical potential as an adaptation strategy to climate change, there remain a number of locally specific barriers to their adoption which will need to be addressed to ensure their successful implementation at the continental scale. These will be discussed in Chapter 5 with respect to three study sites located across Africa (i.e. Burkina Faso, Ethiopia, and Tunisia).

Chapter 4

Characterizing growing season dry spells from CMIP5 climate change projections

4.1 Introduction

Water-constrained rainfed agricultural systems contribute to the livelihoods of over half a billion people worldwide (Rockström and Karlberg, 2009). With climate change, intra-seasonal rainfall patterns are likely to change beyond the range of past experiences (IPCC, 2013b). Specifically, an increase in the frequency of long dry spells at critical stages of crop growing seasons could increase pressures on rainfed agricultural production (Barron et al., 2003) and exacerbate global food insecurity. In fact, intra-seasonal dry spell events, which occur almost every growing season, have the potential to be more detrimental to crop production than low cumulative rainfall amounts (Barron et al., 2003, Falkenmark et al., 2001). Rainwater harvesting has been recognized for its ability to bridge dry spell events, and reduce negative impacts on crop yields associated with water stress (c.f. Chapter 2). However, the magnitude of changes in intra-seasonal dry spell events has yet to be fully explored. Several studies have attempted to characterize changes in dry spells, and extreme climate events more generally in the CMIP5 ensemble at the global or continental scale, but only to a limited degree (e.g. Fischer et al., 2013, Sillmann et al., 2013, Bouagila and Sushama, 2013). In order for the characterization of CMIP5 data to produce metrics relevant to agriculture in Africa, dry spell analyses first have to be conducted at relevant timescales. That is, looking at maximum consecutive dry days on an annual basis is not particularly relevant for agricultural planning. It can, at best, inform us relative to changes in the length of the growing season, without providing intra-seasonal information. Here, an attempt is made to describe potential changes in dry spell characteristics with respect to current cropping practices. Analyses are conducted at the global scale, to assess whether changes in Africa may be more severe than elsewhere in the world. Changes in precipitation patterns during the cropping season can have significant impacts on crop yields. Equally, the timing and duration of such dry spell events are critical in assessing potential impacts on crop production.

As discussed in Chapter 2, GCM data outputs come with high levels of uncertainties, particularly on daily timescales which are required for dry spell analyses. This Chapter comprise two distinct analyses. In the first part, simple bias correction methods for daily precipitation and other climate variables are evaluated at the local level for a field site in Northern Burkina Faso. The corrected climate datasets will be used in Chapter 6 as input for the SWAT model. Limitations to the methodology for the purpose of dry spell analyses are discussed. In the second part of this Chapter, only bias corrected precipitation data using a method analogous to simple bias correction (i.e quantile mapping) is sourced for a global scale analysis of projected changes in seasonal dry spell characteristics. Dry spell characteristics in terms of frequency, duration, and timing are established and implications for climate change adaptation are discussed.

4.2 Downscaling GCM data for applications in crop and hydrological modelling

4.2.1 Methodology

Most climate change impact studies are based on General Circulation Models, which have coarse spatial and temporal resolutions. Ideally, for crop modelling, daily data is required in order to adequately represent intra-seasonal variations. As established previously, GCM data outputs are riddled with uncertainties. In addition, they come with intrinsic biases, for which calibration is increasingly recommended to be performed. For example, daily rainfall data has poor time structure and biases in frequency and intensity distributions (Ines and Hansen, 2006, Ines et al., 2011). That is, precipitation frequency is overestimated while intensity is underestimated, leading to simulations of light drizzle on a quasi-daily basis over several regions. In fact, while the correlations between mean monthly GCM data and observations is generally good, this is far from being the case at a higher temporal resolution (i.e. daily data). In order to calibrate climate data, one usually establishes biases with regards to historical observations, and assumes that these biases remain unchanged into the future simulations.

4.2.1.1 Defining calibration for daily climate data

GCM data outputs can be used in several ways in the context of climate impacts modelling, requiring different levels of transformation or calibration. Six of these approaches are identified by Hawkins et al. (2013):

i. Use the raw GCM data
ii. Use coupled crop-climate models
iii. Dynamical downscaling (i.e. use a Regional Climate Model to downscale coarser GCM)
iv. Statistical downscaling (e.g. use a weather generator)
v. Simple bias correction (i.e. nudging)
vi. Delta method or change factor (i.e. adding monthly mean changes to daily observations)

Prior to its use in crop/hydrological modelling (c.f. using the SWAT model in Chapter 6), the daily climate change data will need to be downscaled through one of the five calibration techniques outlined above, as raw GCM data is likely to yield poor crop/hydrological modelling outcomes. Furthermore, dynamical downscaling and the use of coupled crop-climate models are not addressed as they do not apply in this context. The applicable methods are discussed below.

First, SWAT has an integrated stochastic weather generator called WGEN (Sharpley and Williams, 1990), but weather generator LARS-WG was found to be more widely used. A comparison of the WGEN weather generator and the LARS-WG under diverse climates found that the latter was generally matching observed data more closely (Semenov et al., 1998). Furthermore, simulations showed that LARS-WG can effectively reproduce extreme precipitation events, but is less effective at reproducing extreme temperature (Semenov, 2008). Also, weather generators allow for the generation of several realizations of the future climate. Nevertheless, the use of a weather generator for this study was discarded for a number of reasons. First, the monthly statistics used in weather generators depend on long, and complete, time series of daily data (Schuol et al., 2008). These are not always readily available, especially in Africa. In addition, it assumes that the statistical model can produce the correct ranges of climatic variability (Hawkins et al., 2013). Using bias correction techniques, as opposed to a weather generator, has the advantage of maintaining the correct time distribution of the data.

The delta method or change factor calibration methodology (CF), uses the observed daily variability, and changes the mean and daily variance as simulated by GCMs. For temperature bias correction, the CF approach was found to be the most robust (Hawkins et al., 2013). In contrast, simple bias correction adds the historical mean difference between the GCM and observations to the future GCM projections, thereby conserving the GCM daily distributions. It can be considered statistical downscaling when used to correct data with weather station observations.

Bias correction for temperature, relative humidity, wind speed, and solar radiation

The simple bias correction method was selected for temperature, relative humidity, wind speed, and solar radiation, and is outlined in Equation 4.1 (Ho et al., 2012). It corrects for both mean and variance, and was preferred to the CF method in order to maintain consistent time structure with the precipitation time-series (i.e. the GCM daily distribution).

$$\boldsymbol{x_{cor}(t) = \overline{O_{REF}} + \frac{\sigma_{O_{REF}}}{\sigma_{x_{REF}}}\left(x(t) - \overline{x_{REF}}\right)} \quad \textbf{(4.1)}$$

Where $\overline{O_{REF}}$ is the monthly mean of observations during the reference period, σ_{OREF} is the monthly standard deviation of the observations, σx_{REF} is the monthly standard deviation of the reference period GCM simulation, x(t) is the daily simulated data on day t for the future period, and $\overline{x_{REF}}$ is the monthly mean of the simulated GCM data during the reference period. In the rare cases where negative relative humidity, wind speed, or solar radiation values were produced, they were replaced with the mean monthly value over the time period of interest.

In order to operate statistical downscaling to the Ouahigouya weather station, the ERA-Interim dataset was selected. The ECMWF ERA-Interim daily data is one of the most recent, complete, and widely used of these products. Data is available on a daily and sub-daily basis from 1979 to 2012. It represents a significant improvement from the previous generation of re-analysis products, in particular with the representation of the hydrological cycle, stratospheric circulation, and consistency in time (Dee et al., 2011). While re-analysis products are not equivalent to observations, they are often considered as such by a number of users. For climate change studies, it has the advantage of providing a range of data for a number of variables with a short time delay at a global scale. The grid cell centre coordinates used for the ERA-Interim data were 13.582N, 2.5W. Finally, the following GCMs were selected for further investigations due to the availability of data for all variables and RCP8.5: BCC-CSM1-1, CanESM2, INM-CM4, MIROC5, MRI-CGCM3, and NorESM1-M. The baseline period is 1986-2005 (1990s), while the future period is 2046-2065 (2050s).

Bias correction for precipitation

While additive functions work well for the variables listed above, precipitation requires a more complex multiplicative approach. Several methods are available, requiring variable levels of processing. For example, Ines and Hansen (2006) and Ines et al. (2011) offer simple bias correction methodologies to improve the usability of daily GCM rainfall data from specific stations for use in crop models. First, the rainfall data is bias-corrected simultaneously for frequency and intensity distributions. However, this procedure does not correct skewness or temporal correlation. Hence, to improve the time structure of bias-corrected GCM time series and attempt to remove excessively long dry spells leading to underestimations of crop yields, coupling of bias-correction and stochastic disaggregation is possible (Ines et al., 2011).

Again, these calibration methodologies for precipitation have a number of limitations. By assuming that all models over-predict the frequency of rainfall events, the bias correction methods described by Ines and Hansen (2006) will be ineffective in the case where rainfall frequency is under-predicted. When a disaggregation method is combined with bias correction, which corrects for both over- and under-predictions of rainfall frequency as in Ines et al. (2011), results can be improved. However, the latter methodology was found to be rarely used in literature. First, it is very complex and computationally demanding. In addition, it has the potential to break the relationship between climate variables and add a level of uncertainty which is difficult to characterize or quantify.

For the purpose of hydrological modelling, the precipitation bias correction method developed by Piani et al. (2010) was selected. The method aims to match the cumulative distribution functions (CDF) of the GCMs to that of the observations, through the use of a transfer function. This approach is analogous to quantile mapping, whereby precipitation data is ranked into quantiles to match an observed CDF. As opposed to the Ines and Hansen (2006) methodology, the transfer function is not a gamma-gamma transformation, but rather one of three types of functions is parameterized and selected for best fit. These are as follow:

$$\boldsymbol{Linear}: \boldsymbol{x_{cor}(t) = a + bx(t)} \ \textbf{(4.2)}$$

$$\boldsymbol{Logarithmic}: \mathbf{ln}(\boldsymbol{x_{cor}(t)}) = \boldsymbol{a + b}\mathbf{ln}(\boldsymbol{x(t) - x0}) \ \textbf{(4.3)}$$

$$\boldsymbol{Exponential\ with\ asymptote}: \boldsymbol{x_{cor}(t) = (a + bx)(1 - e^{(-(x(t)-x0)/\tau)})} \ \textbf{(4.4)}$$

Where, *x* is the raw GCM precipitation value for a given day, and x_{cor}(t) the corrected value of x(t). The parameters *a*, *b*, x_0 and τ are selected through the minimization of the square error. Furthermore, the dry day correction factor $x_0 = -a/b$, and is the value of precipitation below which modelled precipitation is set to zero. For dry months, a simple multiplicative correction can be applied as in Equation 4.5:

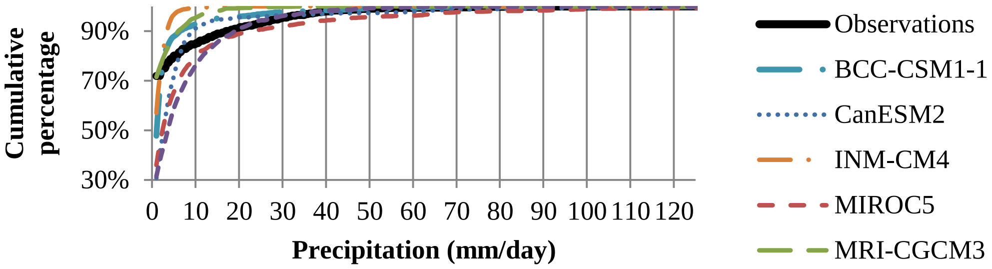
$$\boldsymbol{x_{cor}(t) = x(t)\left(\frac{\overline{O_{REF}}}{\overline{x_{REF}}}\right)} \ \textbf{(4.5)}$$

For the purpose of hydrological modelling in Chapter 6, the precipitation bias correction method developed by Piani et al. (2010) was selected, and was slightly modified to meet the specific needs of this study. First, the cumulative distribution functions (CDF) for each wet month were established over 20 years from 1986-2005, with bins starting at 1mm/day to represent measurement error in observations (i.e. below 1mm/day, a day is considered dry). Increments of 2.5%, from the start of the distribution at the cumulative dry day frequency, up to 100% of the distribution, were used to establish points to fit the transfer functions. That is, the rainfall intensities from observations and historical GCM runs were manually plotted against each other so as to obtain the observation intensity in y and the simulated intensity in x. No normalization of the precipitation data was conducted prior to processing. In addition, despite improvements since the last generation of re-analysis products, important deficiencies remain with regards to constraining precipitation in ERA-Interim. In many cases, the re-analysis product behaves in a similar manner to GCMs, and frequency and intensity of rainfall events will be poorly represented. In order to mitigate this issue, daily precipitation observations were also sourced for the Ouahigouya weather station.

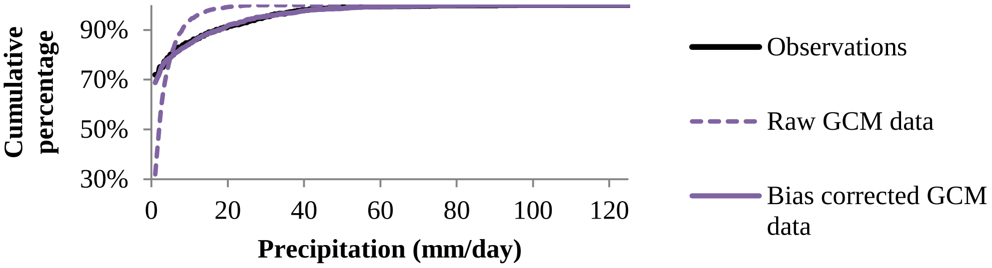
4.2.2 Results and discussion

In the case of statistical downscaling of precipitation data for the purpose of dry spell analyses and hydrological modelling, it was found that the largest uncertainty arises from the choice of input data for the correction (i.e. station data versus ERA-Interim), rather than from the correction methodology. Figure 4.1 (a) presents the CDFs of the historical time series for the rainy months of June to August, prior to bias correction. As expected, all models are shown to overestimate the frequency of rainfall events, while underestimating their intensity. In fact, some models estimate as few as 30% dry days (precipitation below 1mm/day) during the rainy season, while observations show this number to be closer to 70% at the Ouahigouya weather station. Results from bias correction show that the CDF fits are very good for all models (Figure 4.1 (b), Appendix C). In the other hand, Figure 4.1 (c) and (d) present precipitation projections before and after bias correction. While models continue to differ between themselves in terms of projections, the bias correction approach reduces errors in terms of frequency and intensity of rainfall events (as in the historical period).

Further uncertainty arises from the climate models themselves, and their ability to reproduce intra-seasonal rainfall distribution/aggregation of rainy days. Climate data analyses shows significantly longer dry spells (i.e. maximum consecutive number of dry days) occurring in the bias corrected GCMs historical datasets than in the observations during the growing season (Appendix C). However, initial hydrological modelling shows no significant variation in sorghum yield simulations across models for the historical period without the implementation of improved water management strategies (Table 4.1). This could relate to the calibration of the model and poor sensitivity of the parameter, or that the variability projected by the models is not as significant as initially thought. Indeed, while extreme events (i.e. >15 consecutive dry days) are more intense in models, historical simulations show that after bias correction they have a relatively similar frequency to the observations (Figure 4.2 (b)). Moreover, the frequency of dry spells of shorter duration (5-15 days), which have implications for RWH effectiveness, is also well represented in models after bias correction (Figure 4.2 (a)). With this in mind, bias corrected rainfall data is thought to be of greater use to dry spell analyses and hydrological modelling than raw GCM data. Hence, the observed rainfall from the Ouahigouya weather station as well as the other bias corrected climate variables using ERA-Interim will be used in more detailed hydrological modelling presented in Chapter 6, along with bias corrected data from the 6 GCMs.



(a)



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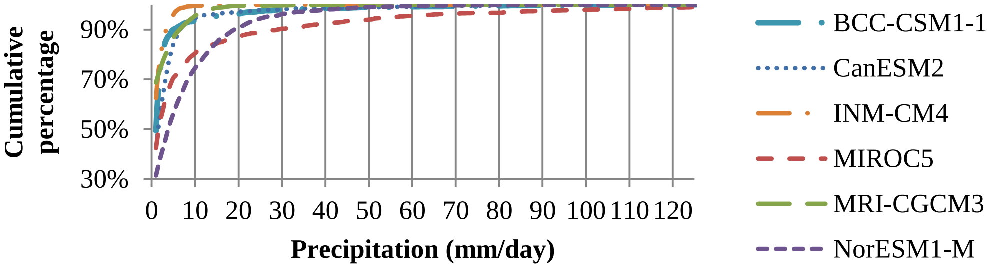

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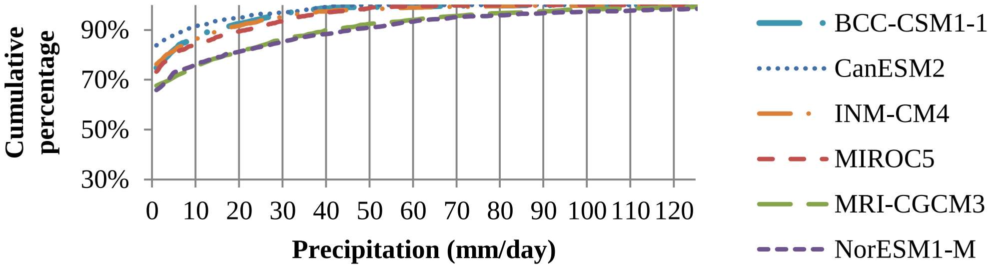
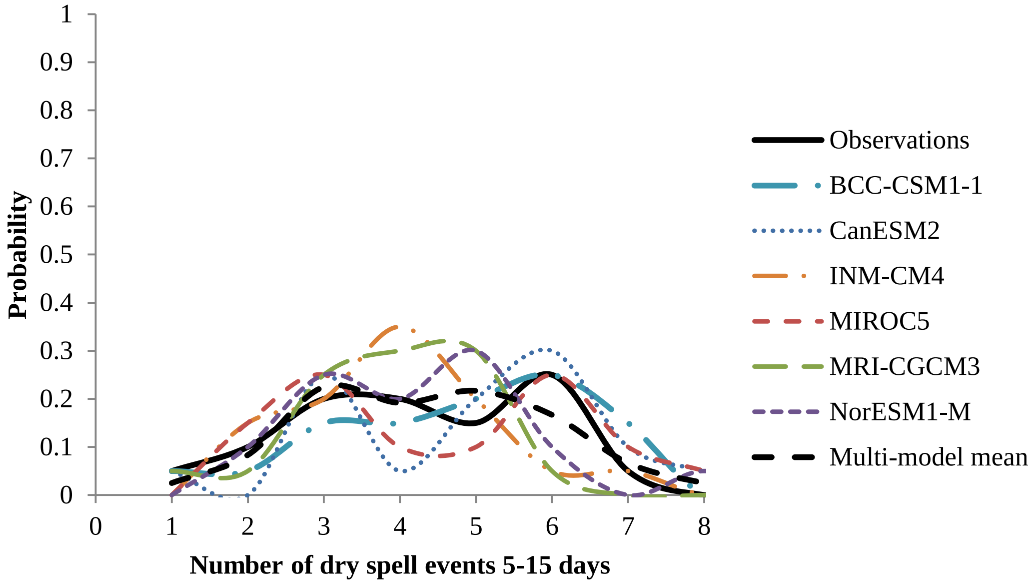
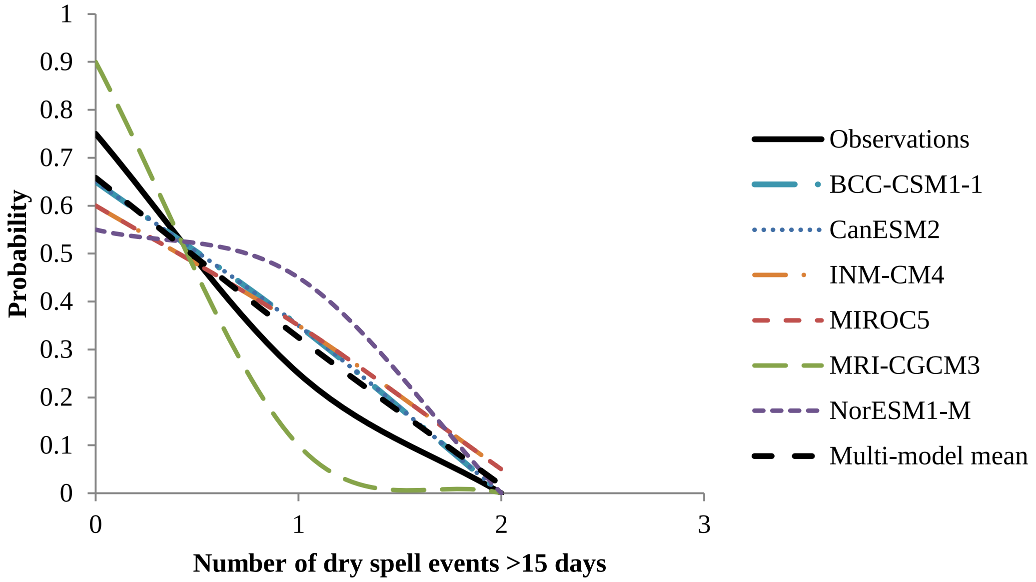


(d)

Figure 4.1 │Cumulative distribution functions (CDF) from 6 GCMs for the June-July-August months. For (a) uncorrected daily precipitation between 1986 and 2005; (b) 1986-2005 correction example for NorESM1-M; (c) uncorrected daily precipitation for 2046-2065; (d) bias corrected daily precipitation for 2046-2065.



(a)



(b)

Figure 4.2 │Probability distributions of different duration dry spell events. Probability distributions of dry spells in Ouahigouya, Burkina Faso, from bias corrected GCM data and observations for June-July-August 1986-2005. In (a) are dry spells of 5 to 15 days inclusively, and in (b) dry spells of more than 15 days.

Table 4.1 │ANOVA of 1986-2005 simulated yields using SWAT for sorghum in Ziga, Burkina Faso. Details of the methodology used to obtain these values can be found in Chapter 6.

SUMMARY					
Groups	*Number of years*	*Average yield (t/ha)*	*Variance*		
Observations	19	0.879	0.036		
BCC-CSM1-1	19	0.863	0.040		
CanESM2	19	0.797	0.027		
INM-CM4	19	0.869	0.054		
MIROC5	19	0.843	0.032		
MRI-CGCM3	19	0.875	0.050		
NorESM1-M	19	0.890	0.046		
ANOVA					
Source of Variation	*SS*	*MS*	*F*		
Between Groups	0.110	0.018	0.450	*P-value*	*F crit*
Within Groups	5.14	0.041		0.844	2.17
Total	5.248				

4.2.3 Summary of daily GCM data output calibration limitations

Substantial work is needed to improve the data outputs from GCMs for hydrological modelling, but also to gain a better understanding of intra-seasonal rainfall patterns. In this thesis, bias correction is used to reduce noise in climate change projections. The corrected datasets are used to evaluate projected changes in dry spell characteristics during crop growing seasons, as well as to improve their usability for hydrological and crop modelling simulations. The correction of climate data has several significant advantages, which can explain why its popularity amongst impacts modellers is rapidly increasing. Indeed, it provides higher correlations with historical observations, can produce a better distribution of rainfall events for hydrological analyses, and reduces inherent biases of the GCMs. While by themselves these advantages are sufficient to promote their use, one has to consider a range of side-effects which can increase (or decrease) the uncertainty range of simulations without physical justification. Furthermore, bias correction can alter spatiotemporal field consistency, as well as relationships between variables. Also, when choosing to correct for both mean and variance, one makes the assumption that the GCM is able to project the correct change in variability. Finally, there is a risk that the climate signal might be modified in an unintended manner.

4.3 Characterizing seasonal dry spells in the global CMIP5 ensemble

4.3.1 Methodology

4.3.1.1 Climate datasets and bias correction

The analysis presented below uses CMIP5 daily precipitation data from 15 General Circulation Models (ACCESS1-0, BCC-CSM1-1, BNU-ESM, CanESM2, CSIRO-Mk3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MPI-ESM-LR, MPI-ESM-MR, and MRI-CGCM3) sourced from Stanford University who conducted the following two steps. First, these models were selected based on the availability of daily precipitation data for the time periods and simulations of interest (i.e. 1986-2005 historical simulations and 2046-2065 RCP8.5 simulations). In order to ensure an equal weight was given to each model, only one ensemble member (i.e. the r1i1p1 simulations) for each model was considered. Second, the data was first spatially interpolated to a common grid of 0.5° x 0.5°. Subsequently, it was bias corrected using a quantile mapping approach (Ashfaq et al., 2010) from monthly GPCP (Adler et al., 2003) historical datasets. Quantile mapping is an appropriate bias correction technique when observational data is presented at a similar spatial scale as the GCM data (such as in the analysis in this section), but should not be used as an alternative to statistical downscaling to the weather station level such as presented in Section 4.2 due to a risk of overcorrection (Maraun, 2013).

4.3.1.2 Growth stage characteristics

Maps of global rainfed agricultural land (FGGD, 2007) were sourced online and used to mask the regions of interest. Global crop calendars (Sacks et al., 2010) were used to establish start and end dates for each of the four crop growth stages for maize, millet, and sorghum through interpolation from the planting and harvest dates at each grid cell using FAO guidelines (Allen et al., 1998). Characteristics of the different crop growth stages, including duration and coefficients used to determine crop water requirements, are presented in Table 4.2.

4.3.1.3 Characterizing dry spell events

Here we define dry spells as any number of consecutive dry days with precipitation ≤1mm/day. Dry spell events are characterized for the growing season of the three selected cereal crops (maize, millet, and sorghum), as opposed to the entire year. We focus on the 1986-2005 period, and compare it to the 2046-2065 period (2050s) under increasing radiative forcings (RCP8.5) over rainfed agricultural land (FGGD, 2007). While extreme dry spells have been characterized on an annual timescale (Fischer et al., 2013) and over specific regions (Singh et al., 2014, Bouagila and Sushama, 2013), it is the first time regularly-occurring dry spells are being described on a global scale for the growing season of key staple crops under a changing climate.

The timing of dry spell events, with respect to crop growth stages, were assessed for each grid cell where rainfed agriculture was deemed possible. First, the maximum consecutive number of dry days was counted for each growing season over each 20-year period under evaluation. Then, each event was assigned to the growth stage where the largest fraction of the dry spell fell into. If the dry spell spanned more than one full stage, it was assigned either to the longest stage fully covered by the maximum duration dry spell event, or in the rare case of two or more consecutive stages with the same duration, to the latest stage. For each grid cell over the regions of interest, the timing of the maximum duration dry spell event over the entire study period was aggregated to obtain the frequency at each crop stage. Box plots were produced based on data from the 15 selected GCMs (c.f. Figure 4.8). Maximum whisker length was assigned as w=1.5. Outliers were defined as models for which values were greater than q3 + w(q3 – q1), or smaller than q1 – w(q3 – q1), where q1 and q3 are the 25th and 75th percentiles, respectively. This would correspond approximately to +/–2.7σ and 99.3% coverage, assuming a normal distribution of the data. Notches were added to evaluate the 95% confidence interval of the median of the distributions. Notches are given by $m \pm 1.58 \times IQR/\sqrt{n}$ (McGill et al., 1978), where m is the median, n the sample size (here 15 GCMs) and IQR the interquartile range (q3 – q1). Where notches from the box plots overlap between the 1990s and 2050s there is no significant change in the median of the distribution, and vice versa (Krzywinski and Altman, 2014).

4.3.1.4 Mapping model agreement

Model agreement was mapped using the method described by Knutti and Sedlacek (2013), introducing calculations of robustness in the context of GCM projections. This approach not only maps the model agreement with regards to the direction of change (e.g. Tebaldi et al., 2011), but also penalizes regions where there is a disagreement in the magnitude of that change. The robustness threshold for the determination of levels of model agreement in projections through the use of stippling was set to R>0.67 (good agreement). Hatching marks were used over areas where less than 20% of models project a significant change. Finally, grey areas represent an inconsistent model response, with a robustness threshold of R<0.33 and the fraction of models projecting a significant change set to at least 50%. A 5% statistical significance level was used for the t-tests assigning significance in the change of means.

Table 4.2 │ Approximated crop growing stages characteristics, interpolated from global cropping calendars (Sacks et al., 2010) and associated crop coefficients from the FAO (Allen et al., 1998)

		Stages of Development					**Approx. planting dates**	**Region**
		Stage 1 (Initial)	**Stage 2 (Crop development)**	**Stage 3 (Mid-season)**	**Stage 4 (Late)**	**Total**		
Stage length (days)	*Maize*	20	30	35	25	110	Oct-Nov	Brazil
		20	25	30	25	100	Mid- to late June	India
		35	50	60	50	195	Mid-Feb to Apr	East Africa
		35	45	50	45	175	Dec-Jan	Southern Africa
	Millet	25	40	70	45	180	Early Dec.	Brazil
		15	20	35	25	95	Early July	India
		25	35	60	45	165	Mar-May	East Africa
		25	45	75	50	195	Mid-Oct to Nov	Southern Africa
	Sorghum	25	45	55	40	165	Late Dec	Brazil
		20	30	40	30	120	Late June to mid-July	India
		30	45	60	45	180	Mar-Apr	East Africa
		25	45	50	40	160	Dec-Jan	Southern Africa
Crop Coefficient (K_c)	*Maize*	0.30	>>	1.2	0.5	-	-	-
	Millet	0.75	>>	1.0-1.15	0.55	-	-	-
	Sorghum	0.7	>>	1.0-1.15	0.55	-	-	-
Yield Response Factor (K_y)	*Maize*	0.40	0.40	1.30	0.50	1.25	-	-
	Millet	0.2	0.55	0.45	0.2	0.9	-	-
	Sorghum	0.2	0.55	0.45	0.2	0.9	-	-

4.3.2 Results

4.3.2.1 Fraction of dry days

Robust increases in the fraction of dry days during the main growing season of the three selected crops are projected over most of rainfed India (Figure 4.3). This is also true for Southern Africa and the Sahel region, with decreases of over 80%. In contrast, the total rainfall for the Sahel, for example, is projected to increase. There are also robust negative changes over northern parts of Queensland in Australia, parts of Central America, and Brazil for millet and sorghum particularly. Projected changes over large parts of Europe seem inconsistent across models and for every crop. Models agree that there is no significant change projected over most northern regions, including large parts of North America and Russia.

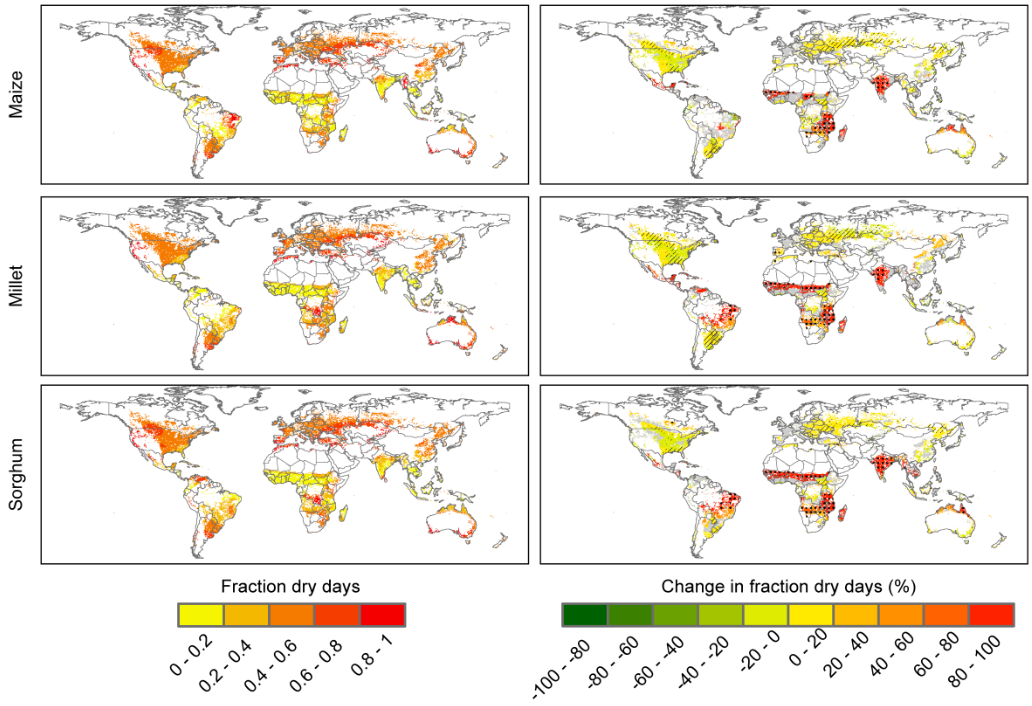


Figure 4.3 | Fraction of dry days per crop growing season. Multi-model mean of dry day fraction for maize, millet, and sorghum (1986-2005, first column) and projected changes from 15 General Circulation Models (GCMs) from CMIP5, RCP8.5 (2046-2065, second column). Dry days are days with 1mm or less precipitation per day. Stippling marks high robustness, hatching marks agreement across models on no significant change, and grey areas inconsistent model responses (c.f. 4.3.1.4).

4.3.2.2 Mean growing season dry spells durations

Across rainfed agricultural land, intra-seasonal dry spells generally lasted between 1 and 5 days (Figure 4.4) during crop growing seasons. Projected changes in the intensity of dry spells events, while significant in a number of locations including India, Southern Africa, the Sahel, and parts of Brazil, are not highly robust at any location. On the other hand, models agree on no significant increase in the mean dry spell duration over large parts of rainfed North America and Russia.

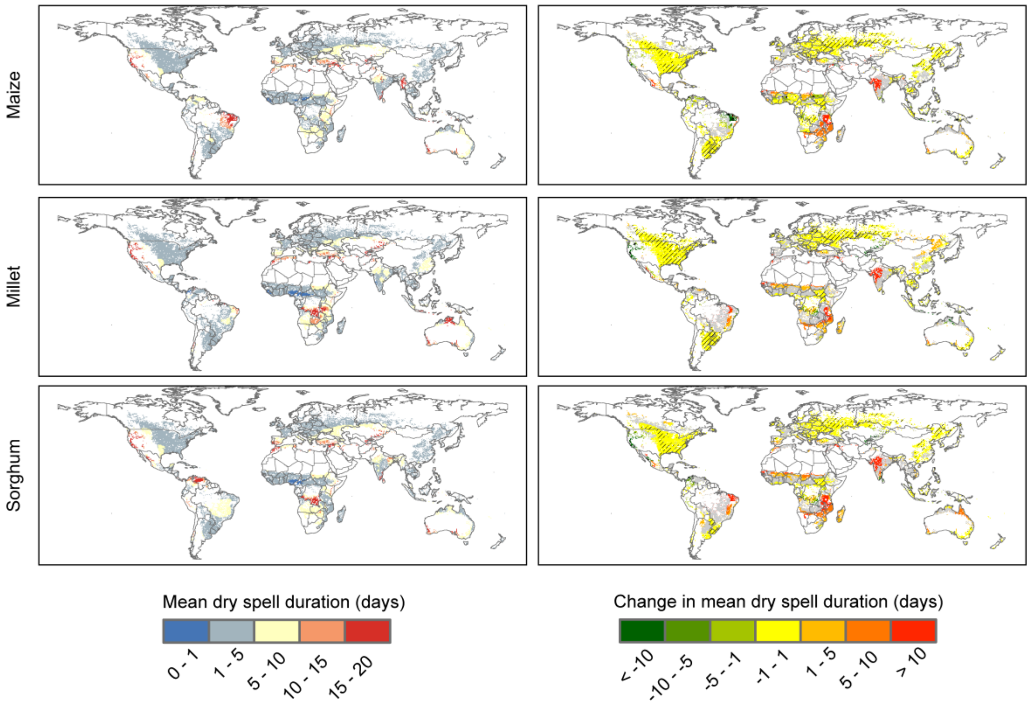


Figure 4.4 | Intra-seasonal multi-model mean growing season dry spell duration. Mean growing season dry spell duration for maize, millet, and sorghum (1986-2005, first column) and projected changes from 15 General Circulation Models (GCMs) from CMIP5, RCP8.5 (2046-2065, second column). Dry spells are any number of consecutive days with 1mm or less precipitation per day. The mean duration is calculated for each growing season, and then averaged over the time period of interest. Stippling marks high robustness, hatching marks agreement across models on no significant change, and grey areas inconsistent model responses (c.f. 4.3.1.4).

4.3.2.3 Dry spells of 5 to 15 days

Dry spells having durations of 5 to 15 days could be of particular interest for *in situ* rainwater harvesting. They are long enough to have the potential to cause some water stress to the crops, yet short enough to allow crop water requirements to be sustained by the harvested water stored in the soil profile. These regular dry spell events lasting between 5 and 15 days (i.e. at least annual recurrence in most regions for 1986-2005), are not projected to increase significantly in many regions of the world (Figure 4.5). Indeed, most models agree on a projection of no significant change for all crops over almost all rainfed agricultural land.

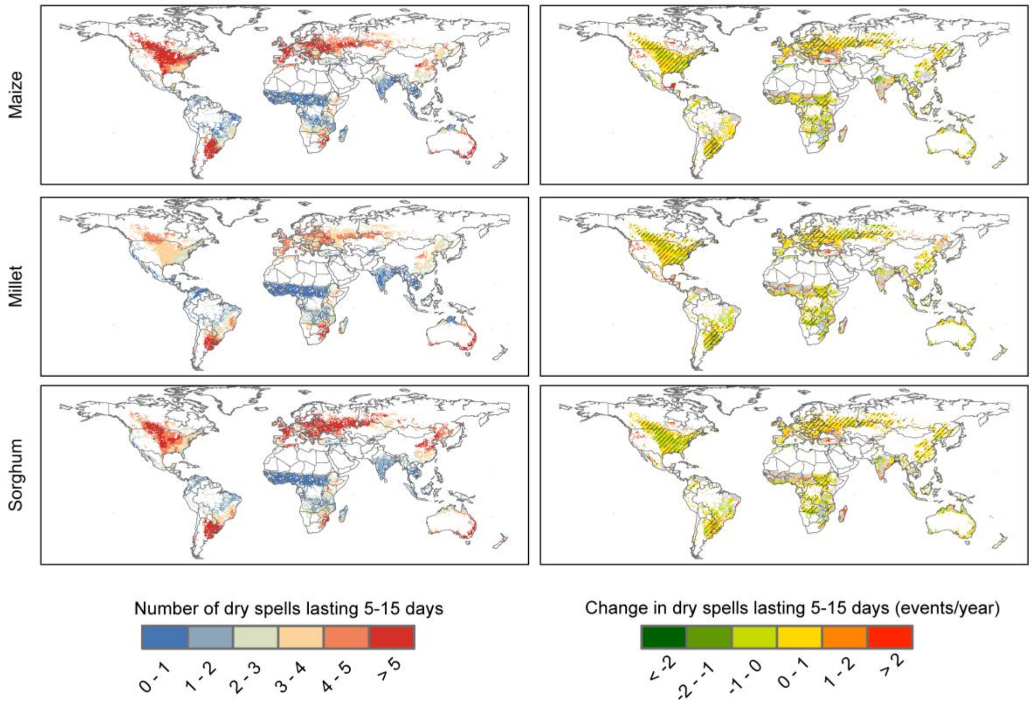


Figure 4.5│ Intra-seasonal multi-model mean number of dry spells of duration 5 to 15 days, inclusively. Multi-model mean of dry spells of a mean duration of 5 to 15 days for maize, millet, and sorghum (1986-2005, first column) and projected changes from 15 General Circulation Models (GCMs) from CMIP5, RCP8.5 (2046-2065, second column). Such dry spells have the most implications for *in situ* rainwater harvesting. Stippling marks high robustness, hatching marks agreement across models on no significant change, and grey areas inconsistent model responses (c.f. 4.3.1.4).

4.3.2.4 Dry spells longer than15 days

Dry spells lasting more than 15 days can be highly detrimental to cereal crop production if proper water management strategies are not in place. Most of the African regions north of the Equator and most of India experienced such events less than one in five years (i.e. 0-0.2 events/year) in the 1986-2005 period. However, robust negative changes in the frequency of these extreme dry spells are particularly important for the Sahel, East and Southern Africa, and India (Figure 4.6). In those regions, these events could occur on an annual basis, and possibly more than once per growing season.

