UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

EXPLORING AGROBIODIVERSITY-BASED CLIMATE CHANGE ADAPTATION IN SEMI-ARID AREAS OF WEST AFRICA: A CASE STUDY IN MALI

BY

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF PHD IN ENVIRONMENTAL SCIENCE DEGREE

INSTITUTE FOR ENVIRONMENT AND SANITATION STUDIES

JULY 2019

DECLARATION

I, Alcade Christel Segnon, hereby declare that this thesis is the result of my own research work carried out at the Institute for Environment and Sanitation Studies, University of Ghana, under the supervision of Prof. Christopher Gordon, Dr. Benjamin D. Ofori, Dr. Robert B. Zougmoré and Prof. Dr. Enoch G. Achigan-Dako. It has never been submitted in whole or in part for any degree in the University or elsewhere. References to other people's works have been duly acknowledged.

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ABSTRACT

Semiarid regions of West Africa are hotspots of climate change exposure and impacts, and this is expected to intensify in the future. Given the close relationship between livelihoods on ecosystem processes and natural resources and the close dependence between ecological sensitivities and social vulnerability, concerted efforts to build resilience of local people to an increasing and potentially irreversible climatic challenge are urgently needed. Achieving these efforts effectively will require a better understanding of location- and context-specificity of adaptation actions and strategies at local level as well as vulnerability patterns to inform policy-decisions making and adaptation planning. Using a multi-scale and multidisciplinary approach, combining a spatially-explicit climate and vegetation trends assessment, participatory research methods and a quantitative modelling approach, this study aimed to contribute to the growing body of knowledge on effectiveness of ecosystem-based adaptation using the lens of agrobiodiversity-based adaptation, with a focus on semiarid areas of Mali, West Africa. Specifically, the study sought to i) to unpack climatic and non-climatic driving forces of vegetation dynamics; ii) assess farmers' perception of impact of climate change on agroecosystems and adaptation strategies; iii) document and analyse agrobiodiversity-based adaptation practices and how these practices influenced household vulnerability patterns. The empirical data was collected in the Cercle of Koutiala, a semiarid area in southwestern Mali.

Both minimum and maximum temperature significantly increased over the study period, albeit with decadal and interannual variability. Minimum temperature increased faster than maximum temperature in the study area, with a figure (1.26°C over the 35-year period) close to global temperature increase since pre-industrial period. The rainfall trend analysis revealed a strong interannual and spatial variability, rather than a clear significant change in rainfall over the study period. Analysis of coarse and moderate resolution NDVI time series illustrated the strong spatial heterogeneity in vegetation cover dynamics. While greening trends was dominant, this trend must be nuanced as it was not homogenous or uniform and some areas experienced browning or degradation as well.

Respondents' social network characteristics such as CBOs membership, diversity of CBOs membership and diversity of source of agricultural knowledge were the main drivers of knowledge of climate change and its impacts. While CBOs membership improved farmer's knowledge and understanding of climate change, the diversity of CBOs membership affected negatively climate change knowledge and understanding, implying that the characteristics of the group matter and that climate information and knowledge is not acquired through all types of CBOs. There was a wide range of environmental and socioeconomic shocks or risks to which farmers were exposed to. Climatic risks were just one among many challenges. Drought and food insecurity were the most important stressors mentioned. Vulnerability patterns analysis indicated three vulnerability archetypes, which cut across all the study communities, illustrating the heterogeneity, within and across communities, in household vulnerability patterns to climatic and non-climatic risks. Key determinants of household vulnerability patterns were socio-demographic status, livelihood strategies, household resources, food security, water security, social network, physical accessibility, and health and sanitation. Environmental and socio-economic shocks or stressors were not discriminant, implying that

household vulnerability patterns in the study area were mainly shaped by household adaptive capacity and sensitivity and that household exposure to risks was similar.

To respond to climatic and non-climatic risks, local communities in the study area relied on a wide range strategies and practices, including a diversity of agrobiodiversity-based adaptation practices, at both individual and household levels. Demographic and socioeconomic factors which define *"who a respondent is"* (gender in this study), *"what he/she knows"* (knowledge of climate change impacts on livelihoods rather that perception of change in climate), and *"where his/her knowledge comes from"* (CBOs membership and number of CBOs membership) drive *"what he/she does"* (the diversity of adaptation strategies adopted). There was a complementarity between agrobiodiversity-based and non-agrobiodiversity-based adaptation strategies in reducing household vulnerability. More than 94% of the respondents adopted at least one agrobiodiversity-based adaptation practices. Agrobiodiversity-based adaptation practices per household ranged from one to nine, with a median number of 7 (mean of 6.24 ± 1.73). Moreover, all respondents who adopted agrobiodiversity-based adaptation practices also relied on other adaptation practices. Not only adoption of agrobiodiversity-based adaptation practices, but also the number of adaptation practices adopted by household affected household vulnerability patterns. Households in low vulnerability archetypes relied on a high number of agrobiodiversity-based adaptation practices and were more likely to have a higher number of total adaptation practices. In comparison to low vulnerability archetypes, households belonging to high or medium vulnerability archetypes were less likely to adopt a high number of agrobiodiversity-based adaptation practices and less likely to adopt a high number of adaptation practices. This implied a synergistic effect rather than mutually exclusive impacts on household vulnerability. In addition, institutional factors such as access to extension services and to credit, training on agricultural practices also influenced household vulnerability patterns.

Our analysis highlighted the diversity in household vulnerability and the context-specific nature of driving forces of vulnerability patterns. Failing to account for this diversity and nuanced understanding in adaptation planning might result in a mismatch between adaptation needs and interventions and maladaptation. Dichotomy agrobiodiversity-based (or ecosystem-based) vs. other adaptation practices/strategies in relation to vulnerability reduction might be misleading and not tell the full story on the ground. Adaptation should be conceptualised or promoted as part of a more holistic approach or process which take into account climatic risks as well as development needs and aspiration to build sustainable and resilient livelihood systems. Future research quantifying risk reduction potentials of adopting a diversity adaptation practices at different scales will provide better insights and understanding on the importance of diversity for risk reduction in semiarid farming contexts. Avenues for future research might also aim to address synergies and trade-offs among multiple climate change adaptation strategies and practices at different scales. Advancing the understanding the synergies and trade-offs in adoption of agrobiodiversity-based adaptation practices (and more generally multiple climate-smart practices and strategies) can provide critical inputs and insights to inform policy decisions for building resilience and upscaling climate-resilient livelihood systems in semiarid areas of West Africa.

DEDICATION

To Oluwafuni, Mawuli and Noukpo

ACKNOWLEDGEMENT

This research was carried out as part of the Adaptation at Scale in Semi-Arid Regions (ASSAR) project. ASSAR is one of four research programs funded under the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA), with financial support from the UK Government's Department for International Development (DFID) and the International Development Research Centre (IDRC), Canada.

I would to express my warmest gratitude and appreciation to my Principal supervisor Prof. Christopher Gordon for the guidance throughout these four years of my PhD program. Many thanks Prof. for guiding me through the university system and findings practical and workable solutions every time that I jump into your office with my challenges and incomprehension.

I gratefully acknowledge the valuable support of Dr. Benjamin D. Ofori in various circumstances and stages of my PhD journey. Thank you for your support.

I would like to express my gratitude to Dr. Robert Zougmoré for accepting to guide this research despite his multiple responsibilities as African Program Leader for CCAFS Program. Dr Robert Zougmoré kindly accepted to promote my work although we had not met before, and was always keen to listen to my ideas and challenges while during my fieldwork. Here, I would like to say many thanks for your support.

I am deeply indebted to my hometown supervisor Prof. Enoch G. Achigan-Dako for his continuous and unparalleled guidance and support throughout this research. More than a supervisor, Prof. Achigan-Dako is an enthusiastic mentor. Thanks so much for keeping me motivated about my work.

I am also thankful to the following persons for their diverse contribution and support for a successful completion of this research: Drs Edmond Totin, Amadou Sidibé and Mary Thompson-Hall (ASSAR project); Drs Hippolyte Affognon and Zemadim Birhanu (for early discussions on orientation of this research); Jourdain Lokossou (for friendship, moral support and scientific contribution during my fieldwork); Mathieu Ayenan, Drs Jaures Amegnanglo, Armel Nonvide, Gilbert Adjimonti, Mouhamed Porgo, Javier Métouolé Méda and Yves Zanmassou for making my PhD journey abroad liveable; Dr Negasi Solomon and Deedi Sogbohossou for happiness and sorrow we shared during our respective PhD journey; and all my course mates, especially Steven Babson for the critical thinking exercises we used to enjoy.

I express my gratitude to all the farmers interviewed during this research for their time and willingness to share their knowledge, without which this study could have not been possible. I express my appreciation to Oumar Samake and NGO AMEDD (*Association Malienne d'Eveil au Développement Durable*) in Koutiala for logistic assistance during my fieldwork.

Finally, my thought goes to my sisters Carine, Corinne and Merveille, and my parents Alphonse and Claire to whom I will always remain indebted. I am grateful to your encouragement, moral and spiritual support while I embarked on this PhD program. Many thank Ruth for the emotional ups and downs.

Last but not least, I would like to thank my wife Fleur for the unconditional support and sacrifice. You supported my absence with patience and a sense of responsibility.

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LIST OF ABBREVIATIONS

CBD	Convention on Biological Diversity
EbA	Ecosystem-based Adaptation
ES	Ecosystem Services
FAO	Food and Agriculture Organization of the United Nations
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LVI	Livelihood Vulnerability Index
MEA	Millennium Ecosystem Assessment
MLVI	Multidimensional Livelihood Vulnerability Index
MODIS	Moderate Resolution Imagery Spectroradiometer
NAPA	National Adaptation Programmes of Action
NbS	Nature-based Solutions
NCP	Nature's Contributions to People
NDC	Nationally Determined Contributions
NDVI	Normalized Difference Vegetation Index
NDVI3g	Global Inventory Modelling and Mapping Studies (GIMMS) NDVI 3rd generation
NTFP	Non-Timber Forest Product
RCP	Representative Concentration Pathways
RESTREND	Residual Trend Analysis
SAR	Semiarid Regions
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER ONE: INTRODUCTION

1.1 Background

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicated that many changes have been observed in the global climate system over the past 50 years (IPCC, 2014). The recent IPCC special report on Global warming of 1.5°C has also shown that global warming has already reached 1°C since the pre-industrial period (IPCC, 2018) and re-affirmed that human activities are the cause of this warming (IPCC, 2014, 2018). According to the IPCC, these changes have caused tremendous impacts on both natural and human systems on all continents and across the oceans, indicating the sensitivity of natural and human systems to changing climate (Hoegh-Guldberg et al., 2018; IPCC, 2014, 2018). For instance, a global warming of 2°C rather than 1.5°C would have irreversible economic, ecological and societal consequences of unprecedented magnitude for humanity and the planet as a whole (Hansen & Cramer, 2015; Hoegh-Guldberg et al., 2018). This underscores the urgency and need for action to reduce greenhouse gas emissions and prepare societies and ecosystems to adapt to the consequences and impacts that cannot be avoided (Hansen & Cramer, 2015; IPCC, 2018).

The situation in Semi-Arid Regions (SARs), especially in SARs of West Africa (Figure 1), is more challenging and calls for more attention. Global warming is particularly enhanced over semi-arid regions, with local temperatures increasing faster than the global average (Huang et al., 2017b; Ji et al., 2014; Sarr, 2012). Surface warming over global drylands has been higher than that over humid lands over the past century and this trend is expected to continue and intensify in the twenty-first century (Huang et al., 2017b). A global warming of 2°C rather than 1.5°C would mean a warming of 3.2-4.0°C over semi-arid drylands, with disastrous impacts including decreased crop yields and runoff, increased long-lasting drought and more favourable conditions for malaria transmission (Hoegh-Guldberg et al., 2018; Huang et al., 2017b). This indicates that temperature in semiarid regions is more sensitive to climate change than in other regions (Huang et al., 2017a). On the other hand, the rapid expansion of SARs globally under a changing climate would reduce carbon sequestration and enhance regional warming (Huang et al., 2016a; Huang et al., 2017a; Huang et al., 2017b; Huang et al., 2016b). The enhanced warming combined with an increasing aridity and rapidly growing population in SARs will exacerbate the risk of land degradation and desertification (Huang et al., 2017b; Huang et al., 2016b).

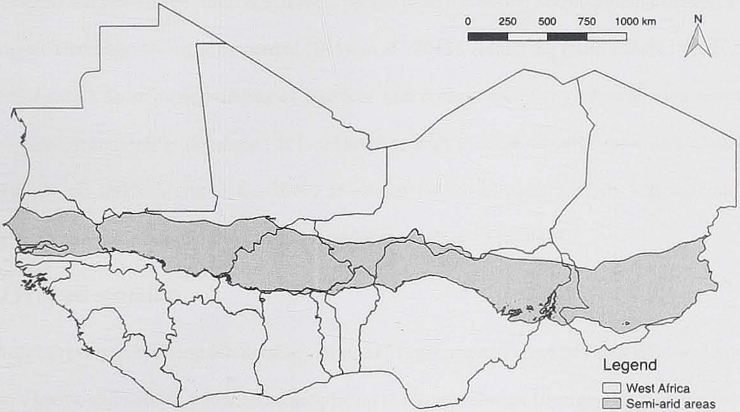

Figure 1. Semi-arid areas of West Africa defined based on Aridity Index ($0.2 < AI < 0.5$)

At regional scale, SARs of West Africa are identified as climate change exposure hotspots (Bathiany et al., 2018; de Sherbinin, 2014; Turco et al., 2015). SARs of West Africa are also hotspots of climate change impacts because the region is characterized by a combination of relatively high likelihoods of negative impacts in all biosphere properties, the possibility of extreme impacts, a large concentration of vulnerable, poor, or marginalized people (de Sherbinin, 2014; De Souza et al., 2015; Diffenbaugh & Giorgi, 2012; Epule et al., 2017; Müller et al., 2014). This identification as climate change hotspots is robust and will be persistent over time independent of emissions pathways considered (Bathiany et al., 2018; Diffenbaugh & Giorgi, 2012; Turco et al., 2015).

Given the observed and projected high ecological and agricultural climate change impacts (Ben Mohamed, 2011; Gautier et al., 2016; Gonzalez et al., 2012; Kilroy, 2015; Serdeczny et al., 2017; Sultan & Gaetani, 2016), the intimate dependence of livelihoods on ecosystem services and natural resources, and the close relationship between ecological sensitivities and social vulnerability (Knauer et al., 2014; Sarr, 2012; Sissoko et al., 2011; Tucker et al., 2015), concerted efforts to build resilience of local people to an increasing and potentially irreversible climatic challenge are urgently needed (Boyd et al., 2013). Achieving these efforts effectively will require a better understanding of location- and context-specificity of adaptation actions and strategies currently developed at local level as well as local adaptive capacities (Antwi-Agyei et al., 2015; Mertz et al., 2009) to inform policy-decisions making and adaptation planning and achieving the Sustainable Development Goal 13 (SDG13).

1.2 Problem statement

There has been an evolving scholarship aiming at identifying and characterizing what we know, don't know, and need to know about adaptation to climate change (Berrang-Ford et al., 2014; Berrang-Ford et al., 2011; Bizikova et al., 2015; Epule et al., 2017; Ford et al., 2015b; Lesnikowski et al., 2015; Lesnikowski et al., 2016). The Paris agreement, which strongly recognises, for the first time, adaptation as a critical component of the global response to climate change, and Katowice Climate Package also give a clear mandate for all states to undertake and document adaptation progress (Berrang-Ford et al., 2019; Ford et al., 2015a; Lesnikowski et al., 2017; Magnan & Ribera, 2016). Although reports of adaptation initiatives to reduce vulnerability documented in Africa and other middle and low-income regions have been increasing (Ford et al., 2015b), adaptation actions are more frequently reported from developed nations (Berrang-Ford et al., 2011; Ford et al., 2011; Lesnikowski et al., 2015;

Lesnikowski et al., 2016). In climate hotspots areas, such as SARs of Africa, documented adaptation initiatives have also increased (Epule et al., 2017; Ford et al., 2015b). In SARs, agricultural sector is the primary focus of reported adaptation initiatives, which are driven mainly at national scale with minimal involvement of lower governance levels (Bizikova et al., 2015; Ford et al., 2015b). In addition, adaptation is taking place in a multiple driver/factor context and climate change is seldom the sole or primary motivator for adaptation action (Berrang-Ford et al., 2011; Epule et al., 2017; García de Jalón et al., 2016). For instance, adoption of adaptation strategies to climate change at farm-level may not be necessarily driven by the magnitude of climate change impacts on agricultural production and may also be associated with governance, financial resources, education and civil rights (García de Jalón et al., 2016). Indeed, over the past decades, local populations in SARs of West Africa developed a range of adaptation and coping strategies as integral part of their livelihoods strategies to reduce their vulnerability to not only climatic stressors but also economic, political and social factors (Barbier et al., 2009; Epule et al., 2017; Mertz et al., 2009; Mortimore, 2010; Nyong et al., 2007; Sissoko et al., 2011; Zougmoré et al., 2016). Adaptation to climatic stressors is inseparable from a developmental context, and takes place in interactions with other drivers such as rapid population growth, market integration, increasing urbanization, migration, land use transformation (Mertz et al., 2010; Mertz et al., 2009; Mortimore, 2010; Zougmoré et al., 2016). The indigenous knowledge systems have been crucial to adaptation strategies developed to reduce their vulnerability to climate variability and change (Lahmar et al., 2012; Nyong et al., 2007; Segnon et al., 2015).

While indigenous knowledge systems regarding climate variability and change have been extensively investigated (Barbier et al., 2009; Kosmowski et al., 2016; Mertz et al., 2012; Mertz et al., 2010; Mertz et al., 2009; Sanogo et al., 2017; Tambo & Abdoulaye, 2013; Traore et al., 2015), very few studies have specifically focused on knowledge and perception of impacts of climate change and variability in SARs of West Africa (an exception is the work by Herrmann et al. (2014) and Sanogo et al. (2017)). Thus, how local people perceive and understand climate change impacts on (agro)ecosystems functioning and benefits derived to inform adaptation decisions remains a knowledge gap in current climate change discussions. This understanding is, however, crucial to better understand farmers decision-making process and inform effective adaptation actions.

Although the wealth of literature on climate change adaptation improved our knowledge of the context of climate change adaptation, detailed understanding of the interactions between impacts on socio-economic trajectories (including adaptation) and natural systems, across multiple stressors remains a knowledge gap (Tucker et al., 2015). Moreover, limited evidence of adaptation actions being targeted at vulnerable populations including socioeconomically disadvantaged populations exists, particularly in semi-arid areas (Berrang-Ford et al., 2011; Ford et al., 2015b; Lesnikowski et al., 2015). Consequently, our understanding of how adaptive capacity and preferred adaptation options may vary among socially-differentiated vulnerable groups remains unclear. These understandings of the local context within which adaptation actions occur are required prior conditions to effective adaptation (Antwi-Agyei et al., 2015; Rasmussen, 2018). In addition, these studies usually reported adaptation initiatives at national or sub-national scales (e.g. Berrang-Ford et al. (2014)) or from policy and planning or projects documents (e.g. Lesnikowski et al. (2015), Bizikova et al. (2015)), and the understanding of how specific adaptation initiative or action is taking place at community or household level is scanty. Indeed, higher-scale adaptation initiatives promoted in the SARs of West Africa remain technical in nature and ill-suited to capture local contexts, aspirations, and adaptation goals (Rasmussen, 2018).

For instance, Ecosystem-based Adaptation (EbA) approaches have been rapidly evolving recently and increasingly supported/recognized at international level (under the UNFCCC, the

CBD, the UNCCD) by various organizations (e.g. UNEP, IUCN, BirdLife International, IIED, FAO, GIZ) as well as several authors as strategies for climate change adaptation (Brink et al., 2016; Chong, 2014; Doswald et al., 2014; Jones et al., 2012; Munang et al., 2013; Muthee et al., 2017; Pramova et al., 2012; Vignola et al., 2015; Vignola et al., 2009; Vohland et al., 2012). EbA has gained visibility as a comprehensive, multifunctional and potentially cost-efficient approach for climate change adaptation (Brink et al., 2016; Jones et al., 2012). EbA refers to the use of biodiversity and ecosystem services to help people adapt to the adverse climate change impacts, with also multiple co-benefits for mitigation, protection of livelihoods and poverty alleviation (Doswald et al., 2014; Jones et al., 2012; Munang et al., 2013). Although the benefits and importance of ecosystem-based climate change adaptation strategies were highlighted (Doswald et al., 2014; Jones et al., 2012; Munang et al., 2013; Vignola et al., 2015; Vignola et al., 2009; Vohland et al., 2012), there was no studies that explored what EbA means in terms of adaptation and how it works at community or household level especially in semi-arid areas, which are climate change impacts hotspots. Doswald et al. (2014) reviewed the state of the evidence of the effectiveness of EbA approach and found that there was knowledge gap on how socially-differentiated groups with different vulnerability patterns could benefit from or take advantage of or adopt EbA approach. In addition, EbA interventions to reduce climatic and non-climatic vulnerability in SARs did not emerge explicitly from the systematic review (Doswald et al., 2014). Pramova et al. (2012) reviewed 44 least developed countries National Adaptation Programmes of Action (NAPAs) to assess the extent to which ecosystem services have been considered. They found that while the importance of ecosystem services is acknowledged in more than 50% of the NAPAs analysed, only 22% of the proposed projects included EbA activities, with most of the project supporting other adaptation measures (Pramova et al., 2012). Regulating and provisioning services were the two main ecosystem services components covered by the activities (Pramova et al., 2012). Muthee et al. (2017)

examined EbA approach in NAPAs documents and 31 NAPAs projects of Burkina-Faso and Mali, two countries in the SARs of West Africa, and found that agriculture was the main area of focus in the studied projects. The analysis has been extended to the whole West Africa and included 168 NAPA projects from 13 countries across West Africa (Muthee et al., 2018). Again, most of the adaptation initiatives under NAPAs fell within the agricultural thematic area (Muthee et al., 2018). Yet, our understanding of what EbA means in the context of agriculture and which practices already in place can be considered EbA appropriate for smallholder farming systems is limited (Vignola et al., 2015), particularly in SARs (Bizikova et al., 2015). The rare studies that explored EbA practices by smallholder farmers are the works by Harvey et al. (2017) and Shah et al. (2019) respectively in smallholder coffee and maize landscapes in Central America and in rural Pakistan. Moreover, most of the NAPA projects analysed fell under sub-national or national or sub-national levels (Muthee et al., 2017, 2018) with limited or no integration of indigenous knowledge and interventions at communities or household levels and interactions across scales were poorly developed.