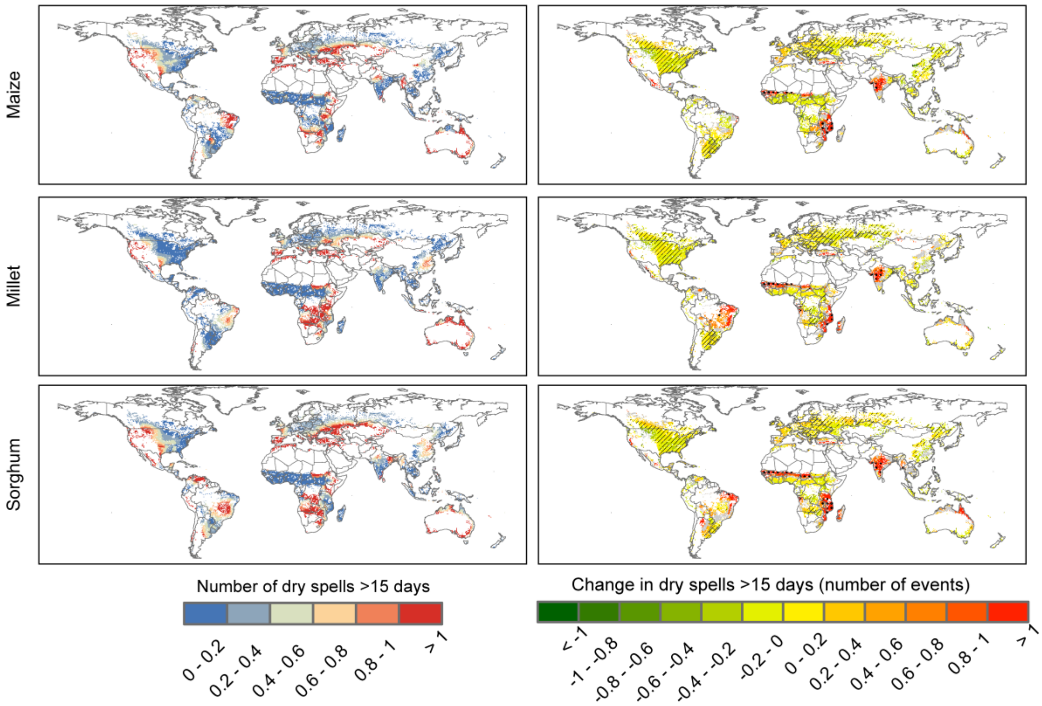


Figure 4.6│ Intra-seasonal mean number of dry spells lasting more than 15 days. Multi-model mean of dry spells of a mean duration greater than 15 days for maize, millet, and sorghum (1986-2005, first column) and projected changes from 15 General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (2046-2065, second column). Stippling marks high robustness, hatching marks agreement across models on no significant change, and grey areas inconsistent model responses (c.f. 4.3.1.4).

4.3.2.5 Wet days above a 5mm/day runoff threshold

The success of rainwater harvesting as an adaptation strategy to changes in the intensity and frequency of dry spell events depends on the occurrence of rainfall events of a minimum intensity to trigger surface runoff for collection and storage. Daily rainfall of 5mm/day is used as a threshold, as it is unlikely that surface runoff will take place below that value on cropped land. Figure 4.7 shows with high robustness that the number of rainfall events with a minimum intensity of 5mm/day will decrease by more than 50% over very large regions, including Brazil, most of Africa, and South Asia by the 2050s, compared to the 1990s.

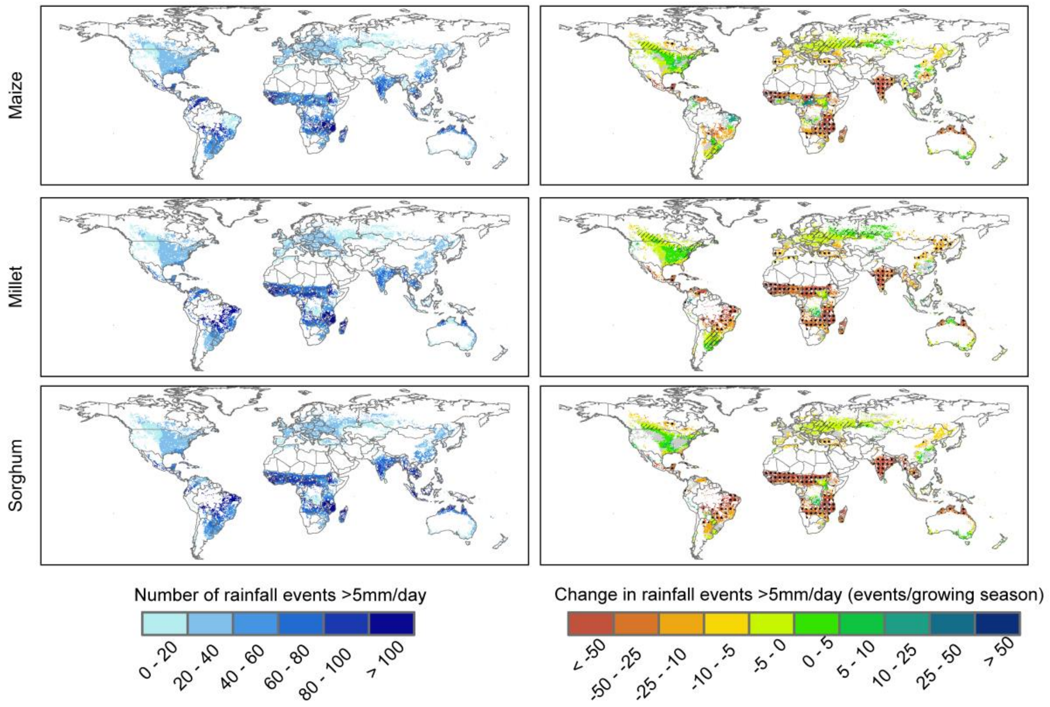


Figure 4.7│ Intra-seasonal multi-model mean number of wet days above a precipitation threshold of 5mm/day during a crop growing season. Multi-model mean of wet days >5mm/day for maize, millet, and sorghum (1986-2005, first column) and projected changes from 15 General Circulation Models (GCMs) from CMIP5, RCP8.5 (2046-2065, second column).This measure is used as an indicator of minimum runoff trigger precipitation events. The count of the number of wet days greater or equal to 5mm/day within each crop growing season is averaged out over the number of growing seasons during the study period. Stippling marks high robustness, hatching marks agreement across models on no significant change, and grey areas inconsistent model responses (c.f. 4.3.1.4).

4.3.2.6 Timing of the maximum consecutive dry days during crop growing season

Crop water requirements vary throughout the growing season, with each developmental stage having specific characteristics (Table 4.1). In response to variable crop water requirements and local rainfall variability, crop calendars have been optimized over generations to meet crop water needs throughout the growing season. The distribution of the longest dry spells is found to generally take a U-shape form (Figure 4.8), whereby crop calendars take advantage of the more reliable rainfall during the most water sensitive stages of the growing season (i.e. Stages 2 and 3). Farmers can cope more easily with long dry spells during less water sensitive Stages 1 and 4, by re-sowing crops in Stage 1, for example. Moreover, changes in cropping calendars are often referred to in agricultural climate change literature as a practical way of coping with intra-seasonal weather variability, due to its flexibility and ease of implementation (Manandhar et al., 2011, Waha et al., 2013, Dharmarathna et al., 2014). These changes usually refer to a change in sowing dates, which addresses the inter-annual variability in the start of the rainy season (Waha et al., 2013). Such variability is illustrated in the high probability of occurrence of the longest seasonal dry spells during Stage 1 of crop growing seasons (Figure 4.8).

Changes that are of most concern for adaptation occur over South Asia and East Africa, where the typical U-shape distribution is lost to the detriment of Stage 3, leading to increased challenges in water management for agricultural production. For millet and sorghum, U-shapes could be slightly more truncated at Stage 1 than maize, due to a lower sensitivity to water stress for the former two crops. The greater model spread present for the South Asia and West Africa regions can be attributed to the natural precipitation variability associated with monsoonal environments, which is poorly represented in many climate models (Sperber et al., 2013, Marsham et al., 2013).

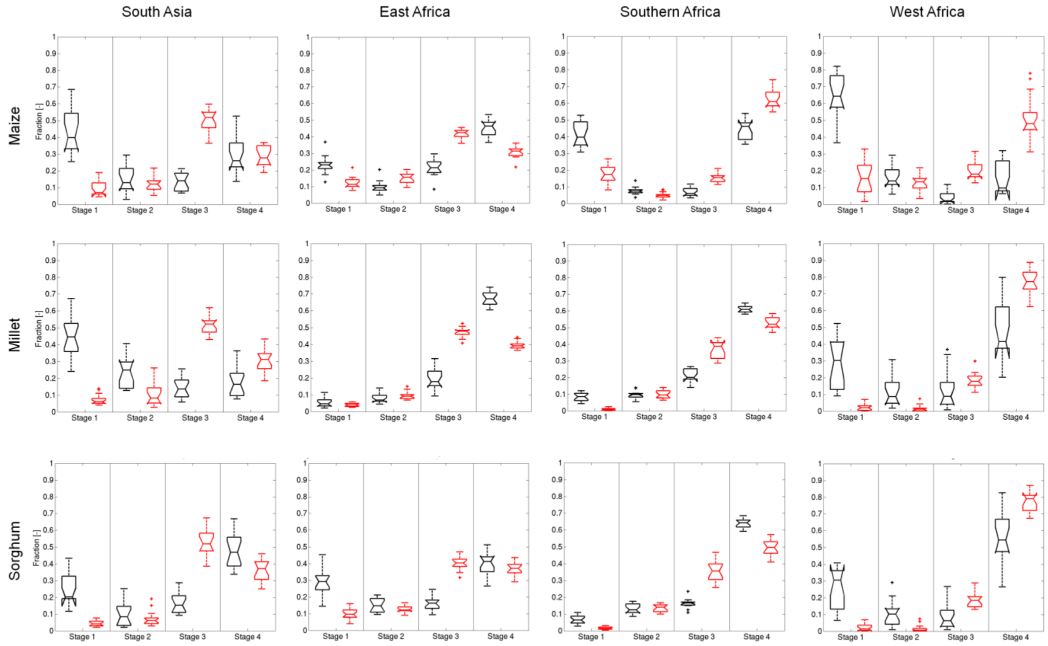


Figure 4.8 │ Timing of the maximum consecutive dry days during crop growing seasons. Box-and-whisker plots representing distribution of the maximum consecutive dry day intra-seasonal timing for maize, millet, and sorghum over selected regions, using 15 GCMs. Boxes show the model spread (25th and 75th percentiles), with the whiskers representing 1.5 times the inter-quartile range (approximately 99.3% coverage for a normal distribution). Any GCM outliers are represented as small crosses. Black boxes represent the 1986-2005 period, and the red boxes the 2046-2065 projections under RCP8.5. Where notches in the red and black boxes overlap, there is no significant difference in the medians of the distributions between the two time periods (Krzywinski and Altman, 2014).

4.3.4 Discussion

4.3.4.1 The intra-seasonal analysis of daily precipitation provides novel insight for impacts and adaptation

Figure 4.9 is a simplified schematization of the findings presented in Figure 4.8. The U-shape of the distribution is representative of an optimized cropping calendar, minimizing risks of crop water stress and decreased yields. Future Case 1 is representative of locations such as Southern Africa and West Africa, while Future Case 2 is representative of the South Asia and East Africa regions. Changes in the future distribution of the extreme dry spells such as in Case 1 could easily be mitigated by adaptation measures such as earlier planting dates. Case 2 is more challenging, and a range of different adaptation measures could be required to maintain current system functions. This could include crop breeding for shorter time to crop maturity, although such practices generally produce lower-yielding varieties.

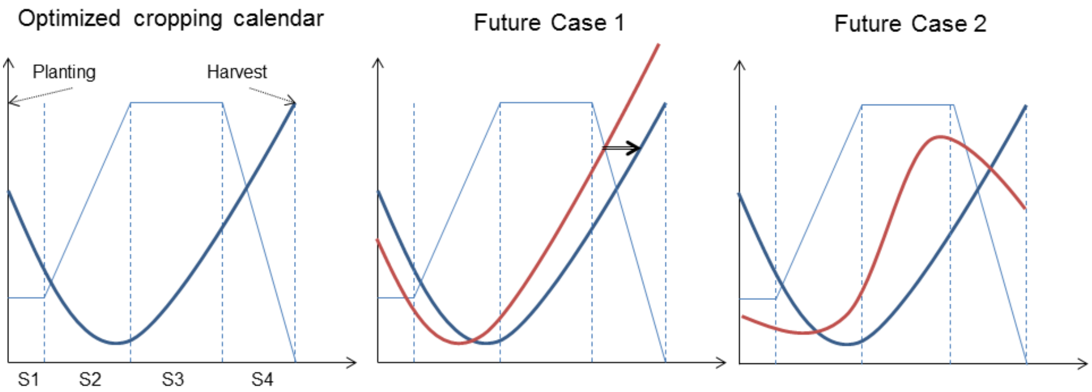


Figure 4.9│ Schematic representation of changes in the intra-seasonal distribution of maximum duration dry spell events. This figure should be seen as an overlay to the previous figure. Light blue lines represent the crop coefficient (Kc), thick blue curves are the optimized intra-seasonal distribution of maximum duration dry spell events (1986-2005), and thick red curves are the projected intra-seasonal distribution of maximum duration dry spell events (2046-2065, RCP8.5). Dotted lines indicate the end of crop growth stages 1-4 (S1-S4), and arrows indicate climate change adaptation measures.

Rapid changes in U-shaped patterns presented in Figure 4.7 could lead to challenging adaptation decisions for farmers. Our analyses show that the probability of having the longest dry spell of a growing season occurring during Stage 1 decreases significantly by the 2050s under RCP8.5 across regions and three different crops, at the expense of later stages. In instances where that shift occurs towards Stage 4 only, it could indicate a shift in the growing season, where earlier planting dates could effectively mitigate the effects of such a change and even benefit farmers (Figure 4.8). However, where changes occur to the detriment of Stage 3 (flowering and grain filling), which is drought-sensitive, changes in sowing dates are highly unlikely to overcome the increased frequency of long dry spells in the middle of the growing season. In those situations, supplemental irrigation from water harvested in *ex situ* structures during high intensity rainfall events or the implementation of full irrigation systems from groundwater resources might be necessary to adapt to those changes.

4.3.4.2 The role of in situ RWH in agricultural adaptation in Africa may be limited

Significant increases in the frequency of dry spell events longer than 15 days in Africa and South Asia entails that these regions might not be able to use simple agricultural water management strategies (e.g. *in situ* rainwater harvesting with soil water storage) to cope with such a significant increase in the frequency of these events. Instead, farmers may need to rely on more complex irrigation systems or *ex situ* rainwater harvesting (i.e. external structure holding excess water, often used in combination with supplemental irrigation). These results, in combination with significant decreases in rainfall events of 5mm/day or more and results from the IPCC AR5 (IPCC, 2013b) showing an overall increase in annual precipitation over these regions, support other work showing an increase in the frequency of heavy precipitation events. For instance, Fischer et al. (2013) showed some substantial increase in the intensity of heavy precipitation events during the 2016-2035 period in CMIP5. Similarly, an increase of 20-70% in the number of very wet days between the 2090s under RCP8.5 and the 1961-1990 period over Africa and South Asia has been projected (Sillmann et al., 2013). Along with results showing an increase in mean dry spell duration and an increasing fraction of dry days, it shows that there will be significantly more intense and temporally isolated rainfall events over large parts of Africa and South Asia during crop growing seasons. Under those conditions, soil and water management practices such as *in situ* rainwater harvesting would fail to provide agricultural systems with a consistent amount of water throughout the growing season. However, they could continue to contribute to the prevention of severe soil erosion associated with heavy precipitation events.

4.3.4.3 Adaptation to changes in dry spell characteristics will require extensive portfolios of various adaptation strategies

Following the analysis presented in this Section, the implications of the main findings for the implementation of most commonly cited adaptation measures for rainfed agriculture are summarized in Table 4.3.

Table 4.3│ Evaluation of agricultural adaptation strategies for rainfed agriculture under intra-seasonal rainfall variability.

Adaptation strategy	Advantages	Limitations
Rainwater harvesting (soil water storage)	-Can reduce soil erosion associated with more intense rainfall events -Can effectively bridge the yield gaps associated with frequent, short dry spells -Low cost strategy	-Increase in the frequency of high intensity rainfall events could reduce their effectiveness -Not effective at bridging extremely long dry spells (>15 days)
Rainwater harvesting and supplemental irrigation (external water storage)	-Effective in harvesting overland flow associated with high intensity rainfall events -Provides irrigation water during more frequent long dry spell events	-May not have sufficient water availability to bridge long dry spells mid-growing season -Larger financial investments required than for *in situ* techniques, but less than full irrigation
Full irrigation	-Fully mitigates the impacts of long dry spell events	-Limited availability of groundwater resources, risk of overexploitation -Important financial investments for implementation and maintenance
Adjusting cropping calendars	-Addresses the inter-annual variability of rainy season onset -Ease of implementation	-Would not effectively deal with changes in the shape of the intra-seasonal distribution of extreme dry spell events
Crop breeding and improved varieties	-Increases crop drought tolerance and decreases the susceptibility to longer dry spell events -In some instances can address changes towards shorter growing seasons	-Would not effectively deal with changes in the shape of the intra-seasonal distribution of extreme dry spell events
Change in type of crop produced	-Increases crop drought tolerance and decreases the susceptibility to longer dry spell events -In some instances can address changes towards shorter growing seasons	-Would not effectively deal with changes in the shape of the intra-seasonal distribution of extreme dry spell events -May not meet food needs in terms of nutritional balance and dietary preferences

4.4 Conclusions

Through an investigation of Coupled Model Intercomparison Project Phase 5 (CMIP5) daily precipitation data, projected changes in dry spell patterns over the world's rainfed agricultural land by the 2050s (RCP8.5) were characterized. There will very likely be a significant and robust increase in the frequency of dry spell events lasting more than 15 days (>1 event/year increase), as well as a significant shift in the timing of maximum seasonal duration dry spell events, particularly over East Africa and South Asia. A shift away from long dry spells occurring during the least water sensitive stages of the growing season is projected to occur to the detriment of the flowering and grain filling stages, when most cereal crops are most sensitive to water stress (Doorenbos and Kassam, 1979). A range of adaptation strategies are already suggested to cope with climate change, including changing cropping calendars (Waha et al., 2013), using supplemental irrigation (Rockström et al., 2002), or *in situ* rainwater harvesting systems (Rost et al., 2009). However, the risk factors identified here have yet to be considered in adaptation recommendations, and an inability to implement suitable adaptation strategies could fail to mitigate negative climate change impacts on yield in rainfed agricultural systems.

The results presented here emphasize the need to investigate further the intra-seasonal characteristics of precipitation patterns, and provide a new avenue for exploring adaptation options in rainfed agricultural systems. Given the reliance of these systems on the temporal characteristics of precipitation patterns, understanding historical intra-seasonal rainfall patterns provides insight into real climate change adaptation needs. A new framework focused on current intra-seasonal best practices based on an optimal use of precipitation patterns to meet crop requirements, such as the U-shape analysis, could better inform adaptation decision-making. Moreover, the first part of this Chapter showed that after bias correction, GCM precipitation time series were sufficiently well distributed to represent the intensity and frequency of different types of dry spell events, validating the approach taken in the U-shape analysis.

Chapter 5

Socio-economic determinants of rainwater harvesting adoption in the context of climate change adaptation

5.1 Introduction

While work presented in earlier Chapters indicates some biophysical potential for the implementation of RWH strategies across Africa, in several regions their adoption remains marginal. Hence, Chapter 5 aims to identify characteristics of agricultural systems where RWH has been adopted, perceived benefits from the use of such strategies by local adopters, as well as potential barriers to the continued expansion of the use of the techniques to adapt to climate change. Three study sites across Africa were selected by the WAHARA project prior to the start of this thesis, and were meant to be representative of their respective agro-climates and agro-ecosystems. These are located in Burkina Faso, Ethiopia and Tunisia. These investigations are intended as case studies, and it is important to note that other factors might prevail in other regions.

First, study site geographical descriptions are presented, along with details of locally prevalent RWH technologies. Then, detailed methodologies for data collection and analysis are presented, with respect to the nature of data collected for each study site. Results are presented with respect to climate and environmental change perceptions and factors affecting RWH adoption. Finally, a discussion of results with their implications for climate change adaptation policy is undertaken.

5.2 Study sites descriptions with attention to locally prevalent RWH practices

5.2.1 Case study site 1: Burkina Faso

5.2.1.1 Introduction

The study site selected in Burkina Faso comprises the villages of Ziga (13°25’12”N, 2°19’12”W), located some 25km south-east of the city of Ouahigouya (Figure 5.1), and Somyaga (13°30’0”N, 2°25’12”W), both in the Yatenga Province (Région Nord).

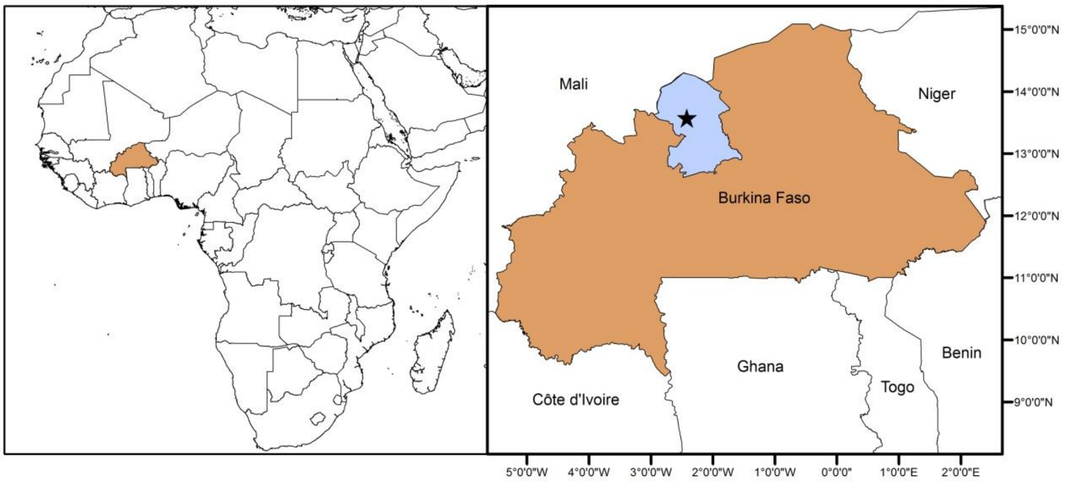


Figure 5.1│Approximate geographical location of both Burkina Faso field sites (star), and Région Nord highlighted in blue.

5.2.1.2 Geographical description

Climate

The climate is characteristic of the Sudano-sahelian zone, whereby average annual rainfall lies between 400mm and 600mm. The region experiences two main seasons; a dry season from November to May, and a wet season from June to October. Temperatures in the region can be extremely high. In May, before the beginning of the rainy season, the average daily maximum temperature can reach 45°C. While most staple crops are grown under rainfed conditions during the rainy season, a number of plots are irrigated during the dry season for vegetable production.

Soils

The Yatenga province is characterized by a large proportion of soils heavily degraded by water erosion (locally known as zipellés). These are soils from which the top horizon has been completely eroded and they are generally completely bare, despite remaining relatively deep soils. Infiltration capacity is generally poor, and thick crusts render agricultural work difficult.

Crops

The most common crops produced are sorghum and millet, which are local staples and are also adapted to the semi-arid climate. These crops are generally kept for household consumption, while crops such as cowpea and groundnut can be directly sold to the markets or transformed into high value products by women.

Water resources

According to the Ministère de l'Agriculture et de l'Hydraulique, the Région Nord of Burkina Faso has a large number of wells, mostly used for drinking water purposes, with low yields of 0.20 to 0.55 l s^{-1} (MAH, 2010). Such yields would not be sufficient to sustain even small scale irrigated agriculture, which require rates of at least 5 l s^{-1} (MacDonald et al., 2012). Therefore, rainfed agriculture is thought to be the only viable form of agricultural production for the region. The Région Nord had over 90 dams in 2010, out of which a majority were small structures with a capacity below 250,000m^3 (MAH, 2010).

Agricultural livelihoods

Most of the farmers in the area are agropastoralists, combining crop and livestock production. In Ziga, a relatively low percentage of households were identified as being poor (27%) in a 2001 survey by the MARP Network Burkina Faso, whereas neighbouring villages had poverty rates ranging anywhere between 57% and 69% (Reij and Thiombiano, 2003). Generally speaking, the first indicator of the level of poverty of a household is its food security status. Ouedraogo et al. (2008) defined socio-economic statuses in the Yatenga province as in Table 5.1.

Table 5.1 | Socio-economic status definitions, Yatenga Province, Burkina Faso (Reproduced from Ouedraogo et al. (2008))

Poor	Middle class	Rich
1. Is self-sufficient for food at most two months after harvests	1. Is self-sufficient for food at most six to seven months after harvests	1. Is self-sufficient and has a production surplus
2. Does not possess any livestock	2. Owns a few small animals	2. Owns a significant livestock herd
3. House is made with straw roof	3. House is made with wooden roof	3. House is made with tin roof
4. Does not own any mode of transportation	4. Owns a bike	4. Owns a motorcycle or a bike

5.2.1.3 Rainwater harvesting strategies

The Burkina Faso site has been widely studied over the years, as it is recognized as the location from which a range of RWH technologies have originated. As of 2008 in Ziga, up to 81% of the land was prepared with RWH such as stone lines, half-moons and zaï pits (Ouedraogo et al., 2008). These techniques are described in the following sections, along with a new technique (i.e. on-farm runoff capture ponds) for which implementation began in 2012.

Rock bunds and stone lines

Following severe droughts in the 1970s, farmers in the Yatenga Province were forced to adapt their agricultural practices to reduce soil erosion and increase water availability at the field level (Critchley, 2010). This has included new RWH strategies such as rock bunds and stone lines (Figure 5.2). These RWH strategies have now become so common that they are sometimes omitted by farmers when asked about soil and water management practices in their fields. As opposed to earth bunds which accumulate water on one side and leave the downstream side of the bund mostly dry, these strategies have the advantage of spreading water upslope and downslope while still trapping sediments (Zougmoré et al., 2000). Rock bunds and stone lines are constructed along contour lines, using a Bunyip water level tool. Farmers and communities are usually trained to use the tool, which can be constructed at fairly low costs from local materials (Antampugre, 1993).

(a)

(b)

Figure 5.2│Rock bunds, Passoré Province of Burkina Faso, May 18th 2012 (a), and Forestry zaïs with concrete blocks used as a stone line, Yatenga Province of Burkina Faso, June 5th 2012 (b) (Photographs taken by Matthew Smiley)

Half-moons

The half-moons are also endemic in the region (Figure 5.3), and can also be found in Niger. Newly constructed half-moons can be used for the first 3 years to grow sorghum, after which they will have exceeded their useful lifespan due to gradual erosion of the structures. Millet will then be grown at those locations until new half-moons are produced. In the case of maize, the half-moons would be used for a maximum of 2 years as that crop has higher drought sensitivity than sorghum and millet. The catchment area : cultivated area ratio for half-moons varies from 1.5:1 to 3:1, and half-moons require 100-200 man-hours/ha to construct (Vlaar, 1992). In addition to the manure/compost/fertilizer applications, half-moons are sometimes used in combination with rock lines or rock bunds to increase crop productivity. These lines or bunds are most efficient when spaced at a distance no greater than 30m, although they have been seen spaced anywhere between 15m and 50m (Vlaar, 1992).

Figure 5.3 │Woman and children applying manure to half-moons. Once the manure has been spread, and sufficient rain has fallen, the crops can be planted. Taken May 18th 2012, near Arbole, Passoré, Burkina Faso.

Zaï pits

The term “zaï pits” comes from the word “zaï” which literally means ”done in a hurry”, but should be interpreted as a way of “getting ready in anticipation” for the upcoming growing season’s climatic variability. The zaï pits are simple strategies whereby holes of about 20cm in diameter are dug out along contour lines (Dakio, 2000), and can reach densities of 10,000 pits/ha (Figure 5.4). Some studies have found various levels of yield improvements with the use of zaï pits in combination with manure or compost. For example, Ouédraogo (2005) found increases of 80% in sorghum yields when using zaï and 10t/ha of organic fertilizers, while Sawadogo et al. (2008) found yield increases above 100% independently of the level of fertilizer application as untreated plots produced no yields at all. Despite the success of the zaï and half-moon technologies in the area, they do not seem to have spread across the wider region and remain marginal at the national level.

Figure 5.4│Zaï pits with minimal mulching (straw). The pits remain to be completed and fertilized with manure or compost. Taken May 18th 2012, near Arbole, Passoré, Burkina Faso.

On-farm runoff capture ponds

As of the beginning of the 2012 cropping season, on-farm ponds were being tested in Ziga by a large number of farmers (Figure 5.5). The approximate dimensions of the structures were 4m by 6m, and 2m in depth, along with a conveyance canal. The structures were dug out by hand, in groups of 6-10 people, and were said to take about 4 days to construct. The main objective was to collect surface runoff to irrigate new reforestation projects.

Figure 5.5 | On-farm runoff capture pond with conveyance canal (in progress – lining not in place), Ziga, Yatenga, Burkina Faso.

5.2.2 Case study site 2: Ethiopia

5.2.2.1 Introduction

In Ethiopia, the selected study site is located in the Tekeze river basin in the Tigray region (Figure 5.6), and comprises three sub-watersheds: Suluh, Genfel, and Agulae (13°46'N, 39°37'E). These are located in the Central Highlands, ranging at about 2000m and 2500m above sea level. Mixed farming systems dominate the agricultural landscape. The region is also well-known for its apiculture.

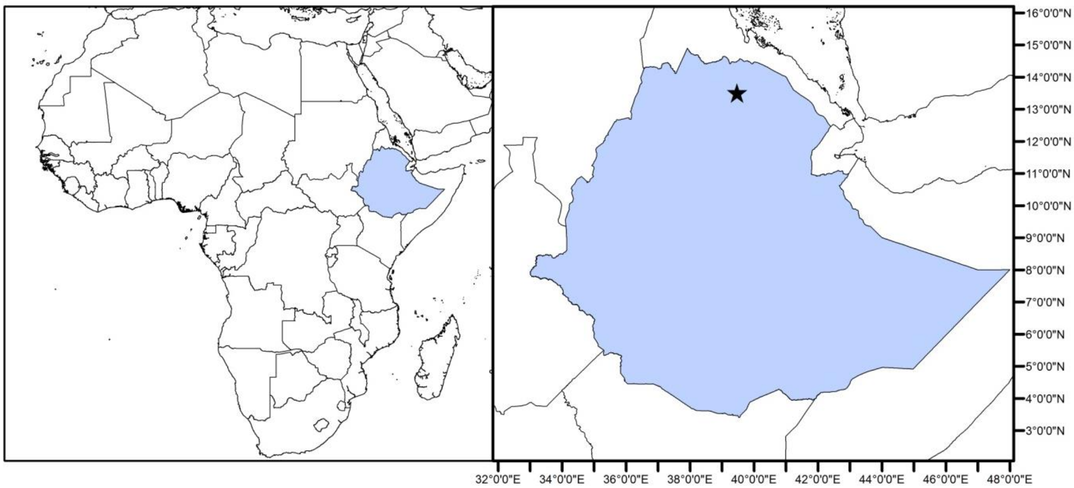


Figure 5.6 │ Approximate geographical location of Ethiopia field sites (star).

5.2.2.2 Geographical description

Climate

As opposed to the other two field sites presented here, annual precipitation distribution in the Tekeze river basin is bimodal (although weakly). The main rainy season, from May to November, lasts about 180 days. In contrast, the short rains from February to April last about 90 days. Annual total precipitation generally ranges from 500 to 1000mm/year, with the highest amounts found in the highest elevations.

Soils

Soils in the area can be characterized as loams having overall low fertility and low organic matter contents. Hence, soil water storage capacity is generally only moderate. Finally, being located in Ethiopia’s Highlands, a number of fields have very high slopes while others located on the valley floors are relatively flat.

Crops

Surveyed households reported widespread production of wheat, teff, and barley (in order of importance). Drought resistant crops such as sorghum and millet, widely grown in Burkina Faso, remain marginal.

Water resources

Groundwater yields from wells in the Tekeze basin are almost five times higher than at the Burkina Faso field site, with median yields of about 2.6 l s^{-1} (MoWE, 2010b). However, these yields remain too low to sustain irrigation projects, remaining below the 5 l s^{-1} threshold presented earlier (MacDonald et al., 2012). While several farmers rely on groundwater resources for household consumption, rainwater and surface water is essential for supplemental irrigation of fields through the use of water diversions for example (see Figure 5.7).

Figure 5.7│Water diversions in Ethiopia are used to route water to fields for supplemental irrigation.

Agricultural livelihoods

Rainfed cereal crop farming on plots of land between 0.5 and 3 ha is predominant in the area (MoWE, 2010b). In the 1980s, land reform has meant the homogenization of land holdings across the region, while grazing land remains common property (Araya and Stroosnijder, 2010). In relation to topographical features, most farmers remain poor and isolated, as road networks are poorly developed (MoWE, 2010a).

5.2.2.3 Rainwater harvesting strategies

Soil and water conservation strategies are common in Ethiopia, and a wide majority of households surveyed reported using at least one RWH strategy. These strategies contribute to increasing crop yields, and are particularly beneficial during lower than average rainfall years (Araya and Stroosnijder, 2010). Below, two common RWH techniques (i.e. terraces and stone bunds), are described as per their Ethiopian specific characteristics.

Landscape transformation

The type of landscape present in the Ethiopian Highlands allows for the integration of RWH within wider landscape transformation. Indeed, widespread terracing leading to the creation of new agricultural land is often combined with other water management measures such as the implementation of check dams and percolation ponds. Through the process, groundwater is being recharged, and farmers across a transformed watershed can benefit from the measures to various extents. This leads to increased water extraction from wells for irrigation in valleys, and thereby agricultural intensification for which long-term and larger scale hydrological impacts are not well understood. The watershed-scale approach to agricultural water management through RWH, rather than at the field scale such as in Burkina Faso, is also widely applied in other regions such as India (Lebel, 2011). Due to the large investments and complexity of the systems, government intervention is often at the cradle of these large-scale projects.

Terraces and stone bunds

A wide variety of terraces are present in the Ethiopian Highlands, with farmers having significantly modified the landscape for generations to suit the needs of agricultural production Figure 5.8). In a large number of cases, terraces are built by stacking stone bunds along contour lines, and the ground is gradually levelled in between bunds through sedimentation. These bunds can be anywhere between 0.5-2.5 m, a base width of 1-1.5 m, and a narrower top width of 0.2-1 m (Ludi, 1999). In some cases, specific vegetation (e.g. legumes and trees) is planted along the stone bunds/walls to protect them from degradation.

Figure 5.8 | Ethiopian highland slopes developed with terraces for agricultural production.

5.2.3 Case study site 3: Tunisia

5.2.3.1 Introduction

The Tunisia field site is located in the southeastern part of the country, comprising the Wadi Hallouf and Oum Zessar watersheds (Figure 5.9) near the city of Medenine (33°21'N, 10°30'E). Pastoralism is very common with almost 50% of the territory being rangeland, and olive production is one of the predominant forms of agricultural production. Rainfed agricultural land covers just over half of the watershed.

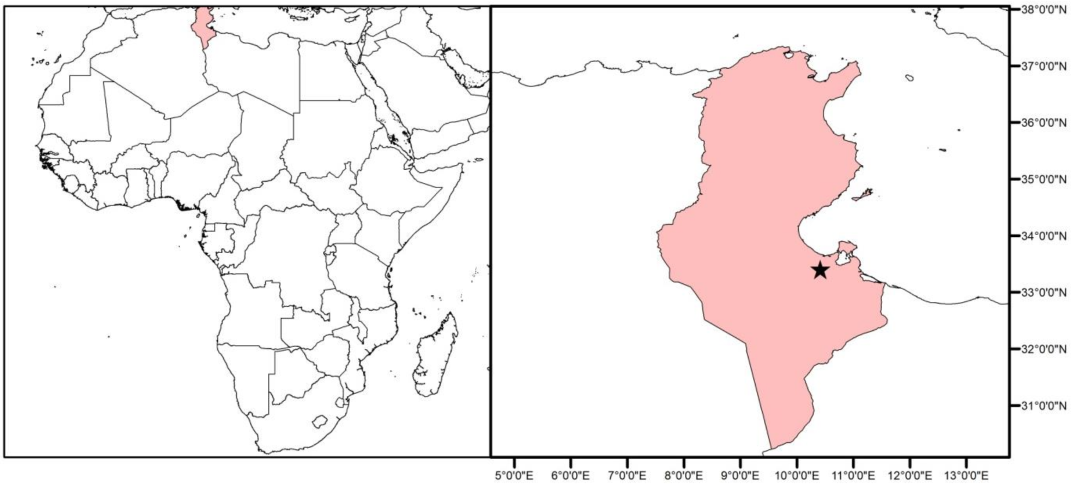


Figure 5.9 | Approximate geographical location of Tunisia field sites (star).

5.2.3.2 Geographical description

Climate

This field site is located in an arid Mediterranean region, with annual mean precipitation ranging between 150 and 230 mm per annum (Ouessar et al., 2004). Rainfall is highly variable, with highest likelihoods of occurrence between the months of November and March (Fleskens et al., 2005).

Soils

Soils at the Tunisian field site are heavily degraded due to factors such as overgrazing and water erosion. They therefore have very low fertility, low organic matter contents, and medium soil water storage capacity.

Crops

Due to the high aridity of the area, farmers focus their agricultural production on drought-resistant fruit trees such as olives (over 80% of cultivable land), figs, and almonds. While not the primary production, it is common in wet years to do some inter-cropping with drought-resistant annual cereal crops such as wheat or barley (Visser et al., 2011, Fleskens et al., 2005).

Water resources

As can be expected, surface water resources are very scarce in the region. Large-scale rainwater harvesting for agriculture and household uses plays a central role in water provision, while groundwater resources are overexploited. Tourism also creates very high water demands, with hotels on the nearby island of Djerba relying on the regional aquifer for instance.

Agricultural livelihoods

As mentioned previously, in the Medenine region farmers rely heavily on olive production as the primary component of their livelihoods, with a smaller fraction of agropastoralists. However, a large fraction of the local population works with the tourism industry (~16%), leading to important socio-economic inequalities between those and traditional rural livelihoods (Riadh et al., 2012).

5.2.3.3 Rainwater harvesting strategies

Two typical rainwater harvesting strategies are used in south-eastern Tunisia: jessour and tabias.

Jessour

Jessour are rainwater harvesting strategies adapted to very dry environments, possibly initially developed for olive groves in mountainous regions (Figure 5.10). Built in similar fashion as terraces, they are complemented by large dykes of trapezoidal shape ranging from 15-50m in length, 1-4m in width, and 2-5m in height with spillways at their edges (Ben Zaied, 2011). While initial investments can be important (Fleskens et al., 2005), their effective lifespan can reach several decades (i.e. much longer than *in situ* structures as presented for Burkina Faso).

Figure 5.10 | Jessour in Tunisia, in the foreground, located on high slopes.

Tabias

Tabias, like jessour, are typical structures found in dry Mediterranean environments to allow for the collection of excess surface runoff (Figure 5.11). As opposed to jessour, they are usually found in piedmont areas on lesser slopes. The earthen dykes range from 50-150 m in length, and 1-2m in height with a central spillway for overflow, and catchment to cropped area ratios (C:CA) ranging from 6:1 to 20:1 (Ouessar, 2011).

Figure 5.11 | Tabia in Tunisia, located in a piedmont area.

5.3 Methodology

Fieldwork conducted in Burkina Faso in 2012 entailed interviews and focus group activities with a range of stakeholders. In contrast, the analyses for Ethiopia and Tunisia are solely based on household surveys conducted by WAHARA partners, with specific questions on environmental perceptions and climate change adaptation prepared by myself, and data collected on my behalf. To complement the climate change perception analysis, trends in changes in rainfall patterns were evaluated and checked against farmers' perceptions of change in Burkina Faso.

With regards to the household surveys, particular attention was given to questions which were common across field sites, for comparative purposes. However, due to field site specificity and parallel questionnaire testing, some questions differed from one field site to the next. For example, Ethiopia investigated which crops were being produced after RWH implementation, while Tunisia asked respondents if they thought they would be able to change crops grown after RWH implementation.

5.3.1 Case study site 1: Burkina Faso

5.3.1.1 Data collection

Fieldwork was conducted in Ziga and Somyaga, Yatenga Province, Northern Burkina Faso. While the region is well documented as a key area for RWH with high levels of adoption, field observations revealed that RWH was not universally adopted in the area. In addition, it had not spread widely to other regions of the country. A range of participatory methods were used to get a better grasp of the challenges farmers face for the implementation and continued use of RWH, and the reasons that have led them to use the technologies in the first place. These approaches include:

1. Six focus groups with exercises to obtain timelines, cropping calendars, factors affecting RWH adoption, and perceptions of environmental change. Groups included were: women groups, young farmers groups, and groups of more experienced farmers.
2. Participatory farm visits with key informants (i.e. innovative farmers with regards to RWH and INERA staff).
3. Thirty household surveys with some open-ended questions.

The selection of the participants was done using a non-probability sampling method, whereby a member of the local research institution was identified as a key informant, and network sampling was used to contact the other informants. Initially, a second field season was planned to sample a larger fraction of the population, through more focus group, interviews, and household surveys. However, due to the deterioration of the 2012 conflict in Mali, it was deemed unsafe by the University of Leeds to conduct a second field season in Burkina Faso.

It is also important to note that questions asked in some instances were not geared towards climate directly, but rather towards broader themes such as environmental risk, uncertainty, and food security. For example, farmers were asked about availability of wood for cooking instead of deforestation, drinking water availability instead of frequency of droughts, crop yields instead of climate extremes, etc. Following the method outlined by Thomas et al. (2007), climate issues were only addressed when raised by the respondents themselves, and questions were non-directional (i.e. interviewers did not guide the responses).

The main objective of the focus groups discussions was to determine if the farmers were able to correctly recognize changes in their environment (particularly the climate), and what were their responses to these perceived changes. Small groups of 3-6 participants were recruited for a variety of activities at both study site locations. In a first set of activities, farmers were asked to recall extreme climatic events guided through the process by the inclusion of important political and/or social events for the community that might trigger recollections of climatic events and crop production. Farmers were also asked to add a “future” section to the timeline, to see what they envisioned might occur in the following decades in terms of climate and agricultural production interactions, and how they might adapt to those envisioned future changes.

The second objective of the focus groups was to establish cropping calendars, and evaluate what types of climatic events have the greatest importance in determining the range of cropping activities, such as planting and harvest dates. The participants were instructed as to the purpose of the activity, and asked to answer based on their personal experience. It was expected that opinions on the timing of these activities might vary across farmers, and questions were asked to identify the factors that cause these variations (e.g. do they all farm on the same soils, do they use the same varieties, do they have access to the same fertilizers, etc.) Following the initial determination of the cropping calendar, a number of rainfall distribution scenarios were introduced to investigate perceptions of intra-seasonal climate variability, and participants were asked how they expected this would change both their cropping practices and the expected yields of their crops.

Finally, focus group activities investigated the adoption patterns of RWH strategies. Participants were brought to discuss the different factors that led them to choose to adopt or not the RWH strategies in the past, and how they foresaw the future of rainwater harvesting in their communities. Further details of the contents of the focus group activities, and examples of questions used to guide discussions during participatory farm visits are presented in Appendix D.

5.3.1.2 Data analysis

The qualitative data analysis software tool NVivo 9 has been used to code the qualitative data collected through interviews, focus groups, and socio-economic surveys. Trends in terms of environmental perceptions, perceptions of benefits associated with the use of RWH, as well as factors affecting RWH technology adoption were identified. Due to the low number of surveys available at the time of data analysis (i.e. 30), focus was given to the qualitative analysis of open-ended questions on environmental perceptions.

5.3.1.3 Climate change perception analysis

Farmers' perceptions of climate were compared with weather records of daily rainfall and temperature. The Mann-Kendall nonparametric trend test was used to establish trends in measured daily historical meteorological data from the study site and checked against farmer perceptions, using software developed by the Finnish Meteorological Institute (Salmi et al., 2002). Daily weather data from 1986 to 2005 was obtained for the Ouahigouya weather station, and used to assess whether there was a good correlation between perceptions and reality of growing season start and end dates, as well as dry spell frequency and duration. It was hypothesized that intra-seasonal variability as opposed to long-term annual trends in precipitation could be better remembered by farmers due to its direct impacts on livelihoods.

Specifically for the dry spell analysis, the agronomic method presented by Ibrahim et al. (2012) for Burkina Faso was used to determine the start and end of the rainy season. That is, the rainy season begins when 3 days with a cumulative rainfall amount > 20 mm, not followed by a dry spell of more than 7 days, take place after April 1st. The season is subsequently terminated by the last rainfall event >5 mm/day after September 1st, followed by any rainfall event >5 mm/day during the next twenty days.

5.3.2 Case study sites 2 and 3: Ethiopia and Tunisia

The statistical analysis software package SPSS was used to analyse the outcomes from socio-economic household surveys in Ethiopia and Tunisia. Local WAHARA partners collected data from 301 respondents in Ethiopia, and 139 in Tunisia. Using a broad definition of

RWH, encompassing both *in situ* and *ex situ* strategies, the surveys revealed approximately 16% of households surveyed in Ethiopia were non-adopters, while that number was only slightly lower at 14.5% in Tunisia. Hence, to be able to conduct the statistical analysis regarding factors affecting the adoption of RWH strategies, most categorical variables had to be converted to a binary form. For example, the plot sizes were converted from an area in hectares to values representing small plots or larger plots, the slope to negligible or non-negligible, education level to literate or illiterate, soil quality to fertile or less fertile, main source of drinking water to public or private, total income to below average/average or above average, and household size to below average/average or above average.

The statistical analysis was guided by the following two research questions and identified factors of interest for which data had been collected. Only factors in italics were used for Tunisia for Q1 due to significant correlations between some variables at that site:

Q1. What factors are affecting RWH adoption?

a) Dependent variable: Adoption of RWH (Boolean, Yes/No)
b) Age
c) Gender
d) Literacy
e) Size of plot
f) Soil quality
g) Plot slope
h) Main source of drinking water
i) Total income per person
j) Household size
k) Livestock holdings
l) Source of RWH funding

Q2. As a consequence of using RWH, what agricultural practices change and what are the perceived benefits?

a) Use of manure
b) Use of chemical fertilizers
c) Migration rates
d) Change in soil fertility

e) Change in crop yields
f) Trend in agricultural (crop) income
g) Stability in crop yields
h) Stability in planting dates
i) Change in crop used
j) Ability to crop new land when using RWH

Q1 was investigated using a binary logistic regression approach, while Q2 was investigated using simple t-tests for changes in means. In the first case, correlation between variables was first tested, and the following variables were rejected because of their significant correlation with the retained variables presented in parenthesis: age and gender (education), size of household (income per person, education), slope (soil quality).

Finally, in Tunisia, an investigation of the perceived ability to change crops produced on a set plot of land following RWH implementation was performed. This complements an investigation of actual reported changes in crops grown in Ethiopia after RWH implementation. In the Tunisian survey, respondents were not asked to report on the type of crops used such as in Ethiopia, but rather asked a direct question regarding their perception of the possibility of changing crops grown with RWH.

5.4 Results

5.4.1 Case study site 1: Burkina Faso

Climate and environmental change perceptions

Focus group activities aimed at establishing climatic timelines revealed contradictory climate change perceptions among farmers. Female farmers reported more flooding events in recent years. While not mentioning the severe droughts of the 1970s and 1980s directly, when probed they recalled the events. In all cases, the resulting impacts of the cited events were reduced crop yields. However, while mentioning an increase in flooding events, female farmers reported that they were seeing a decrease in rainfall, with the rainy season starting later and an increasing dry spell frequency. They defined dry spell events as periods of between 10 and 20 days without rainfall, and they estimated that a good rainfall event was needed every 3 days for an ideal growing season. Male farmers also reported a delayed start to the growing season, but also an earlier end to it and an overall decrease in total rainfall. Specifically, they pointed to a decrease in the intensity of rainfall during the month of August. They however nuanced their thoughts, by pointing to the fact that for as long as they could remember, there had always been famines (sic) and production had always been too low. On the other hand, female farmers also pointed to an increase in the frequency of extreme events, and linked a perceived increase in temperatures to widespread deforestation in the area, and therefore less shade to protect them from the heat. Table 5.2 summarizes the reported perceptions of changes in the local climate, in comparison with the results from the meteorological data analysis.

Table 5.2 │Comparison between farmers' perceptions of climate change and measured meteorological information

Climate characteristic	Female farmers perceptions	Male farmers perceptions	Meteorological data analysis result
Temperature	Long-term increase	Long-term increase	No trend over 1986-2005
Annual precipitation	Long-term decrease	Long-term decrease	Increase over 1975-2006, no trend over 1986-2005
Start of growing season	Delayed start	Delayed start	No trend over 1986-2005, high inter-annual variability
End of growing season	N/A	Early end	No trend over 1986-2005, low inter-annual variability
Dry spell duration	Increase in frequency of long dry spells	N/A	No trend over 1986-2005, low inter-annual variability
Dry spell frequency (5 or more consecutive dry days)	Increase in frequency of long dry spells	N/A	No trend over 1986-2005, high inter-annual variability
August precipitation	N/A	Decrease	No trend over 1986-2005, moderate inter-annual variability
Flood	Increase in frequency	N/A	No trend over 1986-2005 in the intensity of rainfall events.

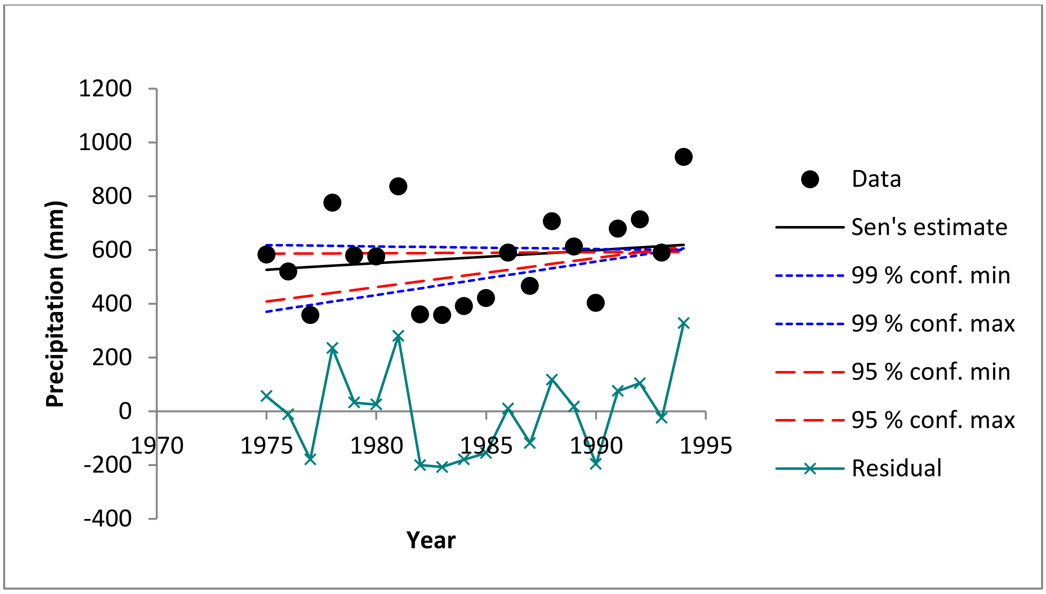


Figure 5.12│**Mann-Kendall trend statistics and Sen's Slope estimate for precipitation in Ouahigouya, 1975-2006**

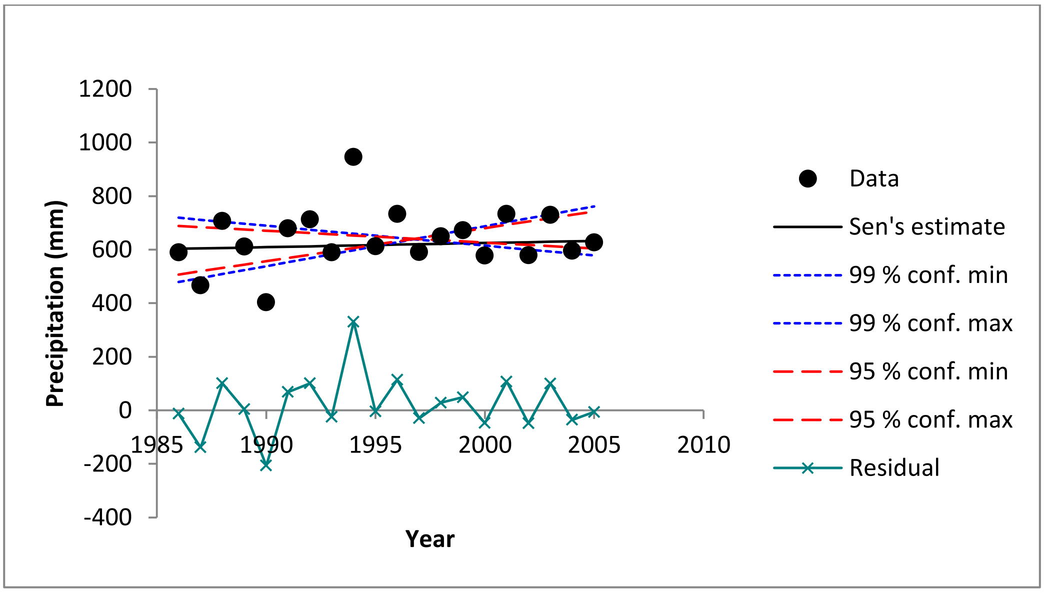


Figure 5.13│**Mann-Kendall trend statistics and Sen's Slope estimate for annual total precipitation in Ouahigouya, 1986-2005**

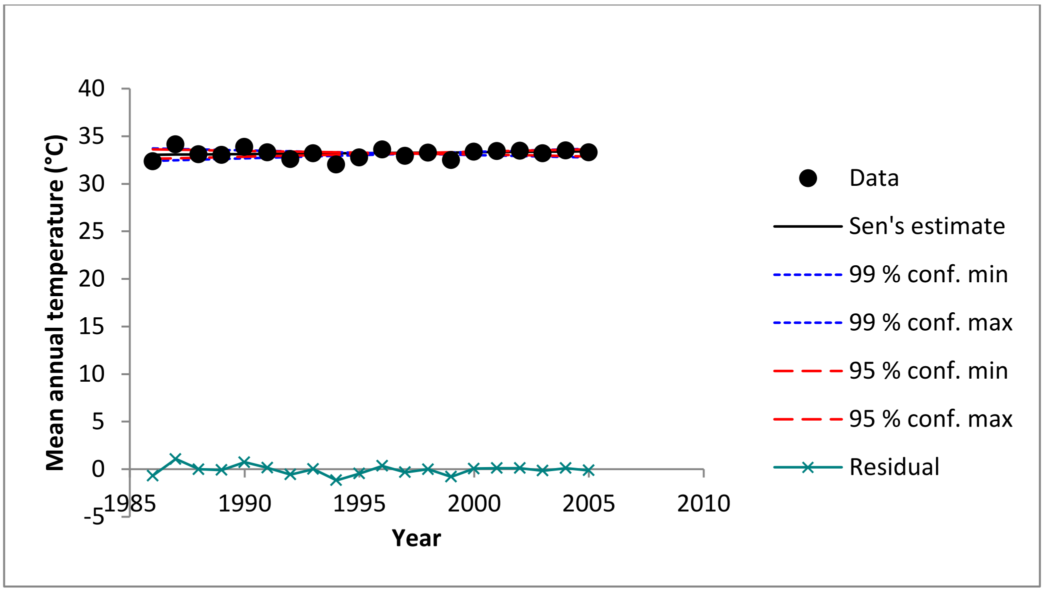


Figure 5.14 | **Mann-Kendall trend statistics and Sen's Slope estimate for temperature in Ouahigouya, 1986-2005**

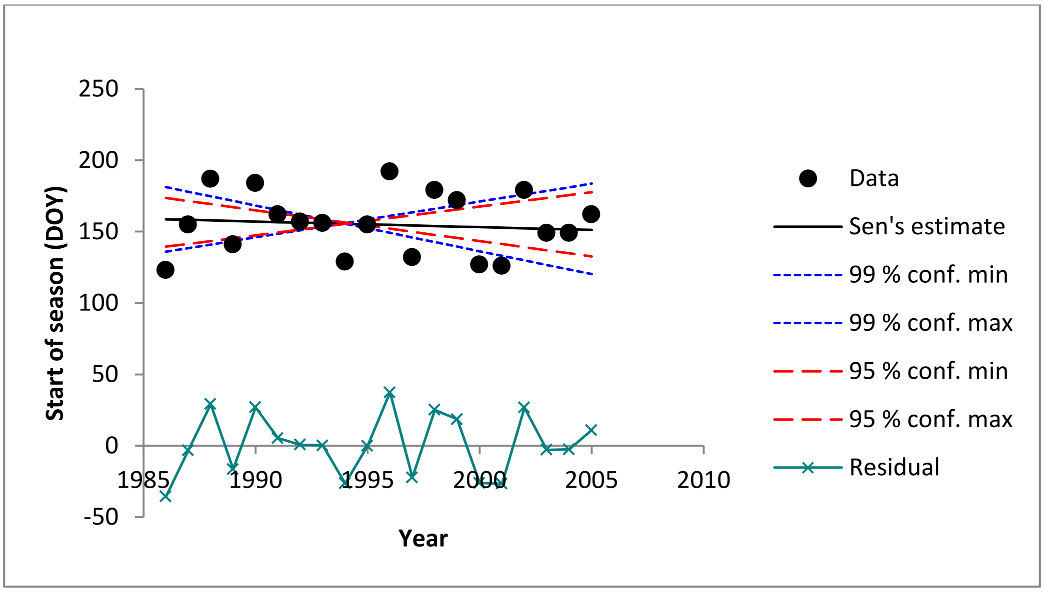


Figure 5.15 | **Mann-Kendall trend statistics and Sen's Slope estimate for meteorological start date of the growing season in Ouahigouya, 1986-2005**

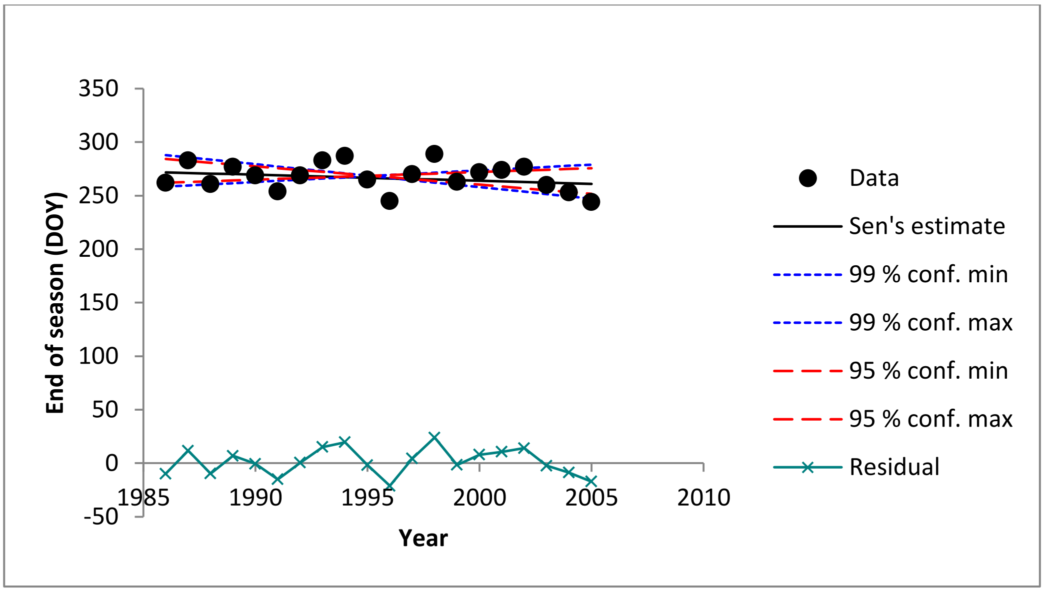


Figure 5.16 | Mann-Kendall trend statistics and Sen's Slope estimate for meteorological end date of the growing season in Ouahigouya, 1986-2005

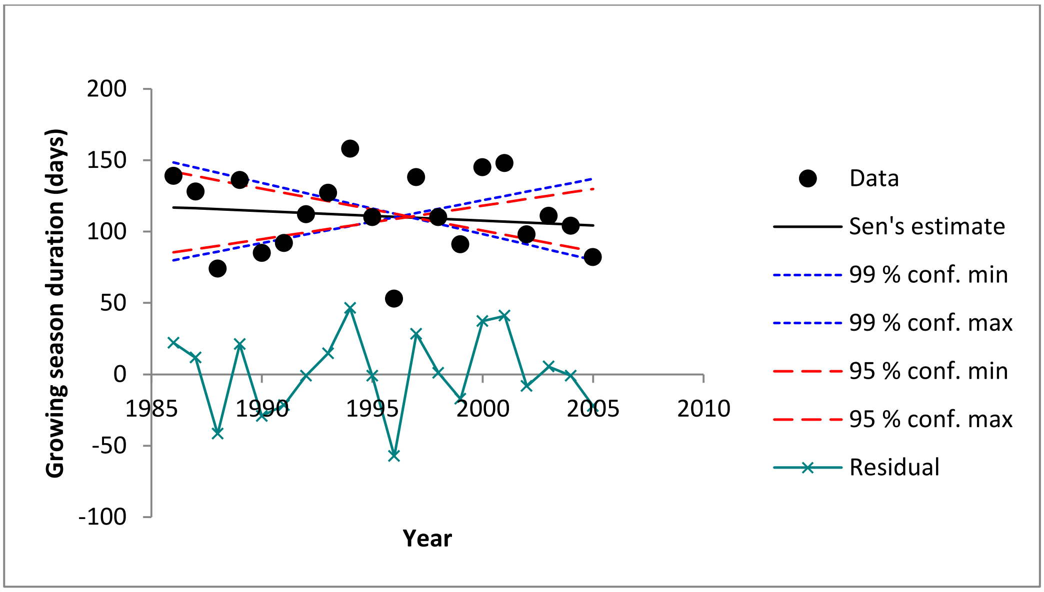


Figure 5.17 | Mann-Kendall trend statistics and Sen's Slope estimate for meteorological duration of the growing season in Ouahigouya, 1986-2005

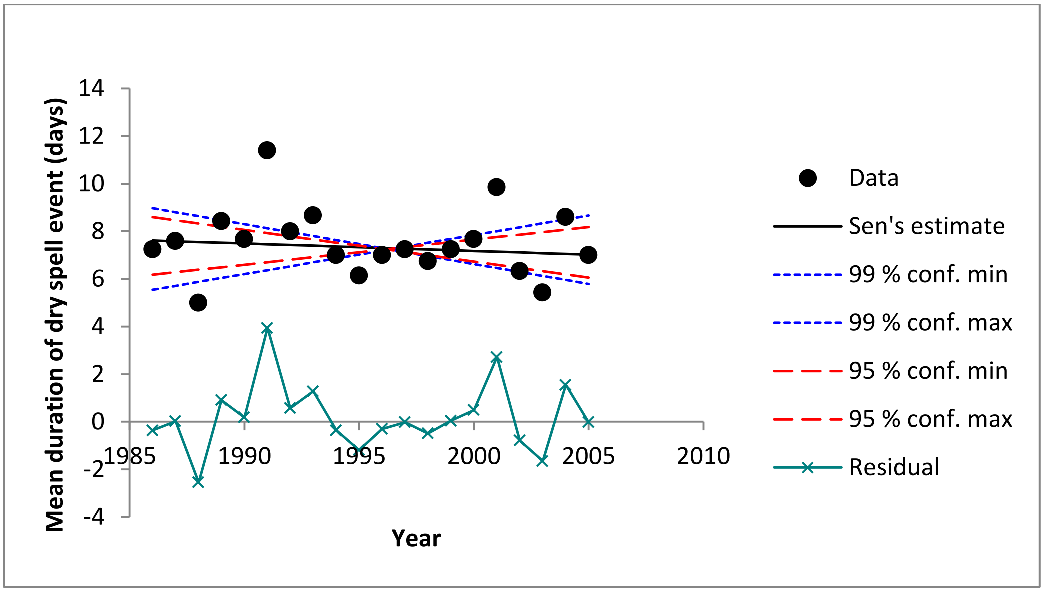


Figure 5.18│Mann-Kendall trend statistics and Sen's Slope estimate for mean duration of dry spell events (5 or more consecutive days with less than 1mm rainfall) in Ouahigouya, 1986-2005

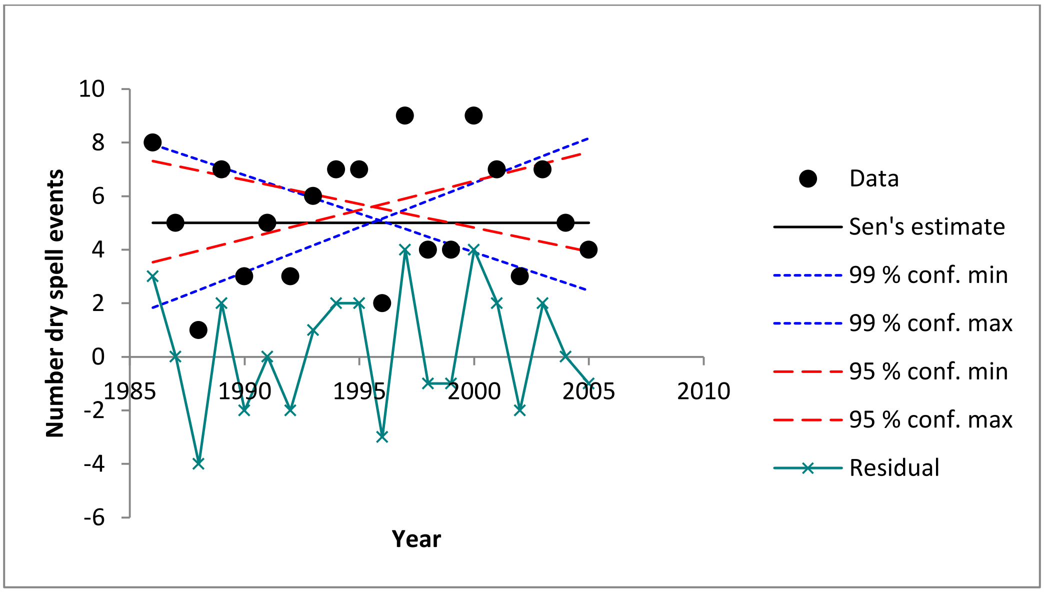


Figure 5.19│Mann-Kendall trend statistics and Sen's Slope estimate for number of dry spells lasting 5 days or more during each growing season in Ouahigouya, 1986-2005

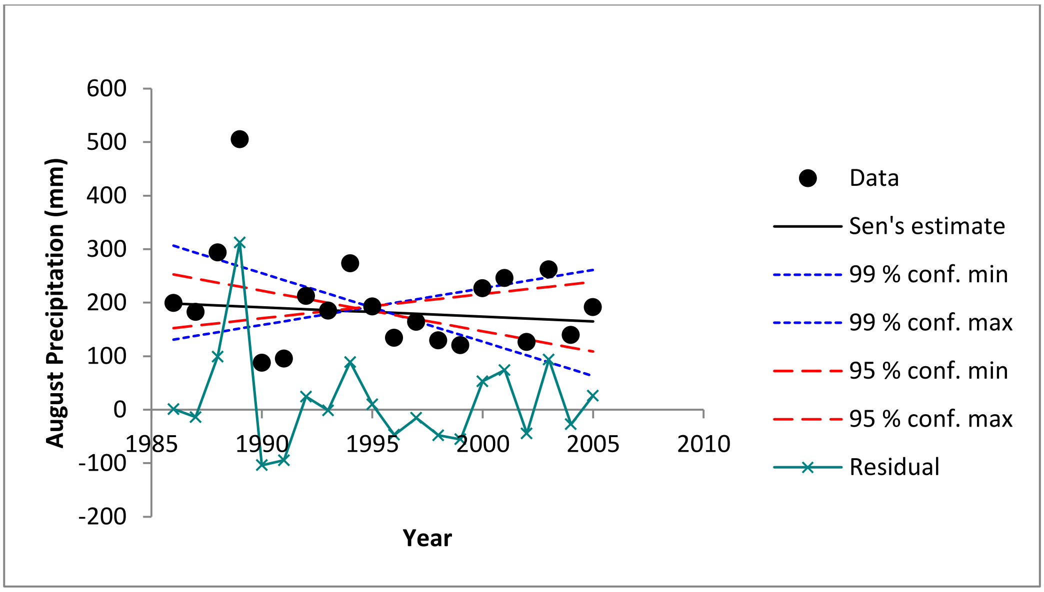


Figure 5.20│Mann-Kendall trend statistics and Sen's Slope estimate for total precipitation in the month of August in Ouahigouya, 1986-2005

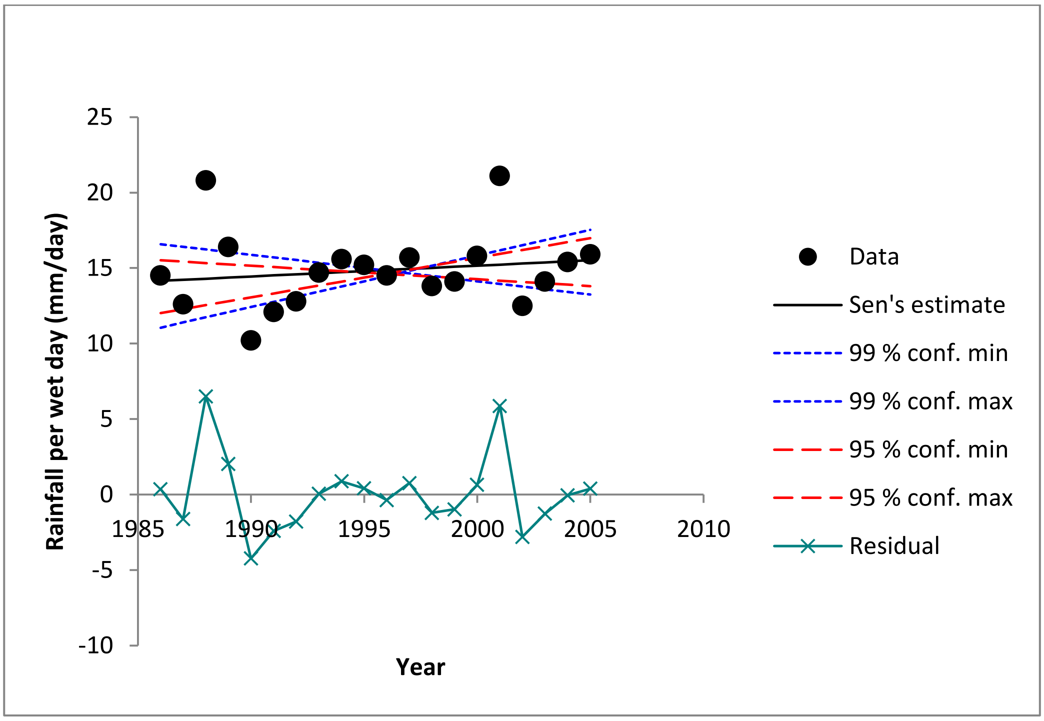


Figure 5.21│Mann-Kendall trend statistics and Sen's Slope estimate for rainfall intensity per wet day during the growing season in Ouahigouya, 1986-2005

Figure 5.12 presents the results from a Mann-Kendall/Sen's Slope analysis, showing a significant increasing annual precipitation trend (α= 0.05 level of significance) between 1975 and 2006. On the other hand, Figure 5.13 does not present any significant trend, rather showing that precipitation has been stable in the two decades between 1986 and 2005. It also shows lower inter-annual variability than in the previous decade, following the severe droughts of the 1970s and 1980s. The same is true for temperature, which has also been stable from 1986-2005 (Figure 5.14). Furthermore, the duration of the growing season (for which meteorological definitions of start and end dates are given by Ibrahim et al. (2012)) does not show any changing trends over the 1986-2005 period (Figure 5.17). However, high inter-annual variability in the growing season duration is observed (i.e. almost 28 days standard deviation from a 112 days mean). Interestingly, there is much higher variability in the start dates of the growing season, as opposed to its end dates (i.e. standard deviation of ~22 days versus ~13 days, Figures 5.15 and 5.16). Female farmers also reported changes in dry spell patterns, but further investigation shows that for 1986-2005, dry spell events (i.e. event with ≥5 consecutive dry days with less than 1mm/day precipitation) were not more frequent nor were they longer on average (Figures 5.18 and 5.19). There is also no significant decreasing trend in rainfall during the month of August (i.e. critical stage of the growing season), and rainfall intensity has not changed significantly in a set direction during the same time period (Figures 5.20 and 5.21).

Adaptation to climate and environmental change

In response to the observed ongoing soil erosion and reduction in soil fertility, exemplified by the significant sedimentation along stone bunds, household survey respondents in Burkina Faso anticipate producing more manure in the future, building more RWH structures, and planting more trees. When asked specifically about adaptation to climate change, farmers cited most often tree planting and RWH as adequate adaptation strategies. Overall, the thirty household surveys conducted in Burkina Faso revealed that farmers perceived significant yield improvements averaging around +50% with the use of RWH.

Factors affecting the adoption of identified climate change adaptation measures

While farmers identified RWH and tree planting as viable adaptation strategies to climate change, a number of factors are affecting their adoption across the study area. These factors seem to be affecting different social group at varying degrees.

First, land tenure was identified as a challenge to tree planting and the implementation of *ex situ* rainwater harvesting structures such as runoff collection ponds. With widespread deforestation due to the use of wood for heating, cooking, medicinal purposes, as well as a primary material for building houses, wood prices are perceived to have been skyrocketing and households struggle to access that resource. In response to this, where possible, farmers plant trees on their fields. Despite their efforts, tree planting remains a marginal activity due to the legal challenges of land ownership. Culturally, tree planting can be perceived as an attempt to take ownership of the land, and is not always welcome. Of two innovative farmers interviewed, the first one did not hold a land tenure certificate, but had inherited the land he developed and considered it his own through tradition. Therefore, he stated to be keen to reforest the area and exploit the forest resources for medicinal purposes. The second innovative farmer, while also conducting some reforestation work, would be unable to make use of the forest/savannah resources for his own profit, as he had only been allocated the land for agricultural purposes and the land remained government owned. In fact, as the city of Ouahigouya slowly encroaches onto neighbouring agricultural land, people have started building houses on the land he has been regenerating with trees (Figure 5.22). Hence, land tenure is likely to be an important barrier preventing some farmers from engaging in both tree planting and some forms of RWH requiring greater structural investments, in order to adapt to climate change.

Figure 5.22 │ Fields of an innovative farmer in Yatenga Province, Burkina Faso. Circled in red are houses being built on the land as the city of Ouahigouya encroaches on the agricultural land. Circled in blue is a traditional stone line, a RWH strategy. A shortage of stones has forced this farmer to seek alternative materials to build stones lines, including using discarded concrete blocks from the construction site of the local hospital.

In second place, some traditional *in situ* techniques are becoming more difficult to maintain and new structures difficult to implement. This is the case for rock bunds and rocks lines, the most widely adopted RWH in the region, where farmers are facing shortages of the lateritic rocks that have been used to build them for the past 30 years (Figure 5.22).

The most important common denominator for the adoption of RWH was the state of degradation of the land. Farmers perceived a much higher marginal benefit from the technologies on heavily degraded land, upslope or mid-slope, where water retention and fertility were normally too low to produce viable crop yields. Indeed, focus group activities showed that farmers were very selective concerning which plots they were focusing their labour and technological investments on. Perhaps counterintuitively, investments in improved soil and water management strategies were preferred on the most degraded land parcels than on more fertile plots of land.

The importance of institutional support for the planning, implementation, and maintenance of RWH systems should not be underestimated. It was observed and reported by key informants that unless farmers were given formal training, it was relatively difficult for them to reproduce the technologies within their fields. This includes for example the construction of stone lines or rows of zaï pits along contour lines, which unless done adequately does not allow for the effective collection of surface runoff. On land with a gentler slope, these technical aspects would not necessarily be obvious for a first-time observer. Female farmers also reported having been trained in the use of on-farm runoff capture ponds over the course of three years, and construction progress was monitored by local authorities who provided lining material for the ponds at adequate stages.

As mentioned earlier, not all factors identified here apply equally to all social groups. This is the case of female farmers, who reported during focus group activities that the number one factor that was limiting their uptake of the simple technologies was access to manure. In fact, on the heavily crusted soil with poor structure and low levels of organic matter, the retention of water in the form of soil moisture is very limited. Therefore, the group of female farmers, who have access to less livestock, reported to be less likely to use *in situ* RWH than their male counterparts, as they could not see benefits from the technologies in the absence of manure to increase soil water storage capacity and fertility. Hence, although a large majority of smallholder farmers in Ziga and Somyaga are aware that RWH can provide significant benefits to their crop production systems, there are still several factors limiting their adoption across different social groups.

5.4.2 Case study site 2: Ethiopia

Climate and environmental change perceptions

A majority of respondents in Ethiopia perceived some inter-annual variability in crop yields, and identified rainfall patterns as the leading cause of this variability. However, Table 5.3 shows that those respondents who did not perceive their crop yields to be variable from one year to the next were significantly more likely to report that the leading cause of inter-annual variability in yields is linked to management interventions, such as the use of fertilizers or improved soil and water management strategies (e.g. rainwater harvesting). Similarly, RWH adopters were slightly more likely (although not statistically significant) to point to management interventions as the cause behind the stability of their crop yields than non-adopters (see Table 5.4). This could indicate that farmers who use sustainable land management practices could be more aware of the potential for these interventions to stabilize crop yields under varying climatic conditions.

With regards to drought perceptions, when asked specifically about the availability of irrigation water, all farmers who did answer the question regarding the timing of shortages in irrigation water identified that they had suffered water shortages in the years between 2001 to 2003. On the other hand, when asked about drinking water shortages in the past 5 years, respondents reported shortages occurring between 2009 and 2011. Of these cases, 40% were reported to be caused by broken wells or pumps, and 60% by perceived droughts or low water tables. Hence, further investigation would be required to establish why the reported droughts in recent years were reported to have an impact on drinking water supplies, but not on irrigation water supplies. One reason could be that the question on drinking water specifically called for the previous 5 years, while the years 2001-2003 could have been years of droughts with much higher intensity which farmers recalled better because of adverse impacts on agricultural production.

Table 5.3 │ Comparison of means between perceived crop stability and factors affecting that stability - Ethiopia

Group Statistics

	Are crop yields stable from one year to the next?	N	Mean	Std. Deviation	Std. Error Mean
Factor affecting crop yield stability (Natural=1, Human management intervention=2)	Yes	195	***1.0872***	.28282	.02025
	No	90	***1.4556***	0.50081	.05279

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Factor affecting crop yield stability (Natural=1, Human management intervention=2)	Equal variances assumed	183.907	*.000**	-7.905	283	.000	-.36838	.04660	-.46010	-.27665
	Equal variances not assumed			-6.515	115.976	***.000***	-.36838	.05654	-.48036	-.25639

*Equal variance cannot be assumed

Table 5.4 | Comparison of means between adopters and non-adopters of RWH for factors affecting crop stability, perceived crop stability, and stability in planting dates - Ethiopia

Group Statistics					
	RWH adopter (Yes/No)	N	Mean	Std. Deviation	Std. Error Mean
Factor affecting crop yield stability (Natural=1, Human management intervention=2)	Yes	248	1.2863	1.38042	.08766
	No	37	1.1892	.39706	.06528
Are the crop yields stable from one year to the next? (Yes=1, No=2)	Yes	250	1.29	.454	.029
	No	45	1.58	.499	.074
Do the planting dates vary from one year to the next? (Yes=1, No=2)	Yes	250	1.14	.343	.022
	No	44	1.27	.451	.068

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Factor affecting crop yield stability (Natural=1, Human management =2)	Equal variances assumed	.474	.492	.425	283	.671	.09710	.22865	-.35296	.54717
	Equal variances not assumed			.888	191.933	.375	.09710	.10929	-.11847	.31267
Are the crop yields stable from one year to the next?	Equal variances assumed	7.131	.008	-3.883	293	.000	-.290	.075	-.437	-.143
	Equal variances not assumed			-3.631	57.816	***.001***	-.290	.080	-.450	-.130
Do the planting dates vary from one year to the next?	Equal variances assumed	16.441	.000	-2.315	292	.021	-.137	.059	-.253	-.020
	Equal variances not assumed			-1.917	52.154	***.061***	-.137	.071	-.280	.006

Adaptation to climate and environmental change

In Ethiopia, adaptation to climate change was not investigated directly in survey questions. However, farmers who adopted RWH were asked to cite any change in crops produced following the adoption of the strategies. This can provide an indication of the potential of RWH to allow for a range of agronomic adaptation strategies to be implemented in parallel with the techniques. Of the 251 RWH adopters in the Ethiopia study site, 30 reported changing the type of crops or trees produced on their plots where they introduced RWH (Table 5.5). In a majority of cases (21 out of 30), farmers reported not growing any crops prior to the implementation of RWH. This might be an indicator of the potential for RWH to reclaim land otherwise unsuitable for agriculture, such as in the case of terraces. The most commonly reported crop grown following RWH implementation was wheat, with 14 of the 30 farmers reporting switching to that cereal crop. Five farmers reported growing guava trees after RWH implementation, but no cereal crops. However, due to the nature of the survey question, it remains difficult to say if non-adopters have also been switching crops on their land in recent years.

Table 5.5 | Actual reported change in crop/tree production after RWH implementation - Ethiopia

Crop/tree before RWH implementation	Crop/tree after RWH implementation	Frequency
None	Karkaeta	1
	Sesame	1
	Sorghum	1
	Teff	2
	Vegetable/Tuber	1
	Wheat	10
	Guava (tree)	6 (1 same as barley to wheat)
	Pepper (tree)	1 (same farmer as none to sorghum)
Barley	Maize	1
	Wheat	4
Teff	Maize	1
Wheat	Maize	1
	Vegetable/Tuber	2
TOTAL **4 origin crops**	9 destination crops/trees	30 farmers (N=251 adopters)

Factors affecting RWH adoption and sustainability

Household size was found to be the main factors linked to the adoption of RWH in Ethiopia. Table 5.6 shows a strong correlation between livestock ownership and household size. Tables 5.7 and 5.8 also show that larger households are more likely to own livestock, and are also more likely to implement RWH. Furthermore, there is an almost significant difference in agricultural income between adopters and non-adopters ($\alpha=0.06$) in Ethiopia. Income seems higher on average for adopters than non-adopters.