As part of EbA, approaches based on utilization or maintenance of agricultural biodiversity (or agrobiodiversity) have also been suggested (Bedmar Villanueva et al., 2017; Doswald et al., 2014; Vignola et al., 2015). Agrobiodiversity refers to the "variety and variability of living organisms that contribute to food and agriculture in the broadest sense, and that are associated with cultivating crops and rearing animals within ecological complexes" (Jackson et al., 2013). Bedmar Villanueva et al. (2017) reviewed the NAPAs of 50 least developed countries to assess to which extent agricultural biodiversity is used in climate change adaptation actions. Their analysis indicated that in most of the NAPAs reviewed, agricultural biodiversity was not included in a comprehensive way (Bedmar Villanueva et al., 2017). Although agrobiodiversity-based strategies for climate change adaptation have been reported in the literature, included in the SARs of West Africa (Epule et al., 2017; Mortimore, 2010; Muthee et al., 2017; Sarr, 2012;

Sissoko et al., 2011), there have been no empirical studies that investigated the link between harnessing or utilization of agrobiodiversity and adaptive capacity/vulnerability pattern at household or community level or how and to what extend harnessing or utilization of agrobiodiversity could improve adaptive capacity or reduce vulnerability to climatic and non-climatic stressors. In addition, how maintenance or harnessing agrobiodiversity is driven by vulnerability patterns is unclear. Unravelling the interactions between adaptive capacity/vulnerability and harnessing agrobiodiversity can improve the understanding of the role or importance of agrobiodiversity in climate change adaptation in SARs and inform policy making and adaptation planning at local level.

To fill these gaps, this study takes a multi-scale and multidisciplinary approach, which combines a spatially-explicit climate and vegetation trends assessment (at district and watershed levels), participatory methods (at community or village level) and a quantitative modelling approach (at household level and individual levels) to shed light on the contribution and role of agrobiodiversity in climate change adaptation in semi-arid of West Africa. The study was conducted in Koutiala cercle, which belongs to the semi-arid part of Mali, West Africa.

1.3 Objectives

The overall objective of this study is to unravel the contribution and importance of agrobiodiversity for climate change adaptation in semi-arid areas of Mali, West Africa. Specifically, the study aims at:

- Unpacking climatic and non-climatic driving forces of vegetation dynamics in semi-arid areas of Mali;
- Assessing farmers' perception of impact of climate change on agroecosystems and adaptation strategies in semi-arid areas of Mali;

- Documenting and analysing agrobiodiversity-based practices for climate change adaptation and factors influencing harnessing agrobiodiversity for climate change adaptation in semi-arid areas of Mali;
- Assessing the effectiveness of agrobiodiversity-based practices for climate change adaptation in semi-arid areas of Mali.

1.4 Research questions

The main research questions that this study seeks to answer are:

- How and to what extent climatic and non-climatic driving forces have affected vegetation dynamics/conditions in semi-arid areas of Mali?
- How does local people's knowledge of climate change and its impacts on agroecosystems and its benefits drive adaptation behaviours?
- How and to what extent local people in semi-arid areas of Mali make use of agrobiodiversity for climate change adaptation?
- How and to what extent harnessing agrobiodiversity for climate change adaptation influences vulnerability patterns of local people in semi-arid areas of Mali?

1.5 Organization of the thesis

This thesis is organized into six chapters. Chapter one introduces the study by presenting the background, problem statement, research questions and objectives of the study. Chapter two critically reviewed literature on current/past and projected changes in climate as well as experienced and projected impacts in West Africa, with a focus on semiarid regions, perceptions of climate change by local people in the SAR of West Africa, and vegetation conditions and the role of climate change in vegetation dynamics. It also reviewed the current knowledge on the concepts of ecosystem services and its importance for people livelihoods, with a particular focus on SAR of West Africa, ecosystem-based adaptation, vulnerability and its assessment, and climate change adaptation. The chapter two concludes with the conceptual framework guiding the study. Chapter three presents the context of identification and selection of the study areas, climate and agroecological features of the study areas as well as livelihoods and socioeconomic dynamics. It also presents the methodological approaches developped to achieve the objectives of the study, with a focus on approach for climate-vegetation dynamics nexus analysis, farmers' knowledge and perception, and adaptation strategies assessment, household vulnerability assessment approach, and method to analysis effectiveness of agrobiodiversity-based adaptation practices. Chapter four presents the key results of the study, organised around climate variability and change, vegetation cover dynamics, perception and knowledge of climate change and its impacts on crop and livestock production, and individual and household level adaptation strategies, including agrobiodiversity-based adaptation practices. Chapter five highlights and discusses the key findings in the light of current knowledge of climate variability and change in the semiarid regions of West Africa, drivers of vegetation cover dynamics and of local ecological knowledge, including knowledge of climate change, heterogeneity in household vulnerability, and diversity and drivers of adaptation strategies. Chapter six summarises the study and provides conclusions and key implications of the findings.

CHAPTER TWO: LITERATURE REVIEW

2.1 Climate change and variability in semi-arid areas of West Africa

2.1.1 Current/Historical changes

In West Africa, a gradual and spatially variable increase in the annual mean temperature has been observed over the last 50 years (Collins, 2011; Daron, 2014; Riede et al., 2016; Sylla et al., 2016b). In SARs of West Africa, observed temperatures have been increasing faster than global warming (Klutse et al., 2018; Sarr, 2012; Sultan et al., 2014). Over the past 50 years, average temperature across the whole West Africa region has increased by about 1°C (Daron, 2014). While higher temperature increases were observed in northern parts of the region, particularly in Mali, temperature increases were lower along the coastal parts (Daron, 2014). Trends in precipitation observations are more complex (Riede et al., 2016). Clear trend of mean precipitation change over West Africa is less evident and mean precipitation change generally varies between −10 and 10 % (Sylla et al., 2016b). However, a pattern of continued aridity has been observed since the late 1960s (Dai, 2011; Nicholson et al., 2000), with a significant reduction in the number of rainy days and an increase in dry spells from 1960 to 1990 (Sarr, 2012). There has been a lasting deficit of the number of rainy days from 2001–2010, while at the same time the extreme rainfall occurrence has been increasing (Panthou et al., 2014). Also, in some areas, the rainy season has shifted towards later rainfall particularly in recent decades (Daron, 2014; Salack et al., 2015; Sanogo et al., 2015). Actually, there has been a substantial spatial and temporal (multi-decadal, annual and seasonal) variability in rainfall patterns over the past 50 years in the West Africa region, especially in the Sahel (Biasutti, 2019; Daron, 2014; Nicholson, 2013; Nicholson et al., 2000; Sarr, 2012). From 1951 to 2010, western and eastern Sahel have experienced a decrease in the annual precipitation, with a very dry period in the 1970s and 1980s (Nicholson, 2013; Riede et al., 2016; Sanogo et al., 2015). After the severe drought episodes until today, the Sahel has slightly recovered, though the precipitation quantity is yet to reach the pre-drought level (Biasutti, 2019; Bichet & Diedhiou, 2018; Druyan, 2011; Nicholson et al., 2018; Panthou et al., 2018; Riede et al., 2016; Sanogo et al., 2015; Sylla et al., 2016b). There is evidence of wetting (water storage, soil moisture, groundwater, and rainfall) trends after the severe drought periods (Ndehedehe et al., 2018). There is also evidence that extreme droughts are consistently more severe after 1970 than they were before (Chamani et al., 2019). The recovery is characterized by new rainfall features including false start and early cessation of rainy seasons, increased frequency of rainy days along with increased precipitation intensity, more frequent dry spells, increasing number of hot nights and warm days (Biasutti, 2019; Salack et al., 2016; Salack et al., 2015; Sanogo et al., 2015). Bichet and Diedhiou (2018) found that the recent increase in precipitation (over the period 1981-2014) in the Sahel results mainly from an increase in the number of wet days over the entire Sahel, and an increase in the precipitation intensity over the central part (decreasing in the western part). However, this overall increase in precipitation is associated with dry spells that are becoming more frequent (Bichet & Diedhiou, 2018). Findings by Panthou et al. (2018) confirmed the hydro-climatic intensification that is taking place in the Sahel, with an increasing intensity of rainy days associated with a higher frequency of heavy rainfall. Rather than a rainfall recovery, the Sahel is experiencing a new era of climate extremes (Biasutti, 2019; Bichet & Diedhiou, 2018; Panthou et al., 2018).

2.1.2 Projected changes

Temperature increases are projected to continue and to be stronger in the future regardless of the emission scenario over West Africa, though with some variations across different climatic zones, with the largest changes in the Sahel (Diedhiou et al., 2018; Klutse et al., 2018; Riede et al., 2016; Sarr, 2012; Sylla et al., 2016b; Vizy et al., 2013). Indeed, temperature in West Africa is projected to increase faster than either in 1.5 °C or 2 °C world (Diedhiou et al., 2018; Klutse et al., 2018). Across the whole region, the projected temperature increase is very likely to exceed the 1986–2005 reference by between 3 and 6 °C by the end of the century under business-as-usual emissions (RCP8.5) scenario (Riede et al., 2016) or between 1.5 and 6.5°C with reference to 1970–2005 baseline, with the Sahel experiencing the largest changes (Sylla et al., 2016b). In the Sahel, temperature variability is projected to increase by up to 10% for each degree of global warming (Bathiany et al., 2018). Heat waves are projected to be more frequent and longer in the West Africa region, with the most intense warming observed over the Sahel (Diedhiou et al., 2018).

Future projections of precipitation change over the region are subject to substantial uncertainties with regards to the magnitude and direction of change (Daron, 2014; Druyan, 2011; Sylla et al., 2016b). Variability on inter-annual, decadal and multi-decadal time scales, as experienced in the past, is projected to continue in the future (Daron, 2014). The range of possible precipitation changes oscillates mostly between −30 and 30 % (Sarr, 2012; Sylla et al., 2016b). In addition, both dry spell length and extreme precipitation intensity are projected to substantial increase in many parts of West Africa (Klutse et al., 2018; Sylla et al., 2016b). Also, it is expected that the shift in rainy season onset may continue to move forward (Sarr, 2012; Sultan et al., 2014) and increased aridity, with a striking pattern that suggests continued drying in the century (Chamani et al., 2019; Dai, 2011). Over most of the Sahel, except in the northwest, around Senegal, summer monsoon rainfall is projected to increase, even at a 1.5 °C global warming (Akinsanola & Zhou, 2019a; Diedhiou et al., 2018; Monerie et al., 2016; Sultan et al., 2014; Vizy et al., 2013), as a result of increased rainfall intensity, not a lengthening of the rainy season (Vizy et al., 2013). In fact, the late-twenty-first-century projected changes in rainfall characteristics indicate a delay in the rainy season onset (Sultan et al., 2014; Sylla et al., 2015) and in the monsoon withdrawal (Monerie et al., 2016). The western and eastern Sahel is expected to become hotspots for delayed rainfall onset and reduced rainy season length regardless of global warming and emission scenarios (Kumi & Abiodun, 2018). The hot nights, daily rainfall intensity, consecutive dry days, extreme rainfall events and the length of dry spells are projected to significantly increase, particularly in the Western Sahel (Akinsanola & Zhou, 2019b; Diedhiou et al., 2018; Klutse et al., 2018). The rainfall intensity of very wet days will also increase, particularly in the Sahel and under the business-as-usual scenario (Sylla et al., 2015). Heat waves will be longer and more frequent in the future even if global warming is kept below 2°C (Weber et al., 2018). These effects will be amplified if the global temperature exceeds the 2°C threshold (Weber et al., 2018).

2.2 Impacts of climate change in semi-arid areas of West Africa

2.2.1 Historical impacts

In SARs of West Africa, climate variability and change experienced over the past 50 years have caused strong climate-related, ecological and agricultural impacts (Gautier et al., 2016; Kilroy, 2015). The new rainfall conditions termed "*hybrid rainy seasons*" induced by global warming and characterized by false start and early cessation of rainy seasons and increased frequency of intense daily rainfall (Salack et al., 2016; Salack et al., 2015) have serious implications for agricultural production, which is mainly rain-fed in the region (Gautier et al., 2016; Salack et al., 2015; Sultan & Gaetani, 2016; Sultan et al., 2014; Sultan et al., 2013; You et al., 2011). Crop production have been significantly affected by climate change in West Africa, with yield reductions of 10–20% for millet and 5–15% for sorghum (Sultan et al., 2019). The average annual production losses across West Africa in 2000–2009 decade due to climate change accounted for 2.33–4.02 billion USD for millet and 0.73–2.17 billion USD for sorghum (Sultan et al., 2019). In the Sahel, variability and changes in temperature and precipitation have led to significant decline in tree density and species richness (Gonzalez et al., 2012). It is very likely that services and functions derived from tree-based ecosystems were also affected/reduced. The combined effect of rainfall, land surface temperature and solar radiation explains approximately 40% of the variation in cropland productivity over West Africa at the

95% significance level (Mechiche-Alami & Abdi, 2020). Changes in number of rainy days and the timing of the rainy season negatively affected vegetation growth in the semiarid Sahel (Zhang et al., 2018). Climate change and variability also led to a southward shift of the climatic zones in West Africa (Gonzalez et al., 2012), with serious consequences for agricultural output and human livelihoods (Sissoko et al., 2011). In addition, the strong spatio-temporal variability in rainfall patterns has far-reaching impacts on water quality and availability, on crop yield and production, and thus on food security in the region (Ben Mohamed, 2011; Gautier et al., 2016; Sissoko et al., 2011; Sultan & Gaetani, 2016; Zougmoré et al., 2016). These highlight the significance of rainfall to natural ecosystems and livelihood systems in these semiarid regions (Gautier et al., 2016; Herrmann et al., 2005; Kilroy, 2015; Knauer et al., 2014; Zhang et al., 2018). Indeed, the livelihoods and economies of people living in SARs of West Africa are mainly agriculture- and natural resource-based, including animal husbandry, and thus, highly sensitive to climate variability and change (Ben Mohamed, 2011; Knauer et al., 2014; Perez et al., 2015; Sarr, 2012; Sissoko et al., 2011; Zougmoré et al., 2016). Consequently, the 1970s and 1980s severe droughts have had devastating negative societal impacts, including famines, population shifts and social upheaval (Druyan, 2011; Gautier et al., 2016; Zougmoré et al., 2016) and contributed to increased vulnerability and poverty (Barbier et al., 2009; Ben Mohamed, 2011; Sissoko et al., 2011; Zougmoré et al., 2016). This emphasizes the close relationship between ecological sensitivities and social vulnerability in semi-arid areas (Tucker et al., 2015). However, vulnerability of local communities in SARs is driven not only by climatic factors but also by non-climatic factors operating at different scales (Barbier et al., 2009; Tucker et al., 2015). In addition to climatic factors, other biophysical and socioeconomic and political factors influence farmers' vulnerability in SARs of West Africa (Barbier et al., 2009; Mertz et al., 2009; Perez et al., 2015) and the dynamics of crop land changes and agricultural production (Mertz et al., 2011; Sissoko et al., 2011). For instance, climate change interacts with land use-land cover chance to drive increase in flood occurrence and magnitude in the Sahel (Aich et al., 2015). This highlights the context- and location-dependent nature of driving forces of vulnerability and changes in SARs of West Africa (Gautier et al., 2016; van Vliet et al., 2013).

2.2.2 Projected impacts

Projected change and variability in the future climate is also expected to have serious impacts on agriculture and food production, with severe risks for food security and negative repercussions for human health and employment (Butt et al., 2005; Guan et al., 2015; Serdeczny et al., 2017; Sissoko et al., 2011). The late 21st century projections reveal an extension of torrid, arid and semi-arid climate regime throughout West Africa, with the recession of moist and wet zones (Sylla et al., 2016a). The current Sahel, mainly semi-arid in present-day conditions, is expected to face moderately persistent future arid climate (Sylla et al., 2016a).

Expected changes in rainfall onset and reduction in growing period length are also a crucial concern for agricultural production in the semiarid areas of West Africa (Guan et al., 2015; Sarr, 2012; Sylla et al., 2015). Changes and variability in precipitation and temperature will have negative impact on crop yields, especially maize, sorghum and millet, three key staple crops in the region, as well as on forage crop yields and livestock weights (Butt et al., 2005; Ebi et al., 2011; Guan et al., 2015; Roudier et al., 2011; Salack et al., 2015; Sultan & Gaetani, 2016; Sultan et al., 2014; Sultan et al., 2013; Traore et al., 2017). At either 1.5 °C or 2 °C global warning and with either current fertilizer use or unlimited fertilizer use, yields of these three key staple crops are projected to decrease (Faye et al., 2018b; Parkes et al., 2018a; Parkes et al., 2018b), with exception to millet which will experience no yield change at current fertilizer use for either scenario (Faye et al., 2018b). Nevertheless, under future climatic conditions, peanut yields are projected to increase both under rain-fed or irrigated dry season conditions

(Faye et al., 2018a). This could be explained by CO_2 fertilization effects (Faye et al., 2018a). In Sikasso region, southern Mali, white (Irish) potatoes, a key cash crop for households, will be the most affected by changing climatic conditions by 2060, with yields decreasing, under both dry and wet conditions, by almost 25% (Ebi et al., 2011).

Cereals yield reduction will be greater in the Sudanian zone, because of the exacerbated sensitivity to temperature changes compared to the Sahelian zone, where crop yields are more sensitive to rainfall change (Guan et al., 2015; Roudier et al., 2011; Sultan & Gaetani, 2016; Sultan et al., 2013). There is also a West-East dipole in crop yield reduction, with yield reduction and year-to-year variability higher in the Western part of the Sahel, while the eastern domain sees much milder impacts (Sultan & Gaetani, 2016; Sultan et al., 2014). In addition, negative impacts on crop productivity increase in severity as warming intensifies (Roudier et al., 2011; Sultan & Gaetani, 2016). In Mali, projected cereal crops yield reductions are expected to reduce food availability and food self–sufficiency, especially of smallholder farmers, who are already food insecure (Butt et al., 2005; Traore et al., 2017).

SARs of West Africa are projected to experience additional water stress in the future (Ben Mohamed, 2011; Sissoko et al., 2011; Sylla et al., 2018b; Sylla et al., 2018c). Crop water demand and irrigation water needs are expected to significantly increase (Sylla et al., 2018c), while irrigation potential is expected to decrease in West African river basins, with largest impacts in the semi-arid Sahel (Sylla et al., 2018c). Potential water availability across major river basins in West Africa is projected to substantially decrease (10 to 40%), with the largest changes in the semi-arid Sahelian river basins (Sylla et al., 2018b). Limiting global warming under 2 °C reduces these impacts by as much as 50%, implying that large-scale irrigation potential will be reduced if global temperature exceeds the 2°C threshold (Sylla et al., 2018c). In business-as-usual scenario (RCP8.5) West Africa will face an unprecedented water deficit during the second half of the twenty-first century (Sylla et al., 2018b).

Climate change could also limit carbon sequestration potentials of semi-arid West African Savannas by reducing carbon storage capacity of various land use classes (Dimobe et al., 2018).

Heat stress is expected to extend spatially over most of West Africa, with regional and seasonal variations (Sylla et al., 2018a). The percentage of human population at discomfort is also projected to increase to more than 50% over most of the region (Sylla et al., 2018a). The Sahel is one of the two regions where new areas where most of the population is at risk will emerge (Sylla et al., 2018a). This implies that from 50% to almost everyone over most of the Sahel countries will be at risk of possible heat exhaustion, heat stroke, and heat cramp in future scenarios (Sylla et al., 2018a). Limiting global warming under the 2°C threshold will reduce the impacts of heat stress and discomfort for humans (Sylla et al., 2018a).

Because of the warming conditions projected, malaria risk for West Africa is expected to fall in the western part or remain constant in the eastern part over the twenty-first century (Yamana et al., 2016). There will be a shift of malaria hotspots from West Africa to the eastern and southern parts of Africa under RCP 8.5 (Semakula et al., 2017).

2.3 Remote sensing of vegetation dynamics in semi-arid areas of West Africa

Triggered by the 1970s and 1980s severe droughts, which have had devastating negative societal impacts, scientific interests on environmental change, particularly the condition of the vegetation in SARs of West Africa have grown and become a matter of global concern over the past four decades (Karlson & Ostwald, 2016; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014). Consequently, the region has become is one of the most studied ecoregions in Africa, by natural as well as social scientists (Karlson & Ostwald, 2016; Mbow et al., 2014; Mbow et al., 2013). As the *in-situ* high quality long-term environmental data are generally scarce, most studies have relied on the use of satellite-based earth observation data (Karlson & Ostwald, 2016; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014; Mbow et al., 2013).

Medium- to coarse-resolution remote sensing observations are widely used for monitoring vegetation dynamics at various scales (Karlson & Ostwald, 2016; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014; Mbow et al., 2013). The Normalized Difference Vegetation Index (NDVI) is the main proxy extensively used to analyse vegetation conditions (de Araujo Barbosa et al., 2015; Herrmann & Tappan, 2013; Karlson & Ostwald, 2016; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014).

Based on analysis of time series of medium- to coarse-resolution remote sensing data, many studies have shown a "re-greening" trend in SARs of West Africa after the 1970s and 1980s severe droughts (Bégué et al., 2011; Brandt et al., 2014a; Brandt et al., 2014b; Dardel et al., 2014; Herrmann et al., 2005; Herrmann et al., 2014; Kaptué et al., 2015; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014; Olsson et al., 2005). However, by combining field-based and satellite observations, Dardel et al. (2014) have shown that, although greenness is the dominant positive trends in SARs of West Africa, degradation trends can also be observed in some areas. This conclusion has been supported by Kaptué et al. (2015) who identified strong spatial variations in the magnitude and direction of change. The observed spatio-temporal dynamics contrast with the simplified labels of "greening" or "degradation" (Brandt et al., 2017b; Brandt et al., 2014b).

Nevertheless, the general greening trend is reflected in increase in woody biomass, changes in vegetation composition and in reduction in woody species richness and diversity (Brandt et al., 2016; Brandt et al., 2019; Brandt et al., 2015; Brandt et al., 2017a; Brandt et al., 2014b; Hänke et al., 2016; Herrmann & Tappan, 2013; Spiekermann et al., 2015). This impoverishment of the vegetation is characterized by loss of large trees, an increasing dominance of shrubs and woody vegetation over herbaceous vegetation, and a shift towards more arid-tolerant species (Brandt et al., 2019; Brandt et al., 2015; Hänke et al., 2016; Herrmann et al., 2014; Herrmann & Tappan, 2013; Spiekermann et al., 2015).

Although the overall greening trend appears to be well documented (Knauer et al., 2014), yet the causes behind and the explanations of these remote-sensing-based results are poorly understood and still lack a consensus (Brandt et al., 2015; Brandt et al., 2014a; Herrmann & Tappan, 2013; Knauer et al., 2014; West et al., 2017). Trends in vegetation have shown to be, at least partly, explained by precipitation change (Brandt et al., 2015; Brandt et al., 2017b; Herrmann et al., 2005; Leroux et al., 2017; Olsson et al., 2005; Rasmussen et al., 2014; Zhang et al., 2018). Climate was responsible for 52% of the greening trends and 25% of the browning trends, with the largest proportions of croplands with greening trends observed in Mali, Niger and Burkina Faso, and the largest proportions with browning trends in Nigeria, The Gambia and Benin (Mechiche-Alami & Abdi, 2020). Indeed, rainfall emerged as a dominant, but not the only, driver of the positive NDVI trend (Brandt et al., 2015; Brandt et al., 2014b; Herrmann et al., 2005; Leroux et al., 2017; Olsson et al., 2005) and increases in woody vegetation (Anchang et al., 2019; Brandt et al., 2019; Brandt et al., 2017a), leaving room for interpretations of potential anthropogenic factors (Brandt et al., 2014a; Herrmann & Tappan, 2013; Tong et al., 2017; West et al., 2017). Cropland changes and expansion, land use transformation, migration and population density have been shown to explain greening trends (Bégué et al., 2011; Brandt et al., 2014a; Olsson et al., 2005; Spiekermann et al., 2015; Tong et al., 2017) and positive woody vegetation cover trends (Brandt et al., 2016; Brandt et al., 2018). Within the other driving factors, changes in phenology explained 18% of the greening and 37% of the browning trends across the region, the use of inputs and irrigation explained 30% of the greening trends and land degradation 38% of the browning trends (Mechiche-Alami & Abdi, 2020). Therefore, explanations for trends cannot be generalized, but are rather heterogeneous and site-specific (Brandt et al., 2014a).

One of the principal challenges in analysing vegetation dynamics is to document the underlying factors coherently (Leroux et al., 2017). Few studies have, however, attempted to link vegetation trends to causative factors, as it is usually done in land use and land cover change (LULCC) studies at finer resolution (Leroux et al., 2017). In addition, while remote sensing data has mainly been used to analyse changes in vegetation conditions and general vegetation types, the use of remote sensing data to assess interactions between vegetation and environmental drivers has been relatively limited (Karlson & Ostwald, 2016). Therefore, local assessments at a higher spatial resolution are needed to verify the medium- to coarse-resolution results and investigate the reasons for greening or degradation as well as the interactions among drivers of trends (Knauer et al., 2014; Mbow et al., 2015). Moreover, to allow multiple perspectives and avoid erroneous explanations, satellite-based findings should be interpreted with contextual knowledge and integrated within local people perceptions and knowledge systems and social dynamics contexts (Herrmann et al., 2014; Mbow et al., 2015).

2.4 Perception of climate change in semi-arid areas of West Africa

Over the years, local people in SARs of West Africa have developed a deep indigenous ecological knowledge system that has enabled them to make use of ecosystem services to support their livelihoods and to survive environmental change (Gautier et al., 2016; Lahmar et al., 2012; Mertz et al., 2009; Nyong et al., 2007; Segnon et al., 2015). This indigenous knowledge systems have also been crucial to adaptation strategies developed to reduce their vulnerability to past climate variability and change in the region (Gautier et al., 2016; Lahmar et al., 2012; Nyong et al., 2007; Segnon et al., 2015).

As climate change became evident and a major concern on the global agenda, interests in local people's knowledge and understanding of climate change have also increased. Several studies have assessed local people knowledge and perception of climate change and variability in the SARs of West Africa (Barbier et al., 2009; Kosmowski et al., 2016; Mertz et al., 2012; Mertz et al., 2009; Ouédraogo et al., 2010; Sanogo et al., 2017; Tambo & Abdoulaye, 2013; Traore et al., 2015). Their findings revealed that local people in SARs of West Africa have perceived increased in temperature and temperature-related stressors (heat waves, number of extreme hot or cold days) over the past years, and this was consistent with the observed meteorological data (Mertz et al., 2012; Mertz et al., 2009; Sanogo et al., 2017; Tambo & Abdoulaye, 2013; Traore et al., 2015). However, local people perception and understanding of rainfall change is more heterogeneous. Local people perception of change (either decrease or increase) in the amount of rainfall was inconsistent with observed meteorological data (Mertz et al., 2012). However, their perception of an increase in dry spells occurrence during rainy season and rainfall variability, changes in rainfall pattern (onset, cessation, rainfall intensity and distribution, etc.) (Barbier et al., 2009; Kosmowski et al., 2016; Ouédraogo et al., 2010; Sanogo et al., 2017; Tambo & Abdoulaye, 2013; Traore et al., 2015) is consistent with the new era of climate extremes experienced in the semiarid Sahel (Biasutti, 2019; Panthou et al., 2018). This new rainfall conditions termed "*hybrid rainy seasons*" induced by global warming and characterized by false start and early cessation of rainy seasons and increased frequency of intense daily rainfall (Salack et al., 2016; Salack et al., 2015).

Key drivers of differential farmers' perception include demographic and socioeconomic factors (such as age, gender, education, age, etc) (Sanogo et al., 2017; Segnon et al., 2015). Being involved in climate-sensitive economic activities also affects perception of climate change (Kosmowski et al., 2016). For instance, smallholders, commercial farmers, pastoralists and sedentary agro-pastoralists living in rural dry areas of Niger have a higher level of awareness of rainfall changes than other inhabitants (Kosmowski et al., 2016). Their perceptions are more consensual and more closely related to observed changes (Kosmowski et al., 2016).

2.5 Ecosystem services: Definition, importance and drivers

2.5.1 Ecosystem services: Definition and conceptualisation

The Millennium Ecosystem Assessment (MEA) defined Ecosystem Services (ES) as the benefits people derive from ecosystems and ecosystem functions (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). Costanza et al. (2017) further clarified this simple and straightforward definition and described ES as the functions and processes of ecosystems that benefit humans, directly or indirectly, whether humans perceive those benefits or not. Ecosystem processes and functions contribute to ES but they are not synonymous (Costanza et al., 2017); Ecosystem processes and functions describe biophysical relationships that exist regardless of whether or not humans benefit (Costanza et al., 2017). The MEA categorized ES in provisioning (e.g. fibre, food, timber, water), regulating (e.g. floods, drought, land degradation, and disease regulation), supporting (e.g. soil formation and nutrient cycling) and cultural (e.g. spiritual, religious, recreational and other nonmaterial benefits) services (Millennium Ecosystem Assessment, 2005). Biodiversity, understood here as the "variability among living organisms from all sources, including diversity within species, between species and of ecosystems", play key roles at all levels of the ES hierarchy: as a regulator of underpinning ecosystem processes, as a final ES and as a good (Díaz et al., 2006; Harrison et al., 2014; Mace et al., 2012). In agroecosystems, agrobiodiversity provide key ES that support the production of food, bioenergy, forage and pharmaceuticals that are crucial to human wellbeing (Power, 2010; Wood et al., 2015; Zhang et al., 2007). Agrobiodiversity refers to the "variety and variability of living organisms that contribute to food and agriculture in the broadest sense, and that are associated with cultivating crops and rearing animals within ecological complexes" (Jackson et al., 2013; Segnon & Achigan-Dako, 2014). ES in the context of agricultural ecosystems will be the overall conceptual lens of this thesis.

Recently, the notion of Nature's Contributions to People (NCP) has been introduced as building on but extending beyond the concept of ES concept (Díaz et al., 2018). NCP refer to "all the contributions, both positive and negative, of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life" (Díaz et al., 2015; Díaz et al., 2018; Pascual et al., 2017). Initially developed within the context of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2015; Pascual et al., 2017), NCP approach recognizes the central and pervasive role that culture plays in defining all links between people and nature (Díaz et al., 2018; Pascual et al., 2017). In addition, the use of NCP elevates, emphasizes, and operationalizes the role of indigenous and local knowledge in understanding nature's contribution to people (Díaz et al., 2018; Pascual et al., 2017).

While NCP aimed to address the key limitation of ES concept, it has received strong criticism and vigorous opposition from the ES research community (see Braat (2018); Kenter (2018); Peterson et al. (2018) and multiple *Science* journal *eLetters*[1]). Replacing ES with a near-synonymous term does little to address the semantic problems associated with ecosystem services (Braat, 2018; Kenter, 2018). NCP still characterises the relation between nature and people as one-way and the value of nature as instrumental (as a provider of benefits), masking human agency and broader values (Kenter, 2018; Peterson et al., 2018). As most of the world's population live in urban ecosystems, and neither urban nor agro-ecosystems are typically considered or classified as "nature", a focus on "nature" therefore de-emphasizes the ecosystems that are home to and provide the necessities of life to most of the world's population (Peterson et al., 2018). Therefore, many researchers in ES science community argue that the NCP term risks unnecessary debates (see *Science eLetters*), and NCP and ES should be

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[1] https://science.sciencemag.org/content/359/6373/270/tab-e-letters

regarded as synonyms and used appropriately for different audiences and purposes (Braat, 2018; Kenter, 2018).

2.5.2 Ecosystem services and human wellbeing

ES provide, directly and indirectly, substantial contributions to the sustainable wellbeing of humans, and represent part of the total economic value of the planet (Costanza et al., 1997; Costanza et al., 2014; Daily et al., 2000; Díaz et al., 2006; Millennium Ecosystem Assessment, 2005). ES provided by natural environments and green spaces enhance well-being (psychological and physical) and immune system regulation (Aerts et al., 2018). Biodiversity supports ES mitigating heat, noise and air pollution, which all mediate the positive health effects of natural environments and green spaces (Aerts et al., 2018). In rural areas of developing countries, particularly in sub-Saharan Africa, ES sustain livelihoods of households and contribute to reduction of vulnerability to poverty and poverty reduction (Suich et al., 2015). Ecosystem services contribute more than twice as much to human well-being as global GDP (Costanza et al., 2014). In 1997, the value of the total global ES was estimated to be around US$ 33 trillion per year, a figure significantly larger than global gross domestic product at the time (Costanza et al., 1997). In 2011, the estimated total value of the global ES was $125 trillion per year (assuming updated unit values and changes to biome areas) and $145 trillion per year (assuming only unit values changed) (Costanza et al., 2014). Based on local case studies across the world, the total values of ES provided by 10 main biomes is considerable and ranges between $490 per year for the total bundle of ES that can potentially be provided by an 'average' hectare of open oceans to almost $350,000 per year for the potential services of an 'average' hectare of coral reefs (de Groot et al., 2012).

2.5.3 Drivers of ecosystem service change

Despite its substantial contributions in supporting human wellbeing, ES have been degraded over time (Costanza et al., 2014; Díaz et al., 2006; Leh et al., 2013; Nelson et al., 2006; Stenchly et al., 2019). For instance, between 1997 and 2011, estimated global loss of ES due to land use change was $US 4.3-20.2 trillion per year (Costanza et al., 2014). Drivers of ES change include both indirect (demographic pressure, economic, socio-political, cultural and religious factors, and scientific and technological development) and direct (biodiversity loss, land use change, climate change, chemical nutrient use, biological invasions and diseases) drivers (Campbell et al., 2017; Díaz et al., 2006; Nelson et al., 2006). Global agricultural production, particularly, is a major driver of planetary boundaries, i.e., Earth system processes, which, if crossed, could generate unacceptable environmental change potentially endangering human existence (Campbell et al., 2017). In West Africa, increasing population, urbanization, extensive agricultural practices, and land use change jeopardizes ES provision (Inkoom et al., 2018; Stenchly et al., 2019).

2.6 Ecosystem services and livelihoods in semi-arid areas of West Africa

Agricultural ES continue to form a significant proportion of the global food basket and support the livelihoods of millions of people across the world (Power, 2010; Wood et al., 2015; Zhang et al., 2007). In SARs of West Africa, agrobiodiversity and its ES provide key inputs into people livelihoods, which are predominantly agriculture- and natural resource-based (Bayala et al., 2014; Félix et al., 2018a; Félix et al., 2018b; Leh et al., 2013; Sinare & Gordon, 2015). Woody vegetation and agricultural landscapes provides an array of provisioning, regulating, supporting and cultural ES that directly support livelihoods (Bayala et al., 2014; Kuyah et al., 2016; Leßmeister et al., 2018; Malmborg et al., 2018; Sinare & Gordon, 2015). Woody species contribute significantly to farmers' livelihoods by providing foods, particularly when other food products are scarce, medicinal products, fodder for livestock, and wood (Faye et al., 2010; Leßmeister et al., 2018; Sinare & Gordon, 2015; Sinare et al., 2016). Agroforestry products and wild edible plants provide the primary source of revenue for some households in the region and constitute an important asset in addressing food security by ensuring availability and accessibility of food (Félix et al., 2018a; Segnon & Achigan-Dako, 2014), especially in the "hunger period" when grain stores are low and farmers are waiting for the next harvest (Faye et al., 2010; Leßmeister et al., 2018; Sinare et al., 2016). Faye et al. (2010) reported that in SARs of Mali, income from Non-timber forest product (NTFP) sales contribute from 26 to 73 % to rural household revenues. ES were found to be modest but significant predictors of household wealth in SARs of Mali, particularly among the poorest households (Liebenow et al., 2012). In Sudanian zone of Burkina Faso, NTFPs represented the second largest income share (45%) of total household income in comparison to other income sources, including crop and livestock production, and off-farm activities (Leßmeister et al., 2018). Agrobiodiversity also provides a number of regulating services, including soil nutrient recycling, carbon storage, soil carbon sequestration, soil and water conservation, soil protection (Leh et al., 2013; Sinare & Gordon, 2015) and, thus, play a major role in enhancing agroecosystem productivity and resilience of drylands (Bayala et al., 2014; Félix et al., 2018b; Kuyah et al., 2016). The diversity of livelihoods benefits illustrates the strong multifunctionality of the Sahelian landscapes (Bayala et al., 2014; Malmborg et al., 2018; Sinare et al., 2016).

2.7 Ecosystem-based Adaptation

Following the Rio+20 United Nations Conference on Sustainable Development, which explicitly recognized, for the first time, that ecosystems are the core element of addressing climate change impacts and paving the way toward achieving sustainable development, the concept of Ecosystems based approaches to Adaptation to climate change (EbA) has been evolving (Munang et al., 2013). EbA refers to the use of biodiversity and ES to help people adapt to the adverse impacts of climate change, with also multiple co-benefits for mitigation, protection of livelihoods and poverty alleviation (Doswald et al., 2014; Jones et al., 2012;

Munang et al., 2013). It has emerged as a comprehensive, multifunctional and potentially cost-efficient approach for climate change adaptation (Brink et al., 2016; Jones et al., 2012) and is increasingly supported/recognized at international level (under the UNFCCC, the CBD, the UNCCD) by various organizations (e.g. UNEP, IUCN, BirdLife International, IIED, FAO, GIZ) as well as several scholars (Brink et al., 2016; Chong, 2014; Doswald et al., 2014; Jones et al., 2012; Munang et al., 2013; Muthee et al., 2017; Pramova et al., 2012; Seddon et al., 2018; Vignola et al., 2015; Vohland et al., 2012). As part of EbA, approaches based on utilization or maintenance of agricultural biodiversity (or agrobiodiversity) have also been suggested (Bedmar Villanueva et al., 2017; Doswald et al., 2014; Muthee et al., 2017; Vignola et al., 2015). It can also be referred to the "implementation of agricultural management practices that use or take advantage of biodiversity, ecosystem services or ecological processes (either at the plot, farm or landscape level) to increase the ability of crops or livestock to adapt to climate change and variability" (Vignola et al., 2015). EbA approach falls under Nature-based Solutions (NbS), an umbrella concept that covers a whole range of ecosystem-related approaches (Cohen-Shacham et al., 2019; Seddon et al., 2018).

Research on EbA has increased rapidly and has covered a diversity of aspects ranging from the state of the evidence of the effectiveness of EbA approach (Doswald et al., 2014), EbA approach in urban areas (Brink et al., 2016), EbA in international legal frameworks (Chong, 2014) to the role of EbA in increasing adaptive capacity of poor (Vohland et al., 2012) and the operationalization of EbA the context of agriculture (Harvey et al., 2017; Shah et al., 2019; Vignola et al., 2015). The extent to which ecosystem services have been considered in NAPAs in least developed countries has also been assessed (Bedmar Villanueva et al., 2017; Pramova et al., 2012) including semi-arid countries of West Africa (Muthee et al., 2017, 2018). Recently, the importance and prominence of NbS (including EbA) in the NDCs submitted to UNFCCC by all signatories of the Paris Agreement were also assessed (Seddon et al., 2018).

In coastal areas, mangroves and revegetation with native species provide mechanical protection of coast against inundation raising from sea level rise and contribute to recovery of coastal ecosystems (Doswald et al., 2014; Jones et al., 2012; Vohland et al., 2012). In urban ecosystems, ES provided by urban forests (green space, wetlands, trees and parks, etc.) are harnessed to adapt to heat waves, control flooding, reduce air pollution and regulate micro-climates (Aerts et al., 2018; Brink et al., 2016; Doswald et al., 2014; Vohland et al., 2012). Coral reefs provide fishing ground to adapt to water temperature increase and acidification of oceans (Doswald et al., 2014; Jones et al., 2012; Vohland et al., 2012). Agroecosystem services provided by termites, agroforestry parklands and cultivated plant diversity contribute to buffer drought, enhance agroecosystem productivity and resilience, and ensure food security (Bayala et al., 2014; Doswald et al., 2014; Félix et al., 2018b; Jones et al., 2012; Vignola et al., 2015; Vohland et al., 2012). In smallholder coffee and maize landscapes in Central America, common EbA practices included live fences, home gardens, shade trees in coffee plantations, and dispersed trees in maize fields (Harvey et al., 2017). Drivers of adoption (probability and intensity) of EbA practices include farmers' characteristics and social capital, farm characteristics and institutional access (Harvey et al., 2017; Shah et al., 2019).

Global assessment of the importance of NbS (including EbA) in the NDCs submitted to UNFCCC by all signatories of the Paris Agreement indicated that a global recognition of the importance of nature-based solutions to climate change impacts (Seddon et al., 2018). About 66% of Paris Agreement signatories include nature-based solutions in their NDCs (Seddon et al., 2018). However, commitments rarely translate into robust science-based targets (Seddon et al., 2018). An assessment of NAPAs documents and projects of developing countries, including semi-arid West African countries, indicated that while the importance of ecosystem services was acknowledged in most NAPAs, EbA activities was not included in a comprehensive way (Bedmar Villanueva et al., 2017; Muthee et al., 2017, 2018; Pramova et al., 2012). Regulating and provisioning services were the two main ES categories covered by the NAPAs activities, with agricultural sector as the predominant focus areas of the activities (Bedmar Villanueva et al., 2017; Muthee et al., 2017, 2018; Pramova et al., 2012). Moreover, most of the NAPA projects analysed fell under national or sub-national scales (Muthee et al., 2017, 2018).