Table 5.6 │ Correlation between selected explanatory variables of RWH adoption - Ethiopia

Correlations

		Literacy	Household size	Age of household head	Gender of household head	Source of drinking water	Plot size	Slope	Soil quality	Income per person	Livestock ownership	Source of funding for RWH
Literacy (Yes/No)	Pearson Correlation	1	***.205*****	***-.138****	***.141****	-.049	-.060	-.048	***-.131****	.013	***-.135****	-.128
	Sig. (2-tailed)		.000	.017	.014	.406	.310	.417	.027	.821	.020	.064
	N	301	301	300	301	288	289	287	287	298	301	211
Household size (< 6 members, or ≥ 6 members)	Pearson Correlation	***.205*****	1	.031	***.210*****	.004	.072	.057	-.055	***-.128****	***-.326*****	-.052
	Sig. (2-tailed)	.000		.598	.000	.942	.223	.340	.355	.027	.000	.453
	N	301	301	300	301	288	289	287	287	298	301	211
Age of household head	Pearson Correlation	***-.138****	.031	1	.034	.096	***.130****	-.029	-.029	-.018	-.021	.010
	Sig. (2-tailed)	.017	.598		.558	.106	.028	.629	.625	.760	.714	.886
	N	300	300	300	300	287	288	286	286	297	300	210
Gender of household head	Pearson Correlation	***.141****	***.210*****	.034	1	.030	.069	.012	.084	-.057	***-.221*****	.102
	Sig. (2-tailed)	.014	.000	.558		.608	.243	.833	.155	.326	.000	.139
	N	301	301	300	301	288	289	287	287	298	301	211
Source of drinking water (public or private)	Pearson Correlation	-.049	.004	.096	.030	1	.065	.022	-.091	.026	.018	***.242*****
	Sig. (2-tailed)	.406	.942	.106	.608		.281	.721	.133	.656	.758	.001
	N	288	288	287	288	288	276	274	274	285	288	198
Plot size (≤ 1ha, or > 1ha)	Pearson Correlation	-.060	.072	***.130****	.069	.065	1	.033	.032	***.132****	-.099	.009
	Sig. (2-tailed)	.310	.223	.028	.243	.281		.577	.593	.025	.092	.902
	N	289	289	288	289	276	289	287	287	288	289	210

Slope (significant or not)	Pearson Correlation	-.048	.057	-.029	.012	.022	.033	1	***-.183*****	.035	-.083	-.001
	Sig. (2-tailed)	.417	.340	.629	.833	.721	.577		.002	.559	.160	.986
	N	287	287	286	287	274	287	287	287	286	287	209
Soil quality (fertile or less fertile)	Pearson Correlation	***-.131****	-.055	-.029	.084	-.091	.032	***-.183*****	1	-.016	.036	.043
	Sig. (2-tailed)	.027	.355	.625	.155	.133	.593	.002		.783	.545	.538
	N	287	287	286	287	274	287	287	287	286	287	209
Income per person (below or above average)	Pearson Correlation	.013	***-.128****	-.018	-.057	.026	***.132****	.035	-.016	1	***.130****	-.071
	Sig. (2-tailed)	.821	.027	.760	.326	.656	.025	.559	.783		.025	.309
	N	298	298	297	298	285	288	286	286	298	298	210
Livestock ownership (Yes/No)	Pearson Correlation	***-.135****	***-.326*****	-.021	***-.221*****	.018	-.099	-.083	.036	***.130****	1	.044
	Sig. (2-tailed)	.020	.000	.714	.000	.758	.092	.160	.545	.025		.524
	N	301	301	300	301	288	289	287	287	298	301	211
Source of funding for RWH (Self or government)	Pearson Correlation	-.128	-.052	.010	.102	***.242*****	.009	-.001	.043	-.071	.044	1
	Sig. (2-tailed)	.064	.453	.886	.139	.001	.902	.986	.538	.309	.524	
	N	211	211	210	211	198	210	209	209	210	211	211
**. Correlation is significant at the 0.01 level (2-tailed).												
*. Correlation is significant at the 0.05 level (2-tailed).												

Table 5.7│Binary logistic regression models from selected explanatory variables - Ethiopia

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Plot size	-.106	.369	.083	1	.773	.899
	Soil quality	.324	.365	.788	1	.375	1.383
	Drinking water source	.290	.404	.515	1	.473	1.337
	Literacy	-.340	.373	.829	1	.363	.712
	Household size	-1.004	.401	6.275	1	.012	.366
	Constant	-1.076	1.560	.476	1	.490	.341
Step 2[a]	Soil quality	.321	.365	.773	1	.379	1.379
	Drinking water source	.289	.404	.510	1	.475	1.335
	Literacy	-.334	.372	.802	1	.370	.716
	Household size	-1.015	.399	6.472	1	.011	.362
	Constant	-1.214	1.486	.667	1	.414	.297
Step 3[a]	Soil quality	.299	.364	.674	1	.412	1.348
	Literacy	-.343	.372	.851	1	.356	.710
	Household size	-1.007	.399	6.376	1	.012	.365
	Constant	-.395	.939	.177	1	.674	.673
Step 4[a]	Literacy	-.381	.369	1.068	1	.301	.683
	Household size	-1.014	.398	6.482	1	.011	.363
	Constant	.117	.698	.028	1	.867	1.124
Step 5[a]	Household size	-1.086	.392	7.663	1	.006	.338
	Constant	-.345	.540	.409	1	.522	.708

a. Variable(s) entered on step 1: Plot size, Soil quality, Drinking water source, Literacy, Household size.

Table 5.8│Comparison of means for livestock ownership and household size amongst RWH adopters

Group Statistics

	RWH adopter (Yes/No)	N	Mean	Std. Deviation	Std. Error Mean
Livestock ownership (Yes/No)	Yes	251	1.2908	.45506	.02872
	No	48	1.7292	.44909	.06482
Household size (< 6 members, or ≥ 6 members)	Yes	251	1.5219	.50052	.03159
	No	48	1.2500	.43759	.06316

5.4.3 Case study site 3: Tunisia

Climate and environmental change perceptions

Of the 139 respondents in Tunisia, 136 reported having heard of soil degradation, and 129 reported experiencing soil degradation on their own land. The most cited causes for such general degradation (i.e. degradation not on their land specifically) were water erosion (cited 122 times first), gullying (cited 5 times first and 49 times second), and lack of personal effort/work (cited 52 times in top 3). The latter tends to suggest that farmers are aware that improved soil and water management could reduce soil erosion caused by water, and perceive that not everyone is putting in the personal effort to invest in such strategies. Otherwise, 43 respondents directly linked the causes of land degradation (e.g. water erosion) to climate change, and a further 55 to climatic events in general (e.g. flooding, intense wind).

Adaptation to climate and environmental change

As opposed to the case of Ethiopia, Tunisian respondents were asked about the perceived benefits of RWH with regards to land reclamation and changing crops grown (Tables 5.9 and 5.10). Approximately 65% of farmers answered that they would be able to change crops grown if they used RWH. In addition, Tunisian respondents were asked whether or not they thought RWH could help reclaim land otherwise unsuitable for agricultural production. About 80% of farmers believed that they would indeed be able to crop land that would otherwise be unsuitable for agriculture, thanks to RWH. In contrast to Ethiopia, in Tunisia crop yields were not reported to be significantly more stable with the use of the RWH techniques. However, at all three case study sites, there were reports of significant increases in yields with the use of RWH.

Table 5.9 | Perceived benefit from RWH with regards to degraded land reclamation

Would you expect RWH to allow you to crop land otherwise unused?					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	85	57.0	80.2	80.2
	No	21	14.1	19.8	100.0
	Total	106	71.1	100.0	
Missing	System	43	28.9		
Total		149	100.0		

Table 5.10 │ Perceived benefit from RWH with regards to varying crops grown

Would you expect RWH to allow you to switch crops?					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	58	38.9	65.9	65.9
	No	30	20.1	34.1	100.0
	Total	88	59.1	100.0	
Missing	System	61	40.9		
Total		149	100.0		

Otherwise, a large majority of respondents in Tunisia identified negative impacts of a changing climate on agricultural production. In response to these negative impacts, respondents were asked to identify adaptation strategies they were most likely to implement, by ranking the top four from a list of eleven pre-defined adaptation strategies. The results are presented in Table 5.11.

Table 5.11 │ Ranking of climate change adaptation strategies selected by respondents in Tunisia

Adaptation strategy	Number of times ranked first	Total of times ranked in top four
Diversification of activities	3	124
Family solidarity	5	25
Flexibility (e.g. cropping choices, agricultural management)	8	32
Complementarity and substitution (e.g. livestock production/arboriculture, annual crops)	33	79
Change and prioritization of objectives	23	70
Mobility of livestock herds	5	27
Spatial distribution of plots of land	6	38
Farm size and livestock holdings (number and type)	41	106
Migration	6	34
Savings and deferred management of revenues	10	116
Social benefits	13	48

Factors affecting RWH adoption and sustainability

Table 5.12 presents the correlation between selected explanatory variables of RWH adoption in Tunisia. Results for Tunisia show little significance, or causation, from the explanatory variables selected and the adoption of RWH. Indeed, a first investigation of this combination of variables revealed that no model combining these factors performed well enough to really predict adoption (Table 5.13). However, model 5 performed best and only source of drinking water and literacy were considered in a further binary logistic regression. These results show that the specific combination of these two variables can predict adoption to some extent (Tables 5.14 and 5.15). The source of drinking water (private or public), can be linked to water availability altogether. While in the case of Tunisia it is difficult to assign causality, overall having a private source of drinking water and being literate (even minimally; this includes religious schooling or basic literacy courses) is associated with higher adoption rates of RWH technologies. There also was no significant difference in agricultural income between RWH adopters and non-adopters in Tunisia.

Table 5.12 | Correlation between selected explanatory variables of RWH adoption - Tunisia

Correlations

		Literacy	Household size	Age of household head	Gender of household head	Source of drinking water	Plot size	Soil quality	Slope	Livestock ownership	Income per person
Literacy (Yes/No)	Pearson Correlation	1	**_.270_***	**_-.474_****	.^{c}	.079	.000	-.135	-.030	.086	**_-.253_***
	Sig. (2-tailed)		.033	.000	.000	.538	1.000	.292	.817	.504	.046
	N	63	63	61	63	63	63	63	62	63	63
Household size (< 6 members, or ≥ 6 members)	Pearson Correlation	**_.270_***	1	-.109	-.139	-.006	-.052	-.148	-.021	-.005	**_-.364_****
	Sig. (2-tailed)	.033		.382	.103	.946	.544	.083	.804	.951	.000
	N	63	139	66	139	139	139	139	138	139	139
Age of household head	Pearson Correlation	**_-.474_****	-.109	1	.^{c}	**_-.248_***	-.026	-.054	.143	-.117	.070
	Sig. (2-tailed)	.000	.382		.000	.045	.834	.669	.255	.348	.574
	N	61	66	66	66	66	66	66	65	66	66
Gender of household head	Pearson Correlation	.^{c}	-.139	.^{c}	1	.144	.071	**_.173_***	-.033	.030	.069
	Sig. (2-tailed)	.000	.103	.000		.091	.406	.041	.701	.729	.420
	N	63	139	66	139	139	139	139	138	139	139
Source of drinking water (public or private)	Pearson Correlation	.079	-.006	**_-.248_***	.144	1	.092	.125	.059	.047	.075
	Sig. (2-tailed)	.538	.946	.045	.091		.280	.143	.493	.584	.378
	N	63	139	66	139	139	139	139	138	139	139
Plot size (≤ 1ha, or > 1ha)	Pearson Correlation	.000	-.052	-.026	.071	.092	1	.151	-.084	-.101	.163
	Sig. (2-tailed)	1.000	.544	.834	.406	.280		.077	.329	.235	.055
	N	63	139	66	139	139	139	139	138	139	139

Soil quality (fertile or less fertile)	Pearson Correlation	-.135	-.148	-.054	***.173****	.125	.151	1	***.169****	.112	.137
	Sig. (2-tailed)	.292	.083	.669	.041	.143	.077		.047	.189	.108
	N	63	139	66	139	139	139	139	138	139	139
Slope (significant or not)	Pearson Correlation	-.030	-.021	.143	-.033	.059	-.084	.169*	1	.060	-.064
	Sig. (2-tailed)	.817	.804	.255	.701	.493	.329	.047		.482	.455
	N	62	138	65	138	138	138	138	138	138	138
Livestock ownership (Yes/No)	Pearson Correlation	.086	-.005	-.117	.030	.047	-.101	.112	.060	1	-.139
	Sig. (2-tailed)	.504	.951	.348	.729	.584	.235	.189	.482		.102
	N	63	139	66	139	139	139	139	138	139	139
Income per person (below or above average)	Pearson Correlation	***-.253****	***-.364*****	.070	.069	.075	.163	.137	-.064	-.139	1
	Sig. (2-tailed)	.046	.000	.574	.420	.378	.055	.108	.455	.102	
	N	63	139	66	139	139	139	139	138	139	139
*. Correlation is significant at the 0.05 level (2-tailed).											
**. Correlation is significant at the 0.01 level (2-tailed).											
c. Cannot be computed because at least one of the variables is constant.											

Table 5.13 │ Binary logistic regression models from selected explanatory variables - Tunisia

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1	Literacy	-.979	.847	1.333	1	.248	.376
	Household size	-.789	.911	.750	1	.386	.454
	Source of drinking water	-1.984	.948	4.380	1	.036	.137
	Plot size	.765	.887	.745	1	.388	2.150
	Soil quality	20.311	9910.084	.000	1	.998	661838398.730
	Slope	-.464	.875	.281	1	.596	.629
	Livestock ownership	.093	.994	.009	1	.925	1.098
	Constant	-34.455	19820.168	.000	1	.999	.000
Step 2	Literacy	-.970	.842	1.329	1	.249	.379
	Household size	-.799	.905	.778	1	.378	.450
	Source of drinking water	-1.985	.948	4.382	1	.036	.137
	Plot size	.767	.887	.748	1	.387	2.153
	Soil quality	20.324	9906.079	.000	1	.998	670551955.609
	Slope	-.456	.870	.274	1	.601	.634
	Constant	-34.383	19812.158	.000	1	.999	.000
Step 3	Literacy	-.939	.829	1.285	1	.257	.391
	Household size	-.776	.897	.750	1	.387	.460
	Source of drinking water	-1.856	.900	4.252	1	.039	.156
	Plot size	.769	.881	.763	1	.383	2.157
	Soil quality	20.039	10069.558	.000	1	.998	504307130.526
	Constant	-34.990	20139.116	.000	1	.999	.000
Step 4	Literacy	-.847	.807	1.102	1	.294	.429
	Household size	-.709	.892	.631	1	.427	.492
	Source of drinking water	-1.732	.881	3.860	1	.049	.177
	Soil quality	19.757	10400.566	.000	1	.998	380407600.993
	Constant	-33.996	20801.133	.000	1	.999	.000
Step 5	Literacy	-.985	.787	1.565	1	.211	.373
	Source of drinking water	-1.536	.826	3.457	1	.063	.215
	Soil quality	19.788	10570.056	.000	1	.999	392603330.628
	Constant	-35.354	21140.112	.000	1	.999	.000
Step 6	Source of drinking water	-1.511	.804	3.536	1	.060	.221
	Soil quality	19.948	10744.496	.000	1	.999	460644299.572
	Constant	-37.279	21488.991	.000	1	.999	.000

Table 5.14│Binary logistic regression models from reduced number of explanatory variables classification table - Tunisia

Classification Table[a]					
			Predicted		
			use RWH yes or no		Percentage Correct
	Observed		Yes	No	
Step 1	Use of RWH (yes or no)	Yes	51	2	96.2
		No	6	4	40.0
	Overall Percentage				87.3

a. The cut value is .500

Table 5.15│Binary logistic regression models from reduced number of explanatory variables - Tunisia

Variables in the Equation							
		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Literacy	-1.312	.742	3.130	1	.077	.269
	Source of drinking water	-1.435	.752	3.646	1	.056	.238
	Constant	4.212	2.313	3.318	1	.069	67.514

a. Variable(s) entered on step 1: Literacy, Source of drinking water.

It is expected that a range of other factors, which were either not captured in the questions from the survey, or for which the abstention rate was too high to be included in the analysis, could have greater impacts on RWH adoption. For Ethiopia and Tunisia, RWH strategies used are generally large-scale structures, requiring larger technical and financial investments. In addition, due to climatic conditions, catchment areas are much larger and may require community coordination and external investments. In fact, while a large majority of household survey respondents in Tunisia mentioned the need for soil and water management strategies (including RWH) to fight land degradation, only 16 reported being involved in the planning/localization of RWH harvesting structures such as jessour or tabias. The respondents who did not want to get involved in such projects cited primarily financial constraints for their lack of involvement.

5.5 Discussion

5.5.1 Can farmers perceive changes in long-term climate?

A wide range of studies have investigated farmers' perceptions of climate change, with conclusions varying widely (c.f. Chapter 2). As opposed to Thomas et al. (2007) and Bryan et al. (2009), no significant correlations between farmers' perceptions of trends in climate and actual observations were found. Rather, the Burkina Faso case study has shown that farmers were not able to recognize any long-term trends in recent climate. Furthermore, the hypothesis that farmers might be able to perceive intra-seasonal rainfall characteristics better than long-term means also proved unjustified. The results presented here are very similar to findings by Simelton et al. (2013), who also found that in Southern Africa farmers perceived shorter growing seasons while meteorological data did not provide supporting evidence for this. They also found, as for the Burkina Faso field site, high inter-annual variability in the timing of the start of the growing season. Several reasons could explain this lack of correlation between perceptions and reality. For example, Osbahr et al. (2011) pointed out that farmers would qualify a "normal" year as one where they would obtain ideal conditions to pursue their livelihoods, as opposed to the use of an actual average climatological definition. Here, several hypotheses are suggested, that apply more specifically to the Burkina Faso case study:

1. First, it is possible that despite the relative proximity of the Ouahigouya weather station, conditions in Ziga and Somyaga were in fact significantly different from those observations.
2. Secondly, years with intense rainfall in the month of August, followed by years with very low rainfall, could have promoted the perception of a longer-term drying in that critical month.
3. In third place, it is possible that more severe trends in climate have occurred between 2005 and the data collection period in 2012, and participants might weigh recent perceived deviations more strongly.
4. Fourth, while this does not correspond to the perceived increase in temperature, it is possible that soil temperatures have indeed been increasing, due to a decrease in canopy cover associated with deforestation which was not considered in observations.
5. Following on the previous hypothesis, a fifth hypothesis is thought to be the most likely and will be investigated in Chapter 6. It was hypothesised that where farmers were found to be unable to accurately recall long-term trends in rainfall and temperature, they might in fact be perceiving other changes in their environment that are affected by those two variables.

The fifth hypothesis is supported by a range of findings from literature and field observations. As mentioned in Chapter 2, severe land degradation in Burkina Faso was found to affect hydrological processes in counterintuitive manners, with increasing surface runoff and river discharge despite years of severe droughts (Mahe et al., 2003, Mahe et al., 2005). This could be related to a perception of decreased rainfall, and simultaneous increased flooding reported by some farmers. Problems of soil erosion were identified by farmers and key informants as the most important factor affecting agricultural productivity in the region. Hence, as land degradation was found to be a major environmental factor affecting production, it seemed logical to further investigate how this might affect climate change perceptions. The ability of farmers to accurately recognize trends in soil moisture, as opposed to rainfall patterns, will be investigated through hydrological modelling (c.f. Chapter 6). This factor is more closely related to farmers' livelihoods, and changes readily felt through impacts on income and food security.

5.5.2 Where does RWH adoption occur?

Through the presentation of three case studies, it has been shown that the adoption of rainwater harvesting occurs in a range of locations, different agro-ecosystems, and is represented by a range of different technologies. The field sites studied here all reported very high adoption rates (i.e. close to 85%), while other studies found adoption rates closer to 33% across Burkina Faso for example (Ouédraogo et al., 2010). In addition to very high adoption rates, these field sites were found to have a range of other important points in common. That is, access to good quality cropping land was severely restricted at all field sites. In Burkina Faso, this was due to severe land degradation and the presence of heavily crusted soils (i.e. zipellés), while in Ethiopia it was a lack of agricultural land which had to be overcome through building terraces, and in Tunisia the arid conditions meant that without RWH structure large parts of the land were unsuitable for crop production. Furthermore, farmers in Burkina Faso reiterated the fact that they were prioritizing zipellés for RWH implementation. In addition, all case study sites were found to have received high levels of institutional support towards the implementation of RWH strategies. For instance, the Région Nord (i.e. Provinces of Yatenga, Passoré, Bam, Zondoma, and Lorum) of Burkina Faso is one of the most extensively studied areas with regards to agricultural water management (e.g. Sawadogo et al., 2008, Dugué, 1986, Doro, 1991, Dakio, 2000, Zougmoré et al., 2003, Smith et al., 2011, Reij and Thiombiano, 2003, Ouedraogo et al., 2008). It is therefore unlikely that farmers' adoption of rainwater harvesting technologies has not been heavily influenced by such extensive research activity, in conjunction with investments of more than US$ 641 million in agricultural water management initiatives across the country over a 40-

year period (Douxchamps et al., 2014). It is thought that to reach such high levels of adoption, such institutional support has played a significant role. This includes training farmers to use the technologies, providing primary material and tools to support their implementation, and more generally involving farmers in the whole implementation process. Hence, it is difficult to say precisely what has led to such high adoption rates of RWH at the study sites. However, the selection of the sites by governments and research organizations for RWH implementation, based on biophysical needs and suitability amongst other things, is probably the primary factor explaining very high adoption rates.

5.5.3Who adopts RWH?

The Ethiopian case study revealed that it is probable that farmers who understand the benefits of improved land management practices are also more likely to put these measures in place to cope with the impacts of climatic variability and environmental change. Furthermore, while causality cannot be directly assigned, there might be a link between the labour intensiveness of RWH implementation (e.g. building and maintaining terraces and stone bunds) and having a larger number of available labourers within the household. The latter could contribute to their successful adoption. In addition, respondents at the Tunisian field site cited primarily financial constraints for their lack of involvement in RWH planning and implementation, which is likely correlated with the type of RWH strategies used in the area (i.e. large *ex situ* structures often requiring community investments).

Otherwise, it is important to note that household surveys were overwhelmingly answered by male head of households, at all study sites. Hence, focus group activities conducted in Burkina Faso with female farmers revealed some key information that allowed identifying a sub-population which was less likely to adopt RWH, in a region where RWH was otherwise common. That is, due to an absence of perceived benefits from the use of RWH strategies without the use of compost or manure, for which access was limited for female farmers, their adoption rates were also lower than for males. Hence, the capacity of female farmers to adapt to climate change is significantly reduced, considering RWH and manure production were identified by farmers as key adaptation strategies to climate change and environmental degradation.

5.5.4 Adapting to real versus perceived changes in the climate

Despite the poor correlation between climate and its perception, farmers in Burkina Faso identified RWH as a key adaptation strategy to climate change. It was a strategy selected in anticipation of a dryer climate, with more frequent and more intense dry spells. However, climate change projections for Burkina Faso are quite different from what farmers anticipate. Generally, farmers will anticipate future climate change as corresponding to historical climate extremes, as opposed to an actually different climate. Climate change projections for the 2020s and 2050s show very little change in Summer precipitation (April-September), while June-August mean temperatures are very likely to rise by 1.5- 2°C during the same period (IPCC, 2013b). Hence, while higher temperatures may result in higher crop water requirements through higher evapotranspiration rates, they may also have more adverse effects on crop physiological processes (Luo and Zhang, 2009, Schlenker and Lobell, 2010). In order to cope with these higher temperatures, reforestation for agroforestry (which was also cited as an adaptation strategy) might be an interesting option to combine with RWH. An increase in canopy cover with the use of trees in fields could lead to microclimatic improvements, and decrease soil temperatures, thereby mitigating the impacts of extreme temperature events on crop yields (Lott et al., 2009, Mbow et al., 2014). While currently selected adaptation measures in Burkina Faso could help cope with some projected changes in climate, robust decision-making at the farm level to adapt to climate change will have to rely on reliable climate information. Perceptions of a decrease in precipitation where projections are of an increase in precipitation could lead to investments in the wrong type of RWH structures for example. Incorrectly perceiving long-term trends in climate might indeed adversely impact farmers' ability to select appropriate adaptation strategies to face future climate change. In the following section, the importance of meteorological information accessibility (i.e. availability, understandability, and accuracy of information) is discussed in the context of farm-scale decision-making for climate change adaptation.

5.5.5 Providing reliable meteorological information to adapt to climate change

Access to meteorological information, such as seasonal or daily weather forecasts or historical records is very limited in Burkina Faso. When asked if they had access to any such information, farmers (both men and women) said that they sometimes heard forecasts on the radio, but did not trust them. In fact, every respondent in the various focus groups conducted in June 2012 cited the poor precision and reliability of the information received. While it is widely acknowledged in the meteorological community that predicting weather in West Africa is still fairly difficult, short-term forecasts (i.e. for a few days rather than seasonal) should still be relatively accurate. It is therefore unclear whether the information provided on the radio lacks precision and reliability as the farmers reported, or if the farmers themselves lack a fundamental understanding of forecast probabilities as presented in weather reports. Female farmers reported abandoning the use of weather forecasts to plan agricultural practices, as a wrong rainfall forecast could mean wasting a day by not doing work in the fields or not going to the markets, and waiting for rains to come.

Within the communities studied, an innovative farmer was found to have a rain gage. It was implemented by a scientist in the late 1990s as part of a research program, and left on site when the project ended. As of 2012, the innovative farmer (who is literate) still maintained the rain gage and recorded rainfall on a daily basis. When asked how he put the rainfall information to use, he mentioned three key points:

1. It allows him to know when the rainy season begins and end.
2. He knows the total annual rainfall.
3. It allows him to adjust his cropping practices from one year to the next by comparing the sowing dates with the crop yields for that year according to rainfall patterns.

Hence, it is clear that the innovative farmer values the meteorological information he has access to, and knows how to take advantage of it to inform his cropping decisions. Unfortunately, while this is information that could be beneficial to most farmers, it is not available to other farmers in the community. For instance, when probed, female farmers mentioned a range of environmental factors which would allow them to know when the first rains are coming, and hence when the growing season would start. For example, they mentioned that geckos turn red when the rains are about to start. Also with regards to predicting seasonal rainfall, traditional knowledge still prevails. Again, referring to fauna, it was mentioned that when people go hunting and bring back a lot of hedgehogs or when a lot of vipers are found during land preparation, there will be a good season. All respondents mentioned the relatively recent relinquishment of cultural practices that needed to be fulfilled before a growing season could begin. Historically, inadequate information products, policies, and institutional processes have prevented smallholder farmers from benefitting from seasonal forecast information (Hansen et al., 2011). Hence, providing farmers with long-term daily records of weather information, training them on the interpretation of weather forecasts, and building links between meteorological services and end-users could be useful towards promoting the widespread implementation by farmers of locally suitable adaptation strategies. That is, beyond increased tree planting and increased use of traditional RWH, more comprehensive adaptation packages should be available to farmers for on-farm application. This could include better adapted cropping calendars based on weather forecasts, or the adoption of crop varieties that are better suited to shorter growing seasons where such conditions were projected.

Finally, it is important to remind ourselves of the uncertainties associated with climate change projections (c.f. Chapter 4). While adaptation options discussed above relate to current projections of one future realization of the climate, one should not discount the fact that there is a real likelihood that local climates will be realized in a different manner. Hence, keeping farmers informed and educated about these uncertainties, be it in seasonal forecasts or long-term climate projections, will be primordial in keeping the adaptation process a flexible one.

5.5.6 Can RWH be used as an adaptation strategy to climate change?

It is argued here that RWH will be a relevant adaptation strategy to climate change, in a range of agro-ecosystems across Africa. However, the technologies will have to be used in combination with several other agronomic and economic measures. For instance, the use of RWH has been found to be associated with a range of good agricultural practices and parallel benefits at the study sites. At the Ethiopian study site, farmers adopting RWH were more likely to report variable planting dates from one year to the next, suggesting that they might be more likely to put a range of adaptation strategies in place, with for example reports of more variable planting dates from one year to the next for RWH adopters ($\alpha = 0.06$, Table 5.4). Respondents also perceived a significant improvement in soil fertility with the use of RWH. The reported widespread use of stone bunds and terraces, allowing trapping sediments directly in the fields, could be a first link to increased soil fertility. However, Ethiopian farmers also reported a significantly higher use of organic fertilizer (i.e. manure) on fields with RWH than those without. This double action could be adding to the benefits from RWH as a means to reduce erosion. Wakeyo and Gardebroek (2013) also found that in Ethiopia the use of RWH was associated with a higher use of fertilizers.

In some cases such as Tunisia, where transformative adaptation measures such as migration are already common, RWH will not be the primary strategy that will allow for the subsistence of the local population. Indeed, farmers' responses presented in Section 5.4.3 provide an interesting contrast with high impact publications focusing on biophysical adaptation strategies such as changing cropping calendars, increased irrigation, or improving genetic resources (Lobell et al., 2008, Burke et al., 2009, Waha et al., 2013), as we see few farmers ranking “Flexibility” (i.e. improved agronomic practices) first. More complex, transformative approaches seem to be preferred by farmers, taking into account changing socio-economic circumstances in addition to changes in the climate (e.g. Change and prioritization of objectives, Savings and deferred management of revenues). Even migration was more likely to be an option for farmers than simple agronomic measures. While not currently widespread, transformational adaptation at the farm-level could be made possible through building partnerships between R&D providers, policy makers, extension agencies, and farmers, and depart from traditional autonomous adaptation (Anwar et al., 2013). This is likely to be particularly important in regions such as Tunisia, where already extreme climatic conditions are likely to be exacerbated in the future.

At the Burkina Faso study site, migration of agricultural labourers is already a pervasive issue, especially within the younger male population. People move to numerous destinations within the country to do vegetable farming amongst others, but most predominantly to go to work in gold mines for periods lasting 4-6 months every year (Ouedraogo et al., 2008). While not cited as an adaptation strategy to a changing climate by farmers directly, and being frequently cited as a problem rather than a solution (e.g. Douxchamps et al., 2014), migration might be part of the adaptation package for a number of farmers.

Adaptation packages, currently understood as a range of agronomic measures which put together mitigate the negative impacts of climate change on agricultural production, are likely to include RWH as a key option. But overall, in no case will technical fixes suffice to adapt successfully to climate change impacts on agricultural livelihoods. Therefore, taking a livelihood approach to climate change adaptation in agriculture, as opposed to a food production approach, could be key (c.f. Chapter 7).

5.6 Conclusions

Through a range of qualitative and quantitative methods, this Chapter has attempted to get a better grasp on what could be the socio-economic barriers to the adoption of RWH as an adaptation strategy to climate change across three study sites in Africa. Climate and environmental change perceptions had previously been associated with farmers' willingness to invest in sustainable land management strategies. Hence, it was first determined that, like others found in other regions, farmers cannot perceive changes in climate. However, it is hypothesized that they perceive real changes in soil water balance which could be better captured through hydrological modelling (c.f. Chapter 6). Access to better meteorological and climate information could be key in allowing farmers to select appropriate adaptation measures, including RWH in some cases. Secondly, it was found that the very high adoption rates of RWH strategies at the study sites could be linked to limited access to quality arable land, and subsequent extensive institutional interventions. Other socio-economic or biophysical factors, such as age, education level, income, or soil characteristics were not universally linked to widespread RWH adoption. Female farmers in Burkina Faso were found to be less likely to adopt RWH than their male counterparts, due to a lack of access to primary resources including manure/compost and tools. Finally, it is thought that RWH will be an interesting adaptation strategy to climate change under certain circumstances, but that it has to be integrated within a wider framework which will also allow for more transformational change to occur where necessary. The complexity of the social-ecological systems should be taken into account in adaptation planning, and development initiatives should integrate climate change adaptation planning (c.f. Chapter 7). Considering how much financial, institutional, and time investments (i.e. about 40 years in Burkina Faso) have been required to reach the level of adoption of RWH strategies at the study sites in Africa, it is a strong reminder that the adaptation process will not be a quick one. Despite this, significant changes in the climate are likely to occur at a much faster rate than what we have been able to achieve in terms of development over these 40 years.

Chapter 6

Investigating the impacts of frequent dry spell events and extreme rainfall on soil water balance and surface runoff yields in RWH systems of Northern Burkina Faso

6.1 Introduction

In Chapter 3, the continental-level potential for RWH as an adaptation strategy to climate change was assessed, yielding results with great spatial variability. For instance, the potential for RWH to stabilize crop yields under a changing climate was found to decrease over Burkina Faso, while farmers cited RWH as a key adaptation strategy in Chapter 5. Monthly mean values of climatic variables were used for the analysis in Chapter 3. A more detailed intra-seasonal analysis of dry spells was conducted in Chapter 4, which revealed that there were likely to be significant changes in the intensity and temporal distribution of very long dry spell events, as well as more intense and isolated rainfall events over Burkina Faso.

Here, the local impacts of these frequent dry spell events and extreme rainfall on soil water balance for the Ziga field site in Northern Burkina Faso are first investigated, and compared with farmer perceptions of climate change presented in Chapter 5. The analysis for this Chapter takes a scenario-based approach, using a watershed-scale process-based model. The SWAT model, incorporating the EPIC crop model, was selected for this purpose (c.f. Chapter 2). Focus is given to sorghum crops grown in zaï pits, a predominant form of food production and key staple crop in the study area. Secondly, to investigate the impact of *in situ* rainwater harvesting strategies on increasing the flexibility of cropping calendars (i.e. flexibility in sowing dates), the impact of inter-annual variability in the rainy season onset and sowing date on crop water stress is assessed. Finally, the performance of RWH strategies, with respect to crop production under a changing climate, is evaluated. Bias corrected climate data (c.f. Chapter 4) is used as input in to the SWAT model.

6.2 Materials and methods

A lack of primary data in Chapter 6 limited the extent of the analysis, which was initially aimed at assessing watershed-scale impacts of the wide range of *in situ* and *ex situ* RWH strategies present at the Ziga and Somyaga field sites on water availability and crop production. These initial objectives explain the choice of SWAT as the modelling tool in this thesis, as opposed to a field-scale model which might have been more appropriate and required less complex datasets for the analyses presented in that Chapter. Despite this, it was possible to obtain a reasonable representation of the hydrological and erosion processes present at the field site location using SWAT and an amalgam of secondary data, with results validated through a review of literature.

6.2.1 Study site description

For this Chapter, the village of Ziga in Burkina Faso was selected, as RWH strategies are widely adopted in the area and farmers anticipate using the technologies to adapt to a changing climate (c.f. Chapter 5). Ziga is located in the Yatenga Province, Région Nord (13°25’12”N, 2°19’12”W). The SWAT-delineated Ziga watershed studied here (Figure 6.1, right panel) has a diameter of about 6km and a total area of ~28 km^2. The topography is relatively flat, with slopes ranging from 0.4% to 2.8% (Dugué, 1986). Detailed biophysical characteristics of the area are available in Chapter 5.

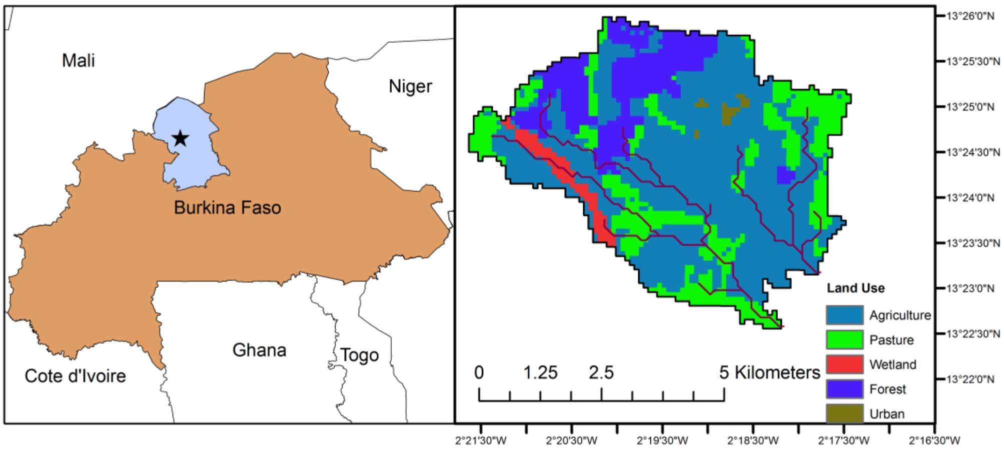


Figure 6.1 | Approximate geographical location of the Ziga field site in Burkina Faso (star), along with a land use map of the watershed under study.

6.2.2 Hydrological model setup

In order to meet this Chapter’s objectives, the Soil and Water Assessment Tool (SWAT) was selected (c.f. Chapter 2 for more details on the model). Baseline simulations were run directly for the first 20 years (1986-2005), while a 60-year warm-up period was used under a current climate, followed by 20-year simulations for the 2046-2065 climate. This aimed to internalise the effects of erosion processes over the time period between the two sets of simulations. Parameter values were selected using a one-factor-at-a-time (OAT) calibration approach.

6.2.2.1Conceptualizing rainwater harvesting in SWAT

During field visits in 2012 female farmers noted that zaï are ineffective without addition of manure. There exist two main reasons for this: a) manure improves soil fertility, and b) increased soil carbon content translates into greater water holding capacity. In order to assess the performance of RWH structures independently in terms of increased water availability and increased nutrient availability (i.e. farmers having access to manure or not), simulations were conducted for situations where zaï pits are used in combination with manure from small animals (here we used goat manure at 500kg/ha), and the case where the pits do not contain manure. However, distinguishing between the role of increased soil carbon in water retention and increased fertility from the use of manure was not feasible in this study. To represent the impact of nutrient concentration, simulations of fertilizer application on a bare surface versus within the soil profile was conducted, by reducing the amount of manure applied to the top 10mm of the soil profile from 80% to 0% (FRT_SURFACE parameter). It was therefore assumed that zaï pits allowed for a better mix of the manure within the soil than a simple application to the soil surface. Other benefits for farmers of using RWH cannot be represented within the model. For example, this includes the fact that zaï protects the seeds from being washed away in the case of important surface runoff events at the start of the rainy season.

In Section 2.5.2, a review of RWH conceptualizations for SWAT modelling was presented, which was used as a basis for the representation of zaï in this Chapter. Similarly to a number of studies, the partitioning parameter of surface runoff water and infiltration (curve number, CN) was deemed a key parameter to represent RWH. However, unlike Andersson et al. (2011) who conceptualized *in situ* rainwater harvesting in Southern Africa solely as change in CN, we allowed provision to prevent the water balance in the model shifting all the excess water to deep percolation, rather than an increase in the soil water storage within the zaï micro-structures. The increase in the soil water storage could have been represented by a change in the available water content parameter, but it was found not to be sensitive enough for the purpose of this study. Hence, the dep_imp (i.e. depth to impermeable layer) value was modified for all scenarios over highly degraded land typically used for zaï implementation from values of several meters, to values of 280mm or 300mm. The curve numbers (CN) were dropped from 94 on the typically heavily crusted soils, to 35 in the presence of zaï. Surface runoff values on these heavily crusted soils (i.e. zipellés) are very high. Sometimes called pavement crusts due to the large gravels present at the surface, these soils typically have very low infiltration rates, ranging anywhere between 0 and 0.2mm/hr (Casenave and Valentin, 1992), leading to a partitioning of rainfall where infiltration is almost nil.

6.2.2.2 Preparation of model inputs

Climate data

SWAT requires a range of daily climate data. These are listed as follows: (a) daily precipitation, (b) daily maximum and minimum temperature, (c) daily solar radiation, (d) daily wind speed, and (e) daily relative humidity. Both the wind speed and relative humidity variables are only required when the Penman-Monteith equation is used to estimate evapotranspiration, which is the method selected here. While there exists a weather generator within SWAT to construct future climates (using a delta approach) or to compensate for missing observations, daily bias corrected GCM data was preferred here for the future period (c.f. Chapter 4 for discussion on climate data calibration). Six GCMs were used to represent the 2046-2065 period (i.e. BCC-CSM-1-1, CanESM2, INM-CM4, MIROC5, MRI-CGCM3, and NorESM1-M). For the historical period, daily observations for precipitation were obtained for the Ouahigouya weather station, while the other required variables were sourced from the ERA-INTERIM re-analysis database.

Land use

A land use map of Ziga from Sawadogo (2006) was digitized and assigned land use codes in SWAT (Figure 6.1, right panel). For the purpose of this analysis, agricultural land was assigned one of three widely grown crops with a spatially-varying distribution: maize, millet, or sorghum. In general, drought-resistant crops such as sorghum and millet are cultivated in zaï on sloping ferruginous soils where zipellés are most likely to occur. On the other hand, lowlands are more likely to see maize production, or even rice in areas more prone to flooding in heavy rainfall years. However, the scope of the scenarios only analyses the sorghum production systems, and downstream effects of RWH are not considered here.

Crop management

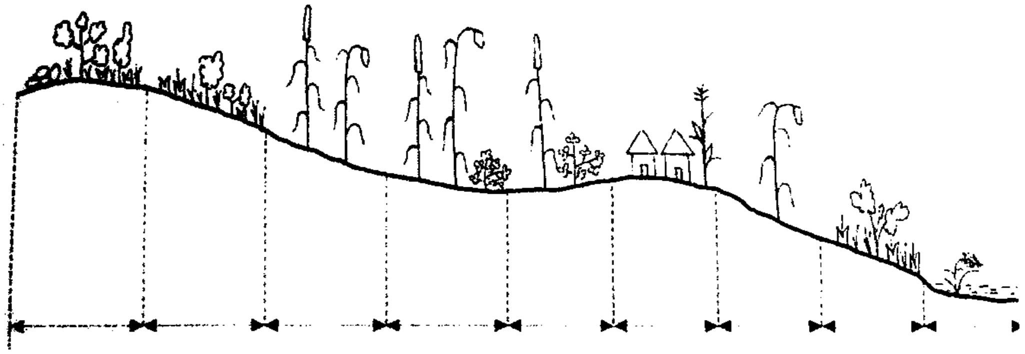
Sorghum was the only crop for which crop management variables were changed within the scenarios described in Section 6.2.3. Otherwise, as crop growth is represented through the use of heat units (HUs), which are accumulated over the growing season to determine yield outputs, HUs for sorghum were increased to 2031HUs in order to gain a better representation of the varieties present in Burkina Faso.

Planting and harvest dates were determined from focus group activities with farmers, and triangulated with the agronomic determination of the rainy season as described in section 5.3.1.3 of this thesis. Farmers reported sowing sorghum mid-June onwards, and harvest it late October. However, as the SWAT model considers a crop is still growing until harvest operations, an earlier harvest operation than what really takes place in the field had to be scheduled. The harvest operations were set 10 days after the average end to the agronomically defined rainy season. That is, sorghum was harvested on October 5th of every year, except under future scenarios K & L (Table 6.2).

Soil maps

Detailed soil maps are required for SWAT simulations. Unfortunately, these were not available at the time of beginning this study, and secondary data was used to produce the maps.