Institutional and legal barriers can pose significant challenges to operationalizing EbA to achieve adaptation objectives (Chong, 2014). There is also a need for multi-stakeholder (scientists, policy makers, civil society, etc.) partnerships and collaboration to promote the role of ES in climate change adaptation and for EbA mainstreaming in policy (Vignola et al., 2009)

2.8 Vulnerability: Conceptualization and assessment

2.8.1 Concept of vulnerability

Rooted in natural hazard and poverty studies, the concept of vulnerability has gradually entered into research on adaptation of people to environmental change impacts, especially climate change (Adger, 2006; Cutter, 1996; Füssel, 2007). Although there are diverse interpretations of vulnerability, according to different fields of study and traditions, the key concepts of exposure, sensitivity, and adaptive capacity are underpinning the most prominent conceptualization of vulnerability in climate change research (Adger, 2006; Cutter, 1996; Ford et al., 2018; Füssel, 2007; Füssel & Klein, 2006; Miller et al., 2010; O'Brien et al., 2007; Smit & Wandel, 2006), that is, the often-cited IPCC fourth Assessment Report conceptualization of vulnerability. Vulnerability is most often conceptualized as the susceptibility of a system to perturbations or stresses determined by its exposure and sensitivity to perturbations or stresses, and the capacity to adapt (Adger, 2006; Füssel, 2007; Nelson et al., 2007; Smit & Wandel, 2006; Tonmoy et al., 2014). Exposure is the nature and degree to which a system experiences environmental or socio-political stress (Adger, 2006; Füssel & Klein, 2006). Sensitivity is the degree to which a system is modified or affected, either adversely or beneficially, by perturbations, such as climate-related stress (Adger, 2006; Füssel & Klein, 2006). Adaptive capacity is the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope (Adger, 2006; Brooks et al., 2005; Engle, 2011; Smit & Wandel, 2006). It represents the preconditions necessary to enable adaptation, including social and physical elements, and the ability to mobilize these elements or resources to anticipate or respond to perceived or current stresses (Brooks et al., 2005; Engle, 2011; Nelson et al., 2007).

The IPCC conceptualization represents an integrative approach to vulnerability and is different from the natural hazards and social vulnerability approach in seeing vulnerability as a function of both "external" (exposure to stresses and shocks) and "internal" (adaptive capacity and sensitivity) factors (Füssel & Klein, 2006; Gerlitz et al., 2017; Tonmoy et al., 2014). Increasingly, vulnerability is conceptualized as a condition, encompassing characteristics of exposure, sensitivity, and adaptive capacity, shaped by physical, social, economic and environmental factors or processes, which increase the susceptibility of a system to the impact of hazards, rather than as a direct outcome of a perturbation or stress (Adger, 2006; Füssel & Klein, 2006; Miller et al., 2010; O'Brien et al., 2007). This framing will be the conceptual lens of viewing vulnerability in this thesis.

Two main approaches to vulnerability assessment can be identified in climate change vulnerability research literature: end-point (*outcome vulnerability*) and the starting-point (*contextual vulnerability*) (Füssel, 2007; O'Brien et al., 2007). The end-point approach considers vulnerability as the end point of a sequence of analyses, that is, a linear result of the projected impacts of climate change on a particular exposure unit (which can be either biophysical or social), offset by adaptation measures (Füssel, 2007; O'Brien et al., 2007). This interpretation is most relevant in the context of mitigation and compensation policy, for the prioritization of international assistance, and for technical adaptations (Füssel, 2007). It is based on the integrated framework or the risk-hazard framework of vulnerability (Füssel, 2007).

The starting-point approach, in contrast, considers vulnerability as a present inability to cope with external pressures or changes (e.g., climate change) (Füssel, 2007; O'Brien et al., 2007). This contextual vulnerability approach assumes that vulnerability is a characteristic of social and ecological systems that is generated by multiple factors and processes (O'Brien et al., 2007). Both climate variability and change are considered to occur in the context of political, institutional, economic and social structures and changes, which interact dynamically with contextual conditions associated with a particular 'exposure unit' (O'Brien et al., 2007). This interpretation addresses primarily the needs of adaptation policy and broader social development and is consistent with the political economy approach (Füssel, 2007).

2.8.2 *Overview on vulnerability research*

Research which aimed to identify who, where, how, and why human systems are vulnerable to changing climate has grown rapidly to generate a large and diverse literature over the last few decades (Ford et al., 2018; McDowell et al., 2016; Räsänen et al., 2016; Tonmoy et al., 2014; Williams et al., 2018). Vulnerability assessment has gained importance for policy purposes and is no longer an academic exercise but a necessity for policy decision making (Hinkel, 2011; Tonmoy et al., 2014). For instance, the needs and calls for adaptation policies are now widely documented as results of identification of incidences of high vulnerability (McDowell et al., 2016).

Vulnerability research has evolved following diverse traditions which generated multiple approaches, with the most prominent being risk-hazard approach (describing vulnerability in relation to biophysical systems), political economy approach (focusses on answering who is vulnerable and why), pressure-and-release approach (synthesizes both physical and human components of hazards and vulnerability), hazard-of-place approach (integrated and geographically centred approach), and resilience approach (Cutter, 1996; Füssel, 2007; Williams et al., 2018).

Vulnerability research has been unevenly distributed globally, with a focus on small rural or farming communities, and an increasing diversity of risks being studied (McDowell et al., 2016; Räsänen et al., 2016). In sub-Saharan Africa, vulnerability assessment has increased over time, with agriculture and development sectors as the most common focus (McDowell et al., 2016; Williams et al., 2018).

Outcome vulnerability approaches guided much early work, where focuses were mainly on quantifying vulnerability directly attributable to climate change, overlooking the social context (Ford et al., 2018; McDowell et al., 2016; Räsänen et al., 2016). Given the concern that early work privileged climatic factors over social, vulnerability research has advanced well beyond a one-dimensional focus on climate in assessing vulnerability, with a rich and well-developed literature viewing vulnerability as a state or condition embedded in socioeconomic processes (Ford et al., 2018; McDowell et al., 2016; Räsänen et al., 2016). In SARs, vulnerability of local communities is driven not only by climatic factors but also by non-climatic factors operating at different scales (Barbier et al., 2009; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Tucker et al., 2015). In addition to climatic factors, other biophysical and socioeconomic and political factors influence farmers' vulnerability in SARs of West Africa (Barbier et al., 2009; Mertz et al., 2009; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Perez et al., 2015).

Commonly reported climate-related risks driving vulnerability were extreme events (e.g. floods, drought), temperature increase, sea level rise and coastal erosion, weather uncertainty (McDowell et al., 2016). In the semiarid Sahel, drought is the most important climatic stressor, followed by floods (Epule et al., 2018; Gautier et al., 2016). However, there are complex interconnections between climatic and non-climatic factors driving human vulnerability (Räsänen et al., 2016). Studies that encompass 'multiple stressors' or non-climatic factors have increased significantly in the last ten years, with Africa being the main focus of the 'multiple stressors' studies (Räsänen et al., 2016; Tonmoy et al., 2014; Williams et al., 2018). Multiple non-climatic stressors operating at different scales drive vulnerability (Räsänen et al., 2016). In the semiarid Sahel, while climatic drivers are dominant, there is however an increasing attribution to non-climatic stressors and drivers (Epule et al., 2018).

Non-climatic factors influencing vulnerability are diverse and include economic stress (e.g. poverty, inability to access credit for adaptive actions), livelihood diversification (e.g. multiple sources of income, which often reduces susceptibility to harm), marginalization (e.g. economic and ethnic stratification), health-related factors (e.g. pre-existing pulmonary conditions that increase sensitivity to heat stress), and cultural change (e.g. erosion of traditional knowledge) (Epule et al., 2018; McDowell et al., 2016; Räsänen et al., 2016; Williams et al., 2018). In Africa, food insecurity is often associated with high vulnerability (McDowell et al., 2016; Williams et al., 2018).

Vulnerability to climate change is unevenly distributed at local scale. This differential vulnerability can be explain by not just by difference in exposure to climate-related and environmental hazards but largely by social and economic processes (Thomas et al., 2019). While recognizing the diversity of factors influencing vulnerability, Thomas et al. (2019) identified four general themes as useful in explaining differential local-scale vulnerability: resource access, governance, culture, and knowledge. Access to resources is one crucial factor that shapes people's ability to plan for and respond to climate change impacts of (Thomas et al., 2019). Access to resources shapes vulnerability by reducing or increasing exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). Social processes of marginalization and disenfranchisement stemming from social stratification play important roles in creating patterns of unequal access to resources, which in turn drives differential sensitivity to climate impacts and capacity to respond (Thomas et al., 2019). At the same time, climate change will increase the exposure of populations to environmental hazards (Thomas et al., 2019).

The processes of governance both shape and respond to climate change vulnerability (Thomas et al., 2019). The ability of different groups to participate in the political processes that establish procedures and influence outcomes is crucial for effective management of climate-related risks (Thomas et al., 2019). Thus, non-representation and non-participation in governance process can partly explain differential vulnerability of different social groups (Thomas et al., 2019).

Culture, the shared and patterned meanings held by members of social groups, shapes people's vulnerability to climate change (Thomas et al., 2019). Culture frames how individuals perceive and explain their environments and affects who is sensitive and exposed to environmental change and how they experience exposure as well as what responses are considered feasible (Adger et al., 2013; Nielsen & Reenberg, 2010; Thomas et al., 2019).

Knowledge and information interact with vulnerability to climate change in various ways, directly and indirectly shaping peoples' adaptive capacity, exposure, and sensitivity (Thomas et al., 2019). Different types and sources of information and modes of knowledge transmission affect how people understand, perceive, and act on information (Thomas et al., 2019). While information is necessary, it is not sufficient alone for reducing vulnerability (Thomas et al., 2019).

Although the wealth of literature on vulnerability research has improved our understanding of the context and factors which drive vulnerability, how vulnerability evolves over time remained a knowledge gap (Ford et al., 2018). Current vulnerability research methods and approaches tend to promote a static understanding of human-environment interactions and the dynamic, continually evolving nature of vulnerability is not captured (Ford et al., 2018; Vincent

& Cull, 2014). Moreover, vulnerability research neglects cross-scale dynamics and interactions and rely excessively on community case studies, downplaying boarder determinants of vulnerability (Ford et al., 2018). In addition, most of vulnerability assessment of smallholder farming systems are not adequately integrative to incorporate different dimensions, particularly in sub-Saharan African (Williams et al., 2018). A lack of clarity in the operationalisation of vulnerability is a gap in most of vulnerability assessment of smallholder farming contexts in sub-Saharan African (Williams et al., 2018).

2.8.3 Vulnerability assessment

Measuring vulnerability is notoriously challenging as assessments must assume theoretically specified relationships between often non-observable elements (Crane et al., 2017). These elements are hypothesized to constitute vulnerability within theoretically informed models that are then measured through sets of diverse proxy indicators (Crane et al., 2017; Hinkel, 2011; Tonmoy et al., 2014).

Based on a systematic review of climate change vulnerability literature, Crane et al. (2017) identified a number of frameworks (and their operationalisations) used to assess vulnerability. The most prevalent frameworks for assessing vulnerability include the IPCC framework, the Vulnerability Patterns (or Patterns of Smallholders Vulnerability) and Vulnerability as Expected Poverty framework (Crane et al., 2017). The IPCC framework conceptualized vulnerability as function exposure to climate-induced shocks, sensitivity of the unit of analysis to such shocks, and the adaptive capacity of the system of analysis to deal with such shocks (Crane et al., 2017). Application of the IPCC framework often creates a context-specific index of vulnerability from measures of the three dimensions of vulnerability (Crane et al., 2017).

The Vulnerability Patterns framework (Kok et al., 2016; Sietz et al., 2011) is similar to the IPCC framework, but offers a substantial elaboration of smallholders' adaptive capacity, specifically on coping capacity to adjust to weather extremes, manage damage or explore alternative livelihood opportunities (Crane et al., 2017). This framework applies the methodology of cluster pattern analysis as a way to deliver useful insights into recurrent combinations of measurements based on similarities among units of analysis, in cases where such a grouping exists (Crane et al., 2017; Kok et al., 2016; Sietz et al., 2011). The method helps identify specific constellations, or groups, of indicator values that suggest the different forms in which a pattern of vulnerability can manifest itself (Kok et al., 2016). This framework serves as a guiding framework for this dissertation.

The Vulnerability as Expected Poverty framework conceives of vulnerability as when the unit of analysis (usually a household) becomes or remains poor in the future, given expected risk of experiencing shocks (Crane et al., 2017). It is an econometric approach that makes forward projections based on cross-sectional data and associated risks of climatic (and sometimes non-climatic) stress (Crane et al., 2017). In some cases, assessments of vulnerability based on expected poverty are then regressed against a series of socioeconomic data to identify predictors of vulnerability (Crane et al., 2017). This framework makes ex-ante estimates of a household's probability of becoming or remaining poor in the face of environmental or economic shocks through exploration of socio-economic backgrounds of households, and biophysical data on expected environmental conditions (Crane et al., 2017).

Assessing vulnerability entails the operationalisation of the vulnerability frameworks selected (Crane et al., 2017; Hinkel, 2011). Indicators constitute one approach to making theoretical concepts operational (Hinkel, 2011; Vincent & Cull, 2014). Indicators are commonly selected and used to operationalise vulnerability, either deductively, based on theoretical frameworks, or inductively based on data used to build statistical models, or using normative approach based on (individual or collective) value judgments (Crane et al., 2017; Hinkel, 2011; Tonmoy et al., 2014; Vincent & Cull, 2014). Vulnerability indicators are only appropriate for identification of vulnerable people, communities or regions, when systems can be narrowly defined and inductive arguments can be built (Hinkel, 2011). Indicator-based vulnerability assessment has been widely used because it allows the incorporation of biophysical and socioeconomic components of vulnerability, and is relatively simple to conduct and easy to communicate to the public and policymakers (Tonmoy et al., 2014).

The Sustainable Livelihood framework has been widely used as a theoretical basis for deductively selecting indicators for vulnerability assessment. The framework is based on understanding people's access to assets that typically include natural, human, social, physical and financial capital (Reed et al., 2013) and has proven useful for assessing the ability of households to withstand shocks such as epidemics or civil conflict (Hahn et al., 2009). The Sustainable Livelihood framework is particularly relevant to understand vulnerability to climate change because it provides a framework for analysing both the key components that make up livelihoods and the contextual factors that influence them (Reed et al., 2013). These components relate closely to the elements that make a household or community more sensitive or exposed to the effects of a changing climate and affect their ability to cope with environmental change (Hahn et al., 2009; Reed et al., 2013). Based on the Sustainable Livelihood framework and IPCC framing of vulnerability, Hahn et al. (2009) developed the Livelihood Vulnerability Index (LVI). The LVI includes seven major components: socio-demographic profile, livelihood strategies, social networks, health, food, water, and natural disasters and climate variability (Hahn et al., 2009). Each is comprised of several indicators selected based on the Sustainable Livelihood framework (Hahn et al., 2009). It offers a pragmatic and flexible tool for vulnerability assessment and have been widely used in the literature (Gerlitz et al., 2017; Hahn et al., 2009; Panthi et al., 2016; Simane et al., 2016). Recently, Gerlitz et al. (2017) expanded the LVI and used the multidimensional index construction approach to develop the Multidimensional Livelihood Vulnerability Index

(MLVI). The MLVI assesses multidimensional livelihood vulnerability to environmental (including climatic) and socio-economic changes with household as unit of analysis (Gerlitz et al., 2017). The MLVI modifies and extends the initial eight components of the LVI, resulting in twelve components so that it addresses factors that are relevant to authors' specific context (Gerlitz et al., 2017). As in the initial LVI, each component is represented by a number of specific and measurable vulnerability indicators (Gerlitz et al., 2017). This MLVI approach is relevant for studies which aim to capture both vulnerability to climatic and non-climatic stressors such as in this dissertation.

Although indicators have been useful in assessing vulnerability to climate change, there is no "one size fits all" blueprint that can be used regardless of the context (Vincent & Cull, 2014). Indicators are context specific and typically cannot be transferred to different scales and context of analysis, since vulnerability is multi-dimensional in nature and a potential state that is time and scale specific (Vincent & Cull, 2014). As indicators can generally only portray a measure of relative potential states (e.g. between places or between time periods), vulnerability is only a snapshot in time and may disguise ongoing evolutions of certain dimensions (Vincent & Cull, 2014).

2.9 Adaptation

2.9.1 Definition

Adaptation in the context of human dimensions of global change usually refers to "a process, action or outcome in a system (household, community, group, sector, region, country) in order for the system to better deal with, manage or adjust to some changing condition, stress, hazard, risk or opportunity" (Smit & Wandel, 2006). Nelson et al. (2007) define adaptation as the decision-making process and the set of actions undertaken to maintain the capacity to deal with current or future predicted change. Adaptation therefore involves building adaptive capacity, thereby increasing the ability of individuals, groups, or organizations to adjust to changes and implementing adaptation decisions (Brooks et al., 2005; Engle, 2011; O'Brien et al., 2007; Smit & Wandel, 2006). Adaptive capacity affects a system's vulnerability through modulating exposure and sensitivity (Engle, 2011). From contextual vulnerability perspective, reducing vulnerability involves altering the context in which climate change occurs, so that individuals and groups can better respond to changing conditions (O'Brien et al., 2007).

2.9.2 Overview on adaptation research

Research aiming at identifying and characterizing what we know, don't know, and need to know about climate change adaptation has rapidly evolved, especially after the Paris agreement, which strongly recognises, for the first time, adaptation as a critical component of the global response to climate change (Berrang-Ford et al., 2019; Berrang-Ford et al., 2014; Berrang-Ford et al., 2011; Epule et al., 2018; Ford et al., 2015b; Lesnikowski et al., 2015; Lesnikowski et al., 2016; Lesnikowski et al., 2017; Magnan & Ribera, 2016). Adaptation initiatives to reduce vulnerability documented in Africa and other middle and low-income regions have been increasing (Ford et al., 2015b), including in climate hotspots areas such SARs of Africa (Epule et al., 2017). In SARs, agriculture is the dominant focus of reported adaptation initiatives (Ford et al., 2015b).

A wide range of adaptation strategies and practices has been adopted by smallholder farmers in the SARs of West Africa including livelihood and income diversification, soil and water conservation techniques, farm input (chemical fertilizer and animal manure) use, water harvesting, dry season vegetable production, forage conservation, use drought tolerant, short cycle crop varieties, use of high yielding varieties, management of planting dates, crop and animal diversification, conservation agriculture, animal fattening, migration and mobility (seasonal or permanent), reduction in crop land and livestock size (Barbier et al., 2009; Epule et al., 2017; Gautier et al., 2016; Harmer & Rahman, 2014; Mertz et al., 2012; Mertz et al., 2010; Mertz et al., 2009; Muchuru & Nhamo, 2019; Ouédraogo et al., 2010; Ouédraogo et al., 2016; Sanogo et al., 2017; Tambo & Abdoulaye, 2013; Traore et al., 2015). Weather-based index insurance, information and early-warning systems, and irrigation are being increasing adopted to manage climate risks and build farming and livelihoods systems resilience (Muchuru & Nhamo, 2019). Some agroecological practices currently implemented in SARs of West Africa can promote adaptation to climate change (Debray et al., 2019). These include conservation and planting of local shrub and tree species on farm (such as soil-improving woody plants species), rehabilitation and conservation of vegetation, soil and water conservation practices (such *Zaï*, half-moons, (vegetated) stone bunds, contour bunding, etc.), organic soil fertilisation (using crop residue compost, manure), introduction of new crops (Debray et al., 2019). Most farmers usually combine different practices to increase overall farming system resilience (Debray et al., 2019). The wide range of adaptation strategies can be grouped into land-based strategies, technology-based strategies, financial adaptations, labour adaptations, cultural strategies and support from others (Harmer & Rahman, 2014)

The wealth of literature on climate change adaptation has improved our knowledge of the context and drivers of climate change adaptation. Adaptation usually takes place in a multiple driver/factor context and climate change is seldom the sole drivers of adaptation action (Berrang-Ford et al., 2011; Epule et al., 2017; García de Jalón et al., 2016). In the semiarid Sahel, adaptation is triggered by not only climatic but also non-climatic driving forces, such as new market opportunities (Barbier et al., 2009; Epule et al., 2017; Jost et al., 2016; Mertz et al., 2010; Ouédraogo et al., 2016). Changes in livelihood strategies and farming practices are driven by adaptation to a range of factors of which climate appears not to be the most important (Jost et al., 2016; Mertz et al., 2010; Mertz et al., 2009; Mortimore, 2010; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Ouédraogo et al., 2016). Adaptation to climatic stressors is inseparable from a developmental context, and takes place in interactions with other drivers such as rapid population growth, market integration, increasing urbanization, migration, land use transformation (Mertz et al., 2009; Mortimore, 2010; Zougmoré et al., 2016).

2.9.3 Factors affecting farmers' adaptation to climate change

As adaptation usually takes place in a multiple drivers context, a diversity of factors was found to affect farmers' adaptation to climate change. Based on a systematic review of factors affecting farmers' adaptation to climate change across the globe, Dang et al. (2019) categorized those factors into: demographic and socioeconomic factors, resources, services and technologies-related factors, institutional and political factors, social and cultural factors, and cognitive and psychological factors (Dang et al., 2019). The review revealed that demographic, socio-economic, technological, institutional and political factors were most extensively investigated while social, cultural and psychological factors remains relatively limited and need further research (Dang et al., 2019).

Demographic and socioeconomic factors include age, gender, ethnicity, caste, education, household size, household income and assets (Dang et al., 2019; Harmer & Rahman, 2014; Ouédraogo et al., 2010; Ouédraogo et al., 2016; Thomas et al., 2019). These demographic and socioeconomic factors which represented the status and economic condition of farm households have an important impact on farmers' adaptation (Dang et al., 2019). Farm household characteristics contribute to whether farmers are willing to and adjust their farming practices, or what adaptive measures they would probably undertake (Dang et al., 2019; Harmer & Rahman, 2014). The differences in the ways of thinking between males and females, but also in access to resources, services, and technologies, determine their variant adaptation decisions (Dang et al., 2019). Education allows farmers to access appropriate information and encourages the adoption of improved technologies in farming practices and is an important factor in farmers' adaptation decision (Dang et al., 2019).

The availability and access to resources, services, and technologies (such as credit/capital, information, agricultural extension, land, labour, irrigation, market, farm input, infrastructure, etc.) have been widely studied as key determinants of farmers' adaptive decisions (Barbier et al., 2009; Dang et al., 2019; Harmer & Rahman, 2014; Ouédraogo et al., 2010; Ouédraogo et al., 2016; Tambo & Abdoulaye, 2013; Thomas et al., 2019). Access to resources influences vulnerability by reducing or increasing exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). For instance, access to agricultural extension was found to have a positive impact on the choice of adaptive measure (Dang et al., 2019; Ouédraogo et al., 2010).

Institutional and political factors such as institutional arrangements about land as well as land ownership have been demonstrated to affect farmers' adaptive strategies (Dang et al., 2019). Institutional structures and governance, access to political power, government policies/directives, restricted rights to natural resources are also key factors influencing farmers' adaptation strategies (Dang et al., 2019).

Social and cultural dimensions have been identified as barriers to farmers' adaptation (Adger et al., 2013; Dang et al., 2019; Nielsen & Reenberg, 2010). Cultural dimensions shape how societies respond and adapt to climate-related risks (Adger et al., 2013; Dang et al., 2019; Nielsen & Reenberg, 2010; Thomas et al., 2019). Culture frames how individuals perceive and explain their environments and affects who is sensitive and exposed to environmental change and how they experience exposure (Thomas et al., 2019). As it informs perceptions of risk, culture also affects the adaptive capacity of those exposed and help to explain differences in responses across populations to the same environmental risks (Adger et al., 2013; Thomas et al., 2019). Place attachment and values (shaped by culture) were key dimensions which shape adaptive responses (Adger et al., 2013; van Valkengoed & Steg, 2019). Social practices such as forging close kin-based or neighbourhood networks can increase the capacity to cope with a threat, as network members share access to information, transportation, or other resources (Thomas et al., 2019).

Cognitive and psychological factors have been investigated in studies of farmers' adaptation to climate change and findings indicated that farmers who had concerns about the impacts of climate change on agriculture had a more positive attitude to the strategies of adaptive management (Dang et al., 2019; Ouédraogo et al., 2010). Nevertheless, the extent to which farmers awareness of climate change, and the link between perception and action, is a debated issue in the literature (Harmer & Rahman, 2014; Mertz et al., 2010). A recent series of meta-analyses of factors motivating climate change adaptation behaviour (van Valkengoed & Steg, 2019) revealed that descriptive norms (perceptions of whether others are engaging in adaptive actions), negative affect, perceived self-efficacy (the extent to which people believe they are capable of engaging in relevant adaptive actions) and outcome efficacy (he extent to which individuals believe that adaptive actions will be effective in protecting them) of adaptive actions were most strongly associated with adaptive behaviour (van Valkengoed & Steg, 2019). Additionally, risk perception was strongly associated specifically with people's intentions to adapt (van Valkengoed & Steg, 2019). In contrast, knowledge and experience, which are often assumed to be key barriers to adaptation, were relatively weakly related to adaptation (van Valkengoed & Steg, 2019).

2.10 Conceptual framework

The aim of this study was to unravel the contribution and importance of agrobiodiversity for climate change adaptation in semi-arid areas of Mali, West Africa. Figure 2 illustrates the conceptual framework guiding this study. Ecosystem services provided by agrobiodiversity and agroecosystems continue to form a significant proportion of the global food basket and support the livelihoods of millions of people across the world (Power, 2010; Segnon & Achigan-Dako, 2014; Wood et al., 2015; Zhang et al., 2007). Harnessing agricultural ecosystems services can help people adapt to the adverse impacts of climate change and reduce their vulnerability, with also multiple co-benefits for protection of livelihoods and poverty alleviation (Doswald et al., 2014; Jones et al., 2012; Munang et al., 2013). This entails the implementation of "agricultural practices that take stock of biodiversity, ecosystem services or ecological processes (either at the plot, farm or landscape level) to increase the ability of crops or livestock to adapt to climate change and variability" (Vignola et al., 2015). Vulnerability is most often conceptualized as the susceptibility of a system to perturbations determined by its exposure and sensitivity to perturbations, and the capacity to adapt (Adger, 2006; Füssel, 2007; Nelson et al., 2007; Smit & Wandel, 2006; Tonmoy et al., 2014). Here, vulnerability is understood as a condition, encompassing characteristics of exposure, sensitivity, and adaptive capacity, shaped by physical, social, economic and environmental factors or processes, which increase the susceptibility of a system to the impact of hazards, rather than as a direct outcome of a perturbation or stress (Adger, 2006; Füssel & Klein, 2006; Miller et al., 2010; O'Brien et al., 2007).

Implementation or adoption of adaptation strategies influences vulnerability patterns by reducing or increasing exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). As it usually takes place in a multiple drivers context, adaptation is affected by a wide range of factors including demographic and socioeconomic factors, resources, services and technologies, institutional and political factors, social and cultural factors, and cognitive and psychological factors (Dang et al., 2019). Here, we contend/propose that demographic and socioeconomic factors which define *"who a respondent is"*, his/her perception of climate change and understanding of climate change impacts on his/her livelihoods (*"what you know"*), and *"where his/her knowledge comes from"* drive the diversity of adaptation strategies implemented/used by a respondent (*"what you do"*) (Figure 3). This analytic framework, developed based a review of climate change adaptation literature as well as adoption and traditional ecological knowledge literature, is depicted in Figure 3 and serves analytical lens in assessment of farmers adaptation strategies (Objective 2).

Vulnerability status or level and livelihoods can affect agroecosystems conditions and services and benefits provided to support livelihoods and adaptation either directly or indirectly through livelihood strategies (crop intensification and/or expansion, livestock grazing, etc.) and other factors such demographic/population pressure, urbanization, economic and socio-political drivers (Figure 2) (Campbell et al., 2017; Díaz et al., 2006; Inkoom et al., 2018; Nelson et al., 2006; Stenchly et al., 2019). Other direct drivers of agroecosystems conditions and services and benefits derived are biodiversity loss, climate change, land use change, chemical nutrient use, biological invasions and diseases (Campbell et al., 2017; Inkoom et al., 2018; Nelson et al., 2006; Stenchly et al., 2019).

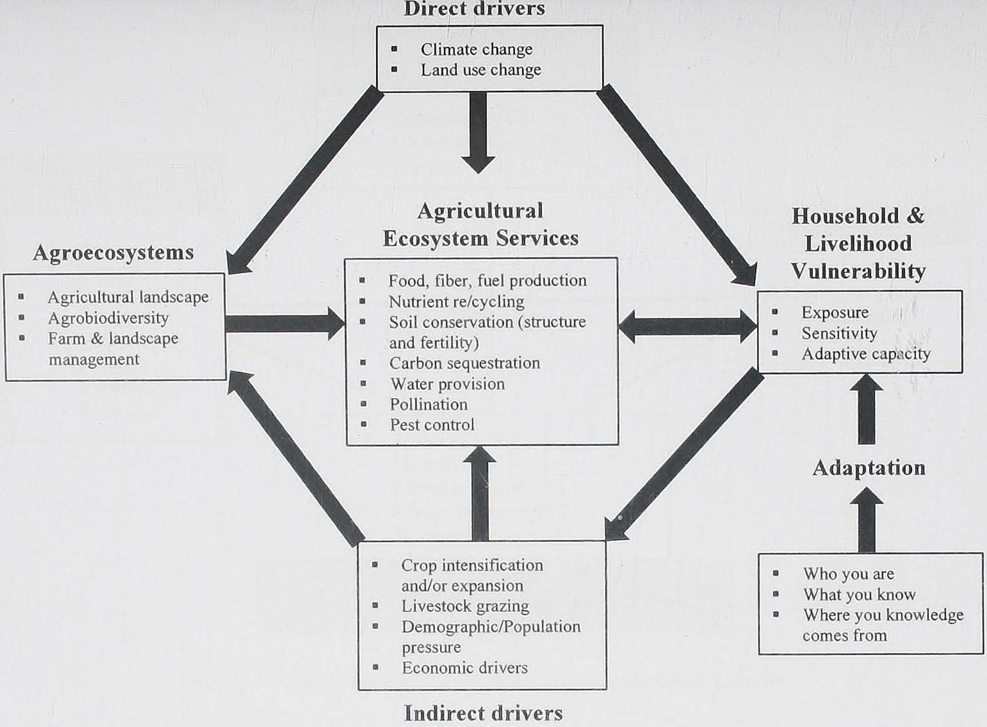

Figure 2. Conceptual framework of the thesis

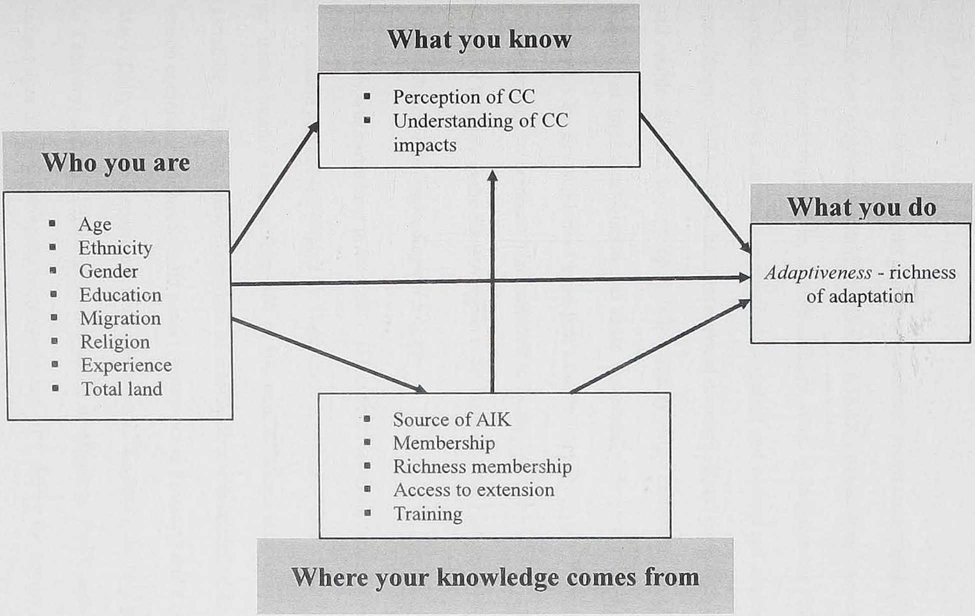

Figure 3. Analytic framework for assessing farmers adaptation strategies

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Context

The study is undertaken as part of a broader research programme "*Adaptation at Scale in Semi-Arid Regions of Africa and Asia*[2]" (ASSAR). ASSAR's overarching research objective is to use insights from multiple-scale, interdisciplinary work to improve the understanding of the barriers, enablers and limits to effective, sustained and widespread adaptation. Over its five-year lifespan (2014-2018), the cross-regional comparison and integration of research findings will enable ASSAR to develop a unique and systemic understanding of the processes and factors that impede adaptation and cause vulnerability to persist. In West Africa, ASSAR focuses on the dry sub-humid band that extends from the Upper West Region of Northern Ghana through to Southern Mali, referred to as the Wa-Bobo-Sikasso transect. In Mali, the Cercle of Koutiala in the Sikasso region is the main ASSAR research site.

3.1.2 Climate and agroecological features

This study was carried out in the Cercle of Koutiala (South-Eastern Mali), which is located in the semiarid part of Mali (Figure 4). The climate is typical of the Sudano-Sahelian region, with an annual rainfall ranging from 400 to 800 mm, with high inter-annual and intra-seasonal variability. The rainy season lasts from June to October with rainfall peaks in August. The dry season comprises a relatively cold period (November to February) and a hot period (March to May). Daily average temperature ranges between 22°C (during the cold period of November to February) and 35°C (during the hot period of March to June), with average maximum temperature of 34°C during the rainy season and 40°C during the hot dry season. The natural

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[2] http://www.assar.uct.ac.za/

vegetation is a tree and shrub savanna with an understory of annual and perennial grasses in a complex mosaic. Soils are poor, of sandy or sand–loamy texture and often gravelly.

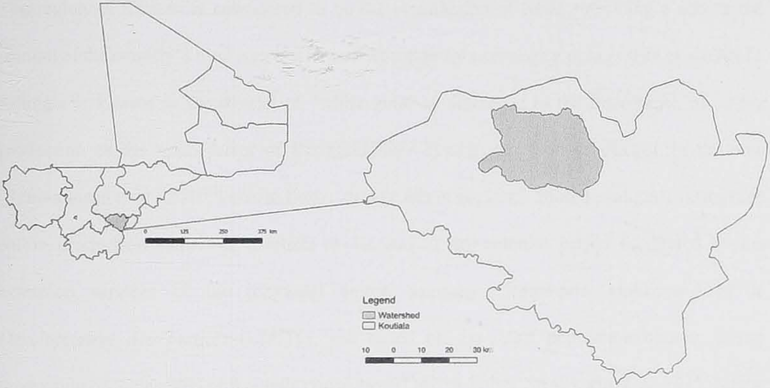

Figure 4. Study area showing a watershed delineated for spatial analysis

3.1.3 *Livelihoods and socio-economic dynamics*

The Cercle of Koutiala belongs to the administrative region of Sikasso, and is 140 km north away from the district of Sikasso. It is located in the North-Western part of Sikasso region and bounded to the North by the Cercle of San, to the South by the Cercle of Sikasso and the Republic of Burkina Faso, and to the East by the Cercle of Yorosso. It covers an area of 8,740 km^2, which is 12.17% of the total area of Sikasso region and 0.7% of the country's total area. The Cercle of Koutiala is composed of 35 rural communes (or districts), one urban commune and a total of 242 villages. According to the latest population census of 2009, Koutiala is home to 575,253 people, with an average density of 52.32 inhabitants per km^2. The dominant ethnic group in Koutiala are the Minianka or Minyanka, who are considered the native people in the Koutiala. Other ethnic groups that have migrated to Koutiala over time are Fulbe (Peulhs), Dogon (from northern Mopti region), Bambara (from Segou region), Sénoufo (from the south, Sikasso region) and Dafing.

The region of Sikasso is considered to be the breadbasket of Mali, providing a substantial amount of the country's food supplies as well as cotton for exchange earnings (Ebi et al., 2011). Koutiala is known as the district of "white gold" in reference to the importance of cotton production as the main driver of the agriculture system and food production in the area (Benjaminsen et al., 2010; Laris & Foltz, 2014; Laris et al., 2015; Sidibé et al., 2018). Rainfed cotton production started in Koutiala at the end of the colonial period facilitated by the extension services of the parastatal cotton company *Compagnie Malienne pour le Developpment des Textiles* (CMDT), and based on the latest population census, cotton production occupies 90% of Koutiala population (Laris & Foltz, 2014; Laris et al., 2015; Sidibé et al., 2018). More than a cash crop, cotton production in Koutiala is critical for food production as well as for national economy and livelihoods for many smallholder farmers (Laris & Foltz, 2014; Laris et al., 2015; Sidibé et al., 2018). As fertilizers are subsidized only for cotton, maize and rice, but not for other food crops, which are also widely grown alongside cotton, membership in cotton cooperatives is considered by farmers to be a strategy for accessing subsidized inputs for crops that are not covered by the subsidy policy (Laris & Foltz, 2014; Sidibé et al., 2018). This fertilizer shifting practice - whereby farmers apply fertilizers designated for cotton to grain crops - has resulted in the decline in cotton and increase in grain yields (Laris & Foltz, 2014; Laris et al., 2015).

While a diversity of crops is cultivated, cotton, maize, sorghum, pearl millet and groundnut are the main crops in Koutiala. After cotton and cereal cultivations, livestock production is the second main livelihood activity in Koutiala. In addition to cereal and cotton production, Sikasso is the country's principal white (Irish) potato growing region, producing potatoes for Mali, as well as for burgeoning export markets in Senegal and Mauritania (Ebi et al., 2011).

While Sikasso is the most productive and most important region in terms of food and cash crop production and supply in Mali (Butt et al., 2005; Ebi et al., 2011), the region is also known for having the worst poverty situation, worst child health and malnutrition statistics (highest infant mortality rate, highest rates of children stunted and children underweight) and high food insecurity (Cooper & West, 2017). There is evidence of a co-association between cotton cultivation, loss of natural capital, and malnutrition at the village level in the region (Cooper & West, 2017). Decades of research have established this phenomenon as the Sikasso paradox (Cooper & West, 2017).

3.2 Methods

3.2.1 Vegetation dynamics-climate nexus analysis

- *Data*

As a component of biodiversity, agricultural biodiversity and ES it provides can be measured using land or vegetation cover as a spatially-explicit proxy (Feng et al., 2010). Indeed, land or vegetation cover can be used as a proxy measure of biodiversity and ES because of its multiple linkages to carbon storage, watershed protection, and other types of services (Feng et al., 2010). A recent systematic review of remote sensing applications in ecosystem services' research indicated a growth of spatially explicit remote sensing assessment for ES valuation and that the dominant ES proxy variables used were land cover and NDVI (de Araujo Barbosa et al., 2015). NDVI has been proved to directly relate to the vegetation cover condition and has been extensively used to estimate vegetation productivity and changes, particularly in SARs of West Africa (de Araujo Barbosa et al., 2015; Feng et al., 2010; Karlson & Ostwald, 2016; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014).

To conduct a spatially-explicit dynamics of climate and vegetation analysis, a watershed has been delineated within Koutiala (Figure 4) based on the Space Shuttle Radar Topography

Mission (SRTM) Digital Elevation Model (DEM) of the world at 90 m horizontal resolution and available through the Consortium for Spatial Information web portal (http://srtm.csi.cgiar.org/). The watershed spans across the districts of M'Pessoba, Tao, Fakolo-Kou, N'Tossoni, Koutiala, and N'Golonianasso in the Cercle of Koutiala.

The Global Inventory Modelling and Mapping Studies (GIMMS) NDVI 3rd generation (NDVI3g) dataset derived from the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer instruments was used for the district level analysis (i.e., Koutiala Cercle). NDVI3g is available at 8km spatial resolution and collected from 1982 to 2015. The NASA Moderate Resolution Imagery Spectroradiometer (MODIS) NDVI dataset at 250 m spatial resolution from 2000-2015 was used for the watershed level analysis. Although limited in terms of temporal scale (available from 2000 onwards) compared to other NDVI data (e.g., NDVI3g), MODIS NDVI has a higher spatial resolution and offers the opportunity for finer-scale analysis. NDVI dataset was obtained at the web portal of the Land Processes Distributed Active Archive Centre (LP DAAC), a component of National Aeronautics and Space Administration (NASA)'s Earth Observing System Data and Information System (EOSDIS).

Climate data (precipitation, temperature) from 1982 to 2015 for the study area was acquired from the National Meteorological Agency of Mali. In addition, Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data from 1982 to 2015 was used for the spatially-explicit trend analysis. CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series relevant for monitoring of agricultural drought and global environmental change over land (Funk et al., 2015). CHIRPS is a new quasi-global (50°S-50°N), high resolution (0.05°), daily, pentadal, and monthly precipitation dataset from 1981-present (Funk et al., 2015).

- *Data analysis*

To assess possible change and variability in climate over the past 30 years, a time-series analysis of climatic parameters was performed. The non-parametric Sen's slope estimator, based on Kendall's tau was used to determine trends in climatic parameters and NDVI (Sen, 1968) and the Mann-Kendall test was used to estimate the statistical significance of the trends at the 95% confidence level.

To investigate the impacts of climatic stressors on vegetation cover, an ordinary least square (OLS) regression was performed, assuming that in the study area changes in biomass productivity occur as gradual and linear processes through time (Leroux et al., 2017). The OLS measures the linear relationship between a dependent (y, NDVI in our case) and independent variables (x, rainfall and/or temperature in our case) and it is widely used in environmental studies (Ibrahim et al., 2015; Leroux et al., 2017). All the statistical analyses were conducted in R software (R Core Team, 2016).

3.2.2 Assessing farmers' perception and adaptation strategies

Data collection

Ten communities/villages located within the watershed defined for spatial analysis (see Figure 4) were selected to investigate farmers perception and adaptation strategies. The selected communities were Danzana, Dentiola, M'Pessoba (in M'Pessoba district), Fonfona (Tao district), Oudiala, Zansoni (in Fakolo-Kou district), N'Tossoni, Diéla (in N'Tossoni district), Ntiesso (in Koutiala district), and Zangorola (in N'Golonianasso district).