A range of datasets from Sawadogo (2006) were used to extrapolate the required information. First, a toposequence of the study area (Figure 6.2) was combined with soil sample details (Table 6.1) to get a better grasp of the spatial distribution of soils in the watershed. The land slopes and drainage networks were determined by SWAT through a 90m resolution SRTM digital elevation model (DEM). Thereafter, using topographical information from the SRTM DEM and a digitized land use map from Sawadogo (2006), soil types were assigned to areas corresponding to the toposequence. While most soil characteristics reported in Table 6.1 were taken from Sawadogo (2006), the following soil parameters were estimated using the SOILPAR software (Acutis and Donatelli, 2003): bulk density, wilting point, field capacity, and available water content (c.f. Appendix E). For the rest of this Chapter, analyses will focus on sorghum produced on a typical medium depth ferruginous soil, generally located at the top of slopes, and where farmers reported the widespread use of RWH strategies.



Geomorphology	**Top of hillock**	**Side of hillock**	**Top of slope**	**Middle of slope**	**Bottom of slope**	**Mound**	**Side of mound**	**Bottom of mound**	**Lowlands**
Soil type	Crude mineral soils	Lithosoils on bedrock	Medium depth ferruginous soils	Tropical eutrophic brown soils	Deep ferruginous soils	Shallow ferruginous soils	Medium depth ferruginous soils	Hydromorphic ferruginous soils	Hydromorphic pseudo gley soils
Land use	Shrubs and pastures	Pastures	Millet or sorghum	Sorghum, millet, legumes (Bambara groundnut)	Millet, legumes	Homesteads, maize	Sorghum	Pastures or sorghum	Rice and vegetables

Figure 6.2 | Toposequence representative of the Ziga/Somyaga region (Sawadogo, 2006)

Table 6.1 | Soil properties in Ziga, adapted from Sawadogo (2006)

Topographical location	Depth (cm)	Acidity				Organic matter			Soil texture (%)			Bulk density ($t\cdot m^{-3}$)	Wilting point (m/m)	Field Capacity	Saturated Hydraulic Conductivity	AWC
		pH		Ac exchange (meq/100g)	Al exchange (meq/100g)	% of TS		C/N	Clay	Silt	Sand					
		pH water	pH KCl			C	N									
Top of hillock	15	5.5	4.7	-	-	0.8	0.03	27	16.8	14.5	68.7	1.64	0.31	0.57	4.72	0.26
Side of hillock	20	5.2-6.0	4.1-5.1	1.8	1.5	0.7-0.9	0.03-0.05	18-23	11.5	23.2	65.3	1.62	0.23	0.5	6.04	0.27
Top of slope	28-40	4.5-6.1	4.1-5.2	1.6	0.7	0.5-0.9	0.02-0.06	15-30	11.4-12.2	9-21.2	66.6-79.6	1.62-1.66	0.22-0.23	0.46-0.5	6.09-8.56	0.24-0.27
Fallow	40	4.9-6.2	4.2-5.2	1.0	0.3	0.7-0.9	0.04-0.08	11-18	16.5	32.1	51.4	1.6	0.32	0.62	3.88	0.30
Mid-slope	52-57	5.7-8.3	4.1-7.7	1.3-1.4	0.5-0.6	0.4-1.2	0.01-0.10	12-50	19.8-40.2	11.2-16.5	43.3-66.1	1.53-1.64	0.31-0.67	0.57-0.89	4.04-5.32	0.20-0.26
Bottom of slope	120	5.9-6.7	4.9-5.6	-	-	-	0.01-0.06	13-30	8.7-31.1	14-34.9	34-77.3	1.6-1.71	0.11-0.42	0.51-0.73	1.82-4.71	0.31-0.4
Hillock	50-120	5.6-7.8	4.3-6.6	-	-	0.6	0.01-0.08	12-18	13.7-36.2	15.8-17.1	48-69.2	1.63-1.64	0.23-0.5	0.49-0.73	2.11-5.76	0.23-0.26
Drainage axis	110	5.7-6.9	4.8-5.6	-	-	-	0.01-0.06	15-20	14.2-46.1	6-6.5	47.4-79.8	1.63-1.71	0.21-0.62	0.54-0.76	3.35-5.49	0.14-0.33

6.2.3 Scenario development

Scenarios were developed to meet the following key objectives: a) identify relationships between climate change perceptions and soil water/land degradation, b) evaluate the performance of RWH at the local level under a changing climate, and c) evaluate the potential for RWH to increase the flexibility of cropping calendars. Therefore, scenarios developed: represent the use or not of rainwater harvesting, incorporate variable planting dates and/or fertility management practices, and compare the climate from the 1990s to six climate realizations from the 2050s based on six GCM simulations. Rainy seasons are characterized for the 1990s, including maximum dry spell duration and timing. Below, each of these scenarios is briefly explained.

6.2.3.1 Soil erosion and soil water balance

To evaluate the links between climate change perceptions and environmental degradation, the following question was asked: How much soil erosion has taken place over the 20 years between 1986 and 2005, and how has that affected the soil water balance over that time period? We assess the water balance throughout the year for the same soils being cultivated without improved water management strategies, and run simulations over the same soils with the use of rainwater harvesting (in this case, sorghum planted in zaï). Temporal trends are assessed again through the Mann-Kendall and Sen’s Slope estimates, as described in Chapter 5.

6.2.3.2 Climate change

Future climate change was assessed through the use of six GCM simulations from the same number of climate models under the RCP8.5 forcings, with bias-corrected time series. Bias correction procedures aimed at maintaining changes in mean and variance projected by the climate models (c.f. Chapter 4).

In addition to a change in the climate variables, historical CO_2 concentrations were set to 369ppm, consistent with concentrations observed in the year 2000. In contrast, future scenarios will see an increase of the CO_2 concentration to 541ppm in the RCP8.5 simulations by the year 2050 (Meinshausen et al., 2011). Impacts from changes in CO_2 concentrations are modelled in SWAT through the modification of the canopy resistance variable used in the Penman-Monteith evapotranspiration equation (Monteith, 1965).

6.2.3.3 Soil fertility versus water availability

As reported in Chapter 5, female farmers perceived no benefits from the use of RWH without organic fertilizers such as manure, particularly in zaï. Hence, how does the impact of improved soil fertility compare and relate to an increase in soil water availability associated with the use of RWH in terms of crop yields? The hypothesis of a relationship existing in terms of yields between the two management options was tested through simulations involving cases where 500kg/ha of goat manure (i.e. a common form of manure available in the region) is added to the zaï pits versus where no soil fertilization is done.

6.2.3.4 Changes in cropping calendars

Changes in cropping calendars are investigated in two distinct manners. First, changes in sowing dates as an adaptation strategy to climate change are investigated. That is, how does a change in sowing date help in stabilizing sorghum crop yields under a changing climate? From Figure 4.7 presented in Chapter 4, it seems that a minimal change in cropping calendars could be implemented to maintain the U-shape intra-seasonal distribution of maximum duration dry spells over West Africa in 2050. Hence, to evaluate modifications of sowing dates to address the change in U-shape, sowing and harvest dates were set 15 days earlier than during the historical period (i.e. sorghum planting occurs on June 1st, and harvest on September 20th for the 2050s GCM projections under Scenarios K & L, c.f. Table 6.2).

In second place, the role of RWH in increasing the flexibility of cropping calendars is investigated. In Chapter 5 it was found that there was a lot more variability in the agronomic start of the rainy season at the Ouahigouya weather station in Burkina Faso between 1986 and 2005, than there was for the end of the growing season. The question to answer is therefore: Does RWH allow earlier sowing dates, thus extending the duration of the growing season? Late sowing is generally practiced when no rainwater harvesting is used, as farmers wait for the first rains before sowing to reduce the risk of replanting. On the other hand, early sowing can result in higher yields, as crops can reach full maturity before the end of the rainy season, may be less sensitive to long dry spells at grain filling, and can benefit from more flushed nutrients during the first few runoff events. However, it also entails higher risks of early crop failure, due to low soil water availability and the crop’s inability to reach water in lower soil layers. To assess these factors and their relationship to RWH, two early sowing dates are set for conditions with and without RWH. That is, planting for sorghum takes place on May 15th or June 1st (Scenarios G – J), as opposed to June 15th for the baseline (Scenarios A - D), without changes to the harvest date.

6.2.3.5 Final scenarios

The final scenarios are summarized in Table 6.2.

Table 6.2 | Summary of scenarios used in the SWAT simulations

Scenario	Climate	Use of RWH (i.e. zaï for sorghum)	Fertilization	Sorghum sowing date	Sorghum harvest date
A	Historical	No	1kg/ha goat manure (i.e. negligible)	June 15th	October 5th
B	Historical	Yes	1kg/ha goat manure (i.e. negligible)	June 15th	October 5th
C	Historical	No	500kg/ha goat manure	June 15th	October 5th
D	Historical	Yes	500kg/ha goat manure	June 15th	October 5th
E	Future (x6 GCMs)	No	1kg/ha goat manure (i.e. negligible)	June 15th	October 5th
F	Future (x6 GCMs)	Yes	1kg/ha goat manure (i.e. negligible)	June 15th	October 5th
G	Historical	No	1kg/ha goat manure (i.e. negligible)	May 15th	October 5th
H	Historical	No	1kg/ha goat manure (i.e. negligible)	June 1st	October 5th
I	Historical	Yes	1kg/ha goat manure (i.e. negligible)	May 15th	October 5th
J	Historical	Yes	1kg/ha goat manure (i.e. negligible)	June 1st	October 5th
K	Future (x6 GCMs)	No	1kg/ha goat manure (i.e. negligible)	June 1st	September 20th
L	Future (x6 GCMs)	Yes	1kg/ha goat manure (i.e. negligible)	June 1st	September 20th

6.3 Results

6.3.1 Perceived and modelled trends in soil moisture and crop yield

6.3.1.1 Calibration

In addition to the uncertainties previously discussed relating to climate models, a range of uncertainties are associated with the hydrological modelling process, including in the way we conceptualize RWH itself. Some of these can be addressed through a calibration process, although in this case a lack of primary data severely impeded the process. Calibration was conducted using the simulated and observed crop yields. Crop yield estimates from the Yatenga province were obtained from INERA in Burkina Faso. These are listed in Table 6.3. While there is likely to be a high level of spatial variability in reported crop yields, the model was calibrated to reproduce sorghum yields which were on average close to the reported yields for the province. For the 1987-2004 period, simulated sorghum yields across all soil types present in the Ziga watershed are 627kg/ha where rainwater harvesting is used (which is generally the case in the area, c.f. Chapter 5), but without fertilization. This compares well to the 660kg/ha over the Yatenga province.

Sawadogo et al. (2008) reported much lower yields in Ziga for field experiments conducted between 2002 and 2004 than the values reported for the Yatenga province. Total precipitation was similar to the Ouahigouya records for 2002 and 2003, while 2004 rainfall was significantly lower in Ziga. While it is unclear on which type of soils or what specific planting and harvest dates were used in the experiments, generally plots with good fertilization and the use of zaï fared better than those using only zaï or no RWH. Crop yields with the use of zaï without fertilization ranged between 200 and 287 kg/ha for 2002 and 2003, and went up as high as 725kg/ha in plots where zaï were used with a combination of composted manure, urea, phosphates, and NPKSB fertilizer. Control plots with no improved management practices had yields of 94 and 200kg/ha in 2002 and 2003 respectively. For those two years, simulated yields in SWAT ranged between 375 kg/ha and 500 kg/ha without the use of zaï, and reached 500kg/ha to 550kg/ha with zaï without fertilization on a top of slope ferruginous soil. With zaï and fertilization, simulated yields ranged from 925 kg/ha to 1250 kg/ha on average on a top of slope ferruginous soil. While the magnitude of yields reported by Sawadogo et al. (2008) for Ziga differs from those simulated in SWAT, the effects of different treatment types are similar. That is, the use of RWH without fertilization provides significantly lower benefits than with the use of manure/fertilizers. Nevertheless, further investigation of total simulated biomass yield, as opposed to grain yield, revealed values of 1000kg/ha and 1400kg/ha for 2002 and 2003 without improved management practices, versus 600 and 1330 kg/ha in the experiments by Sawadogo et al. (2008). This leads to believe that biomass partitioning between grain and straw yields may not be optimized for the sorghum varieties present in Ziga, but that overall biomass production and management impacts (e.g. RWH and fertilization) are well represented in SWAT.

Table 6.3 │ Crop yields for the Yatenga Province, Burkina Faso (kg/ha) obtained from INERA

YEAR	MAIZE	MILLET	SORGHUM
1984	438	473	594
1985	284	413	577
1986	517	543	623
1987	222	381	483
1988	728	556	694
1989	1,036	281	662
1990	322	234	165
1991	617	786	807
1992	806	596	824
1993	922	463	554
1994	908	858	-
1995	401	355	199
1996	663	728	858
1997	457	608	452
1998	889	1,022	1,230
1999	773	620	587
2000	368	466	432
2001	924	887	474
2002	575	428	746
2003	742	937	1,020
2004	499	962	1,026
Average	***623***	***600***	***650***
Maximum	***1,036***	***1,022***	***1,230***
Minimum	***222***	***234***	***165***

6.3.1.2 Trends in soil moisture

Temporal trends in soil moisture were investigated throughout the growing season for the historical period, for the top of slope ferruginous soil type used to grow sorghum (cf. Figure 6.2 and Table 6.1). A closer investigation of the soil water content at the beginning and end of the growing season was undertaken in scenarios A and B. That is, soil water content at the start of July, or two weeks after the selected sowing date, did not reveal any significant temporal trend in either scenario. However, in scenario A soil water at the end of September, towards the end of the sorghum growing season, showed a significant decrease between 1987 and 2005 (1986 was ignored, as it was considered as the warm-up period of the SWAT model) at the $\alpha = 0.05$ significance level (Figure 6.3). Although less pronounced, simulated soil moisture in the month of September is also decreasing significantly on plots where RWH is applied (scenario B). Despite this, simulated soil moisture remains on average 28% higher at the end of September when RWH is applied.

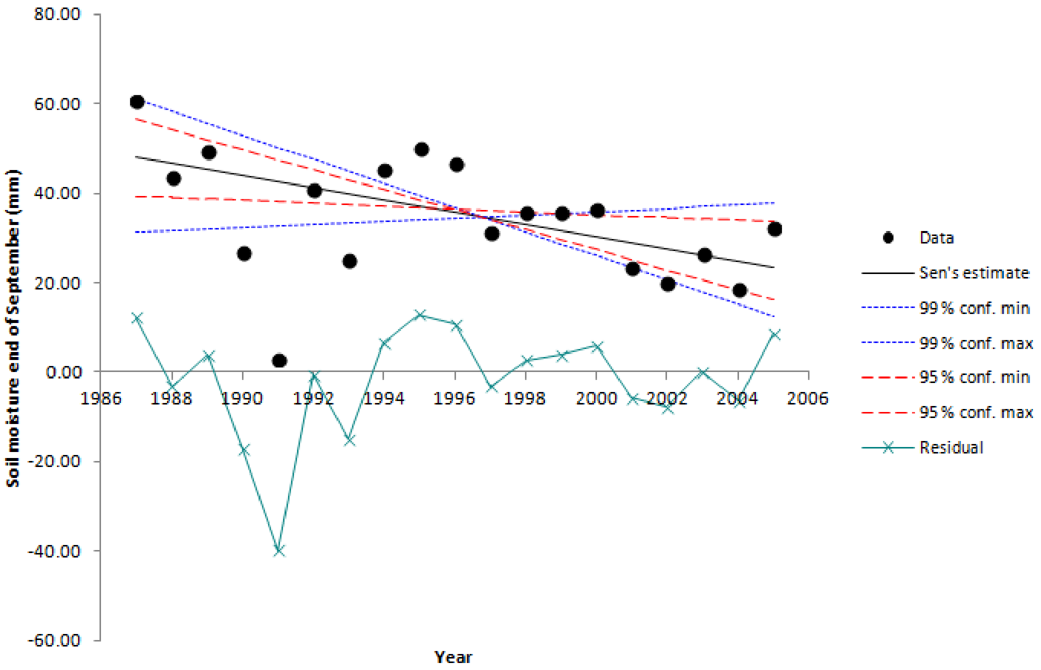


Figure 6.3 | Simulated soil moisture trends at the end of September on top of slope ferruginous soils, 1987-2005, no RWH.

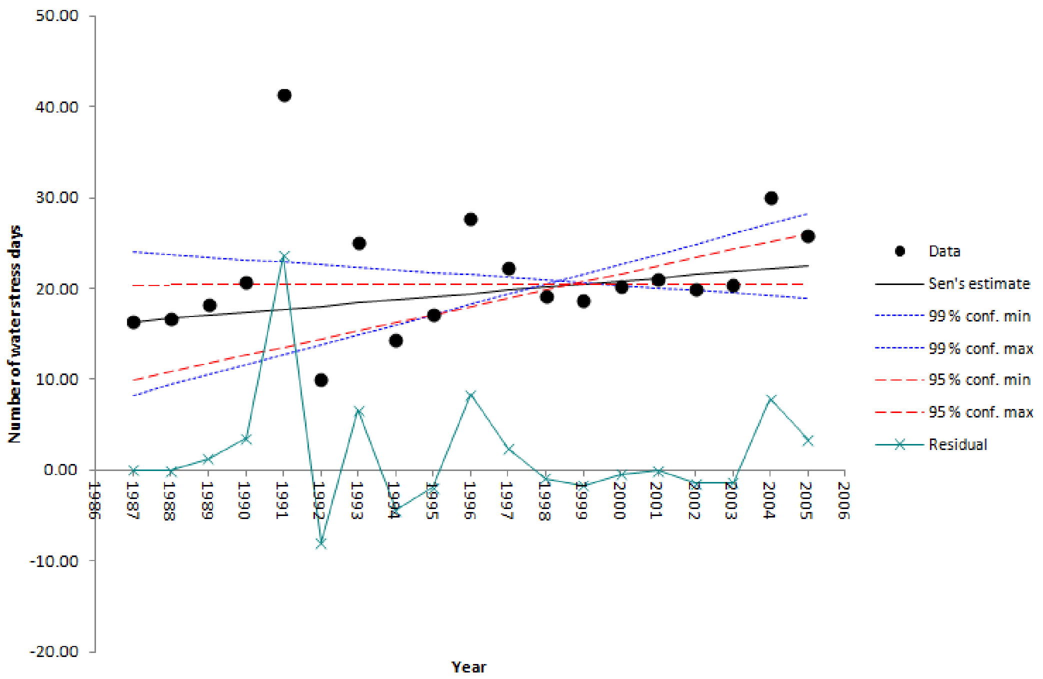


Figure 6.4 | Simulated number of water stress days for a sorghum crop on top of slope ferruginous soils, 1987-2005, no RWH.

Also, an increasing trend in the number of water stress days for the sorghum crop was found at α = 0.10 significance level (Figure 6.4), supporting a perception of decreasing rainfall amounts. However, in this case, the increasing trend is more likely caused by soil erosion and decreased soil water holding capacity, as no decreasing trends in rainfall was found in the observation records for that time period (c.f. Chapter 5). Similarly, one obvious cause of the reduction in soil water content at the end of the growing season could be a loss of soil water holding capacity, associated with soil erosion. Simulated annual soil loss due to erosion averages 6.5 ton/ha/year (±2.7), using the universal soil loss equation (USLE), without any significant changes over time being observed. This corresponds well to values ranging between 5 and 10 ton/ha/year estimated through the Global Land Degradation Information System (Nachtergaele et al., 2010), while the USDA estimated a high vulnerability to water erosion in the region based on global soil maps (USDA, 1998). While not necessarily critical on deep soils, the shallowness of the soils used for crop production observed at the Ziga field sites renders this level of soil erosion critical. In simulations where RWH is applied, annual soil erosion drops by over 80%, to 1.2 ton/ha/year (±2.0).

The simulated annual water balance of soils where sorghum was produced (Figures 6.5 & 6.6) reveals consistently higher actual evapotranspiration values for the case where RWH is used, which can be translated to yield improvements. In addition, deep percolation possibly leading to groundwater recharge is significantly increased in all years, from no deep percolation at all without RWH. This can be associated with very low infiltration rates on the heavily crusted soils.

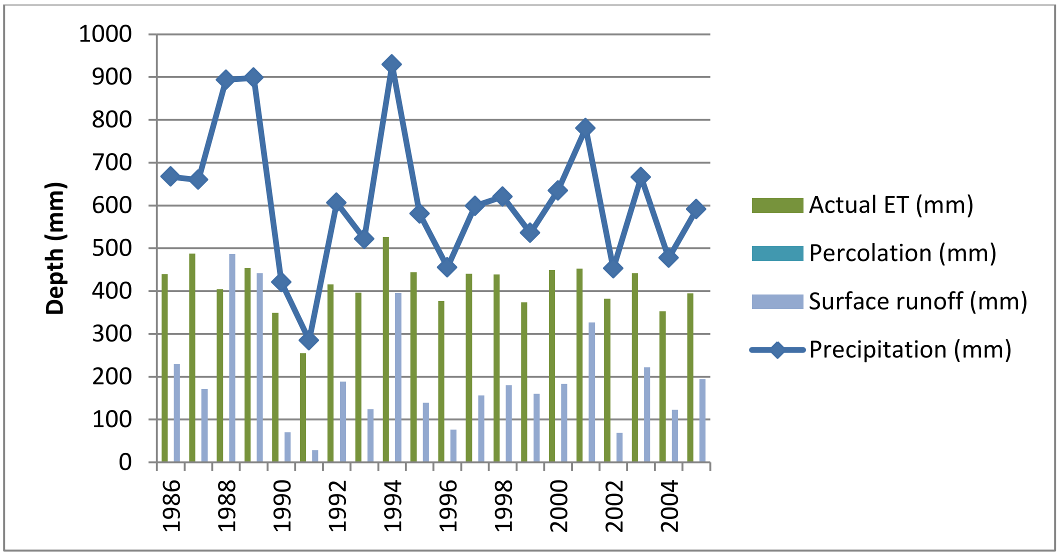


Figure 6.5 | Simulated annual water balance for Scenario A, without RWH.

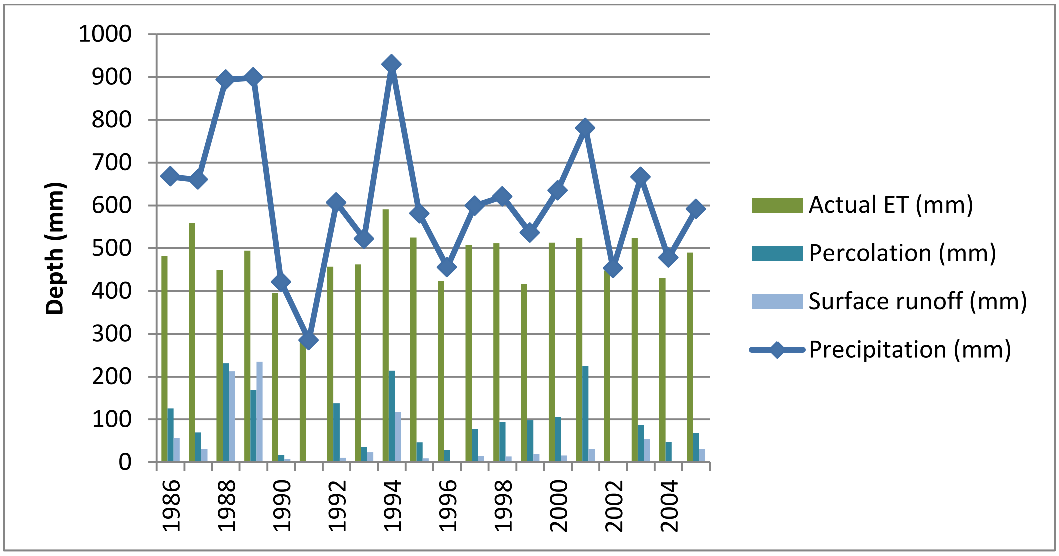


Figure 6.6 | Simulated annual water balance for Scenario B, with RWH.

6.3.1.4 Evaluating crop water productivity and yield benefits from improved soil fertility

A comparison between the number of water stress days and nitrogen stress days reveals that there are on average 4.6 times more days where the crops are under nitrogen stress than water stress between 1987 and 2005 where neither fertilization nor RWH is used (i.e. 90 versus 21 days per year). However, a paired-sample t-test also shows a significantly lower number of water stress days with the use of RWH, while the number of nitrogen stress days increase at the α = 0.001 significance level. This could indicate a lower crop water productivity where crop growth is nutrient-limited.

Crop water productivity (CWP) can be defined as the ratio of crop yield to actual evapotranspiration (Huang and Li, 2010), as simulated in SWAT. As expected, where RWH is used, CWP is indeed lower than when it is not used (although not statistically significant). Without the use of goat manure, CWP is very low, at around 0.13 (Table 6.4), similar to the lowest values of about 0.1 reported by Rockström et al. (2002). However, in Scenarios C and D, fertilizer use more than doubles CWP to a mean of 0.27. This entails that for the same amount of water available, yields can be increased by more than two-fold.

Table 6.4 | Anova two-factor with replication for sorghum water productivity with or without fertilizer and use or not of RWH

Anova: Two-Factor With Replication			
SUMMARY	RWH	No RWH	Total
Fertilizer			
Number of years	20	20	40
Average CWP (kg/m^3)	0.26	0.28	0.27
Variance	0.0034	0.0039	0.0039
No Fertilizer			
Number of years	20	20	40
Average CWP (kg/m^3)	0.12	0.13	0.13
Variance	0.0038	0.0044	0.0040

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.39	1	0.39	102.17	1.04E-15	3.97
Columns	0.0049	1	0.0049	1.27	0.26	3.97
Interaction	0.0011	1	0.0011	0.28	0.60	3.97
Within	0.29	76	0.0039			

In order to further evaluate the effects of fertilizer use versus rainwater harvesting on crop yields, as well as possible interactions between the two, four simulations were conducted to obtain a factorial design. In the case where manure is considered to be applied below the soil surface (i.e. 0% in top 10mm of soil profile), it is found that the use of rainwater harvesting has little impact on crop yields (Table 6.5). Rather, doubling in sorghum yields can be attributed to an increase in soil fertility. In addition, the simulations predict no interaction between the two factors when it comes to crop yields. Overall, simulations of simple RWH without fertilizer use result in sorghum yield benefits of about 7%. This is a value consistent with the findings presented in Chapter 3, where sorghum yields with increased water availability due to RWH were expected to be of 5-6% on average across rainfed Africa.

However, this is likely a poor representation of the ability of RWH to concentrate nutrients and protect them from being flushed away during surface runoff events. Zaï pits are in fact a soil fertility management and fertilizer application approach as well, as fertilizers are unlikely to be otherwise applied within the soil profile on those heavily crusted soils. Table 6.6 reveals that when fertilizers are not applied within zaï, but rather remain on the soil surface, they are not made accessible to the crops and therefore yields are not improved significantly compared to a case without fertilization. The significant interaction between treatments in this case corresponds better to field observations, whereby farmers who use RWH are also more likely to invest in fertilizer use. This also suggests that doubling of yields associated with fertilization would not be possible unless applied through these pits.

Table 6.5 | Effect of fertilizer applied below the top 10mm of the soil profile on sorghum yields, with the use or not of RWH.

Anova: Two-Factor With Replication			
	RWH	No RWH	Total
Fertilizer			
Number of years	20.00	20.00	40.00
Average yield (ton/ha)	1.20	1.15	1.17
Variance	0.08	0.08	0.08
No fertilizer			
Number of years	20.00	20.00	40.00
Average yield (ton/ha)	0.58	0.54	0.56
Variance	0.09	0.09	0.09

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample (Fertilizer use)	**7.47**	**1.00**	**7.47**	**86.03**	**0.00**	**3.97**
Columns (RWH)	0.04	1.00	0.04	0.43	0.51	3.97
Interaction	0.00	1.00	0.00	0.01	0.91	3.97
Within	6.60	76.00	0.09			
Total	14.10	79.00				

*SS refers to sum of squares, df degrees of freedom, and MS to mean square error.

Table 6.6 | Effects of 80% of fertilizer applied to the top 10mm of the soil profile without RWH versus below the top 10mm of the soil profile when RWH is in use, on sorghum yields.

Anova: Two-Factor With Replication			
SUMMARY	RWH	No RWH	Total
Fertilizer			
Number of years	20.00	20.00	40.00
Average	1.20	0.55	0.88
Variance	0.08	0.09	0.19
No fertilizer			
Number of years	20.00	20.00	40.00
Average	0.58	0.54	0.56
Variance	0.09	0.09	0.09

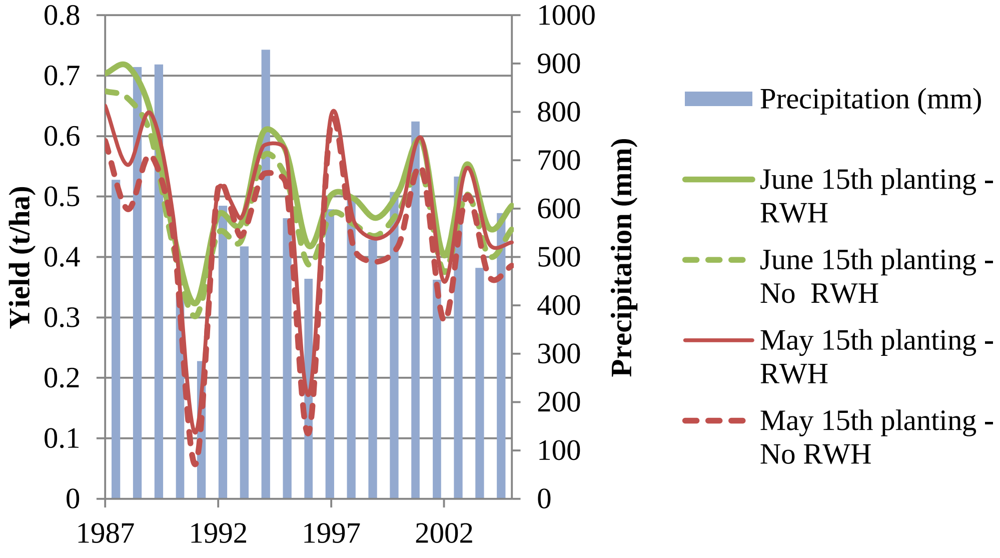
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1.95	1.00	1.95	21.74	0.00	3.97
Columns	2.33	1.00	2.33	25.96	0.00	3.97
Interaction	1.87	1.00	1.87	20.84	0.00	3.97
Within	6.83	76.00	0.09			
Total	12.99	79.00				

6.3.2 Increasing cropping calendars flexibility through RWH

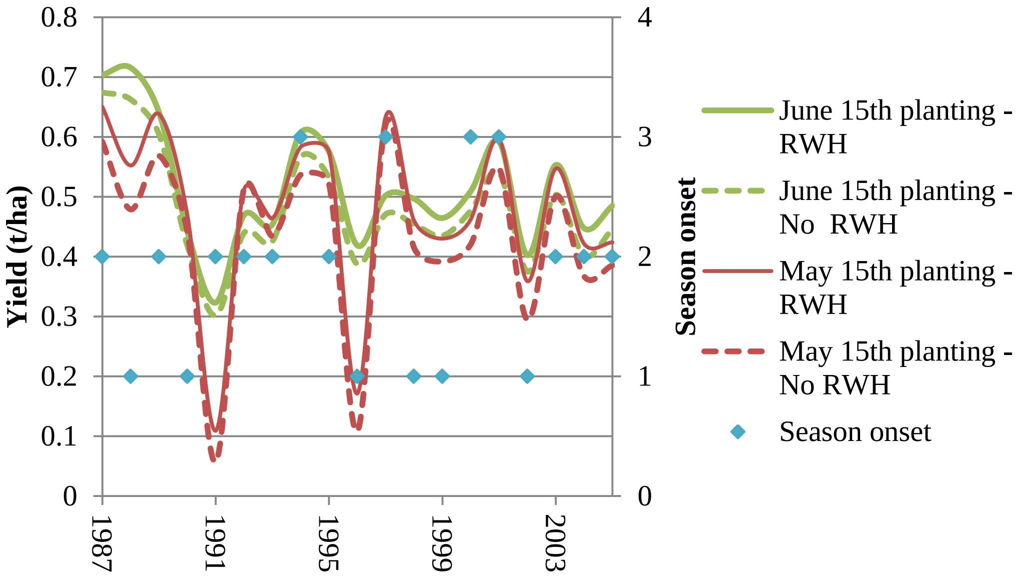
6.3.2.1 Identifying the impacts of intra-seasonal rainfall patterns

A priori, the SWAT simulations show no increase in the flexibility of cropping calendars (i.e. allowing earlier sowing dates) with the use of RWH. Overall, crop yields are lower (although not significantly) with earlier sowing dates, suggesting the inability of the modelled zaï pits without fertilizer to fully mitigate the impacts of intra-seasonal rainfall distribution, and particularly the variability in rainy season onset.

Years in which simulations of early sowing were particularly detrimental to sorghum yields were 1991, 1996, and 2002 (Figure 6.7). All of these years had agronomically defined growing seasons significantly shorter than the normal (Table 6.7). In 1991, there was a normal season onset, but with a below average season length (despite not being the shortest). A number of dry spells longer than normal, with a particularly long one (i.e. 19 days) in mid-July to early August, most likely contributed to poor yields. With early sowing, this very long dry spell would have occurred at the most critical stage of the growing season, but not quite for mid-June sowing. In contrast, 2001 saw its longest duration dry spell (of equal length as in 1991) occur in mid-May to early June, which clearly did not affect crop yields negatively. Season onset was early and soil moisture was sufficient to meet the relatively low needs of the sorghum crops at that early stage. On the other hand, 1997 was the only year where early sowing provided a significant improvement in yields. This is also a year where the season onset was only 3 days before the sowing date, with a significantly longer than average growing season. The longest dry spell occurred in September where water requirements would have been lower, and dry spells were of slightly shorter duration than average. Finally, years where mean dry spell durations were greater than normal saw lower levels of benefits from RWH.



(a)



(b)

Figure 6.7│Annual sorghum crop yields for different combinations of planting dates and use of RWH. (a) Total annual precipitation, (b) Season onset with respect to the mean of the 1986-2005 distribution were categorized as Late = 1, Normal = 2, and Early = 3.

Table 6.7 | Rainy season characteristics from 1986-2005 observations in Ouahigouya.

Year	**Season onset date**	**Season end date**	**Season duration**	**Mean dry spell duration (≥5 consecutive dry days)**	**Number of dry spells**	**Longest dry spell (days)**	**Timing of longest dry spell**
1986	May 3rd	Sept19th	139	7.3	8	11	End May/Early June
1987	June 4th	Oct10th	128	7.6	5	11	Early Oct
1988	July 6th	Sept 18th	74	5	1	5	Mid-July
1989	May 21st	Oct 4th	136	8.4	7	13	Mid- to late June
1990	July 3rd	Sept26th	85	7.7	3	12	Mid-Sept
1991	June 11th	Sept11th	92	11.4	5	19	Mid-July to early Aug
1992	June 6th	Sept 26th	112	8	3	10	Mid-June
1993	June 5th	Oct10th	127	8.7	6	14	Mid- to late June
1994	May 9th	Oct 14th	158	7	7	10	Mid-June
1995	June 4th	Sept22nd	110	6.1	7	8	Mid-July
1996	July 11th	Sept 2nd	53	7	2	9	Mid-Aug
1997	May 12th	Sept27th	138	7.3	9	11	Mid-Sept
1998	June 28th	Oct 16th	110	6.8	4	12	Early Oct
1999	June 21st	Sept20th	91	7.3	4	13	Mid-Sept
2000	May 7th	Sept 29th	145	7.7	9	15	Late June to Early July
2001	May 6th	Oct 1st	148	9.9	7	19	Mid-May to Early June
2002	June 28th	Oct 4th	98	6.3	3	7	Late July to Early Aug
2003	May 29th	Sept17th	111	5.4	7	6	Several occurrences
2004	May 29th	Sept10th	104	8.6	5	13	Mid-June
2005	June 11th	Sept 1st	82	7	4	12	Mid- to Late July
Average	*June 6th*	*September 25th*	*112*	*7.5*	*5.3*	*11.5*	*NA*

Based on the analysis of season onset, the rainy season had started by 15th of May in 25% of years, by June 1st in 40% of years, and by 15th of June in 70% of years between 1986 and 2005. Reported sorghum sowing dates from 15th of June onwards illustrate the risk-averseness of farmers exploiting rainfed agricultural systems with regards to crop management practices. However, it also shows that farmers have already optimized their cropping calendars to reduce the risk of a failed crop early on during the growing season.

It is possible that when reporting being able to sow crops as early as May when using RWH, farmers were in fact perceiving years of early growing season onset. From the analysis of end of rainy season dates presented in Chapter 5, it was shown that there exists little variability between years in those dates. Further investigation of the years of early growing season onset (i.e. on or before May 15th) and those years where late onset was more likely (i.e. after June 15th) again shows no significant benefits from the use of RWH in those specific years. However, in years of early season onset, the model projected yields almost double those of a year of late season onset, independently of the sowing date (Appendix F, Tables F1.1 to F1.3).

On the other hand, yields were significantly lower when crops were sown on May 15th in a year of late rainy season onset. This can be explained by a poor distribution of soil moisture throughout the season when late onset occurred, not allowing crops to reach their full potential. Overall, years with early onset see between 19 (June 15th planting) and 25 (May 15th) water stress days per year, whereas years with a late season onset see between 21 (June 15th planting) and 38 water stress days (May 15th) when no RWH is used. That is, there is no significant difference between June 15th planting dates in the number of water stress days depending on the season onset dates, whereas it is significant at the $\alpha = 0.05$ level for mid-May planting dates. Moreover, crops see a significantly lower number of water stress days when RWH is used ($\alpha = 0.05$) in all cases, despite this not being reflected in crop yields.

6.3.4 RWH harvesting performance under a changing climate

Following bias correction of the daily GCM data, the historical crop yield simulations did not differ significantly between GCMs or observations. On the other hand, significant differences were found between models in yield projections. Specifically, where RWH is used, CanESM2 projects average sorghum yields on a top of slope ferruginous soil of just under 300kg/ha and BCC-CSM-1-1 yields just over 400kg/ha under unaltered cropping calendars. On the other hand, the other four models present statistically similar yields ($\alpha = 0.01$), averaging 508kg/ha. Hence, all models agree on the direction of change; crop yields are projected to decrease on average across models by about 27%, which corresponds well to values of 25-50% decreases in crop yields projected for the specific area by other researchers (UNEP, 2014). These changes could be attributed to a range of factors, including increased temperatures, increased rainfall variability, and increased CO_2 concentrations. However, after closer investigation of simulated potential evapotranspiration values (a proxy for impacts of changes in temperature, wind speed, solar radiation, and relative humidity), it was found that these values were not significantly different from the historical values for May to October in 5 of 6 models (CanESM2 being the exception, with a projected significant increase in potential evapotranspiration). On the other hand, increases in CO_2 concentrations are normally associated with an increase in plant productivity and a reduction in crop water requirements (Neitsch et al., 2011). This leads to the conclusion that the majority of crop yield reductions can be associated with changing rainfall patterns, which are not fully mitigated by increased CO_2 concentrations.

RWH continues to perform similarly in the 2050s as it has during the 1990s. That is, yield increases associated with the technology remain modest when compared to combined water and fertility management, at about 10% on average across models.

RWH systems' ability to reduce soil erosion decreases slightly, with 8 ton/ha on average lost without RWH, and 2.7 ton/ha with RWH (65% reduction). The increase in soil erosion can be attributed to an increase in the intensity of rainfall events in half of the models, for which the current *in situ* RWH strategies may not be best suited. Indeed, the rainfall intensity for days with at least 1mm rainfall is projected to increase significantly ($\alpha = 0.05$) from 14.8mm/wet day during the 1990s to 16.2-18.5mm/day in three of the six models (INM-CM4, MIROC5, and NorESM1-M), while the other three models project no significant change in wet day rainfall intensity. On the other hand, two of the three models projecting an increase in rainfall intensity (MIROC 5 and NorESM1-M), also project a significantly higher frequency of years where total annual surface runoff is higher than in the historical period when no RWH is used (see Figure 6.8). The difference in the annual surface runoff distribution is not significant for BCC-CSM-1-1, INM-CM4, or MRI-CGCM3, but the frequency of years with high runoff totals are significantly lower under CanESM2. Statistical significance between cumulative distribution functions was assessed using the Kolmogorov-Smirnov Statistical Test.