First, a focus group discussion (FGD) was conducted in each of the villages to have a broader picture on how communities are experiencing climate change and how are they adapting to its impacts. Specifically, the discussions evolve around perception of climate change, impacts and implications of climate change for their livelihoods and strategies adopted to limit the impacts or take advantage of opportunities. Responses from the FGDs were used to design a semi-structured interview questionnaire

Individual semi-structured interviews were conducted with a sample of farmers selected using proportional random sampling approach in the selected communities within the watershed where FGDs were conducted. The sampling size was determined by using the following equation by Dagnelie (1998)

$$n = \frac{U^2_{1-\alpha/2} \times p(1-p)}{d^2}$$

Where n represents the total number of farmers to be surveyed; $U^2_{1-\alpha/2}$ represents the value of the normal random variable for a probability value α ; with $\alpha = 0.05$, $U_{1-\alpha/2} = 1.96$; p is the proportion of population (in our case the population of farmers in Koutiala) that are knowledgeable of climate change ($p = 0.50$); a recent study in the study area indicated that fifty percent of farmers have observed changes in both temperature and rainfall patterns (Sanogo et al., 2017); d is the estimated margin error from the survey, which is fixed at 0.05 (5%). The sample size following the above formula is 384. Oversampling was done to increase the sample to 501 respondents. A large sample size allows to minimize the sampling error and gives better statistical reliability for estimates. The sample was composed of 50% male and 50% of female respondents. The distribution of respondent per village is presented in Table 1.

Table 1. Number of respondents interviewed and households surveyed per village

Districts	Villages/Communities	Number of individual respondents	Number of households
Fakolo-Kou	Oudiala	50	50
	Zansoni	50	50
Koutiala	Ntiesso	50	51
M'Pessoba	Danzana	50	50
	Dentiola	50	50
	M'Pessoba	51	50
N'Golonianasso	Zangorola	50	50
N'Tossoni	Diéla	50	49
	N'Tossoni	50	51
Tao	Fonfona	50	50
Total		501	501

The semi-structured interview questionnaire covered respondent socio-cultural and socioeconomic information (age, gender, ethnicity, education, occupation, main source of income), livelihoods activities (type and orientation), perception of changes in selected climatic parameters (precipitation, temperature, perception of the impacts of climatic stressors on crop and livestock production and adaptation strategies. Agrobiodiversity-based adaptation practices were specifically elicited. Agrobiodiversity-based adaptation practices entails the implementation of "agricultural practices that take advantage of biodiversity, ecosystem services or ecological processes (either at the plot, farm or landscape level) to increase the ability of crops or livestock to adapt to climate change and variability" (Vignola et al., 2015).

The questionnaire was composed of a number of items and categorized into constructs. The items were identified from an extensive literature review on climate change and variability, climate change impacts on socioecological in semi-arid areas of West Africa (see Sections 2.1-2.3) and results from the FGDs conducted in each village. Each item was presented as a statement, and participants were asked to indicate their level of agreement using a 5-point Likert scale, ranging from strongly disagree to strongly agree (Babbie, 2013; Segnon et al., 2015).

Data analysis

Descriptive statistics were used to describe patterns and dynamics in respondents' perception and knowledge. To test the reliability and internal consistency of multiple item constructs, Cronbach's alpha (α) (Cronbach, 1951) was computed using the package psych (Revelle, 2013). Cronbach's alpha (α), an index of inter-item homogeneity, determines the internal consistency or average correlation of items in a survey instrument and is used to gauge its reliability (Cronbach, 1951; Segnon et al., 2015).

To understand factors that drive the diversity of adaptation strategies adopted by a respondent, a Structural Equation Modelling (SEM) approach was used. SEM was guided by an analytical framework developed based on a review of climate change adaptation literature as well as adoption and traditional ecological knowledge literature (see Figure 3). Based on current knowledge and literature, the analytical framework proposed that demographic and socioeconomic factors which define *"who a respondent is"*, his/her perception of climate change and understanding of climate change impacts on his/her livelihoods (*"what you know"*), and *"where his/her knowledge comes from"* drive the diversity of adaptation strategies implemented/used by a respondent (*"what you do"*) (see Figure 3).

Structural equation models are probabilistic models that unite multiple predictor and response variables in a single causal network (Lefcheck, 2016). SEMs strengths reside in its ability to simultaneously accommodate multiple relationships between multiple variables by estimating multiple models. In doing so, SEMs allow to estimate both indirect, mediating and covarying relationships, and direct relationships. Traditionally, SEMs have been estimated using a maximum likelihood approach to select parameter values that best reproduce the entirety of the observed variance-covariance matrix (Lefcheck, 2016). However, the restrictions of this variance-covariance matrix approach (observations to be independent, all variables follow a normal distribution, high sample size to provide sufficient degrees of freedom) led to the development of piecewise SEMs based on applications from graph theory (Lefcheck, 2016). In piecewise SEM, the path diagram is translated to a set of linear (structured) equations, which are then evaluated individually allowing for the fitting of a wide range of distributions and sampling designs (Lefcheck, 2016). *piecewiseSEM* package (Lefcheck, 2016) in R statistical environment (R Core Team, 2016) was used to be able to accommodate non-normal distributions of some variables in the dataset.

The goodness-of-fit of the SEM model was evaluated by performing the test of directed separation. This procedure tests the assumption that all variables are conditionally independent, implying that there is no missing relationships among unconnected variables in the model (Lefcheck, 2016). The hypothesized relationships are considered to be consistent with the data when there is weak support for the sum of the conditional independence claims, that is where the collection of such relationships represented by a test statistic, Fisher's C, could have easily occurred by chance, in which case *p*-value for the chi-square test is greater than the chosen significance threshold ($\alpha = 0.05$) (Lefcheck, 2016).

3.2.3 Household vulnerability assessment

Data collection

To assess household vulnerability to climatic and non-climatic stressors, a household survey was designed and conducted in the 10 villages selected above. The household survey sample size was determined as follows (Krejcie & Morgan, 1970):

$$s = \frac{X^2 N_p(1-p)}{d^2(N-1) + X^2 p(1-p)}$$

Where s is the number of farm household to be surveyed; X^2 is the table value of chi-square for 1 degree of freedom at the desired confidence level fixed at 95%; N is the total population of household in Koutiala; p represents the proportion of farm household. In Sikasso region, where the study area is located, about 60% of households are farm households; d is the degree of accuracy expressed as a proportion and fixed at 0.05 (5%). The sample size following the above formula is 368 households. Oversampling was done to increase the sample size to 501 households. Households in each community were randomly selected and number of household per community is presented in Table 1. A household is defined as "a group of people living in the same dwelling space who have at least one common plot together or one income-generating activity together (for example, herding, business, or fishing) and acknowledge the authority of a man or woman who is the head of household" (Beaman & Dillon, 2012).

The MLVI framed within the IPCC vulnerability framework (vulnerability as a function of exposure, sensitivity, and adaptive capacity) (Gerlitz et al., 2017) was adopted and modified to suit the context of the semiarid study area to assess household vulnerability to climatic and non-climatic factors. The MLVI is a modified version of the LVI developed by Hahn et al. (2009). The MLVI is composed of 12 components which address factors that are relevant to authors' specific context (Gerlitz et al., 2017). In this study, components which were not relevant to the study area context were removed resulting in 10 components (Table 2). As in the initial LVI, each component was operationalised by a number of specific and measurable vulnerability indicators (Gerlitz et al., 2017).

Table 2. Vulnerability dimensions, components, and indicators following MLVI approach

Dimensions	**Components**	**Indicators**	**Description**
Adaptive capacity	Socio-demographic status	Education	Educational attainment of household head
		Dependency ratio	Ratio of No. of household member under 15 and over 65 years of age to household member between 19 and 64 years of age
		Household productive members	No. of household member under 15 and over 65 years of age
	Livelihood strategies	Agricultural livelihood diversity	No. of primary livelihood strategies
		Non-agricultural livelihood diversity	No. of secondary or tertiary livelihood strategies
		Total livelihood diversity	No. of all livelihood strategies
	Resources	Agricultural land	Household total farmland size (ha)
		Livestock (TLU)	No. of livestock (TLU – Tropical Livestock Unit)
		Diversity of livestock types	Number of livestock types
		Agricultural equipment (plough, cart, seed drill, sprayer, draught animal, donkey)	No. agricultural equipment (plough, cart, seed drill, sprayer, draught animal, donkey) owned by the household

	Social networks	CBOs membership	Does the household belong to a community-based groups (Yes/No)?
		Diversity of CBOs membership	No. of CBOs in which household belong to
		Political voice	How easy is it to access political powers in the community (5-point Likert scale response from 1-Not easy all to 5-Very easy)
	Physical accessibility	Road practicability	Is the road leading from household to feeder or tarred roads practicable all year round (1-Not practicable, 2-Fairly practicable, 3-Practicable all year round)
		Market orientation	Does household sell part or entire production (Yes/No)
Sensitivity	Food security	Source of household food	Where does the household get most of its food (1-Own production only; 2-Own production [2/3] & purchase [1/3]; 3-Own production [1/3] & purchase [2/3])
		Food self-sufficiency	Food self-sufficiency
		Number of month with insufficient food	No. of month household struggles to get sufficient food to cover its needs
		Crop diversity	No. of crops grown by household
	Health & Sanitation	Drinking water quality	Does household use a source that, by nature of its construction, adequately protects the water from outside contamination, in particular from faecal matter
		Toilet facility quality	Does household use sanitation facilities that hygienically separate human excreta from human contact
		Illness (Health case number)	No. health case in household
		Household member with chronic illness	No. household member with chronic illness
		Average time to closest health facility	Average time to closest health facility
		Availability of health facility in the village	Availability of health facility in the village
	Water security	Diversity of water source	Number of water source used by household
		Water sufficiency	Water sufficiency
		Number of month with insufficient water	No. of month household struggles to get sufficient water to cover its needs
Exposure	Environmental shocks	Environmental shocks experienced over the past 12months	Environmental shocks experienced over the past 12 months

	Socio-economic shocks	Socio-economic shocks experienced over the past 12months	Socio-economic shocks experienced over the past 12 months

The first part of the questionnaire consisted of questions to measure the indicators (see Table 2). The second part of the questionnaire covered agrobiodiversity management and specifically its exploitation for climate change adaptation. Agrobiodiversity-based adaptation practices were elicited using free listing technique.

Data analysis

The vulnerability pattern approach (Kok et al., 2016; Sietz et al., 2011) was adopted in analysing household vulnerability. This framework applies the methodology of cluster pattern analysis as a way to deliver useful insights into recurrent combinations of measurements based on similarities among units of analysis, in cases where such a grouping exists (Crane et al., 2017; Kok et al., 2016).

To analyse the household vulnerability patterns, archetypes of vulnerability were constructed using Factor Analysis of Mixed Data (FAMD) (Pagès, 2014) combined with a Hierarchical Cluster Analysis using the package *FactoMineR* (Lê et al., 2008). FAMD is similar to Principal Component Analysis but allows to simultaneously quantify categorical and quantitative variables while reducing the dimensionality of the data (Pagès, 2014). To identify the relevant number of components to retain, the eigenvalues of the components were analysed and components with eigenvalue greater than 1 were kept (Abdi & Williams, 2010).

Afterwards, a Hierarchical Clustering on Principal Component (HCPC) analysis (Husson et al., 2017) was performed on factors constructed from FAMD to identify homogenous archetypes. The package *FactoMineR* (Lê et al., 2008) was used to perform the HCPC analysis. Before performing the HCPC analysis, the clustering tendency of the data was assessed using the Visual Assessment of cluster Tendency (VAT) algorithm (Bezdek & Hathaway, 2002).

Assessing clustering tendency was performed to determine whether the data sets contained meaningful clusters (i.e., non-random structures) or not, in another word the feasibility or validity of the clustering analysis on the data. The VAT approach presents a pair wise dissimilarity information about the set of objects as a square digital image, after the objects are suitably reordered so that the image is better able to highlight potential cluster structure (Bezdek & Hathaway, 2002). The VAT detects the clustering tendency in a visual form by counting the number of square shaped dark blocks along the diagonal in a VAT image (Bezdek & Hathaway, 2002). The VAT reordered dissimilarity image will often indicate cluster tendency in the data by dark blocks of pixels along the main diagonal (Bezdek & Hathaway, 2002).

To evaluate the clustering validity and identify the optimal number of clusters, the silhouette method (Rousseeuw, 1987) was used. The average silhouette width provides an evaluation of clustering validity, and can be used to select an appropriate number of clusters (Rousseeuw, 1987). It measures the quality of a clustering by determining how well each object lies within its cluster and can be also used with any clustering approach (Rousseeuw, 1987). A high average silhouette width indicates a good clustering and the optimal number of clusters k is the one that maximizes the average silhouette over a range of possible values for k (Rousseeuw, 1987). Descriptive statistics was used to describe the archetypes identified. All the statistical analyses were performed in R statistical environment (R Core Team, 2016).

3.2.4 Assessing effectiveness of agrobiodiversity-based adaptation practices

To assess the effectiveness of agrobiodiversity-based adaptation practices in reducing household vulnerability and building resilience, a multinomial logistic regression was performed (Finch et al., 2014). The probability that a household belong to a given vulnerability patterns cluster (vulnerability patterns cluster as dependent variable) was affected by the diversity of agrobiodiversity-based adaptation practices used by the household (independent variables) was tested. Other potential confounding predictors were also tested, including total number of adaptation practices adopted by or used/implemented in the households, age of the household head, access to extension, market orientation, access to credit, and training on agricultural practices. Low vulnerability cluster was assigned (one of the dependent variable categories) as a reference category (or baseline) against which all other vulnerability categories were compared (Finch et al., 2014). All the statistical analyses were performed in R statistical environment (R Core Team, 2016).

CHAPTER FOUR: RESULTS

4.1 Climate variability and change

4.1.1 Precipitation trends

The observed precipitation trends from 1981 to 2015 at Koutiala weather station is presented in Figures 5 and 6. The total annual precipitation recorded ranged between 516.3 mm and 1358.4 mm (Figure 5), with a long-term mean of 869 mm and a standard deviation of 181.66 mm. Three quarters of the observations are less than or equal to 986.2 mm (75th percentile). Trend analysis indicated a slight increasing precipitation trend, though not statistically significant (Figure 5, Kendal tau=0.22, p-value=0.066). From 1981 to 2015, precipitation in Koutiala has increased at a rate of 5.1 mm per year, with 178.4 mm increase over the entire period.

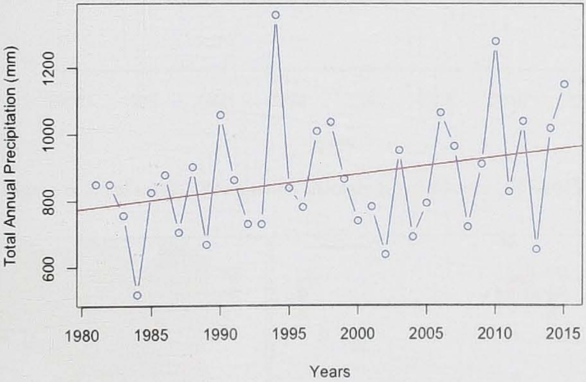

Figure 5. Total annual precipitation recorded in Koutiala station from 1981 to 2015

Analysis of Figures 5 and 6 indicated that there was a strong interannual variability in rainfall patterns in Koutiala. The 1980s and early 2000 (1999-2002, 2004-2005) experienced below normal precipitation while rainfall seemed to be recovering after 2005, though with year to year variability (Figure 6).

Spatially-explicit trend analysis of CHIRPS data (1981-2018) showed that total annual rainfall varied spatially over Koutiala (Figure 7). Some areas experienced an increasing trend while other areas recorded a decreasing rainfall trend (Figure 7, left panel). However, very few pixels within the study area experienced significant (decreasing or increasing at 5%) rainfall trends (Figure 7, right panel), implying that rainfall pattern has become more variable over the study period.

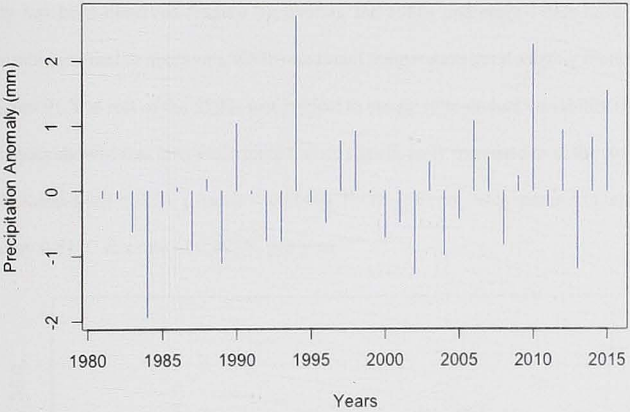

Figure 6. Total annual precipitation anomaly Koutiala over 1981-2015

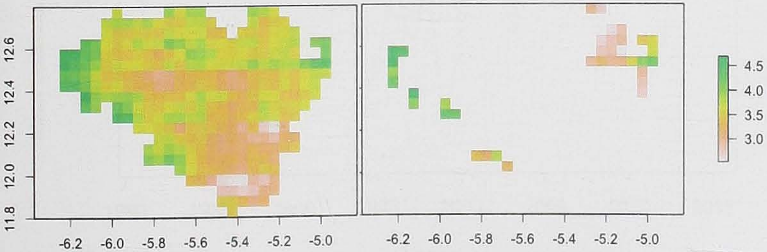

Figure 7. Spatial variation in total annual precipitation trends in Koutiala over 1981-2018; left: overall trends, right: 5% significant trends

4.1.2 Temperature trends

The annual mean maximum temperature recorded at Koutiala weather station from 1981 to 2015 is illustrated in Figures 8 and 9. The annual mean maximum temperature varied between 33.61°C (the lowest over the period, recorded in 1986) and 35.36°C (the highest over the period, recorded in 2013) (Figure 8). The long-term annual mean maximum temperature was 34.38°C, with a standard deviation of 0.41°C. A decadal variability rather than inter-annual variability has been observed (Figure 9): overall, the 1980s and early 1990s have recorded below normal maximal temperature, while maximum temperature trend roughly increased after 2000 (Figure 9). The rest of the 1990s was subject to strong inter-annual variability (Figure 8). Trend analysis showed that maximum temperature significantly increased over the study period (Figure 8, Kendal tau = 0.53, p-value < 0.0000). From 1981 to 2015, maximum temperature increased by 0.81°C at a rate of 0.023°C per year.

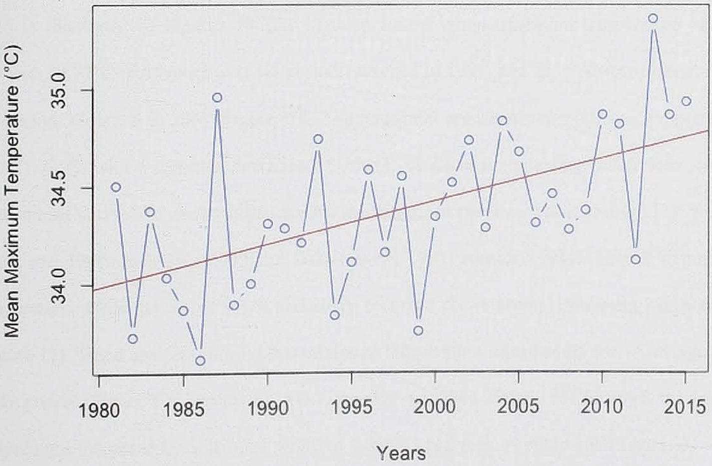

Figure 8. Maximum annual temperature recorded in Koutiala station from 1981 to 2015

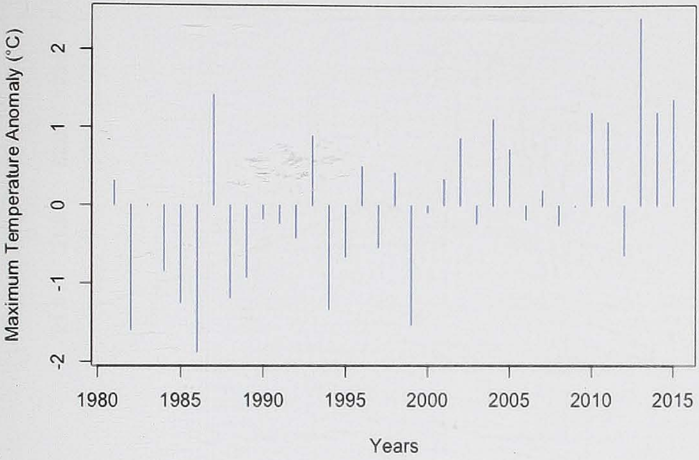

Figure 9. Maximum temperature anomaly in Koutiala over 1981-2015

The annual mean minimum temperature recorded at Koutiala weather station from 1981 to 2015 is illustrated in Figures 10 and 11. The annual mean minimum temperature varied between 20.77°C (the lowest over the period, recorded in 1981) and 22.79°C (the highest over the period, recorded in 205) (Figure 10). The long-term annual mean minimum temperature was 21.72°C, with a standard deviation of 0.52°C. A decadal variability rather than strong inter-annual variability clearly characterised minimum temperature trends (Figure 11): all the 1980s and 1990s including 2000 and 2001 (except 1993) recorded below normal minimum temperature, while the rest of 2000s and 2010s recorded above normal minimum temperature (Figure 11). Trend analysis showed that minimum temperature significantly increased over the study period (Figure 10, Kendal tau = 0.4, p-value = 0.001). From 1981 to 2015, minimum temperature increased by 1.26°C at a rate of 0.036°C per year. A comparative analysis with maximum temperature (Figures 8 and 9) indicated that from 1981 to 2015, minimum temperature increased faster than maximum temperature in the study area.

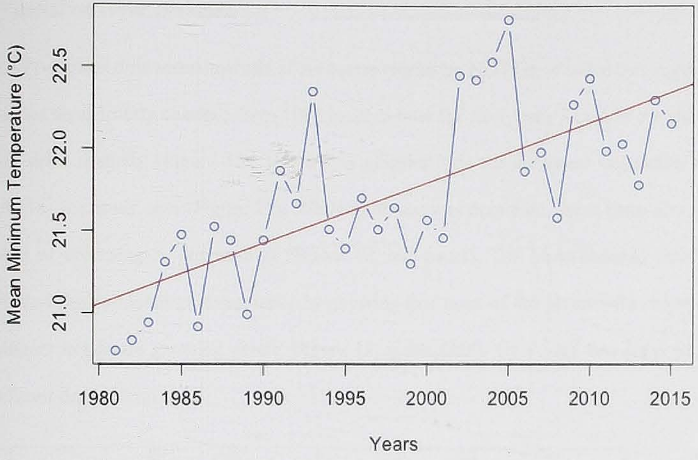

Figure 10. Minimum annual temperature recorded in Koutiala station from 1981 to 2015

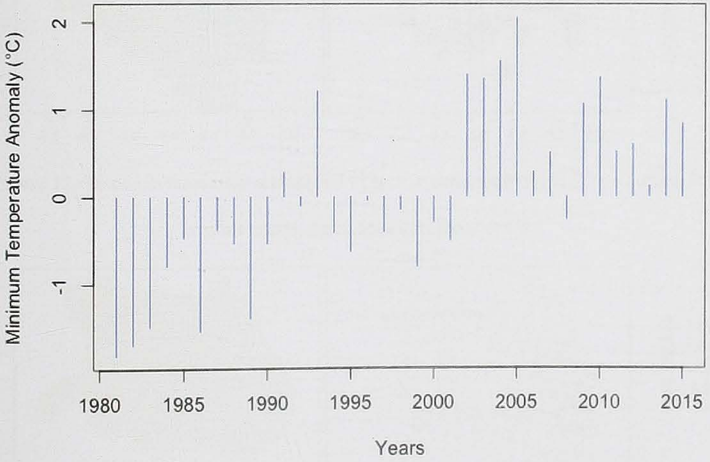

Figure 11. Minimum temperature anomaly over 1981-2015

4.2 Vegetation cover dynamics

Spatially-explicit time series analysis of the coarse resolution NDVI3g revealed that vegetation cover has significantly changed from 1981 to 2015 over the study area Koutiala and that this trend varied spatially (Figure 12). Vegetation greening was the dominant vegetation cover trend over the study area (Figure 12). While greening was dominant, there were also some patches of browning or degradation (Figure 12, left panel). The Mann-Kendall trend test confirmed the dominant greening trend by showing that most of the pixels with statistically significant trends are greening pixels (Figure 12, right panel). Only very few areas showed significant degradation trend.

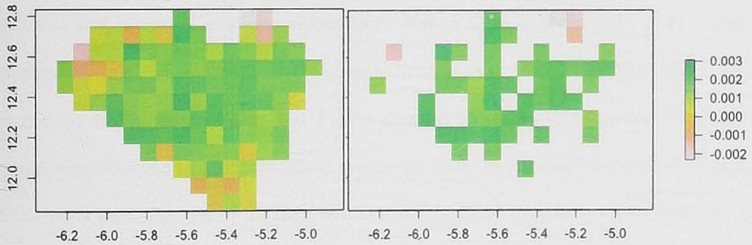

Figure 12. Trends in maximum annual NDVI3g time series (1981-2015) in Koutiala; left: overall trends, right: 5% significant trends

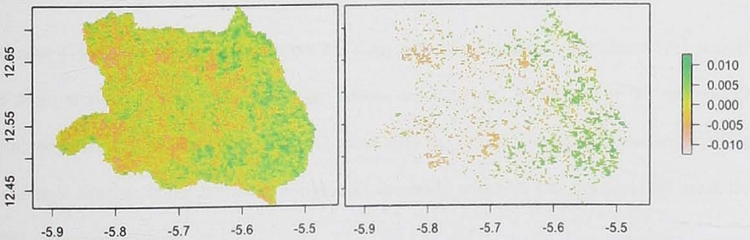

Figure 13. Trends in maximum annual MODIS NDVI time series (2000-2015) at watershed scale; left: overall trends, right: 5% significant trends

Analysis of the moderate resolution MODIS NDVI time series (2000-2015) at finer scale (a watershed level) within Koutiala further supported the strong spatial variability in vegetation cover trends and nuanced the dominant greening trends (Figure 13). From 2000 to 2015, vegetation cover has significantly changed in the watershed and this vegetation dynamics varied strongly in space (Figure 13, left panel). Vegetation cover has significantly increased in some areas and decreased in other (Figure 13, left panel).

4.3 Perception of climate variability and change

4.3.1 Socioeconomic characteristics of respondents

Table 3 presents a summary of sociodemographic characteristics of the respondents. It indicated that about 51% of the respondents were male and about 49% were women. Respondents' age ranged from 19 to 77 years, with an average of 45.7 (± 12.28) years. Three quarters of the respondents were less than or equal to 55 years old. More than 87% of the respondents belonged to Minianka ethnic groups which is the dominant sociolinguistic group in the study area. The rest of the respondents (roughly 13%) were from other ethnic groups (including Peulh or Fulbe, Bambara, Sonike and Senoufo). About 78% of the respondents were born and grown up either in the study villages/districts or in the Cercle of Koutiala, while the rest of them (22%) were born and grown up outside the study area.

Almost 47% of the respondents did not have any formal education, while about 18% and 4% of them attained primary and secondary school respectively. About 8% of the respondents attained Islamic or Koranic education and about 23% has been trained to read and write in local language. Muslim is the dominant religion in the study area and was practiced by more that 95% of the respondents.

About 64% of the respondents belonged to at least one farmer- or community-based organisations. On average, each respondent had three (3.08 ± 1.41) sources of agricultural knowledge. Three quarters of the respondents relied on less than or equal to 4 agricultural knowledge sources. Respondents' source of agricultural knowledge was diverse and ranged from one to eight, including parents (96.21%), social network (80.44%), learning from own experience (32.73%), local media programmes (30.34%), extension services (28.34%), inputs suppliers (18.76%), NGOs (15.97%), and Research for Development (R&D) projects or programmes (4.99%). About 26% of the respondents had ever received a training on agricultural practices and production.

Table 3. Sociodemographic characteristics of the respondents

Characteristics	**Percentage (%)**	**Mean (Stand. dev.)**	**Median (min-max)**
Gender			
Male	51.10		
Female	48.90		
Age		45.7 (11.57)	45 (19 – 77)
Ethnic groups			
Minianka	87.43		
Others	12.57		
Education			
None	46.91		
Islamic/Koranic	7.78		
Literacy	23.55		
Primary	17.96		
Secondary	3.79		
Religion			
Muslim	95.61		
Others (Traditional, Christian)	4.39		
Origin			
Native	78.04		
Non-Native	21.96		
CBOs membership			
Yes	64.27		
No	35.73		
Diversity of CBOs membership		0.88 (0.88)	1 (0 – 3)
Diversity of source of agricultural knowledge		3.08 (1.41)	3 (1 – 8)
Training on crop production			
Yes	25.95		
No	74.05		

4.3.2 Perception and knowledge of climate change and its impacts

Table 4 summarises the knowledge construct scores of respondents' knowledge and perception of climate change and its impacts. Cronbach's α coefficient ranged from 0.70 to 0.87 (Table 4), indicating a good reliability of the multiple item constructs. Pearson's correlation test indicated that respondents knowledge and perception of climate change is significantly correlated with their knowledge of climate change impacts on crops and livestock ($r = 0.37$, $t = 8.9968$, $df = 499$, p-value < 0.0001).

About 86% of the respondents were in agreement (19% agree and 67% strongly agree) that heat was more intense in dry season, and 85% (30% agree and 55% strongly agree) of them indicated this was more exacerbated than in the past. However, there was less agreement among respondents regarding temperature patterns during cold season (Harmattan period): 51% of the respondents disagreed (37% strongly disagree and 14% disagree) and 48% agreed (12% agree and 36% strongly agree) that cold season temperature decreased. About 52% of the respondents agreed (12% agree and 40% strongly agree) and 47% disagreed (19% strongly disagree and 28% disagree) that cold season temperature increased.

About 96% of the respondents agreed (23% agree and 73% strongly agree) that rainy season onset has become unpredictable, while 97% of them agreed (23% agree and 74% strongly agree) that the end of the rainy season has become highly variable. About 95% of the respondents agreed (26% agree and 69% strongly agree) that rainy season has slightly changed compared to the past. About 78% of the respondents stated (25% agree and 53% strongly agree) that rains started late in the season compared to the past, while 21% of them disagreed (8% strongly disagree and 13% disagree). About 99% of the respondents agreed (20% agree and 79% strongly agree) that rains stopped earlier than in the past. About 97% of the respondents perceived (18% agree and 79% strongly agree) that number rainy days has decreased, while

99% of them reported (32% agree and 67% strongly agree) that dry spells has become more frequent intense.

All the respondents agreed (22% agree and 78% strongly agree) that dry spells and heat waves during crop growth, especially flowering stage can have serious negative impacts on crop yields. Negative impacts can also be caused by rainfall extremes and associated floods during crop growth (26% agree and 74% strongly agree). According to the respondents, water stress (dry spells and floods) and heat stress can cause yield reduction up to 100% yield loss. About 99% of them explained (31% agree and 78% strongly agree) that water and heat stress affect crops differently because of the differential sensibility of crops to water and heat stress. According to 99% of the respondents (21% agree and 78% strongly agree), heavy rains can degrade soil structure and texture.

About 98% of the respondents stated (36% agree and 62% strongly agree) that water and heat stress can decimate livestock herd, while 99% of them perceived (42% agree and 57% strongly agree) that climate variability and change has led to the scarcity of some forage species in the local environment.

Table 4. Median scores and internal consistency of the knowledge constructs

Knowledge constructs	**Key themes/subjects**	**Number of items**	**Cronbach α**	**Median**	**1st – 3rd Q**	**Range***
Climate variability and change						
Rainfall and related stresses or risks	Onset and end of rainy seasons; Rainfall patterns (distribution, intensity, frequency); Variability in the season	18	0.80	59	57 – 61	18 – 90
Temperature and related stresses or risks	Seasonal variability; Patterns (distribution, intensity, frequency)	09	0.87	29	28 – 30	09 – 45
		–	–	**88**	**85 – 91**	**27 – 135**
Climate change impacts						
Impacts of crop production	Crop growth and yields;	10	0.83	42	38 – 43	10 – 50
Impacts of livestock	Livestock production and forage species	2	0.70	9	8 – 10	2 – 10
		–	–	**51**	**48 – 52**	**12 – 60**

* Range refers to the possible scores for each construct.

4.4 Household vulnerability to climatic and non-climatic stressors

4.4.1 Household socioeconomic profiles

Analysis of household socioeconomic and demographic characteristics (Table 5) indicated that over 98% of households interviewed were headed by a male. Household head's age ranged from 19 to 84 years, with mean age of 48.33 (± 12.28) years. Three quarters of the head of the households interviewed were less than or equal to 57 years old. More than 86% of the households interviewed belonged to Minianka ethnic groups which is the dominant sociolinguistic group in the study area. The rest of household interviewed were either Peulh (about 4%) or belonged to other groups (6%) which were Bambara, Sonike and Senoufo.

Table 5. Sociodemographic characteristics of the surveyed households

Characteristics	**Percentage (%)**	**Mean (Stand. dev.)**	**Median (min-max)**
Gender of HH head			
Male	98.40		
Female	1.60		
Age of HH head		48.33 (12.28)	48 (19 – 84)
Ethnic groups			
Minianka	86.62		
Peulh	4.19		
Others	6.19		
Education			
None	34.13		
Islamic/Koranic	10.98		
Literacy	28.94		
Primary	20.96		
Secondary	4.99		
Religion			
Muslim	95.80		
Traditional	3		
Christian	1.2		
HH productive members		9.01 (6.52)	7 (1 – 58)
Dependency ratio		1.42 (0.79)	1.25 (0.167 – 6.5)

About 34% of household heads did not have any formal education, while about 21% and 5% of them attained primary and secondary school respectively. About 11% of the household heads attained Islamic or Koranic education and about 28% had been trained to read and write in local language. Muslim is the dominant religion in the study area and was practiced by more than 95% of the households interviewed. On average, households interviewed had about nine productive members, but this varied largely, from 1 to 58 productive members. Three quarters of the households had less than or equal to 11 productive members. Dependency ration ranged from 0.17 to 6.5, with an average of 1.42. More than 63% of the households had a dependency ratio greater than one and 39% of them had a value greater or equal to 1.5.

Farming was the main livelihood activity in the study area and was the principal activity of all the surveyed households. Figure 14 illustrates the diversity and importance of cultivated crops in the study area. Cultivated crops per household ranged from two to 22, with an average of 10.42 ± 3.65. Three quarters of the surveyed households cultivated less than or equal to 13 crops. In total, 25 different crops were cultivated by the surveyed households. While there was a diversity of crops (Figure 14), maize (cultivated by more than 99% of the surveyed households), sorghum (about 97% of the surveyed households), pearl millet (about 95% of the surveyed households), cotton (about 92% of the surveyed households), groundnut (about 89% of the surveyed households) and cowpea (88% of the surveyed households) were respectively the most cultivated crops by households in the study area (Figure 14). Crops cultivated by few households were soybean, Taro, Fonio, banana and watermelon (Figure 14).

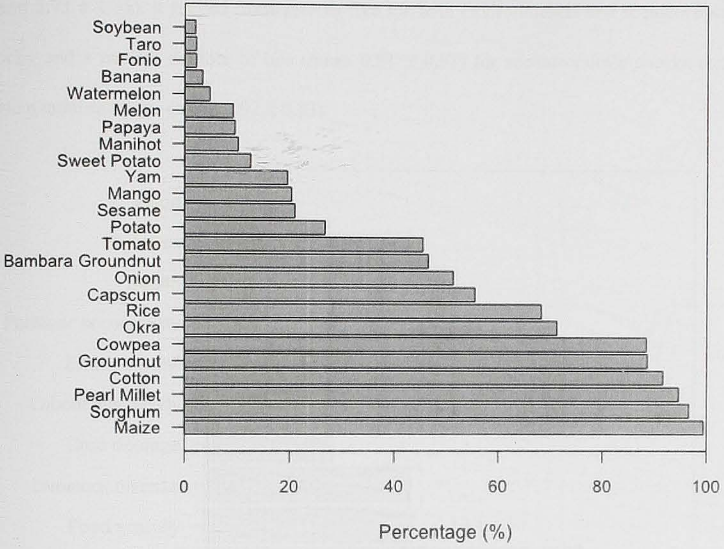

Figure 14. Diversity of cultivated plants and their importance

4.4.2 Diversity of climatic and non-climatic shocks experienced

Stressors or shocks that drive household vulnerability in the study were of both climatic and non-climatic nature. Figure 15 shows the diversity of environmental and socioeconomic stressors or shocks to which households were exposed. Environmental stressors evoked included drought which were experienced by the majority of surveyed households (77.25%). Other environmental stressors were food scarcity (42.32%), livestock disease (41.72%), erratic rainfall patterns (21.16%) and floods (9.58%). Socioeconomic stressors or shocks experienced by households were damage to crop farm by livestock (25.55%), unavailability of labour on timely manner to perform farm activities (24.95%), inability to access fertilizer (10.98%), and the death (9.98%) or sickness of a household member (9.78%).

Over the past 12 months prior to the surveyed, the total number of shocks experienced by households ranged between one and seven, with a median number of three per households (mean 2.73 ± 1.35). it ranged from zero to five for both environmental and socioeconomic shocks, and a median number of one (mean 0.81 ± 0.93) for socioeconomic shocks and a median number of two (mean 1.92 ± 0.83).

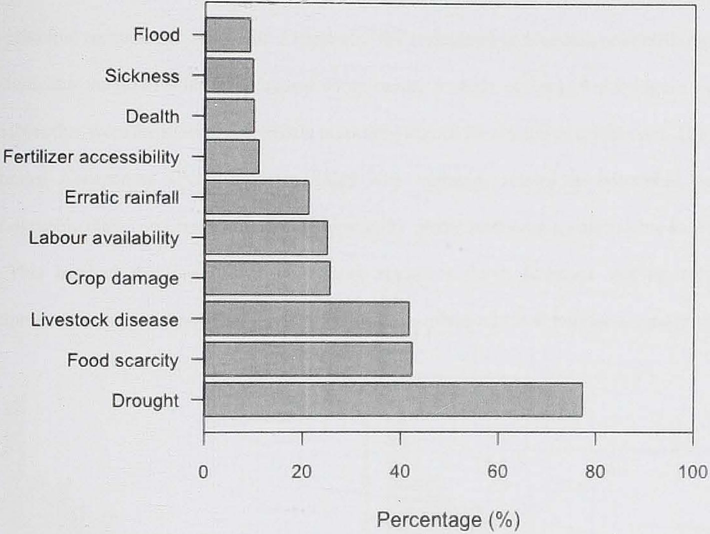

Figure 15. Environmental and socioeconomic shocks/stressors experienced by households

4.4.3 Household vulnerability patterns

The Factor Analysis of Mixed Data (FAMD) analysis showed that the first 12 Principal Components (PC) have eigenvalues greater than one and accounted for 61.20% of the total variance (Figure 16). In addition to these first 12 PCs with eigenvalues greater than one, the next four components with eigen values closes to 1 (above 0.9) were included in order to increase the total variance to be used in the further analysis (i.e., the cluster analysis). The first 16 components accounted for 71.61% of the total variance and were considered in the Hierarchical Clustering on Principal Component (HCPC) analysis. Figure 16 presented the eigenvalues and the percentage of variance explained by the first 16 PCs included in the cluster analysis. Appendix 1 presented a summary of the outputs of the FAMD analysis.

Table 6 presented the correlation of the indicator variables with the first five principal components and Figure 17 illustrated the quality of representation (co2) of these variables on the principal components. Appendix 2 illustrated the correlation and loading or contribution of the indicator variables with the principal components. A study of Table 6 and Figure shows variables that were the most characteristic according to each dimension or component. The first Principal Component (PC1) was correlated with variables related to household socio-demographic status and resources, and food security proxy such crop species richness (Table 6). This implied that households with more resources (land, livestock and agricultural equipment), usually has more household productive members and tend to cultivate more crops.

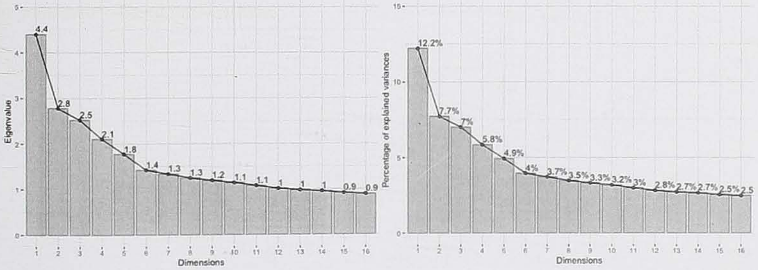

Figure 16. Eigenvalues (left panel) and percentage of explained variances (right panel) of the principal components from FAMD analysis

The second Principal Component (PC2) is correlated with variables related to environmental shocks, food security and water security. Households which has experienced a higher number of environmental shocks over the last 12 months prior to the survey tended to report a higher number of months in which they has insufficient food and water to cover household needs.

These households reported to be food self-insufficient and sourced a larger part of food they consumed in the households from external sources.

The third Principal Component (PC3) was correlated with agricultural livelihood diversity and variables related to water security such as diversity of water source and number of month with insufficient water. Households with a diverse agricultural livelihood activities and a diversity of water source reported a lower number of months where households had insufficient water to cover household needs.

The fourth Principal Component (PC4) was correlated with variables related to livelihood diversity and diversity of water source. Households with a high number of livelihood activities had a low number of water source to satisfy household needs. The fifth Principal Component (PC5) was correlated with variables related to social network, namely the diversity of farmer- or community-based organisations.

Table 6. Correlation of the initial variables to the first five principal components

Dimensions	**Components**	**Indicators**	**Principal Components***				
			PC1	**PC2**	**PC3**	**PC4**	**PC5**
Adaptive capacity	Socio-demographic status	Education	0.03	0.02	0.06	0.05	0.14
		Household productive members	**0.67**	0.27	-	-0.12	-
		Dependency ratio	-0.13	-	-	0.09	-
	Livelihood strategies	Agricultural livelihood diversity	0.31	-	**0.55**	0.45	-
		Non-agricultural livelihood diversity	0.27	-	-	0.38	0.24
		Livelihood diversity	0.44	-	0.43	**0.63**	0.13
	Resources	Agricultural land	**0.76**	0.27	-0.10	-0.10	-
		Livestock (TLU)	**0.74**	-	-	-	-
		Diversity of livestock types	**0.51**	-	0.11	0.15	-
		Number of plough	**0.60**	0.15	-0.24	-0.14	-
		Number of draught animal	**0.72**	-	-0.12	-0.12	-0.09
		Number of donkey	**0.61**	-0.09	-0.11	-0.15	-0.14
		Number of cart	**0.59**	-	-0.19	-0.19	-0.14
		Number of pesticide sprayer	**0.58**	-	-	-0.16	-
		Number of seed drill	**0.52**	-	-	-0.15	-0.25
	Social networks	CBOs membership	0.08	0.01	-	-	0.05
		Diversity of CBOs membership	0.38	-	-	-	**0.42**
		Political access	-	-	0.13	0.09	0.17
	Physical accessibility	Market	-	-	0.12	0.01	0.14
		Road practicability	-	-	0.13	0.08	0.25
Sensitivity	Food security	Source of household food	0.05	**0.47**	0.07	0.07	0.25
		Food self-sufficiency	0.07	**0.59**	0.01	0.01	-
		Number of month with insufficient food	-0.29	**0.73**	-	-	-
		Crop diversity	**0.49**	0.19	0.39		0.21
	Health & Sanitation	Drinking water quality		0.11	0.35	0.35	0.03
		Toilet facility quality	0.12	0.07	0.06	0.03	0.01
		Illness (Health case number)	0.19	-	-0.18	0.20	-
		Household member with chronic illness	0.09	0.11	-	-	0.12
		Average time to closest health facility	-0.10	0.11	-	-0.21	0.19
		Availability of health facility in the village	-	0.01	0.03	0.01	0.04
	Water security	Diversity of water source	-	0.21	**0.54**	**-0.61**	-0.17
		Water sufficiency	0.01	0.15	0.28	0.07	0.11
		Number of month with insufficient water		**0.45**	**-0.44**	0.24	-0.35
Exposure	Environmental shocks	Environmental shocks experienced over the past 12months		**0.54**			0.21

	Socio-economic shocks	Socio-economic shocks experienced over the past 12months		0.24	-0.19		0.22

* Values in the column are correlation coefficients. All values are significant at the threshold p = 0.05; Underlined and bold values indicate the indicators that are the most characteristic to each component.