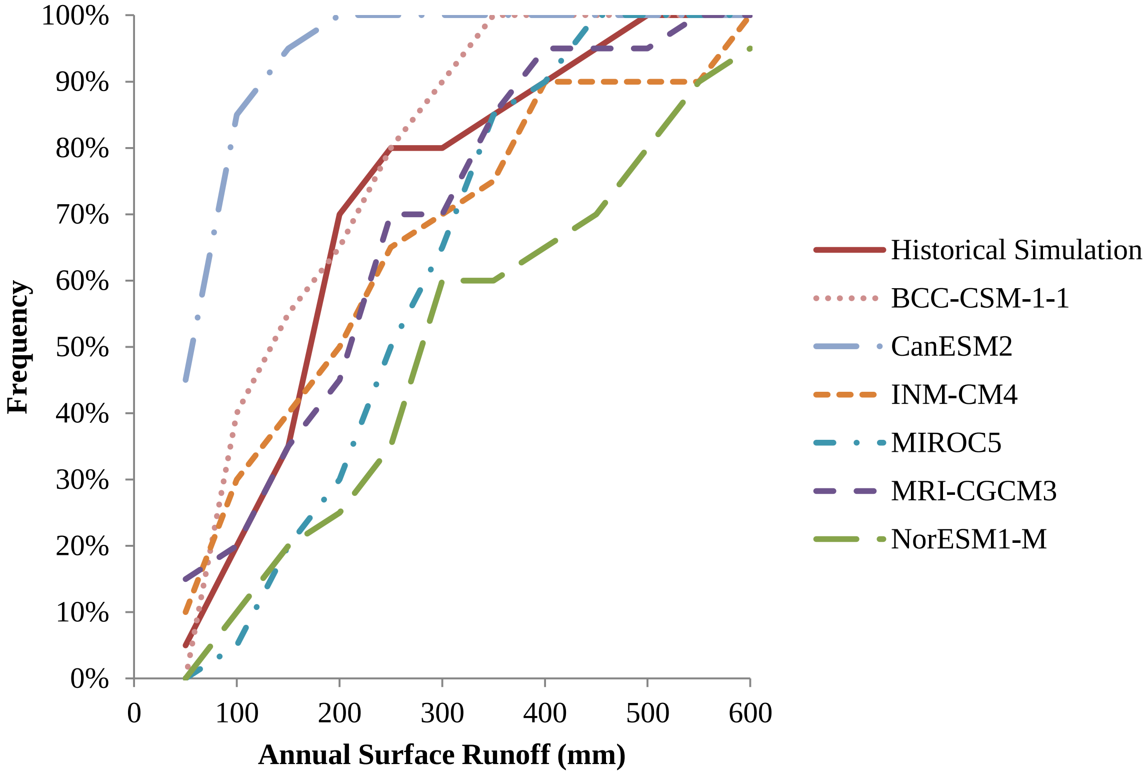


Figure 6.8│Cumulative distribution functions of simulated annual surface runoff totals for 1986-2005 versus six future simulations for the 2046-2065 time period.

6.3.5 Shifting sowing dates to adapt to climate change

The shift to earlier cropping seasons did not produce significant increases in crop yields, reflecting the lack of statistically significant change in the U-shape curve observed for West Africa for the sorghum crop. Rather, the increase in the frequency of longer dry spell events (c.f. Chapter 3) is likely to be the leading cause of decreased crop production by the 2050s. Water stress days indeed show a significant increase of 32% on average across models, from 21 days/year in the 1990s to 28 days/year by the 2050s. Unlike for the historical period, the use of RWH does significantly reduce the number of water stress days in the future.

6.4 Discussion – Adapting to climate change in Ziga

6.4.1Soil moisture trends and climate change perceptions

Chapter 5 outlined the risks associated with a poor perception of climatic changes, which could lead to maladaptation. At the Ziga field site, farmers were reporting lower rainfall amounts, where in fact there was an opposite historical trend. In addition, farmers reported RWH as an adequate adaptation strategy to cope with those perceived changes in the climate. Here, an attempt was made to correlate these perceptions with other environmental factors which may have an impact on crop production. It was found that soil moisture levels were in fact becoming significantly lower with time towards the end of the growing season. Indeed, the number of water stress days was also found to be increasing. This could be attributed to changing intra-seasonal rainfall patterns, but also to the accumulated effect of soil erosion. RWH can contribute to increasing soil moisture availability throughout the growing season, particularly towards the month of September. However, simulated effects on yields were not found to be significant. As harvest occurs in reality towards the end of October, rather than early October (c.f. Section 6.2.2.2), it can only be speculated that yield effects of reduced soil water availability towards the grain filling stages may be greater in reality than in simulations.

6.4.2 RWH as a combined strategy to improve water availability and soil fertility

While longer dry spells are unlikely to be fully mitigated through the use of strategies such as zaï pits, the latter should not be discarded through a fear of maladaptation. Rather, a range of strategies need to be considered in parallel with each other. In the case of Ziga, this could entail the implementation of a greater number of larger *ex situ* RWH structures to harvest excess surface runoff water from more frequent high intensity rainfall events. Water could be used to bridge longer dry spell events for which *in situ* RWH could be insufficient. In addition, RWH can have positive impacts on groundwater resources. In a survey conducted in the Yatenga province of Burkina Faso by Ouattara (2003), it was clear that farmers perceived positive impacts on groundwater availability due to RWH implementation: after RWH implementation the estimates of wells never drying out during a dry year increased from 56% to 77%, while estimates of the proportion of wells drying out shortly after the end of the rainy season in a dry year decreased from 9% to 3% (Reij and Thiombiano, 2003). This is supported by the simulations presented above, where deep percolation having the potential to recharge aquifers was significantly increased to the expense of surface runoff, simply with the use of zaï pits.

In addition to the high rainfall variability, soil fertility poses great challenges for crop production in Northern Burkina Faso. As this analysis has shown, the majority of yield improvements associated with the use of zaï pits cannot be attributed to increased water availability. Rather, the crops are severely limited by nutrient deficiency, as exemplified through the annual number of nitrogen stress days. Indeed, it has been reported in numerous studies that RWH strategies which are not combined with fertility management strategies often do not yield significant improvements in productivity (Sawadogo et al., 2008, Zougmoré et al., 2003).

Hence, several farmers use compost and/or manure, sometimes in conjunction with chemical fertilizers, in combination with RWH strategies. The composted manure is finer and of higher quality than the raw manure from small livestock, and generally produces higher yields (Sawadogo, 2012). A study using field measurements in Ziga in 2007 found that no manure/compost was used on 24% of fields, 1-5t/ha of manure/compost was applied on 56% of fields, and 5-10t/ha was used on the remaining 20% of fields (Ouedraogo et al., 2008). Interestingly, the same study noted that fields without RWH used on average 0.94±0.27t/ha of manure or compost, and fields with RWH used 2.1±0.29t/ha, showing that the two land management strategies go hand in hand. However, compost production is a difficult and expensive endeavour. One is required to have a number of tools and implements, including: a cart, a wheelbarrow, a shovel, and a fork. In addition, one needs a fair amount of straw from sorghum or millet, in addition to livestock manure. While compost needs to be watered and kept at a certain moisture content, water availability is not as much of a limiting factor as access to tools and compost raw material (Doro, 1991). Furthermore, Lowenberg-DeBoer et al. (1994) estimated that 1 m^3 of compost takes on average 16 hours of work to produce, and is hence quite labour intensive.

The role of RWH in the case of Ziga, while not only related to water as often portrayed, is nevertheless non-negligible. In fact, by reducing soil erosion, zaï pits trap nutrient locally and reduce the amount of manure or fertilizer necessary to apply to the otherwise heavily crusted soils. Furthermore, the long-term benefits of RWH from reducing soil erosion are very important. In a context where soils are already shallow and erosion by water is likely to increase significantly in the future (e.g. from 6.5ton/ha/year to 8ton/ha/year without RWH on the top of slope ferruginous soils), RWH could contribute to the preservation of agricultural land for future generations and therefore already forms a sustainable land management strategy.

6.4.3 RWH and cropping calendar flexibility

It was hypothesized that RWH could reduce the susceptibility of rainfed cropping systems to the high inter-seasonal variability in the start of the rainy season. Overall, this analysis shows little potential for RWH to increase the flexibility of cropping calendars. Rather, the future selection of better sowing dates based on long-term climate data observations and projections, as well as in-season rainfall monitoring and forecasts would be more beneficial in reducing risk. While RWH does significantly reduce water stress on crops and improve soil moisture, it cannot fully address the issue of low rainfall totals throughout the growing season, as well as more frequent dry spells of long duration. Current planting dates around June 15th or later seem already optimized to take advantage of an early rainy season onset, while mitigating the impacts of a later season onset.

Greater availability of relevant meteorological information, through forecasts and real time rainfall measurements for example, could lead to improved management decisions at the field level. Chapter 5 already discussed the implications for an innovative farmer of access to daily rainfall measurements in his decision-making process. This analysis re-iterates the need for wider access to long-term rainfall time series, as well as daily in-season rainfall data, to help farmers optimize cropping calendars under a changing climate, amongst other things. The simple methodology to determine agronomical rainy season onset presented in Chapter 5 (Ibrahim et al., 2012) could be adapted for use at the farm level under a changing climate.

6.4.4 Shifting sowing dates to adapt to climate change

The 2050s represent an interesting period for climate change analyses, as it is projected to be the first time where climate will depart from its recent natural variability (Mora et al., 2013). Indeed, it was shown in Chapter 4 that GCMs project robust increases in the frequency of dry spells lasting longer than 15 days over the Sahel, as well as changes in the growing season distribution of maximum duration dry spell events. Changing cropping calendars to address the latter changes was suggested earlier as a possible adaptation strategy. However, in the case of sorghum in West Africa, the changes in the distribution of maximum duration dry spells were not found to be statistically significant, and therefore a shift in sowing dates was not found to be particularly beneficial, nor was it detrimental, in the case of Ziga. Otherwise, in some instances, growing varieties with a shorter growth cycle could be beneficial.

6.5 Conclusions

In this Chapter, the different roles *in situ* RWH can play in current and future agricultural systems of Northern Burkina Faso were investigated using integrated hydrological and crop modelling. Overall, while the identification of the causes of the changes in water availability by farmers was erroneous, it was linked to real changes in soil moisture and crop water stress.

Importantly, it has been shown that while zaï pits have been termed RWH strategies, they are in fact integrated soil and water management strategies. Farmers indeed use zaï pits in combination with manure, but also with a range of other management strategies such as stone lines which also reduce overland flow velocity. These form complex, integrated, and optimized natural resources management systems which cannot fully be modelled in SWAT. Hence, benefits such as the protection of seeds from being flushed away in early season runoff events, the relative ease of removal of the soil surface crusts through digging small pits rather than ploughing when faced with a lack of agricultural implements or animals, or the fact that fertilizers are being concentrated for direct uptake by the plants, can easily be overlooked.

It is likely that *in situ* RWH will be a key strategy to adapt to climate change due to its ability to maintain (or increase, in the case of zaï with manure) soil water holding capacity in the longer term. RWH was found to continue to improve yields in the 2050s, with sorghum yield increases of 10% on average across GCMs. However, an overall significant decrease in yields associated with a changing climate renders the benefits from increased water availability through RWH marginal. An overall increase in high intensity rainfall events, leading to greater surface runoff totals and equivalently higher soil water erosion is of concern for the sustainability of agricultural production in the region.

No one solution will be able to address all climate change impacts on crop production in Northern Burkina Faso, and a range of adaptation strategies will be required to address the different changes in the climate. Unlike what is often thought, adaptation will not need to occur in a distant future. In fact, as the widespread adoption of improved soil and water management practices has taken several decades and serious institutional investments (c.f. Chapter 5), planning ahead and current investments will be required. This will involve the continued spread of *in situ* rainwater harvesting to mitigate the long-term impacts of soil water erosion, but also the development of strong meteorological networks to allow farmers to implement adequate short-term coping strategies such as optimized planting dates in the future.

Chapter 7

From impacts to transformation: A critical review of climate change adaptation literature in the field of agriculture and the framing of this thesis

7.1 Introduction

Throughout this thesis, an attempt has been made to assess the potential of rainwater harvesting strategies as an adaptation strategy to climate change. In Chapter 7, I undertake a meta-analysis of the agricultural adaptation literature, with a view of putting analyses in previous Chapters into the broader context of climate change adaptation research. The bibliometric analysis points to some significant changes occurring in the use of the term adaptation in the climate change literature. The approach used here provides further insight into why these changes might be taking place, and why it is important to acknowledge them to avoid omitting important implications for food security and to reduce the risk of maladaptation. Hence, I also investigate how global food security is being addressed within the agricultural adaptation literature, and what are the implications.

First, the methodology developed to analyse the very large body of adaptation literature is described, along with its limitations. Key findings are then highlighted with respect to their relationship with topics addressed throughout this thesis (e.g. uncertainties and perceptions). Subsequently, the first part of the discussion addresses the implications of the bibliometric analysis findings for global food security. This opens up a critical assessment of the methodological approach selected for this thesis, and whether or not it has fully reached its stated objectives. Finally, suggestions for innovative methodological approaches based on this integrated learning process are made.

7.1.1 Background

Climate change came to the forefront of the global policy agenda in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was ratified, aiming to reduce greenhouse gas emissions. Since then, emissions have continued to rise and climate change is now taking place at an unprecedented pace for which humanity faces the immediate need to adapt. Hence, the body of climate change adaptation literature has boomed in recent years, with the concept of adaptation having taken many forms. Several conceptualizations of the term have been suggested (e.g. Bassett and Fogelman, 2013, Smit and Wandel, 2006), and some have proposed that adaptation could be a new science (Meinke et al., 2009) or policy field (Massey and Huitema, 2013). Due to the rate at which adaptation literature has been evolving, there remains some confusion within the research community as to what climate change adaptation is and how can it contribute to meeting the global needs for food in the face of global environmental change. In fact, global food security is likely to be adversely affected by a changing climate, with a large body of literature outlining the negative impacts on crop production, for example (IPCC, 2014a).

7.2 Materials and methods

A search of the agricultural climate change adaptation literature was conducted in mid-August 2013 within the Web of Knowledge database. The search was limited to English language journal articles, for the key terms “climat*”& “chang*”& “adapt*”&“agricultur*” within the topic field. This search yielded 2308 journal articles published between 1992 and August 2013. The methodological process is summarized in Figure 7.1.

7.2.1 Data cleaning

As the evaluation of climate change impacts is often linked to adaptation recommendations, the difference between impacts and adaptation studies was not always discernible through the initial use of search terms. Furthermore, as the term “adaptation” originates from evolutionary biology (Smit and Wandel, 2006), results often referred to natural adaptations to environmental changes other than climate. Reading the abstracts to refine the search results was necessary to select only those with a key focus on climate change adaptation, using the definition of adaptation suggested by Moser and Ekstrom (2010) as presented in Chapter 1. Briefly, this definition of climate change adaptation calls for social-ecological systems responses to climate impacts that can range from short-term coping to deeper transformations, and that may not always be successful in meeting their stated impacts mitigation objectives.

Two types of papers were identified within the resulting body of literature. First, there are the publications which integrate adaptation options in impacts assessments (these were retained). Second, there are those that conclude climate change impacts assessment by saying there is a need for adaptation actions to mitigate the impacts of climate change. Such papers could be identified by phrases such as “these results might be used to inform adaptation” or “understanding impacts is important for adaptation”, and were excluded.

Of the total 2308 abstracts selected through the initial search, 32% (737) had adaptation to climate change in agriculture as a key focus. While some journals have a definite focus on climate change adaptation, the results from this analysis show that the literature is heavily scattered across a range of journals. While *Climatic Change* published more than 11%

of the journal articles analysed, the final body of literature came from 265 different journals (see Table 7.1).

Table 7.1 | Journals in which climate change adaptation for agriculture is most commonly discussed between 1992 and August 2013

Rank	Journal name	Abstract count	Fraction of all abstracts
1	Climatic Change	83	11.2%
2	Mitigation and Adaptation Strategies for Global Change	31	4.2%
3	Global Environmental Change	30	4.1%
4	Regional Environmental Change	18	2.4%
5	Climate Research	17	2.3%
6	Agricultural and Forest Meteorology	15	2.0%
7	PLOS ONE	13	1.8%
8	Climate and Development	9	1.2%
9	PNAS	8	1.1%
10 (1)	Climate Policy	7	0.9%
10 (2)	Environmental Research Letters	7	0.9%

7.2.2 Data classification

Through a second reading, the 737 abstracts were manually classified according to their geographical focus (i.e. Africa, North America, Latin America, Europe, West and Central Asia, China, Asia [other], Australia and New Zealand, Pacific, or no geographical focus) and their scale of analysis (i.e. field, local, regional, national, transnational, global, or no scale definition). This second reading of the selected abstracts identified key terms and themes used in keyword searches to identify trends in those topics within article titles and abstracts. These terms included: crop, drought, yield, livestock, climate analogue, post-harvest, vulnerability, perceptions, uncertainty, transformation, and impacts.

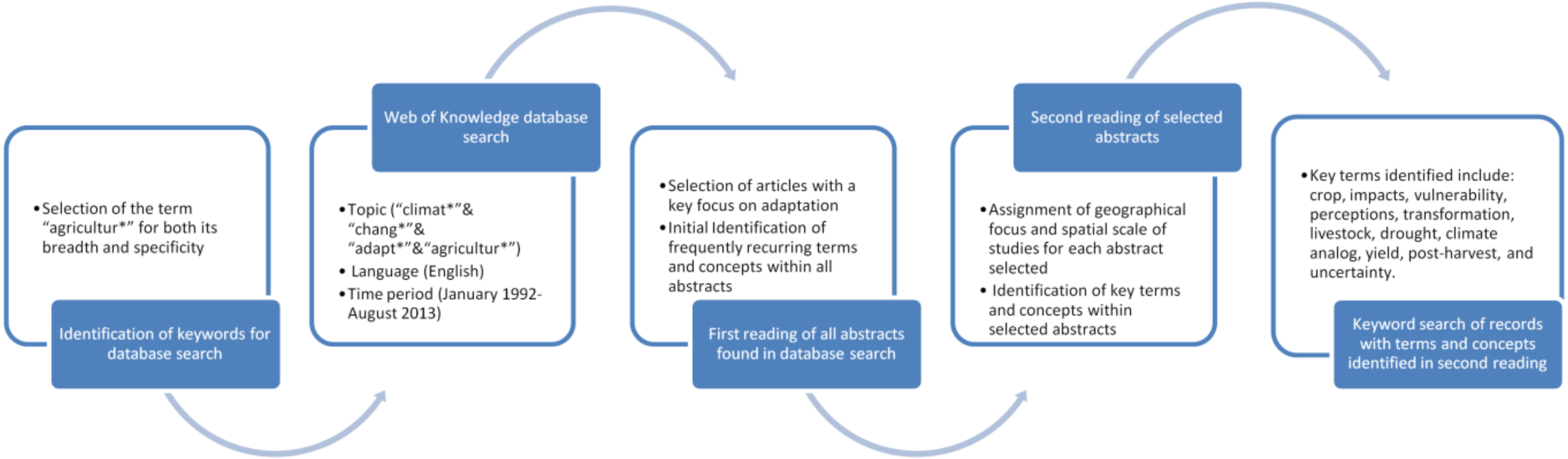


Figure 7.1 | Methodological process represented as a flowchart.

7.2.3 Methodological limitations

As in studies using a similar approach (e.g. Janssen et al., 2006), there are downsides to this methodology. For instance, other terminology can be used to describe forms of adaptation to climate change, including for example “climate resilient development” (Zaitchik et al., 2012), which can limit the retrieval of relevant publications. This is also the case for the selection of the term “agricultur*” rather than “food” or “food system” for example. The term “agricultur*” was preferred to these terms, as it relates specifically to a socio-ecological system (rather than any other biological system) and has more breadth than the latter term. Indeed, a search for the term “food system” rather that “agricultur*” yielded only 13 relevant results which were otherwise not found with the search term “agricultur*”. Complementary searches (e.g. food system, health sector) were performed for quick checks without in-depth analysis. Furthermore, limiting the search to English language publications is likely to induce a bias in the geographical distribution of the research.

7.3 Results

7.3.1 The geographical focus of agricultural adaptation literature has shifted from North America to Africa

Figure 7.2 depicts the evolution of the geographical focus in the selected literature from 1992 to 2013. It is clear that the focus has radically shifted from developed regions, especially North America, to least developed regions, particularly Africa. As early as 1996, a first review entitled “Adapting North American agriculture to climate change in review” was published (Easterling, 1996), an indicator that much of the earlier work in this field was being concentrated in those regions. While 32 articles focusing on North America were published between 1992 and 2006 (more than 25% of publications in that time period), only 48 were published in the period between 2007 and 2013 (7.7% of publications). In comparison, there were only 17 publications focusing on Africa in the early period from 1992 to 2006 (14% of publications), while there have been over 150 since 2007 (25% of publications). The shift towards Africa, occurring from 2008, could be explained by the increasing prevalence of the vulnerability approach to adaptation (Janssen et al., 2006), as consensus has grown towards Africa being highly vulnerable to climate change impacts in agriculture.

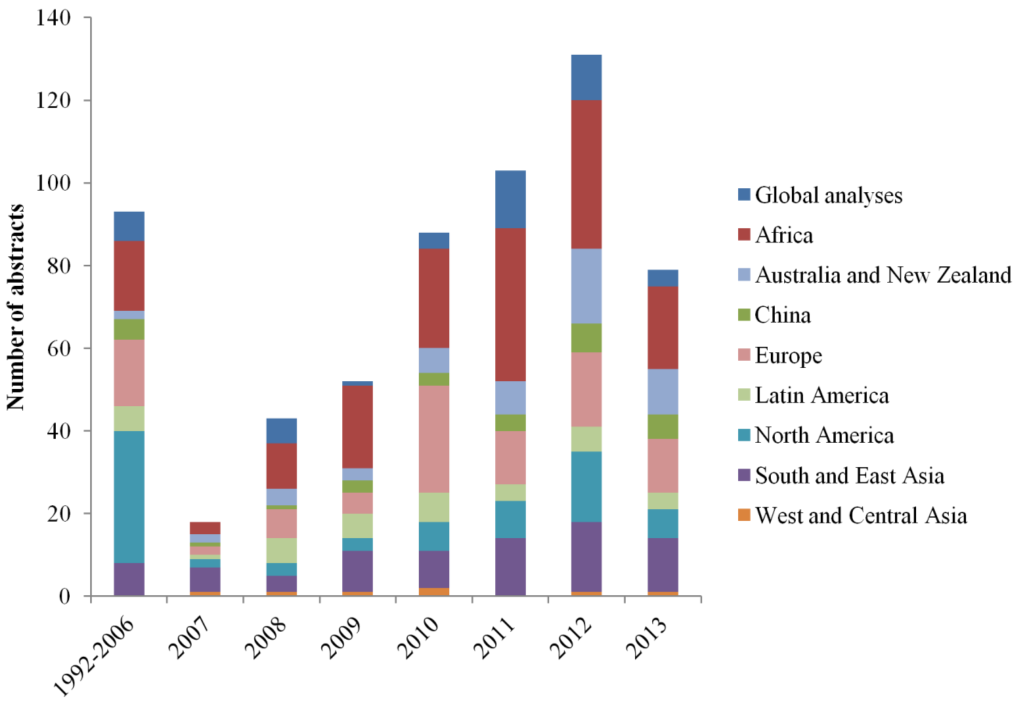


Figure 7.2 | Distribution of geographical focus of articles on climate change adaptation in the agricultural sector from 1992 to mid-2013. Due to the low number of early publications, annual data for 1992 to 2006 was aggregated to better visualize the recent trends in research.

7.3.2 Regional scale studies are the most common

Adaptation is a multi-scale process where understanding the interactions between scales is primordial to the successful implementation of adaptation policies and strategies (Adger et al., 2005). Here regional scale studies are found to have long been, and remain, the dominant form of adaptation studies (Figure 7.3). Field and local studies have become more prominent since 2007, as we move towards the implementation of recommendations from early large-scale impact studies. Simultaneously, the proportion of studies at a coarse spatial resolution (i.e. global, transnational, or national scale) has been decreasing (from as high as 50% over the 1992-2006 period to 36% since 2007), underlining the general consensus that adaptation is a highly localized and spatially dependent process. While national and regional adaptation studies can be useful in the policy realm to guide research investments, in practice anything beyond the local scale is difficult to implement (Wheeler and von Braun, 2013).

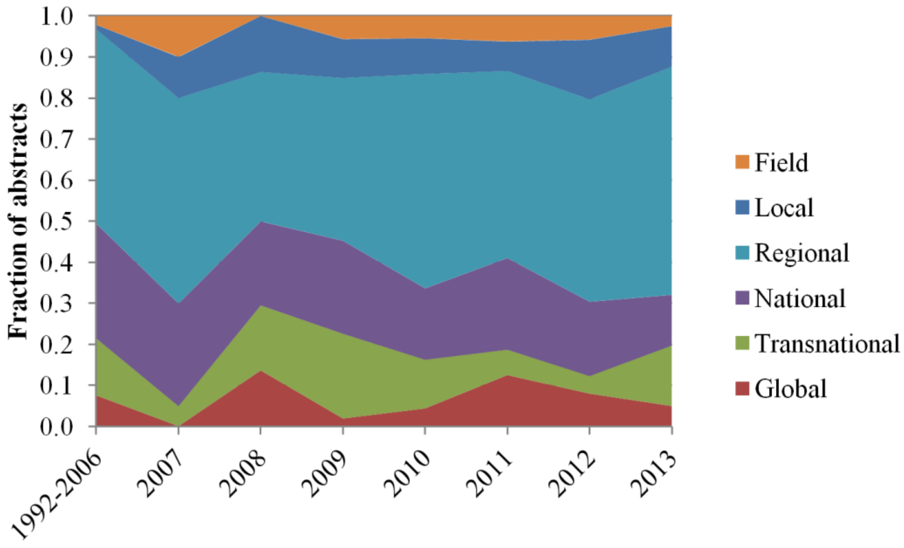


Figure 7.3 | Fraction of abstracts falling into each study scale category.

7.3.3 Perceptions of climate change and associated risk are increasingly being addressed

Adaptation research and policy has long been focused on quantifiable, material aspects of climate change, often ignoring its cultural dimensions (Adger et al., 2012). Human behaviour, including the willingness of farmers to address climate change impacts and invest in adaptation is greatly affected by their perceptions of climate change and associated risk. This aspect has been explored and seems to have gained momentum in adaptation research recently (Figure 7.4). There have been many studies regarding perception of climate change itself (e.g. Thomas et al., 2007, Mertz et al., 2009, Deressa et al., 2011, Manandhar et al., 2011, Osbahr et al., 2011, Silvestri et al., 2012, Simelton et al., 2013), but also of the perceptions of risks. Factors that affect the willingness of farmers to adapt to climate change have been explored more recently (e.g. Tucker et al., 2010, Saleh Safi et al., 2012, Asplund et al., 2013). The positive trend observed in Figure 7.4, especially between 2008 and 2012 (375% increase), regarding human perceptions could indicate that the importance of culture in adaptation is being acknowledged by the research community. However, little information is available regarding how a better understanding of these perceptions can inform adaptation policy.

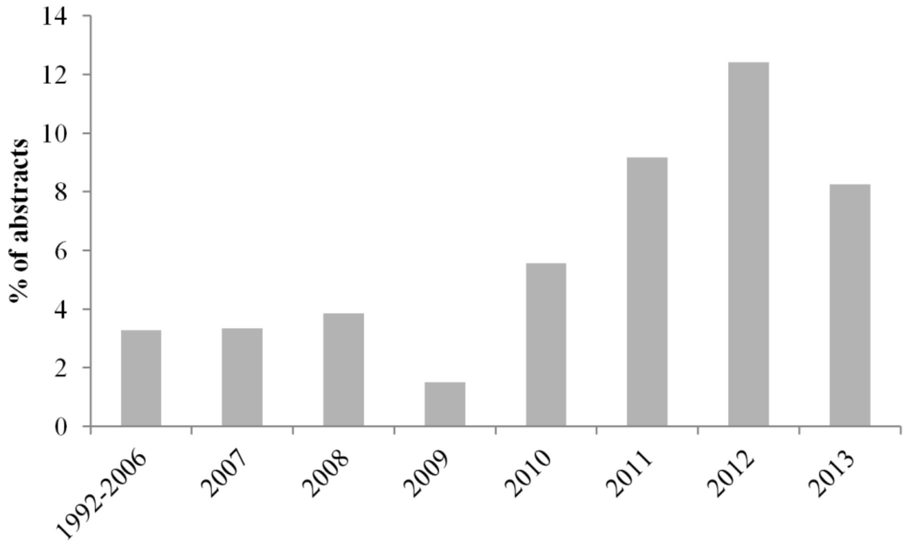


Figure 7.4 | Annual fraction of abstracts on climate change adaptation and agriculture including declinations of the term “perception”.

7.3.4 Few studies address the implications of uncertainties in adaptation decisions

At the core of climate change impact studies, as well as adaptation policies, are uncertainties. Despite the renewed awareness of the implications of the cascade of uncertainties in the climate change adaptation decision-making process (Wilby and Dessai, 2010), less than one fifth of the 737 abstracts reviewed were found to mention uncertainties, and often addressed them only to a very limited degree. A further investigation of the context in which the term is being used revealed that uncertainties in the agricultural climate change adaptation literature can be divided into three categories. First, the term is used to qualify the future climate, or more generally a state (e.g. “uncertain times”, “uncertain circumstances”, “uncertain future”), while not being directly addressed in the context of adaptation. Second, uncertainties can be quantified and characterized. For modelling specifically, the scenarios approach is generally used to handle the uncertainties associated with climate projections. Third, the concepts of risk management and vulnerability are used to address uncertainty. For example, it is being used a number of times in the context of agricultural insurance. A recurring assumption is that uncertainties are inherent to the climate and food systems. Adaptation should go on despite uncertainties, while addressing a range of possible outcomes. This widespread assumption could explain the lack of studies actually characterizing or quantifying uncertainties associated with climate change adaptation.

7.3.5 Transformation is increasingly used as a conceptualization of adaptation

Generally, two types of adaptation pathways are identifiable in the literature: incremental adaptation, and transformational adaptation. Park et al. (2012: 119) distinguish the two by "[...] the extent of change, in practice manifesting in either the maintenance of an incumbent system or process, or in the creation of a fundamentally new system or process". It was clear from the first reading of the 2308 retrieved abstracts from the initial database keyword search that the agricultural climate change adaptation literature is still strongly embedded within the impacts literature (c.f. section 7.2.1), and therefore generally use the incremental conceptualization of adaptation. Similarly to Bassett and Fogelman (2013), only a small fraction of abstracts selected here were found to refer to transformative adaptation (Figure 7.5). However, from 2010, the term "transformation" really began to emerge within the climate change adaptation literature. While the abstracts mentioning transformation still represent a minority of publications (just over 5% for 2013 up to mid-August), the trend since 2010 is clearly increasing (Figure 7.5). Moreover, the 2012 publication by Rickards and Howden entitled "Transformational adaptation: agriculture and climate change" is within the five most cited publications in that year (Table 7.2). The term "transformation", used in the context of adaptation, seems to have emerged from Australia, as about 44% of articles talking about transformative adaptation have been lead by Australian institutions. This could be linked to the fact that Australian agriculture is already facing a tipping point, going beyond the coping capacity of farmers, triggering the need for more than incremental adaptation (Marshall et al., 2012, Rickards and Howden, 2012).

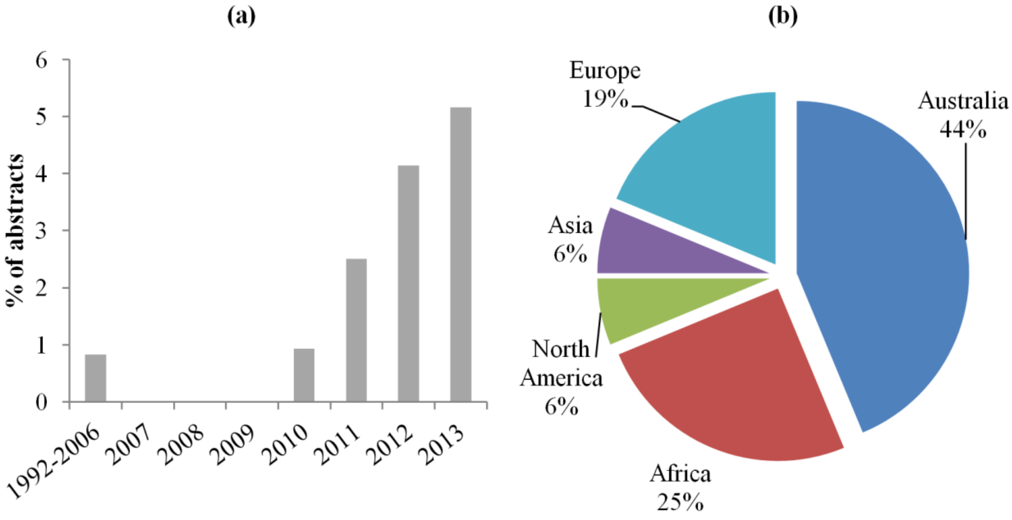


Figure 7.5 | Percentage of agricultural abstracts with the term "transform*" (a), and distribution of agricultural abstracts containing the term "transform*" by location of lead author institution (b).

7.3.6 The agricultural adaptation literature largely emerges from crop modelling impact studies

The keyword searches based on common terms or themes identified within the refined database (c.f. Figure 7.1) showed that a large fraction of research is addressing the production part of the food system. For instance, 26% of abstracts explicitly mention crop yields, of which 50% concern maize, wheat, and/or rice (Figure 7.6). Otherwise, 18.5% of articles focus specifically on climate change induced drought, especially in dryland areas which are highly vulnerable to changes in precipitation patterns. Less than 1% of articles mention nutrition (including the “food systems” additional abstracts). The lack of research on the links between agricultural production and nutrition could be due to the cleavage between the agricultural and health sectors. However, further investigation revealed that within the health sector as well, nutrition is addressed in less than 9% of publications in the context of climate change adaptation.

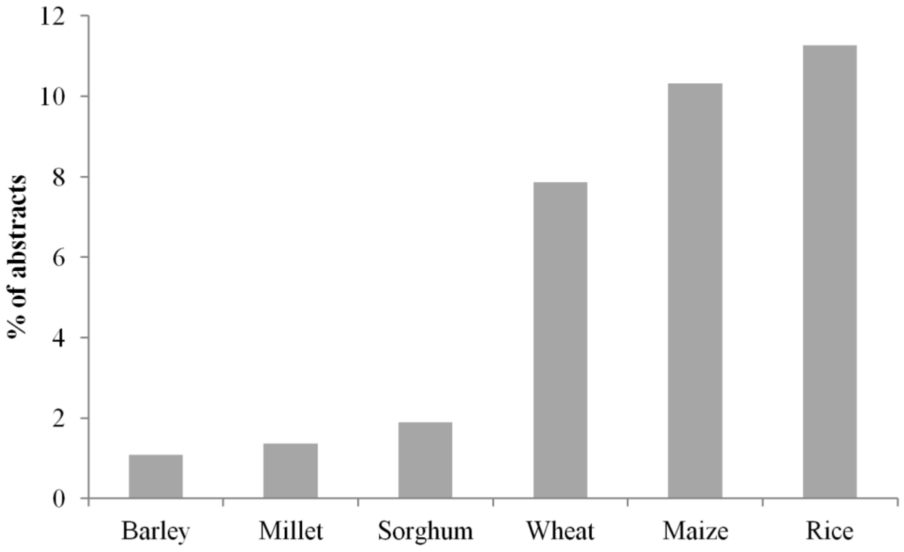


Figure 7.6 | Identification of the most frequently studied crops for climate change adaptation.

Of the ten most cited articles throughout the entire time period investigated (Table 7.3), none mention livestock, post-harvest technologies, or transformation. Only 3 mention vulnerability, while a majority (6) talk of impacts. Furthermore, within the top five most cited papers of each of the last 5 years (i.e. a total of 25 abstracts), 44% explicitly mention impacts, while only 12% explicitly mention vulnerability. Only 16% have a focus on livestock, while 48% included the term “crop” in their abstracts. These basic statistics reiterate the roots of the majority of the current adaptation literature: climate change impacts assessments through crop production modelling.

Table 7.2│Top 5 most cited papers on climate change adaptation for agriculture, for each year between 2008 and 2012[2]

Times cited	Year	Authors	Title	Journal
34	2008	Ben Salem, H; Smith, T	Feeding strategies to increase small ruminant production in dry environments	SMALL RUMINANT RESEARCH
30	2008	Jagadish, SVK; Craufurd, PQ; Wheeler, TR	Phenotyping parents of mapping populations of rice for heat tolerance during anthesis	CROP SCIENCE
27	2008	Reenberg, A; Birch-Thomsen, T; Mertz, O; Fog, B; Christiansen, S	Adaptation of Human Coping Strategies in a Small Island Society in the SW Pacific-50 Years of Change in the Coupled Human-Environment System on Bellona, Solomon Islands	HUMAN ECOLOGY
27	2008	Seo, SN; Mendelsohn, R	An analysis of crop choice: Adapting to climate change in South American farms	ECOLOGICAL ECONOMICS
27	2008	Ingram, JSI.; Gregory, PJ.; Izac, AM	The role of agronomic research in climate change and food security policy	AGRICULTURE ECOSYSTEMS & ENVIRONMENT
62	2009	Thornton, PK.; Jones, PG.; Alagarswamy, G; Andresen, J	Spatial variation of crop yield response to climate change in East Africa	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS
59	2009	Jeppesen, E; Kronvang, B; Meerhoff, M; Sondergaard, M; Hansen, KM.; Andersen, HE.; Lauridsen, TL.; Liboriussen, L; Beklioglu, M; Ozen, A; Olesen, JE	Climate Change Effects on Runoff, Catchment Phosphorus Loading and Lake Ecological State, and Potential Adaptations	JOURNAL OF ENVIRONMENTAL QUALITY
48	2009	Mertz, O; Mbow, C; Reenberg, A; Diouf, A	Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel	ENVIRONMENTAL MANAGEMENT
44	2009	Burke, MB.; Lobell, DB; Guarino, L	Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS
41	2009	Deressa, TT; Hassan, RM; Ringler, C; Alemu, T; Yesuf, M	Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS
72	2010	Ahuja, I; de Vos, RCH; Bones, AM; Hall, RD	Plant molecular stress responses face climate change	TRENDS IN PLANT SCIENCE
48	2010	Schlenker, W; Lobell, DB	Robust negative impacts of climate change on African agriculture	ENVIRONMENTAL RESEARCH LETTERS
42	2010	Thomson, LJ; Macfadyen, S; Hoffmann, AA	Predicting the effects of climate change on natural enemies of agricultural pests	BIOLOGICAL CONTROL
40	2010	Tirado, MC; Clarke, R; Jaykus, LA; McQuatters-Gollop, A; Franke, JM	Climate change and food safety: A review	FOOD RESEARCH INTERNATIONAL
39	2010	Falloon, P; Betts, R	Climate impacts on European agriculture and water management in the context of adaptation and mitigation-The importance of an integrated approach	SCIENCE OF THE TOTAL ENVIRONMENT
26	2011	Tscharntke, T; Clough, Y; Bhagwat, SA; Buchori, D;	Multifunctional shade-tree management in tropical agroforestry	JOURNAL OF APPLIED ECOLOGY

		Faust, H; Hertel, D; Hoelscher, D; Juhrbandt, Jana; Kessler, M; Perfecto, I; Scherber, C; Schroth, G; Veldkamp, E; Wanger, TC	landscapes - a review	
24	2011	Thornton, PK; Jones, PG; Ericksen, PJ; Challinor, AJ	Agriculture and food systems in sub-Saharan Africa in a 4 degrees C+ world	PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL PHYSICAL AND ENGINEERING SCIENCES
18	2011	Bindi, M; Olesen, JE	The responses of agriculture in Europe to climate change	REGIONAL ENVIRONMENTAL CHANGE
17	2011	Lal, R; Delgado, JA; Groffman, PM; Millar, N; Dell, C; Rotz, A	Management to mitigate and adapt to climate change	JOURNAL OF SOIL AND WATER CONSERVATION
16	2011	Lin, BB	Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change	BIOSCIENCE
9	2012	West, JS; Holdgate, S; Townsend, JA; Edwards, SG; Jennings, P; Fitt, BDL	Impacts of changing climate and agronomic factors on fusarium ear blight of wheat in the UK	FUNGAL ECOLOGY
7	2012	Hakala, K; Jauhiainen, L; Himanen, SJ; Rotter, R; Salo, T; Kahiluoto, H	Sensitivity of barley varieties to weather in Finland	JOURNAL OF AGRICULTURAL SCIENCE
6	2012	Ziska, LH; Bunce, JA; Shimono, H; Gealy, DR; Baker, JT; Newton, PCD; Reynolds, MP; Jagadish, KSV; Zhu, C; Howden, M; Wilson, LT	Food security and climate change: on the potential to adapt global crop production by active selection to rising atmospheric carbon dioxide	PROCEEDINGS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES
6	2012	Rickards, L; Howden, S M	Transformational adaptation: agriculture and climate change	CROP & PASTURE SCIENCE
5	2012	Chhetri, N; Chaudhary, P; Tiwari, PR; Yadaw, RB	Institutional and technological innovation: Understanding agricultural adaptation to climate change in Nepal	APPLIED GEOGRAPHY

[2] Results presented from search conducted mid-August 2013 in the Web of Knowledge database.

Table 7.3 | Top ten most cited articles on climate change adaptation for agriculture, between 1992 and mid-2013[1]

Times cited	Year	Authors	Title	Journal
515	1994	Rosenweig, C; Parry, ML	Potential impact of climate change on world food supply	NATURE
408	2008	Lobell, DB; Burke, MB; Tebaldi, C; Mastrandrea, MD; Falcon, WP; Naylor, RL	Prioritizing climate change adaptation needs for food security in 2030	SCIENCE
272	2002	Olesen, JE; Bindi, M	Consequences of climate change for European agricultural productivity, land use and policy	EUROPEAN JOURNAL OF AGRONOMY
227	2000	Smith, B; Burton, I; Klein, RJT; Wandel, J	An anatomy of adaptation to climate change and variability	CLIMATIC CHANGE
204	2007	Howden, SM; Soussana, JF; Tubiello, FN; Chhetri, N; Dunlop, M; Meinke, H	Adapting agriculture to climate change	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA
121	2003	Luers, AL; Lobell, DB; Sklar, LS; Addams, CL; Matson, PA	A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS
108	1997	Smithers, J; Smit, B	Human adaptation to climatic variability and change	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS
86	2003	Tan, GX; Shibasaki, R	Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration	ECOLOGICAL MODELLING
80	2007	Morton, JF	The impact of climate change on smallholder and subsistence agriculture	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA
79	2008	Ortiz, R; Sayre, KD; Govaerts, B; Gupta, R; Subbarao, GV; Ban, T; Hodson, D; Dixon, J A.; Ortiz-Monasterio, JI; Reynolds, M	Climate change: Can wheat beat the heat?	AGRICULTURE ECOSYSTEMS & ENVIRONMENT

Results presented from search conducted mid-August 2013 in the Web of Knowledge database.

7.3.7 Implications of adaptation for supply chain management are rapidly emerging

Very few articles seemed to address primarily climate change adaptation and post-harvest management (Stathers et al., 2013) or implications for the agricultural supply chain (Jacxsens et al., 2010, Bellon et al., 2011, Ramirez-Villegas et al., 2012). Similarly, of the numerous agriculture-specific adaptation options mentioned in the IPCC AR4 (IPCC, 2007b), none related specifically to post-harvest agriculture. However, a closer investigation of the top five most cited papers of each of the last 5 years (Table 7.2) revealed that there is in fact a growing body of literature addressing post-harvest management relative to food safety and climate change (c.f. Tirado et al., 2010). An updated investigation of articles citing the work of Tirado et al. (2010) conducted in March 2014 revealed that a significant number of new publications are beginning to address implications of climate change impacts on food safety for adaptation, including supply chain management (van der Spiegel et al., 2012, Tirado et al., 2013, Stathers et al., 2013, Lake et al., 2012, Dwivedi et al., 2013, Dasaklis and Pappis, 2013, Balbus et al., 2013).

7.4 Discussion

7.4.1 Critique of meta-analysis results

Climate change will very likely impede our ability to consistently provide not only a sufficient amount of food to a growing world population, but also safe and nutritious food. This is what the Food and Agriculture Organization of the United Nations (FAO) has coined “food security”; a four-dimensional concept comprising the availability of sufficient food, access by individuals to this food, utilization of food in a safe and nutritional manner, and stability through consistent access to food independently of external shocks including climate extremes (FAO, 2008). Without adequate adaptation of the agricultural sector to the impacts of climate change, food insecurity could become ubiquitous in several regions. Hence, this Chapter attempted to answer the following question: How is global food security being addressed within the agricultural adaptation literature, and what are its implications?

First, the climate change adaptation literature focuses predominantly on food availability through crop production. An obvious cause of the heavy focus by impacts modellers on crop production is the complexity of the global food system, and the limited ability of current agronomic models to reproduce these intricacies (Wheeler and von Braun, 2013). This scientific approach to adaptation has led to shortcomings in the analysed literature which could have important repercussions for food availability at different levels. One of them is the quasi-absence of post-harvest agriculture in the adaptation literature, other than food safety. However, implementing better post-harvest strategies will be necessary to sustain a growing need for food, as climate change might be associated with greater post-harvest losses (Milgroom and Giller, 2013). Also, very little attention has been given up to now to malnutrition in the context of climate change adaptation in agriculture. However, several studies have shown that the nutritional value of food is likely to change with a changing climate (IPCC, 2014a). A change in the nutritional value of different crops could mean that the assumptions made about production needs are wrong, as the edible portion of these agricultural products could be changing.

Another weakness of the body of literature analysed is the heavy focus of recent studies on increasing African agricultural productivity in the face of increasing climate stresses, rather than taking a global approach to food availability and access involving global trade for example, and potentially exploiting benefits from a changing climate in northern regions. Furthermore, new transportation needs could arise from the changes in the types of crops produced, and various climate pressures on the infrastructure could reduce the supply of food for some communities (Attavanich et al., 2013).

7.4.2 Critique of related thesis outcomes

This thesis presents several similarities with the bulk of the literature presented above. I list those main similarities below:

1. Like most adaptation researchers, I began this work with a mainstream understanding of adaptation as an incremental and science-based concept. Using this conceptualization means that I did not consider complex social changes (taking place now and in the future) to the systems I was studying. Therefore, it is difficult to fully assess the potential of RWH as an adaptation strategy.
2. My work has been very much embedded in the impacts literature, especially assessing impacts on yields such as Chapter 3. I also looked at a limited number of staple crops, with a production-centric approach, when perhaps I should have looked at impacts on access to a nutritious diet both in terms of calories and contents. For instance, RWH could help achieving a balanced diet by allowing intercropping between cereal crops and groundnuts for example, which is a great alternative source of proteins.
3. Like the bulk of the recent research on climate change adaptation in agriculture, my work has focused on Africa, a region deemed highly vulnerable to a changing climate, and for which rainwater harvesting has often been cited as a potential adaptation strategy.
4. Uncertainties were addressed with regards to climate change projections, were quantified and characterized. I used a range of scenarios, models, and bias correction methods to address such uncertainties (c.f. Chapters 4 and 6). Model uncertainty was addressed more in depth in the dry spell analysis in Chapter 4, through the computation of the robustness, which evaluates the signal to noise ratio (i.e. if uncertainties are larger than the projected change).
5. Like a growing number of academics, I addressed climate change perceptions as the entry point for adaptation decision-making. I also addressed the issue of maladaptation due to institutional push for certain technical solutions, which is not necessarily based on good science and an understanding of uncertainties. For instance, results

> from dry spell analyses and biophysical modelling lead me to question whether RWH will continue to be beneficial for farmers in Northern Burkina Faso, despite farmers being convinced that RWH is one of the best ways to adapt to a changing climate.

Fully taking such considerations into account might not have been feasible in the framework of this PhD thesis, considering the large uncertainties associated with human behaviour and decision-making processes. Suggestions are made in the next section to promote innovation in adaptation science research.

7.4.3 Suggestions for future research based on integrated learning outcomes

The current rapid increase in the body of adaptation literature and the lack of agreement on its definition poses the risk that the root causes of poverty and vulnerability to climate change will be circumvented, and that research will continue to yield technical solutions to a deeply socio-economic issue. In fact, as adaptation literature is shifting significantly towards least developed regions and particularly Africa, one should expect to see a recrudescence in literature taking a climate change mainstreaming approach. That is, vulnerability and adaptation measures should be assessed in the context of general development policy objective (Halsnaes and Traerup, 2009), rather than independently. This could be taking the form of transformational adaptation, as livelihood transitions occur through poverty reduction, and the rural contexts are likely to be changing rapidly.

Finally, the prevalence of the incremental conceptualization of adaptation also means that the body of literature is largely based on the assumption that one aims to maintain, or stabilize, the functions of the agricultural systems in the face of climate change. A good example is the assumption that in the future people will continue to have diets similar to the ones they have today, reflected in how research outputs chiefly focus on a limited number of staple crops (i.e. wheat, maize and rice). To ensure a good utilization of food in the future, more consideration will have to be given to high protein crops such as chickpeas or groundnuts (Frison et al., 2011), but also to climate change adaptation in the area of livestock production due to a growing global demand for meat. In addition, focusing on the stability of agricultural systems can reduce their resilience by reducing their diversity, and diminish their adaptive capacity by eliminating feedback mechanisms that make adaptation possible (Berardi et al., 2011). Moving to forms of adaptation involving deeper socio-economic transformations could allow handling more intense climatic shocks, but also possibly very different climates altogether. Indeed, adaptation cannot continue to be about the conservation of things we currently value (Rickards, 2013), as this could lead to the inability of agricultural systems to deal with unprecedented weather events and cause severe shocks to the food system. While it has been argued elsewhere that there are limits to adaptation of social systems, and that transformation occurs as a failure to adapt (Dow et al., 2013), shifting concerns away from maintaining current system functions would promote outside the box thinking and truly innovative solutions to unprecedented environmental challenges.

Chapter 8

Synthesis, key findings, and future directions for research

8.1 Introduction

In this thesis, focus is given to one of the world's most vulnerable regions to climate change: the rainfed agricultural land of Africa. The potential of simple technologies categorized as rainwater harvesting to help rural populations of Africa adapt to climate change is evaluated, using a comprehensive approach. This approach ranges from climate data analysis and biophysical modelling at different scales, to an analysis of factors affecting adoption, before analysing the conceptualizations of the term adaptation in the agricultural literature. While the methodological limitations have been discussed in Chapter 7, this Chapter summarizes the key findings from this thesis, and identifies areas of interest for future research.

8.2 Synthesis and key findings

Assessing the potential of RWH as an adaptation strategy is a complex procedure, illustrated by the range of methodologies used to address this question throughout this thesis. It has been shown that RWH can be used as an adaptation strategy to climate change in rainfed Africa, but the magnitude of benefits may be lower than anticipated. Below are summarized the thesis key findings from Chapters 3 to 6, providing clear evidence of this positive, yet limited, ability of RWH systems to mitigate the negative impacts of climate change.

First, it was shown in Chapter 3 through a simple modelling approach using publicly accessible climate datasets, that several regions of Africa can benefit today from the increased water availability provided by RWH. Benefits will continue to be seen in the 2050s, but will often be of a lower magnitude. Due to an increase in aridity in some regions, the technologies may require lower cropping densities to provide sufficient water to improve yields. That is, RWH may not provide sufficient yield improvements to justify the reduction in the total crop production per land area cropped associated with lower cropping densities. The Chapter 3 analysis provides a "big picture" of the RWH potential at the continental-scale, but is limited as it does not consider daily rainfall patterns or the relationships between soil fertility and water (e.g. water use efficiency).

Key findings from Chapter 3:

- A decrease in cropping density with RWH use to fully meet crop water requirements by the 2050s is projected for Southern Africa, while the Sahel does not see significant changes in RWH design requirements.
- Projected changes in crop water requirements vary between 1% and 25% increases, on average.

- Southern and Eastern Africa, as well as small parts of the Sahel, are key regions which are expected to see increasing benefits from rainwater harvesting for crop production.
- Rainwater harvesting could help bridge on average 31% of crop water deficits by the 2050s (~25% less than the 1990s), a non-negligible amount which could contribute to reducing the dependence on groundwater resources.
- Maize crops, as opposed to less water stress sensitive crops such as sorghum and millet, benefit significantly from rainwater harvesting with projected mean yield increases of 14-50% (5-6% for sorghum and millet).

Second, Chapter 4 addresses the issue of changing intra-seasonal rainfall patterns at the global scale, which are likely to also impact RWH performance in the future. Findings show that Africa and South Asia are the two regions which are most likely to see significant changes in rainfall patterns during crop growing seasons, and which will likely have adverse effects on crop production. Analyses are conducted for the CMIP5 ensemble, for the growing seasons of maize, millet, and sorghum.

Key findings from Chapter 4:

- There will likely be a significant increase in the frequency of very long dry spells (i.e. more than 15 consecutive dry days) by the 2050s compared to the 1990s over large parts of the Sahel and Southern Africa.
- The fraction of dry days is likely to increase significantly, while rainfall totals are projected to increase over large regions. This leads to the conclusion that high intensity rainfall events will be more frequent, yet highly interspersed throughout crop growing seasons.
- A significant shift in the timing of maximum seasonal duration dry spell events, particularly over East Africa and South Asia, occurs at the detriment of water sensitive growth stages.
- Dry spells analyses provide greater insight for agricultural adaptation than previous studies limited to annual timescales (e.g. long-term planning for crop breeding).
- Analyses of current intra-seasonal best practices based on the optimization of precipitation patterns to meet crop water requirements, such as the U-shape analysis, could inform adaptation decision-making.
- RWH alone is likely not going to be sufficient to address the significant changes in intra-seasonal rainfall patterns described.

Third, Chapter 5 uses a mixed-methods approach to investigate socio-economic barriers to the adoption of RWH, and how it might relate to climate change adaptation potential. It is found that very few key socio-economic factors can be consistently linked to RWH adoption across three selected field sites in Burkina Faso, Ethiopia, and Tunisia. However, farmers perceive a range of benefits from RWH which could be interesting for adaptation purposes. In Burkina Faso, focus group activities revealed that farmers thought of RWH as a core adaptation strategy.

Key findings from Chapter 5:

- Adoption rates of RWH are higher at the three field sites studied than presented in other studies, which could be attributed to extensive institutional interventions promoting the use of such technologies.
- In Burkina Faso, adoption of RWH is linked to access to fertilizer inputs (particularly manure). Female farmers are therefore less likely to use RWH.
- A majority of farmers believed that RWH would allow them to produce higher value crops and a greater diversity of crops.
- Several farmers reported that RWH allowed them to crop land otherwise too degraded for production.
- There is no clear correlation between climate change perceptions by farmers in Burkina Faso and local trends in climate observations.
- Despite the discrepancy between climate change perceptions and reality, farmers in Burkina Faso anticipate using more RWH to adapt to the impacts of a changing climate.

Finally, Chapter 6 uses Burkina Faso as a case study, to evaluate how climate change perceptions identified in Chapter 5 relate to other environmental change. Furthermore, it attempts to clarify at a higher spatio-temporal resolution than Chapter 3 the biophysical potential of RWH, specifically zaï planting pits as an *in situ* RWH strategy. For instance, an attempt is made to quantify the constraints and opportunities for crop production of factors such as increased dry spell intensity and frequency, reduction of soil erosion, and the combined effects of RWH and fertilizers. Results should not be interpreted as a perfect representation of the system, but rather help identify areas of concern for RWH performance. This includes, for example, concerns about the impact of future rainfall intensity on the ability of RWH to reduce soil erosion and the role of RWH in trapping nutrients.

Key findings from Chapter 6:

- Perceptions of decreased rainfall could be linked to decreased soil moisture and increased crop water stress, associated with reduced soil water storage capacity due to long-term soil erosion.
- Zaï pits without manure provide marginal sorghum yield benefits of 7% on average for the 1990s and 10% for the 2050s.
- Zaï pits reduce soil erosion significantly, but a greater frequency of high intensity rainfall events in the 2050s will reduce their ability to mitigate erosion to sustainable levels (i.e. ~ 1ton/ha/year) on their own.
- Unlike for the 1990s, the use of RWH does significantly reduce the number of water stress days in the 2050s.
- Zaï pits were not shown to significantly increase the flexibility in sowing dates.
- *In situ* RWH help maintain and/or increase soil water holding capacity in the long term.
- Effective and affordable soil fertility management is an integral part of the benefits brought by zaï pits.
- Zaï pits are really integrated soil and water management strategies.

Overall, RWH could be an integral part of “adaptation packages” aimed at addressing the negative impacts of climate change on crop production and reducing the food insecurity across Africa. It will be key for institutions responsible for agricultural development to take a holistic approach to adaptation, and avoid promoting single technical solutions, which could otherwise reduce the adaptive capacity of farmers. To gain levels of adoption which could have a significant impact on national level production, it will take time and significant investments in training, raw materials, and agricultural implements. Yield improvements associated with an increase in water availability remain marginal when compared to additional production needs related to an increasing population, unless they are combined with improved fertility measures. Indeed, *in situ* RWH as found in Northern Burkina Faso (e.g. zaï pits) was found to be not only a micro-catchment for water storage, but also an effective fertilization method where soils have low infiltration rates and mechanical ploughing may be too expensive of an alternative. *In situ* RWH can also act to reduce soil erosion, which is an important long-term benefit, and reduces the vulnerability of rainfed agricultural systems to intense rainfall events.

8.3 Future directions for research

Several opportunities for future research have been identified throughout this thesis, which are of particular interest to agricultural development in Africa. These have been divided into two main themes: 1) Mainstreaming climate change adaptation, and 2) Reconceptualising adaptation research for greater impact.

8.3.1 Mainstreaming climate change adaptation

The question of funding climate change adaptation is one that is not widely addressed in the climate change literature. While specific funds have been created for adaptation finance in developing countries, such as the UN Adaptation Fund and the Green Climate Fund, it remains somewhat unclear what is an adaptation project versus what constitutes an attempt to meet general development goals. Funding projects to address specific impacts such as flood defences in response to seas level rise is relatively straightforward. On the other hand, when it comes to agriculture, the problems are more complex. For instance, should we ensure that seemingly short-term coping strategies such as the use of *in situ* rainwater harvesting are eligible for climate change adaptation specific funding? And if so, is it because it might increase adaptive capacity at the farm level?

Moreover, distinguishing between short-term coping strategies and long-term adaptation needs is more complex in the field of agriculture, but is of consequence for adaptation planning. As presented in Chapter 4, novel approaches to climate change adaptation could be based on a better understanding of the current meteorological processes that lead to certain decisions at the field level (e.g. cropping calendars). If adaptation goals are to remain independent from development objectives, understanding changes in seasonal meteorological processes would be valuable in determining short-term needs versus long-term strategies, and perhaps inform adaptation funding needs.

On the other hand, the current tendency of considering climate change adaptation and general development objectives in isolation may be counterproductive. Gaining a better understanding of the common objectives, as well as how their governance structures relate to each other, could provide a more effective way of tackling adaptation challenges. A key question which remains with regards to the WAHARA project is how climate change adaptation is institutionalized across the 3 study sites in Africa, and how are these institutional environments affecting current uptake of climate-smart agriculture, or even rainwater harvesting? How can climate change adaptation projects be mainstreamed into development objectives, to avoid overlapping projects and waste of highly needed development money?

8.3.2 Reconceptualising adaptation research for greater impact

The meta-analysis presented in Chapter 7 revealed some important discrepancies between adaptation research and on-the-ground needs of communities and policy-makers. For instance, while supply chain management and post-harvest agriculture are barely addressed in the mainstream climate change literature, they are key initiatives which are of interest to governments and agricultural businesses, as well as part of projects regularly funded by the UN Adaptation Fund (UNAF, 2014). Again, this tends to show that adaptation research is disconnected from the reality of policy-making, with a heavy focus on quantifiable climate impacts and the preservation of current biophysical systems functions (i.e. incremental adaptation). The concept of transformational adaptation may not be the best alternative to incremental adaptation, as it may be difficult to apply to adaptation research and planning. However, conceptualizing adaptation as a process of change rather than a set outcome would be an important step forward. This would allow for considerations of uncertainties in adaptation decisions, and particularly of the uncertainties involved in human responses to a changing climate (e.g. mitigation of greenhouse gas emissions). This could mean going back to the fundamental concepts of climate change vulnerability, both biophysical and socio-economic, for the adaptation research community. And indeed, another important question may be: How is vulnerability to climate change related to adaptation conceptualizations and research outcomes in the field of agriculture?

Finally, to promote food security under a changing climate, more research is required on developing trade networks for example, and socio-economic change has to be taken into account for research outputs to be of relevance to policy-makers. Addressing the complexity of food systems’ resilience to climate change will require novel, holistic, and interdisciplinary research approaches which are currently slowly arising (e.g. community-based adaptation), and for which projects such as WAHARA could be key entry points.

Appendix A

General Circulation Models Summary Table

Model name	Modelling Group	Country	Resolution
ACCESS1-0	Australian Community Climate and Earth-System Simulator	Australia	1.25 x 1.875 deg
BCC-CSM1-1	Beijing Climate Center	China	2.8125 x 2.8125 deg
BNU-ESM	Beijing Normal University—Earth System Model	China	2.8125 x 2.8125 deg
CanESM2	Canadian Centre for Climate Modelling and Analysis	Canada	2.813 × 2.790 deg
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization	Australia	1.875 x 1.875 deg
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	USA	2.5 x 2.0 deg
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	USA	2.5 × 2.0 deg
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	USA	2.5 × 2.0 deg
INM-CM4	Institute for Numerical Mathematics	Russia	2 x 1.5 deg
IPSL-CM5A-LR	Institut Pierre Simon Laplace	France	3.75 x 1.875 deg
IPSL-CM5A-MR	Institut Pierre Simon Laplace	France	3.75 x 1.875 deg
IPSL-CM5B-LR	Institut Pierre Simon Laplace	France	3.75 x 1.875 deg
MIROC5	Model for Interdisciplinary Research on Climate - AOEI, NIES, JAMSTEC	Japan	1.40625 x 1.40625 deg
MPI-ESM-LR	Max Planck Institute for Meteorology	Germany	1.875 x 1.875 deg
MPI-ESM-MR	Max Planck Institute for Meteorology	Germany	1.875 x 1.875 deg
MRI-CGCM3	Meteorological Research Institute	Japan	1.125 x 1.125 deg
NorESM1-M	Norwegian Climate Center	Norway	2.5 x 1.875 deg

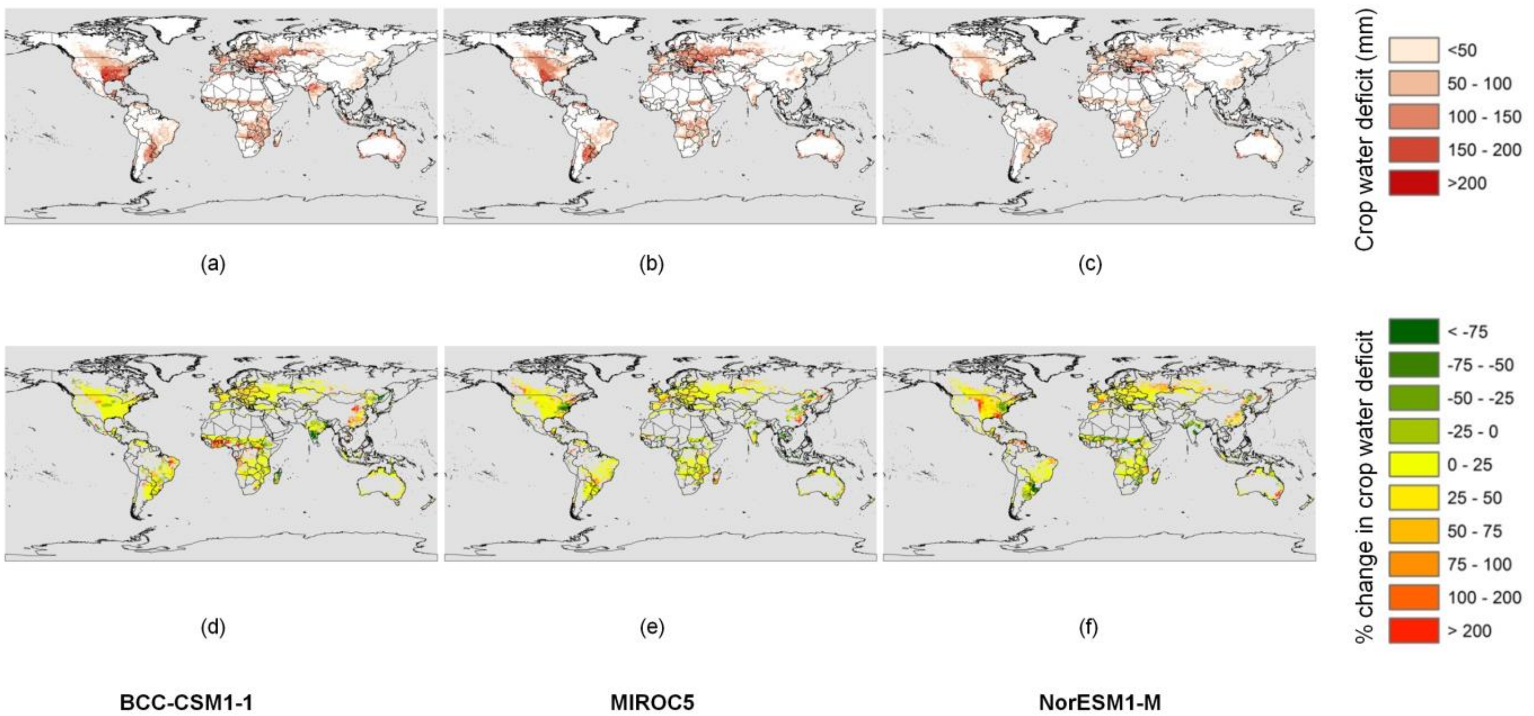


Figure A1.1 Peak monthly water deficits for millet. The peak water deficits that a millet crop might experience for one month during the main growing season for the historical period (1986-2005) in mm (a,b,c), and the % change (d,e,f) between that period and the future period (2046-2065, RCP8.5), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

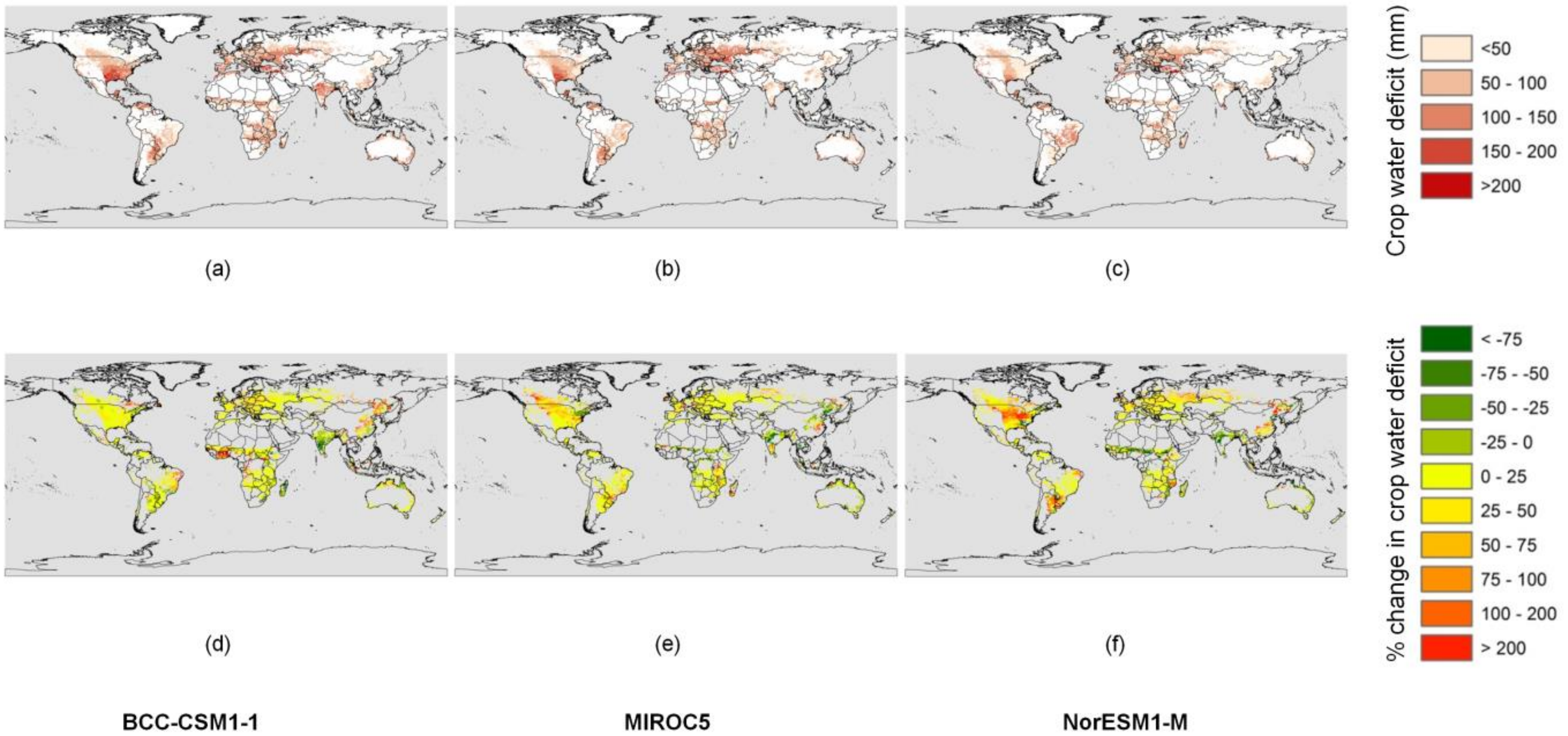


Figure A1.2 Peak monthly water deficits for sorghum. The peak water deficits that a sorghum crop might experience for one month during the main growing season for the historical period (1986-2005) in mm (a,b,c), and the % change (d,e,f) between that period and the future period (2046-2065, RCP8.5), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

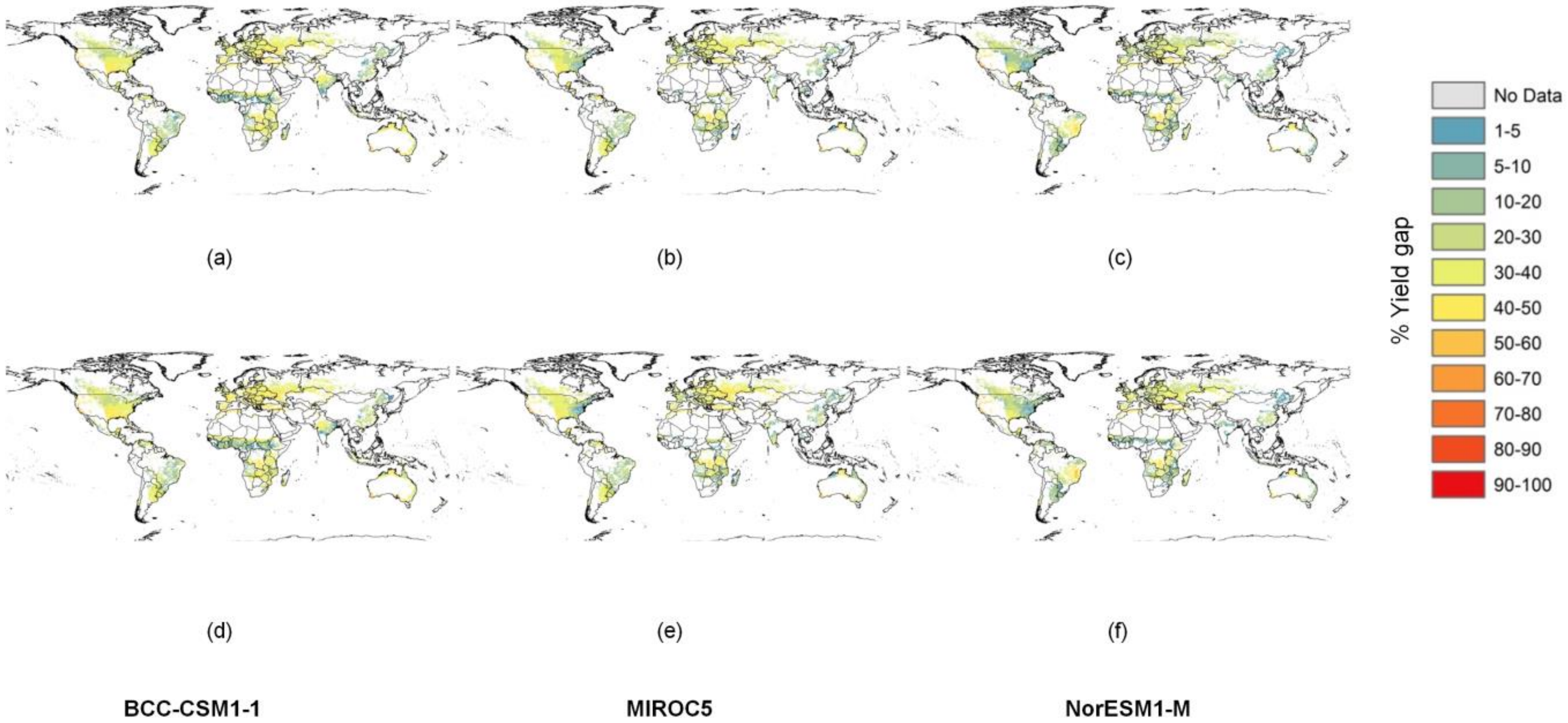


Figure A1.3 Minimum yield gap attributable to water deficits for millet. The minimum percentage yield below potential (yield gap) that a millet crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and for the future period (2046-2065) (d,e,f), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

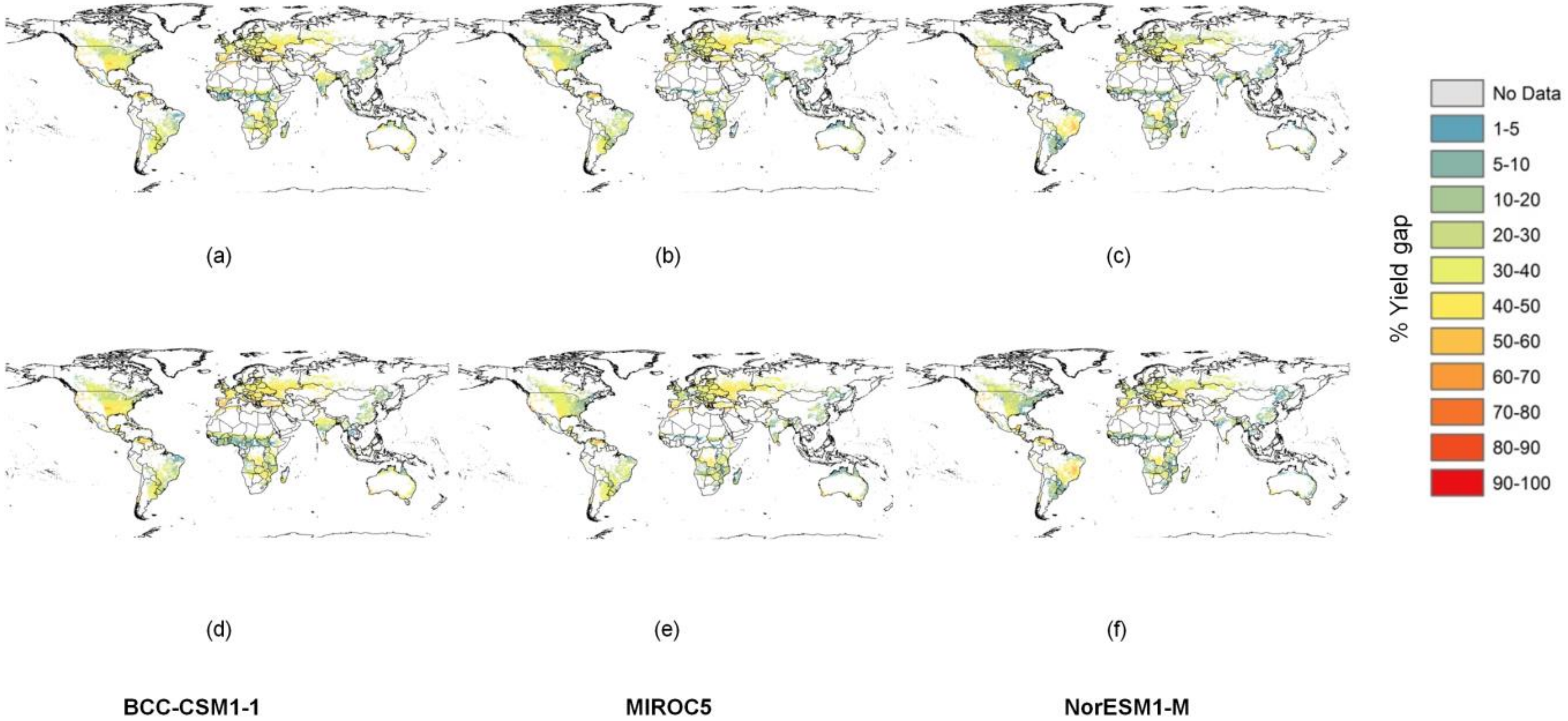


Figure A1.4 Minimum yield gap attributable to water deficits for sorghum. The minimum percentage yield below potential (yield gap) that a sorghum crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and for the future period (2046-2065) (d,e,f), were estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]) under rainfed conditions without rainwater harvesting.

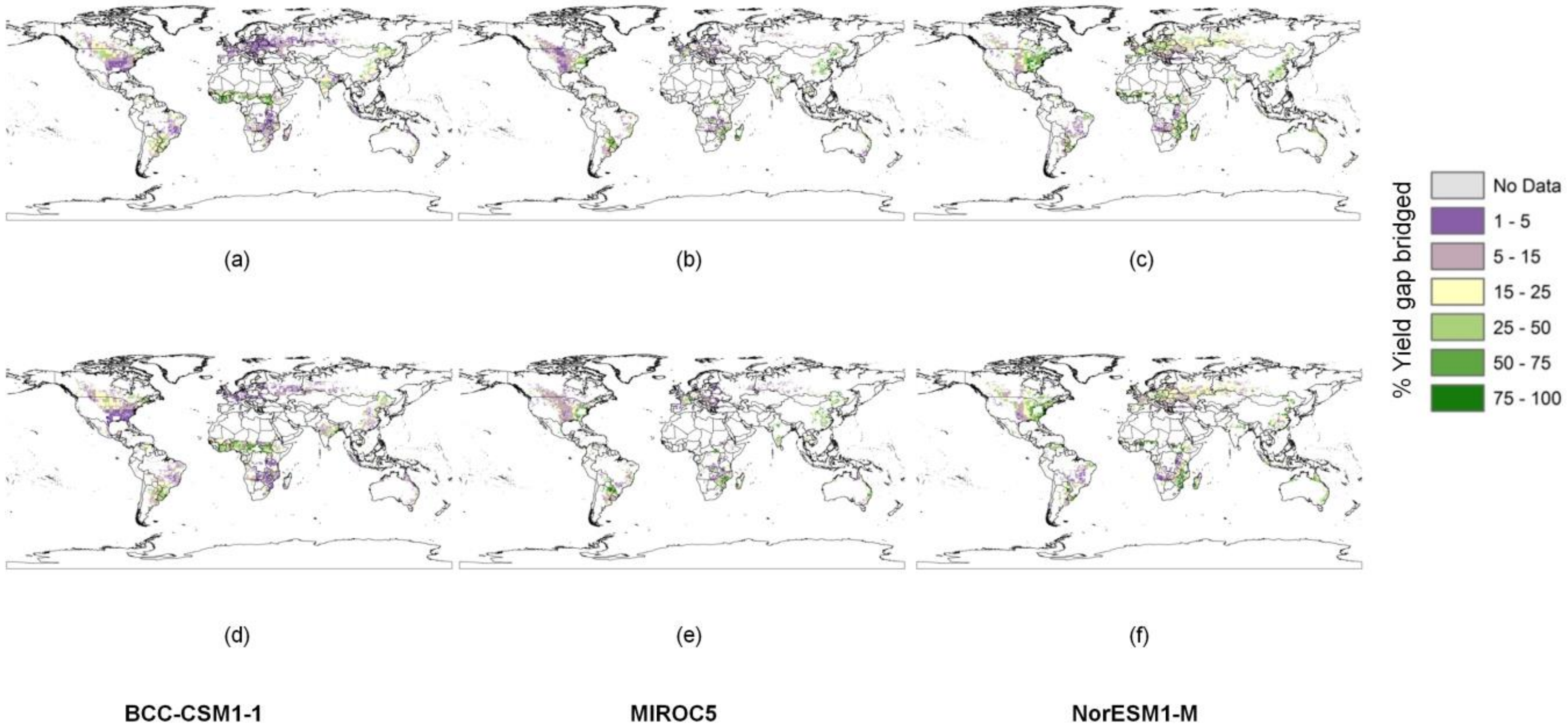


Figure A1.5 Percentage of the minimum yield gap attributable to water deficits bridged through rainwater harvesting for millet. (a,b,c) represent the historical period (1986-2005) (a,b,c), and (d,e,f) the future period (2046-2065), estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]).

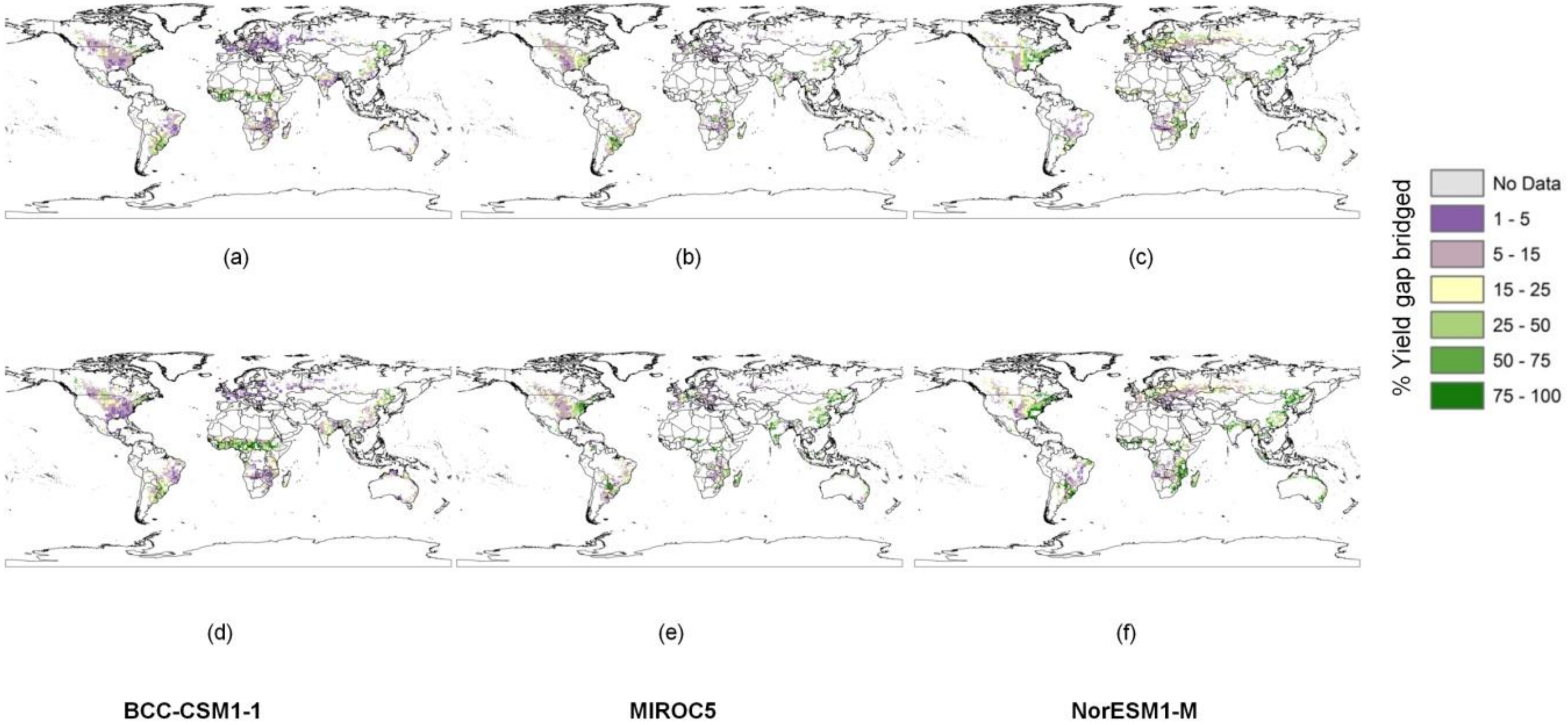


Figure A1.6 Percentage of the minimum yield gap attributable to water deficits bridged through rainwater harvesting for sorghum. (a,b,c) represent the historical period (1986-2005) (a,b,c), and (d,e,f) the future period (2046-2065), estimated using CMIP5 data (BCC-CSM1-1[a,d], MIROC5 [b,e], and NorESM1-M [c,f]).

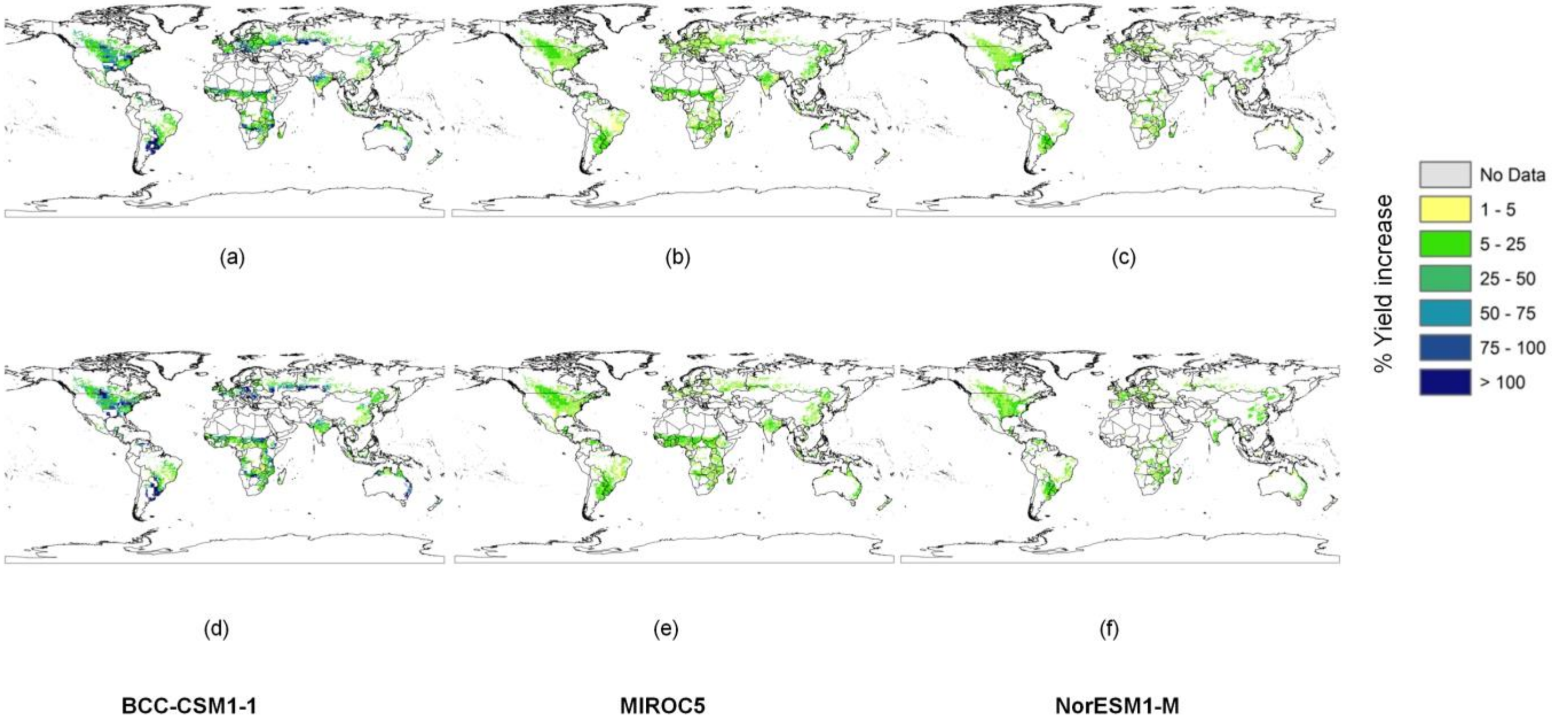


Figure A1.7 Percentage millet yield increase attainable through rainwater harvesting. The minimum yield increase that a millet crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and during the future period (2046-2065) (d,e,f), were estimated using the calculated design C:CA ratios and maximum crop water requirements throughout the main growing season. Three GCMs were used: BCC-CSM1-1 (a,b), MIROC5 (c,d), and NorESM1-M (e,f).

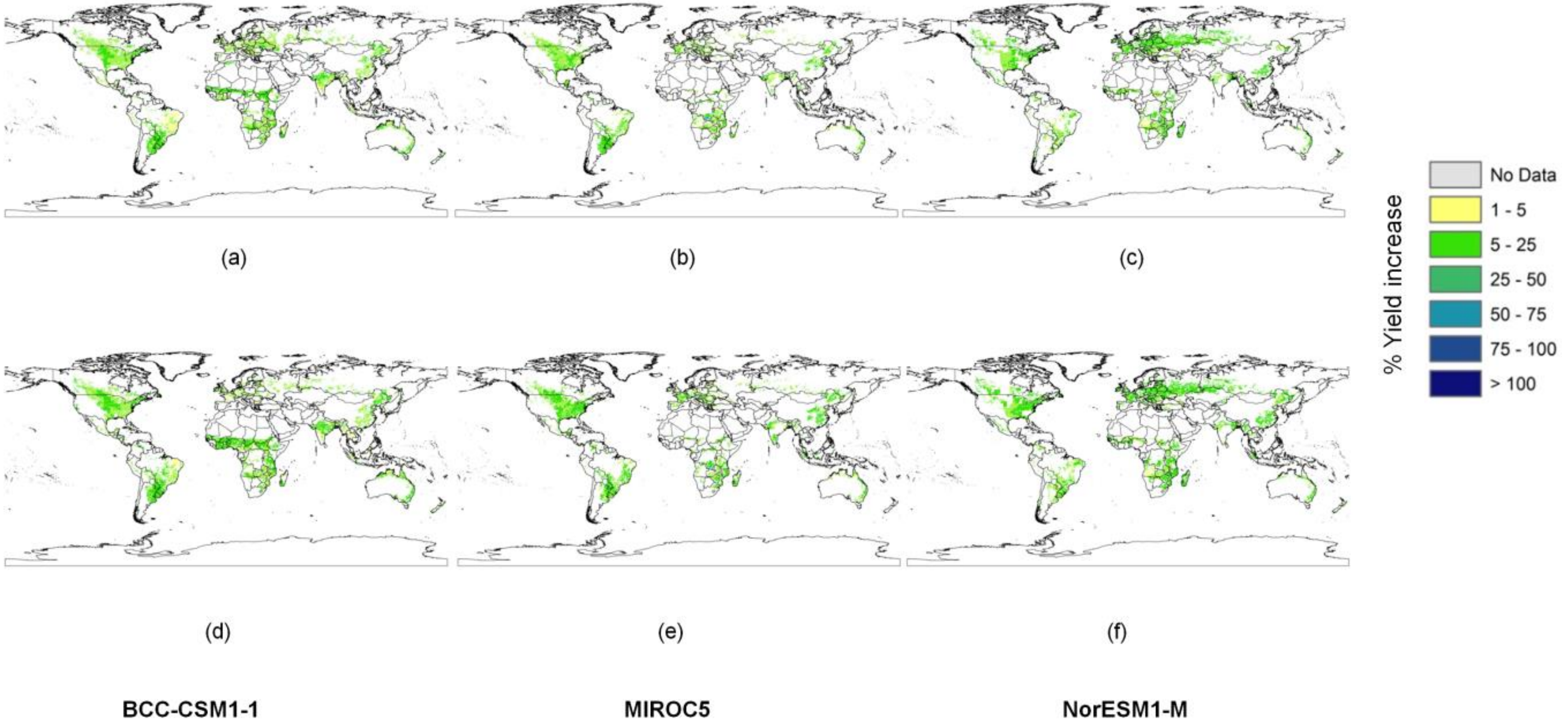
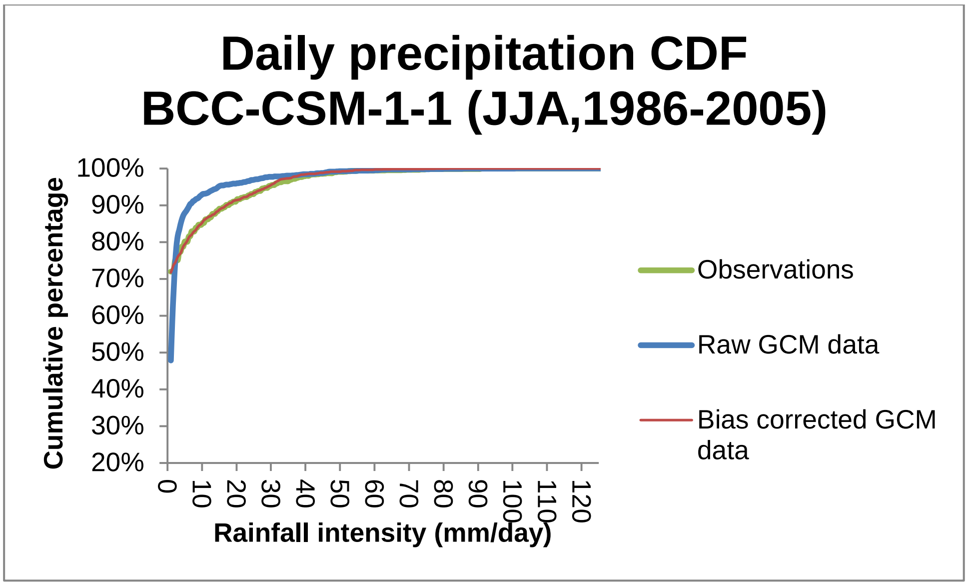
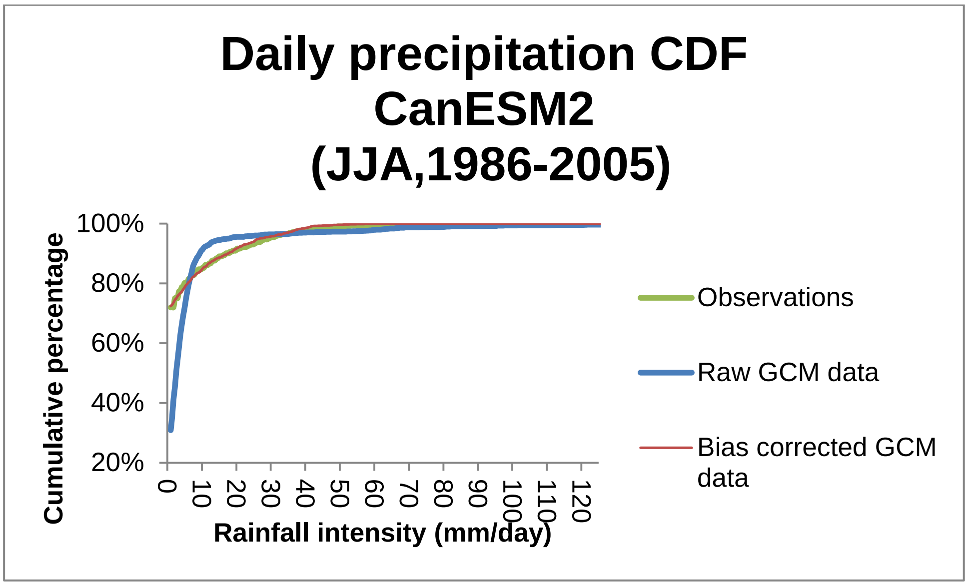


Figure A1.8 Percentage sorghum yield increase attainable through rainwater harvesting. The minimum yield increase that a sorghum crop might experience in the driest of three years for the historical period (1986-2005) (a,b,c), and during the future period (2046-2065) (d,e,f), were estimated using the calculated design C:CA ratios and maximum crop water requirements throughout the main growing season. Three GCMs were used: BCC-CSM1-1 (a,b), MIROC5 (c,d), and NorESM1-M (e,f).

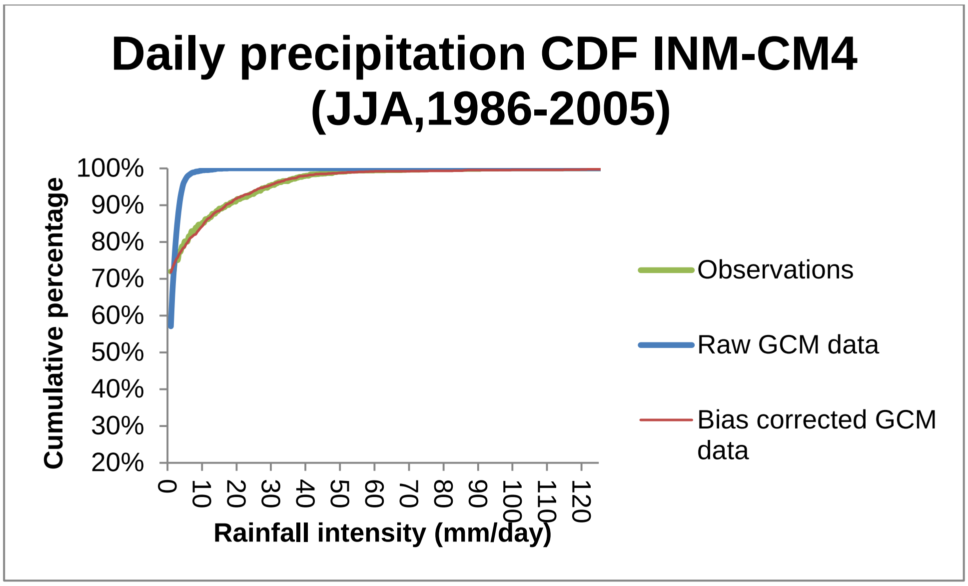
Appendix C
Daily precipitation bias correction results



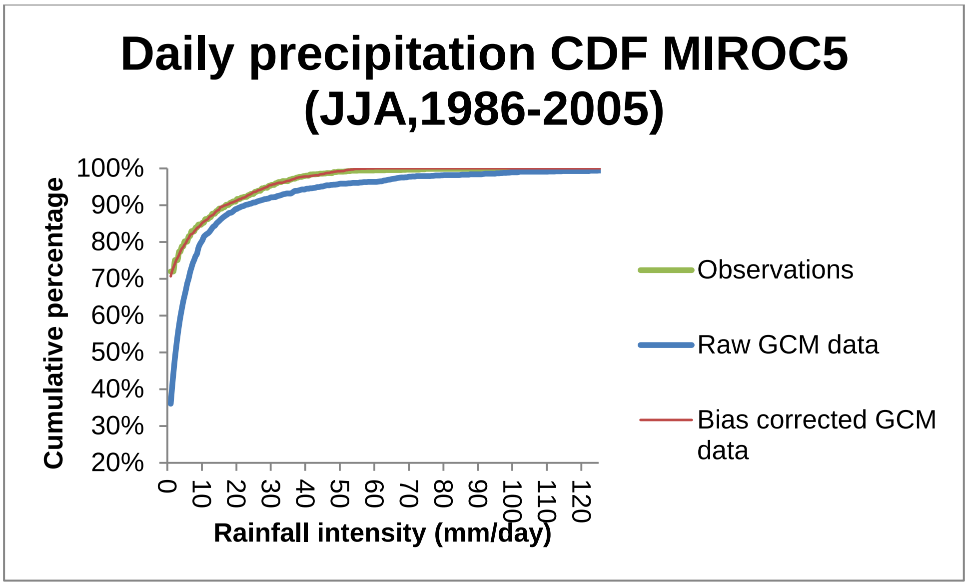
Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	92	0	6	7	5	8
1987	92	0	10	10	4	8
1988	81	1	3	11	4	12
1989	92	0	5	8	4	9
1990	92	0	3	11	4	10
1991	92	0	3	14	4	8
1992	92	0	6	7	7	13
1993	92	0	8	20	8	10
1994	92	0	5	9	5	10
1995	92	0	4	14	4	11
1996	92	0	5	24	7	10
1997	92	0	2	16	9	11
1998	92	0	5	8	3	12
1999	92	0	5	24	6	6
2000	92	0	5	8	3	12
2001	84	1	3	19	5	9
2002	92	0	5	31	2	10
2003	92	0	3	15	4	10
2004	92	0	4	9	3	10
2005	92	0	4	8	5	17
Mean	91.05	0.1	4.7	13.65	4.8	10.3
Std dev	2.96	0.31	1.87	6.80	1.79	2.30



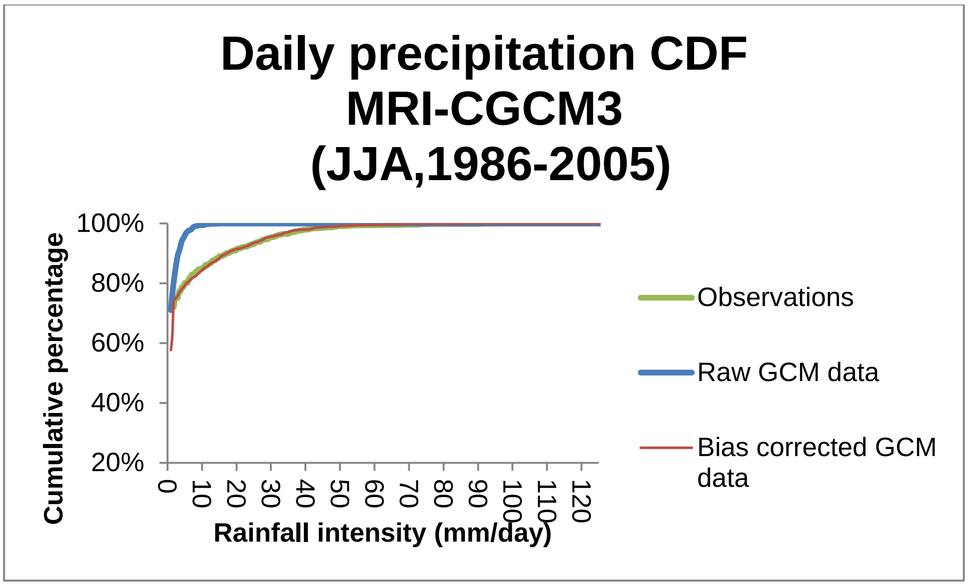
Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	81	1	5	10	5	8
1987	92	0	5	12	4	8
1988	92	0	6	14	4	12
1989	92	0	5	10	4	9
1990	92	0	4	18	4	10
1991	92	0	4	12	4	8
1992	62	1	4	23	7	13
1993	92	0	3	9	8	10
1994	92	0	3	17	5	10
1995	92	0	8	8	4	11
1996	92	0	5	9	7	10
1997	92	0	5	9	9	11
1998	92	0	3	16	3	12
1999	92	0	4	10	6	6
2000	92	0	5	24	3	12
2001	84	2	2	12	5	9
2002	92	0	6	13	2	10
2003	92	0	3	11	4	10
2004	92	0	5	32	3	10
2005	92	0	4	18	5	17
Mean	89.55	0.2	4.45	14.35	4.8	10.3
Std dev	7.13	0.52	1.36	6.19	1.79	2.30



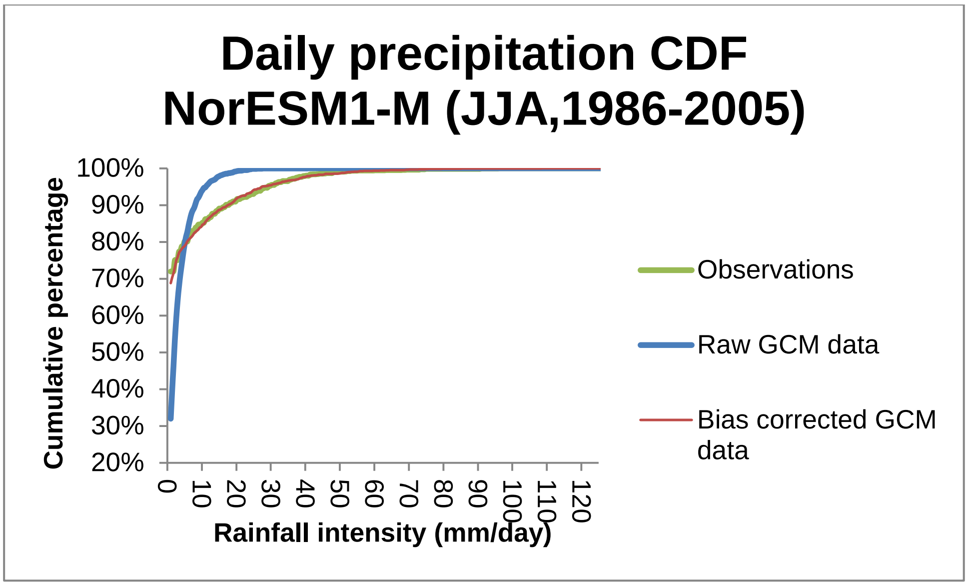
Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	19	4	4	15	5	8
1987	18	3	5	7	4	8
1988	16	2	4	9	4	12
1989	18	2	4	12	4	9
1990	14	4	2	13	4	10
1991	11	3	3	21	4	8
1992	14	2	4	11	7	13
1993	20	7	3	26	8	10
1994	39	4	5	7	5	10
1995	20	3	4	16	4	11
1996	19	3	4	8	7	10
1997	18	4	6	17	9	11
1998	9	5	3	18	3	12
1999	28	1	4	10	6	6
2000	20	5	3	28	3	12
2001	17	2	5	12	5	9
2002	13	4	5	13	2	10
2003	14	3	3	8	4	10
2004	23	2	6	9	3	10
2005	11	5	5	18	5	17
Mean	18.05	3.4	4.1	13.9	4.8	10.3
Std dev	6.64	1.43	1.07	6.03	1.79	2.30



Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	92	0	4	8	5	8
1987	92	0	3	8	4	8
1988	92	0	3	12	4	12
1989	92	0	5	19	4	9
1990	92	0	3	6	4	10
1991	92	0	7	19	4	8
1992	92	0	5	17	7	13
1993	92	0	3	8	8	10
1994	92	0	4	18	5	10
1995	92	0	4	13	4	11
1996	92	0	8	14	7	10
1997	92	0	6	7	9	11
1998	92	0	3	13	3	12
1999	92	0	3	8	6	6
2000	92	0	5	7	3	12
2001	92	0	5	7	5	9
2002	92	0	5	7	2	10
2003	92	0	5	12	4	10
2004	92	0	4	18	3	10
2005	92	0	7	7	5	17
Mean	92	0	4.6	11.4	4.8	10.3
Std dev	0	0	1.50	4.69	1.79	2.30



Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	92	0	21	8	5	8
1987	92	0	8	7	4	8
1988	92	0	13	13	4	12
1989	92	0	31	14	4	9
1990	92	0	15	11	4	10
1991	92	0	25	6	4	8
1992	92	0	29	15	7	13
1993	92	0	12	13	8	10
1994	92	0	27	11	5	10
1995	92	0	24	11	4	11
1996	92	0	15	8	7	10
1997	92	0	15	6	9	11
1998	92	0	13	15	3	12
1999	92	0	24	20	6	6
2000	92	0	12	14	3	12
2001	92	0	15	11	5	9
2002	92	0	13	15	2	10
2003	92	0	33	9	4	10
2004	92	0	31	9	3	10
2005	92	0	10	19	5	17
Mean	92	0	19.3	11.75	4.8	10.3
Std dev	0	0	7.97	3.97	1.79	2.30



Year	Maximum consecutive wet days (raw)	Maximum consecutive dry days (raw)	Maximum consecutive wet days (bias corrected)	Maximum consecutive dry days (bias corrected)	Maximum consecutive wet days (obs)	Maximum consecutive dry days (obs)
1986	92	0	5	10	5	8
1987	74	1	7	11	4	8
1988	92	0	4	11	4	12
1989	92	0	6	8	4	9
1990	87	1	5	11	4	10
1991	92	0	5	10	4	8
1992	92	0	5	12	7	13
1993	92	0	3	9	8	10
1994	70	1	5	11	5	10
1995	54	1	5	14	4	11
1996	92	0	6	17	7	10
1997	92	0	5	23	9	11
1998	50	1	7	19	3	12
1999	92	0	7	17	6	6
2000	47	1	4	14	3	12
2001	92	0	5	11	5	9
2002	92	0	6	12	2	10
2003	81	1	5	9	4	10
2004	92	0	5	12	3	10
2005	92	0	4	9	5	17
Mean	82.95	0.35	5.2	12.5	4.8	10.3
Std dev	15.47	0.49	1.06	3.83	1.79	2.30

Appendix D
Focus group activities and participatory farm visits

Focus group activity 1

Prepared by Sarah Lebel and Matthew Smiley

Title: How do your cropping calendars change with different amounts of rainfall?

Participants: Young farmers/Older farmers

1. **Introduction of interviewer**
2. **Introduction of topic**
3. **Introduction of consent form**
4. **Introduction of activity**

We are going to ask you show us where and in what amount the rains are on this timeline when it is a good year. We will then ask you questions about your farming in that year.

We will then change the amount and move the position of the rains and ask you questions about what you have to do differently in your fields.

5. **Set up activity.**

Timeline. 30 small rocks. 15 larger rocks. 6 millet bags. 6 sorghum bags.

6. **General questions (their farms, fields, soil, management practices etc).**

How many hectares of land do you farm? Where is it/what is the slope?

Do you use zai, half-moons or stone lines? How long have you been using them for?

When do you prepare the zai and half-moons?

What do you grow? How many days in a good year of rainfall does it take from sowing to harvesting?

What is your soil like? Is erosion a problem?

Do you have animals?

7. **Demonstrate rainfall amount with rocks.**

Big pile of rocks = lots of rain. Small pile of rocks = small amount of rain. Wide spacing = longer dry spells. Small spacing = short dry spells.

8. Cropping calendar

a. Average year

Please show me where the rains are in an average year.

i. Crop stages (sowing, flowering, grain filling, harvest)

If the rains were like this please show me when your crops be:

Crop stage	When and why?
Sown	
Flower	
Fill with grain	
Harvest	
Sensitive to drought	
Sensitive to flooding	

ii. Management/Fertiliser/Pesticides

If the rains were like this, when would you:

Management	When/why/how much?
Prepare zai	
Need labour	
Apply fertiliser/manure/urea	
Weeding	
Mulching	

b. Rainfall scenarios

If the rains were_______ what would management practices and yield be like and why?

(sowing, fertiliser (manure/NPK), weeding, and harvesting)

Scenario	Management	Yield
Earlier and longer		
Earlier but shorter		
Later and longer		
Later but shorter		
Drought when sensitive to drought		
Good rain when sensitive to drought		
Drought when sensitive to flooding		
Good rain when sensitive to flooding		

Focus group activity 2

Prepared by Sarah Lebel

Title: Establishing a climatic timeline of importance for agricultural production

Participants: Older farmers/Women

The following events of possible importance to farmers (social, political, climatic) were established after consultation with local INERA staff in Tougan, June 2012.

3 janvier 1966: Soulèvement populaire qui retire le premier Président Maurice Yamyogo du pouvoir. Général prend le pouvoir.

1973-1974 : Grande famine.

1980 : Le parrain du Général reprend le pouvoir, le colonel Sayezerbo.

1982 : Colonel Sayezerbo renversé par Jean-Baptiste Ouédraogo.

Mai 1983 : Manifestations ; Thomas Ankara est arrêté et emprisonné.

4 août 1983 : Coup d'état ; le capitaine Thomas Ankara est porté au pouvoir ; proclamation de la révolution CNR.

1983-1984 : Grande famine.

1983-1987 : Sous le CNR, travaux d'intérêt commun où tous les villages participent à bâtir les cités, etc.

15 octobre 1987 : Coup d'état ; assassinat de Thomas Ankara où le Front Populaire de Blaise Compaoré prend le pouvoir.

1990 : Grande famine.

2 juin 1991 : Adoption de la constitution sous la 4ième République.

1998 : Coupe d'Afrique au football.

13 décembre 1998 : Assassinat de Norbert Zongo, journaliste à l'Indépendant. Importantes manifestations.

30 mars 2001 : Journée du pardon pour calmer la tension sociale.

2003-2005(?) : Famine. Les gens sont forcés d'acheter le riz pour faire le Tô et le prix du maïs est plus cher que le riz, contrairement à la normale.

2008 : Crise de la vie chère ; arrestation de Nanan Tibo (conseiller municipal ?)

1er septembre 2009 : Grande inondation à Ouagadougou et autres villes, beaucoup de dégâts.

2011 : Crise cotonnière, crise militaire, monde scolaire, mort de Justin Zongo.

Using some of the events listed above to guide recollections of extreme climatic events, some or all of the following questions were asked to the different groups:

Q1: Can you remember any extreme climatic events that occurred during your lifetime?

Q2: Have you perceived any changes in rainfall?

Q3: Judging from the events that you have described earlier, what adaptation strategies have you adopted?

Q4: What do you expect the climate to be like in the future?

Q5: Do you access any weather forecasts?

Q6: How can you tell that the rains are coming?

Q7: How do you know when you can sow?

Q8: What do you mean by a “good season”?

Q9: What is a dry spell?

Q10: When are these dry spells most critical?

Q11: Have you had good or bad years recently?

Q12: What do you expect the climate to be like in the future?

Q13: How will you adapt to these changes?

Focus group activity 3

Prepared by Sarah Lebel

Title: Factors of adoption of rainwater harvesting strategies

Participants: Older farmers/Women

Description: Identify and classify by order of importance the factors that lead to the adoption of rainwater harvesting strategies

Some of the following questions were used to guide the discussions.

Q1: What types of RWH do you use in your fields?

Q2: When did you start using these techniques?

Q3: Why did you choose to adopt these techniques?

Q4: How did you hear about these techniques?

Q5: Can you name and rank the factors that were most important in choosing to adopt these RWH?

Q6: Have you noticed any changes in the availability of water?

Q7: Are there any other RWH technologies that you have heard of and that you would like to try?

Q8: Do you encounter any difficulties with the rock lines?

Q9: Do you encounter any difficulties with half-moons and the zai?

Q10: Why have you decided to use these RWH?

Q11: Are you using the RWH as much as you would like?

Q12: Who helps you prepare/crop your fields?

Q13: Which advantages do you see in using RWHs?

Q14: Which disadvantages do you see in using RWHs?

Q15: Do you fertilize your fields?

Q16: Have you noticed any changes in soil fertility with RWH?

Q17: Have you heard of runoff harvesting?

Q18: How do you build them, what do you need to build them?

Q19: How long does is take you to build?

Q20: Is there water in the structures already?

Q21: What do you plan to use the water for?

Q22: What kind of maintenance do you have to do on the structures?

Q23: How many people are using it this year?

Q24: Do you use RWH?

Q25: Why do some people use it and some not?

Q26: Do you use RWH on all your fields?

Q27: Do you use zai and half-moons as well?

Q28: Which crops do you grow with these 2 technologies?

Q29: Are there any technologies that you have tried in the past but have abandoned since?

Q30: Are there any other RWH technologies that you have heard of and that you would like to try?

Participator farm visits: Examples of questions to guide discussion

A list of questions used to guide the discussions is provided below for illustrative purposes:

1. What are the main factors that affect agricultural productivity?
2. What are the soil types?
3. Are there any issues with soil fertility?
4. What are the water sources, where are they located, and what are they used for?
5. What types of rainwater harvesting strategies are used, where, and what is their level of performance?
6. How did you first hear about and/or decide to use these strategies?
7. Have you changed the types and/or varieties of crops that you grow over the years?
8. What did this area used to look like 10, 15, 20 years ago?
9. Have you noticed erosion problems in your fields? If so, where, and what are the main causes?
10. Which crops do you grow?
11. Why have you chosen to grow these crops?

Appendix E
Detailed soil properties in Ziga

Sample	Topographical location	Depth (cm)	Acidity				Organic matter			Soil texture (%)			Bulk density ($t\cdot m^{-3}$)	Wilting point (m/m)	Field Capacity	Saturated Hydraulic Conductivity	AWC
			pH		Ac exchange (meq/100g)	Al exchange (meq/100g)	% of TS		C/N	Clay	Silt	Sand					
			pH water	pH KCl			C	N									
Ziga PZ1	Top of hillock	0-15	5.5	4.7	-	-	0.8	0.03	27	16.8	14.5	68.7	1.64	0.31	0.57	4.72	0.26
Ziga PZ2	Side of hillock	0-6	6.0	5.1	-	-	0.8	0.04	20	11.5	23.2	65.3	1.62	0.23	0.5	6.04	0.27
Ziga PZ2		6-12	5.7	4.3	-	-	0.9	0.05	18	-	-	-					0.00
Ziga PZ2		12-20	5.2	4.1	1.8	1.5	0.7	0.03	23	-	-	-					0.00
Ziga PZ3	Top of slope	0-6	6.1	5.0	-	-	0.9	0.06	15	12.2	21.2	66.6	1.62	0.23	0.5	6.09	0.27
Ziga PZ3		6-14	5.9	4.6	-	-	0.6	0.02	30	-	-	-					0.00
Ziga PZ3		14-28	4.5	4.1	1.6	0.7	0.5	0.02	25	-	-	-					0.00
Ziga PZ4	Top of slope	0-7	5.7	5.2	-	-	0.5	0.02	25	11.4	9.0	79.6	1.66	0.22	0.46	8.56	0.24
Ziga PZ4		7-18	-	-	-	-	-	-	-	-	-	-					0.00
Ziga PZ4		18-40	-	-	-	-	-	-	-	-	-	-					0.00
Ziga PZ4	Fallow	0-7	6.2	5.2	-	-	0.9	0.08	11	16.5	32.1	51.4	1.6	0.32	0.62	3.88	0.30
Ziga PZ4		7-18	5.9	4.6	-	-	0.8	0.07	11	-	-	-					0.00
Ziga PZ4		18-40	4.9	4.2	1.0	0.3	0.7	0.04	18	-	-	-					0.00
Ziga PZ6	Mid-slope	0-6	7.1	6.0	-	-	0.7	0.04	17	19.8	15.4	64.8	1.63	0.32	0.58	4.18	0.26
Ziga PZ6		6-20	6.8	5.8	-	-	0.5	0.03	17	35.8	13.5	50.7	1.57	0.63	0.83	4.63	0.20
Ziga PZ6		20-39	8.1	7.6	-	-	0.5	0.02	25	37.6	15.7	46.7	1.56	0.62	0.85	4.32	0.23
Ziga PZ6		39-57	8.3	7.7	-	-	0.6	0.02	30	40.2	16.5	43.3	1.53	0.67	0.89	5.32	0.22
Ziga PZ7	Mid-slope	0-15	5.7	4.5	-	-	0.9	0.06	15	19.9	14.0	66.1	1.64	0.31	0.57	4.04	0.26
Ziga PZ7		15-28	6.2	4.9	-	-	0.5	0.02	25	-	-	-					0.00
Ziga PZ7		28-52	6.1	4.7	-	-	0.4	0.01	-	-	-	-					0.00

Sample	Topographical location	Depth (cm)	Acidity				Organic matter			Soil texture (%)			Bulk density (t·m^{-3})	Wilting point (m/m)	Field Capacity	Saturated Hydraulic Conductivity	AWC
			pH		Ac exchange (meq/100g)	Al exchange (meq/100g)	% of TS		C/N	Clay	Silt	Sand					
			pH water	pH KCl			C	N									
Ziga PZ9	Mid-slope	0-12	5.6	4.6	-	-	1.2	0.10	12	23.7	12.2	64.1	1.63	0.41	0.67	4.15	0.26
Ziga PZ9		12-22	5.5	4.2	-	-	0.8	0.06	13	-	-	-					0.00
Ziga PZ9		22-47	5.2	4.1	1.4	0.6	0.5	0.01	50	36.0	11.4	52.6	1.57	0.63	0.83	5.28	0.20
Ziga PZ9		47-55	5.1	4.1	1.3	0.5	0.4	0.01	40	33.0	11.2	55.8	1.60	0.57	0.78	4.28	0.21
Ziga PZ10	Bottom of slope	0-15	6.7	5.6	-	-		0.06	13	8.7	14.0	77.3	1.71	0.11	0.51	4.71	0.40
Ziga PZ10		15-35	6.4	5.1	-	-		0.03	17	-	-	-					0.00
Ziga PZ10		35-70	6.3	4.9	-	-		0.02	20	31.1	34.9	34	1.6	0.42	0.73	1.82	0.31
Ziga PZ10		70-120	5.9	4.9	-	-		0.01	30	-	-	-					0.00
Ziga PZ11	Hillock	0-12	6.6	5.5	-	-	0.6	0.04	15	13.7	17.1	69.2	1.63	0.23	0.49	5.76	0.26
Ziga PZ11		12-30	6.4	5.0	-	-		0.02	-	36.2	15.8	48.0	1.63	0.5	0.73	2.12	0.23
Ziga PZ11		30-120	5.6	4.3	-	-		0.01	-	31.9	16.5	51.5	1.64	0.45	0.68	2.11	0.23
Ziga PZ12	Hillock	0-18	7.2	6.1	-	-		0.08	12	-	-	-					0.00
Ziga PZ12		18-30	7.7	6.6	-	-		0.05	16	-	-	-					0.00
Ziga PZ12		30-50	7.8	6.6	-	-		0.04	18	-	-	-					0.00
Ziga PZ13	Drainage axis	0-20	5.7	4.8	-	-		0.06	15	14.2	6.0	79.8	1.71	0.21	0.54	5.49	0.33
Ziga PZ13		20-36	6.5	5.2	-	-		0.03	20	46.1	6.5	47.4	1.63	0.62	0.76	3.35	0.14
Ziga PZ13		36-53	6.6	5.1	-	-		0.02	-	-	-	-					0.00
Ziga PZ13		53-110	6.9	5.6	-	-		0.01	-	-	-	-					0.00

Appendix F

Supplementary statistical analysis results from Chapter 6

Table F1.1│Anova two-factor with replication analysis of sorghum yields for three sowing dates and the use or not of RWH

Anova: Two-Factor With Replication			
SUMMARY	RWH	No RWH	Total
June 15			
Count	20.00	20.00	40.00
Sum	11.61	10.90	22.51
Average	0.58	0.54	0.56
Variance	0.09	0.09	0.09
June 1			
Count	20.00	20.00	40.00
Sum	11.44	10.75	22.19
Average	0.57	0.54	0.55
Variance	0.10	0.10	0.10
May 15			
Count	20.00	20.00	40.00
Sum	10.78	9.90	20.67
Average	0.54	0.49	0.52
Variance	0.10	0.10	0.10
Total			
Count	60.00	60.00	
Sum	33.83	31.54	
Average	0.56	0.53	
Variance	0.09	0.10	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.05	2.00	0.02	0.25	0.78	3.08
Columns	0.04	1.00	0.04	0.44	0.51	3.92
Interaction	0.00	2.00	0.00	0.00	1.00	3.08
Within	11.18	114.00	0.10			
Total	11.27	119.00				

Table F1.2 │ Anova two-factor with replication for sorghum crop yields at three sowing dates and the use of RWH, for years where the rainy season onset is on or before May 15th

Anova: Two-Factor With Replication			
SUMMARY	RWH	No RWH	Total
June 15			
Count	5.00	5.00	10.00
Sum	4.02	3.84	7.86
Average yield (ton/ha)	0.80	0.77	0.79
Variance	0.32	0.32	0.29
June 1			
Count	5.00	5.00	10.00
Sum	4.01	3.83	7.83
Average yield (ton/ha)	0.80	0.77	0.78
Variance	0.32	0.33	0.29
May 15			
Count	5.00	5.00	10.00
Sum	3.99	3.82	7.82
Average yield (ton/ha)	0.80	0.76	0.78
Variance	0.27	0.28	0.24
Total			
Count	15.00	15.00	
Sum	12.02	11.49	
Average yield (ton/ha)	0.80	0.77	
Variance	0.26	0.26	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.00	2.00	0.00	0.00	1.00	3.40
Columns	0.01	1.00	0.01	0.03	0.86	4.26
Interaction	0.00	2.00	0.00	0.00	1.00	3.40
Within	7.34	24.00	0.31			
Total	7.35	29.00				

Table F1.3│Anova two-factor with replication for sorghum yields at three sowing dates and the use of RWH, for years where the rainy season onset is after June 15th

Anova: Two-Factor With Replication			
SUMMARY	RWH	No RWH	Total
June 15			
Count	6.00	6.00	12.00
Sum	2.94	2.73	5.67
Average yield (ton/ha)	0.49	0.46	0.47
Variance	0.01	0.01	0.01
June 1			
Count	6.00	6.00	12.00
Sum	2.94	2.73	5.67
Average yield (ton/ha)	0.49	0.46	0.47
Variance	0.01	0.01	0.01
May 15			
Count	6.00	6.00	12.00
Sum	2.44	2.13	4.57
Average yield (ton/ha)	0.41	0.36	0.38
Variance	0.02	0.02	0.02
Total			
Count	18.00	18.00	
Sum	8.32	7.60	
Average yield (ton/ha)	0.46	0.42	
Variance	0.01	0.01	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.07	2.00	0.03	2.47	0.10	2.43
Columns	0.01	1.00	0.01	1.08	0.31	2.79
Interaction	0.00	2.00	0.00	0.02	0.98	2.43
Within	0.41	30.00	0.01			
Total	0.49	35.00				

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