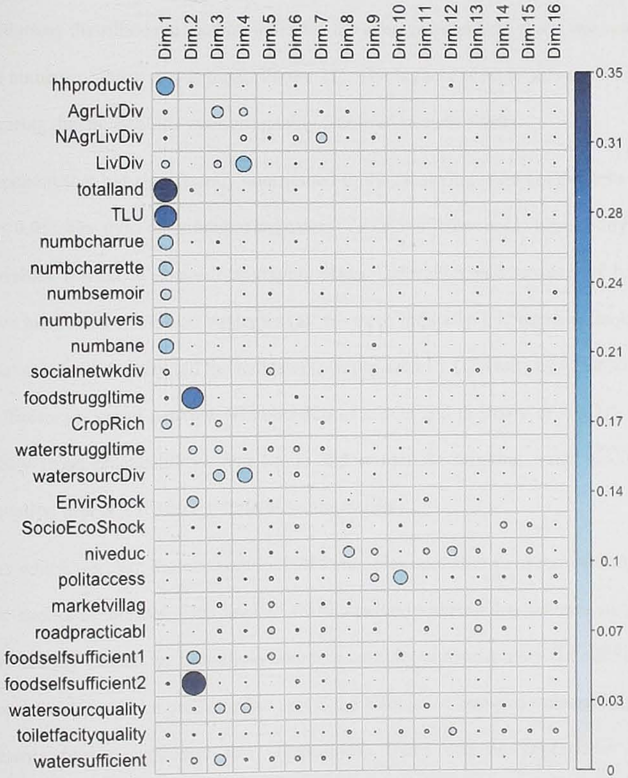

Figure 17. Quality of representation of the initial variables on the principal components

The results of the feasibility of clustering analysis performed using the Visual Assessment of cluster Tendency (VAT) algorithm is illustrated in Figure 18. The VAT reordered dissimilarity matrix image confirms that there is a cluster structure in the data (Figure 18). The dark diagonal blocks in Figure 18 clearly indicate the presence of clusters, as well as the isolated singleton in data. The Hierarchical Clustering on Principal Component (HCPC) analysis showed three clusters (Figure 19) of household vulnerability patterns. This was supported by the analysis of the dendrogram (Figure 20) which clearly revealed three classes. Cluster validity analysis performed using the silhouette method indicated the average silhouette width was maximized when the number of clusters was three (Figure 21). The highest average silhouette width was 0.4, indicating that households were acceptably clustered in each cluster.

The component that has significantly contributed to the clustering were components 1-4, 6-7 and 9 ($p < 0.05$). The most discriminant indicators (Table 6) of household vulnerability patterns were variables related to socio-demographic status (education and number of household productive members), livelihood strategies (all the three indicators), household resources (all the indicators), food security (all the indicators), water security (diversity of water source and water sufficiency), social network (membership of CBOs and diversity of CBOs), physical accessibility (road practicability), and health and sanitation (drinking water quality, toilet facility quality, illness and average time to health facility).

Indicators which were not discriminant included variables related to environmental and socio-economic shocks or stresses. This implied that household vulnerability patterns in the study area were mainly shaped by household adaptive capacity and sensitivity. In addition, Chi-square test of independence performed to assess the association between vulnerability classes and stressors further supported this conclusions. There was no dependence between vulnerability clusters and either overall stressors (Chi-squared = 20.845, df = 18, p-value = 0.287), environmental stressors (Chi-squared = 13.802, df = 8, p-value = 0.087) or socio-economic stressors (Chi-squared = 6.2593, df = 8, p-value = 0.618), implying that stressors were not specific to any clusters and that household exposure to stressors did not vary.

Figure 18. Ordered dissimilarity images generated by VAT algorithm

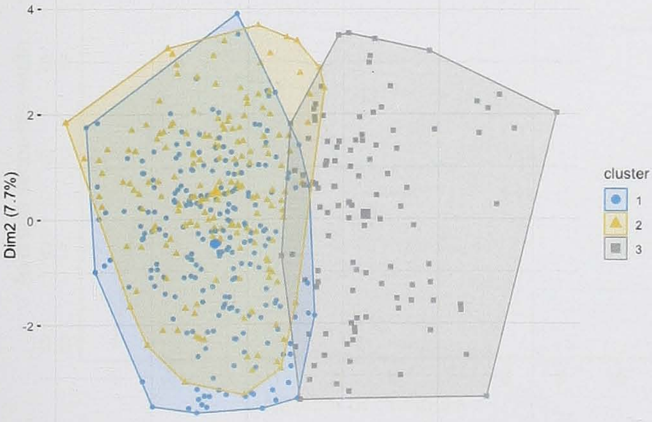

Figure 19. Clusters of household vulnerability patterns

Figure 20. Dendrogram showing the grouping of households into vulnerability clusters

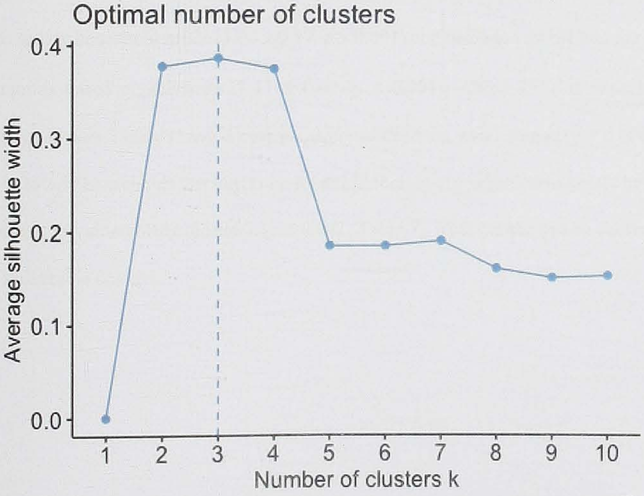

Figure 21. Identification of optimal number of clusters

Table 7 presents the description of the three vulnerability clusters according to the initial vulnerability indicators. Detailed descriptions of clusters by the initial indicators variables are given in Appendix 3. Appendix 4 presents the descriptive statistics of initial indicators.

Vulnerability cluster 1 was composed of households with low resource endowment and limited livelihood activities (Table 7) and comprised 43.31 % of surveyed households. Households in this vulnerability cluster had smaller land area (9.40 ± 3.66 ha, $p < 0.001$), fewer livestock (4.38 ± 4.18 TLU, $p < 0.001$) and lower agricultural equipment (number of plough, drought animal, cart, donkey, seed drill, and pesticide sprayer; $p < 0.001$, Table 7) than average. They had limited household productive members (6.88 ± 3.58, $p < 0.001$), were involved in few livelihood activities (2.68 ± 0.88, $p < 0.001$), especially agricultural livelihood activities (1.91 ± 0.71, $p = 0.023$), cultivated low number of crops (9.22 ± 2.93, $p < 0.001$), had a limited water source to satisfy household needs (1.04 ± 0.19, $p < 0.001$) and belonged to low number farmer- or community-based organisation (1.11 ± 0.49, $p < 0.001$). About 75% of households in vulnerability cluster 1 didn't have access to improved drinking water source ($p < 0.001$, Table 7). About 28% of households that buy more food than their own production to satisfy household needs belong to vulnerability cluster 1 ($p < 0.001$, Table 7). This cluster can be characterized as mild vulnerable cluster.

Table 7. Characterisation of household vulnerability patterns in Koutiala by discriminant variables

Indicators	**Cluster 1 (43.31% HH)**	**Cluster 2 (35.12% HH)**	**Cluster 3 (21.56% HH)**	**Global average or percentage**	**P-value**
Education					<0.001
None		49.71 (48.30)	12.87 (20.37)	34.13	
Literacy		28.28 (23.30)	28.28 (37.96)	28.94	
Primary		22.86 (13.64)		20.96	
Household productive members	6.88 (3.58)	7.45 (4.22)	15.83 (9.10)	9.01 (6.52)	<0.001
Agricultural livelihood diversity	1.91 (0.71)		2.15 (0.80)	1.99 (0.74)	0.023
Non-agricultural livelihood diversity		0.66 (0.64)	1.08 (0.72)	0.80 (0.68)	<0.001
Livelihood diversity	2.68 (0.88)	2.65 (0.87)	3.23 (1.02)	2.79 (0.94)	<0.001
Agricultural land	9.40 (3.66)	9.71 (4.49)	18.88 (6.39)	11.55 (6.04)	<0.001
Livestock (TLU)	4.38 (4.18)	3.79 (3.75)	14.34 (8.63)	6.32 (6.80)	<0.001
Diversity of livestock type	3.03 (1.43)	2.99 (1.47)	3.96 (0.79)	3.22 (1.39)	<0.001
Number of plough	1.86 (1.07)	1.81 (1.08)	3.58 (1.79)	2.21 (1.45)	<0.001
Number of draught animal	2.29 (1.25)	2.23 (1.35)	4.74 (1.73)	2.79 (1.73)	<0.001
Number of donkey	1.22 (0.63)	1.19 (0.83)	2.45 (1.18)	1.48 (0.99)	<0.001
Number of cart	1.04 (0.36)	1.01 (0.35)	1.84 (1.06)	1.20 (0.67)	<0.001
Number of pesticide sprayer	0.52 (0.55)	0.64 (0.66)	1.28 (0.65)	0.72 (0.68)	<0.001
Number of seed drill	0.47 (0.52)	0.49 (0.51)	1.04 (0.53)	0.60 (0.57)	
CBOs membership					0.041
Yes			22.67 (99.07)	94.21	
No			3.45 (0.93)	5.79	
Diversity of CBOs membership	1.11 (0.49)		1.44 (0.60)	1.19 (0.56)	<0.001
Road practicability					0.015
Not practicable year round	66.67 (10.14)	12.12 (2.27)		6.59	
Practicable year round		38.53 (74.43)		67.86	
Source of household food					<0.001
Own + Buying High	28.07 (7.37)	57.89 (18.75)		11.38	
Own Production		18.90 (13.64)	32.28 (37.96)	25.35	
Own + Buying Low			18.61 (54.63)	63.27	
Food self-sufficiency					<0.001
Not food self-sufficient		39.67 (81.82)	17.08 (57.41)	72.46	
Food self-sufficient		23.19 (18.18)	33.33 (42.59)	27.54	
Number of month with insufficient food		2.39 (1.71)	1.37 (1.44)	1.97 (1.64)	<0.001
Crop diversity	9.22 (2.93)		12.68 (3.55)	10.42 (3.64)	<0.001
Drinking water quality					<0.001
Improved	77.46 (25.35)	2.82 (1.14)		14.17	

Not Improved	78.26 (74.65)	0.00		41.32	
Both	0.00	78.03 (98.86)		44.51	
Toilet facility quality					<0.001
Not Improved		40.13 (69.32)	14.14 (39.81)	60.68	
Improved			28.76 (40.74)	30.54	
Both		11.36 (2.84)	47.73 (19.44)	8.78	
Illness (Health case number)		1.45 (1.76)	2.50 (2.80)	1.99 (2.28)	<0.001
Average time to health facility	13.27 (11.47)	17.03 (14.77)		14.61 (13.02)	0.009
Diversity of water source	1.04 (0.19)	2.07 (0.26)		1.52 (0.57)	<0.001
Water sufficiency					0.001
Water sufficient		44.34 (53.41)	16.98 (33.33)	42.32	
Not water sufficient		28.37 (46.59)	24.91 (66.67)	57.68	

Vulnerability cluster 2, composed of 35.13 % of surveyed households, was also composed of households with low resource endowment and limited livelihood activities (Table 7), but was characterised by prevalent food insecurity conditions. Households in vulnerability cluster 2 had smaller land area (9.71 ± 4.49 ha, $p < 0.001$), fewer livestock (3.79 ± 3.75 TLU, $p < 0.001$) and lower agricultural equipment (number of plough, drought animal, cart, donkey, seed drill, and pesticide sprayer; $p < 0.001$, Table 7) than average households. They had limited household productive members (7.45 ± 4.22, $p < 0.001$), were involved in few livelihood activities (2.65 ± 0.87, $p < 0.001$), particularly non-agricultural livelihoods activities (0.66 ± 0.64, $p < 0.001$). More than 81% of households in vulnerability cluster 2 were not food self-sufficient and unable to feed their households with their own production all the months of the year ($p < 0.001$). The number of months in which households of the this vulnerability cluster did not have sufficient food to satisfy household needs were higher than the average (2.39 ± 1.71 vs. 1.97 ± 1.64, $p < 0.001$). About 58% of households that bought more food than they produced to satisfy household needs belonged to vulnerability cluster 2 ($p < 0.001$, Table 7). Only about 14% of households in this vulnerability cluster produced enough food to satisfy household needs ($p < 0.001$, Table 7). More than 98% of households in this vulnerability cluster used both improved and non-improved drinking water source and more than 69% of them did not have access to improved toilet facility ($p < 0.001$, Table 7). Households in this cluster had, however, more water sources than average households or households in other clusters (2.07 ± 0.26, $p < 0.001$) and about 53% of them had enough water to satisfy household needs year round ($p = 0.001$, Table 7). Compared to other clusters, vulnerability cluster 2 was composed of more of less educated households: about 48% of them received no education and almost 50% of households with no education belong to this cluster, while only about 12% of them received primary education. Households in this vulnerability cluster can be characterized as highly vulnerable.

Vulnerability cluster 3 included 21.56% of surveyed households and was composed of households with high resource endowment and livelihood activities, a diverse social network and food security (Table 7). Households in this vulnerability cluster had larger land (18.88 ± 6.39 ha, $p < 0.001$), larger (14.34 ± 8.68 TLU, $p < 0.001$) and diverse (3.96 ± 0.79 livestock type, $p < 0.001$) livestock resources, and high agricultural equipment (number of plough, drought animal, cart, donkey, seed drill, and pesticide sprayer; $p < 0.001$, Table 7) than average. They had large household productive members (15.83 ± 9.10, $p < 0.001$), and were involved in a large variety of livelihood activities (3.23 ± 1.02, $p < 0.001$), both agricultural (2.15 ± 0.80, $p = 0.023$) and non-agricultural (1.08 ± 0.72, $p < 0.001$) livelihoods activities. About 99% of households in vulnerability cluster 3 were members of at least one farmer- or community-based organisation ($p = 0.041$, Table 7), with most of them having more diverse membership than average (1.44 ± 0.60, $p < 0.001$). They cultivated higher number of crops (12.68 ± 3.55, $p < 0.001$) and reported less month than average (1.37 ± 1.44, $p < 0.001$) in which households did not have sufficient food to satisfy household needs. Households in this cluster either produced enough foods to satisfy household needs year round (about 38% of households in the cluster) or sourced in addition an amount of food lower than their own production from an external sources (about 55% of households in the cluster). About 43% of households in this cluster were food self-sufficient ($p < 0.001$, Table 7). However, more than 66% of households in this cluster did not have enough water to satisfy household needs year round (p = 0.001, Table 7); only 33% of them were water sufficient. This vulnerability cluster was composed of less households with no education (20.37%) and more households with literacy level (37.97%). Households in this vulnerability cluster can be characterized as less vulnerable.

4.5 Individual and household level adaptation practices

4.5.1 Diversity of adaptation responses at individual level

To respond to climatic and non-climatic risks, local communities in the study area relied on a wide range of strategies and practices. Figure 22 shows individual level adaptation strategies adopted by the respondents. An analysis of Figure 22 indicates that respondents responded to risks and shocks using a diversity of strategies. The number of adaptation practices per respondent ranged from 1 to 17, with an average of 8.06 ± 2.94. Three quarters of the respondents used less than or equal to 10 adaptation practices. The diverse set of practices or strategies (Figure 22) used by respondents can be grouped under sowing date management (e.g., early or progressively sowing), soil and water conservation practices (e.g., Zaï, contour barriers), input uses (e.g., organic or chemical fertilizer use), farm size management practices (e.g., shrinkage or expansion of farm or livestock size), climate information use, livelihood diversification (e.g., dry season vegetable farming, migration), religious practices (e.g., prayers), varietal diversity use and management practices (e.g., use of drought tolerant varieties or short cycle varieties), crop diversity use and management practices (e.g., cultivation of more adapted crops, crop association), and tree-based practices (e.g., tree planting or preservation on farm, NTFPs harvesting). The most mentioned adaptation practices by the respondents were organic (about 87% of respondents) and chemical (about 71% of respondents) fertiliser use, sowing date management (86% of respondents), crop rotation (70% of respondents), use of short cycle varieties (about 60% of respondents) and dry season vegetable production (51% of respondents).

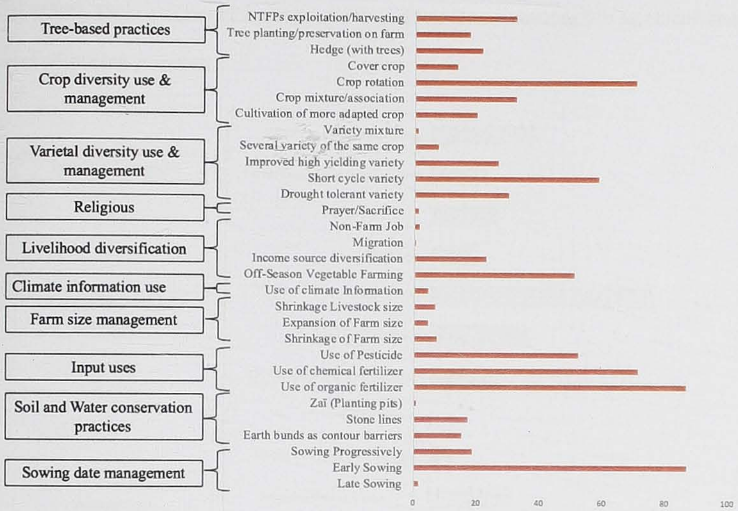

Figure 22. Diversity of adaptation practices at individual level in the study area

4.5.2 Agrobiodiversity-based adaptation practices

Figure 23 shows the diversity of agrobiodiversity-based adaptation practices elicited from the respondents. Agrobiodiversity-based adaptation practices were categorized (Figure 23) into varietal diversity use and management practices (e.g., use of drought tolerant varieties or short cycle varieties), crop diversity use and management practices (e.g., cultivation of more adapted crops, crop association), and tree-based practices (e.g., tree planting or preservation on farm, NTFPs harvesting). The most mentioned practices were crop rotation (70% of respondents), use of short cycle (about 60% of respondents) and drought tolerant (30% of respondents) varieties, crop association/mixture (32% of respondents), NTFPs harvesting (32% of respondents), and cultivation of more adapted crop (about 20% of respondents).

More than 94% of the respondents adopted at least one agrobiodiversity-based adaptation practices. The number of practices per respondent ranged from one to nine, with an average of

3.31 ± 2.21. Three quarters of the respondents used less than or equal to five agrobiodiversity-based adaptation practices.

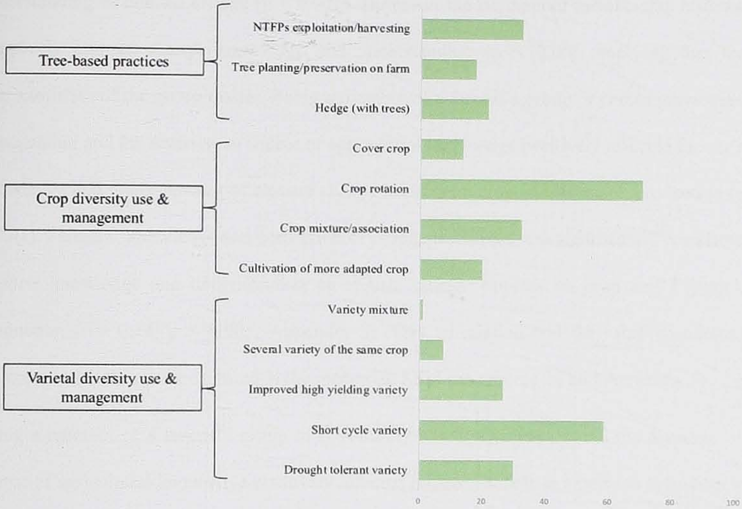

Figure 23. Agrobiodiversity-based climate change adaptation practices

4.5.3 *Drivers of adaptation responses and perception of climate change*

Tables 3 and 4, and Figure 22 present the descriptive statistics for the variables used in the SEM analysis, which investigated the empirical model outlined in Figure 3. The global goodness-of-fit test indicated that the piecewise SEM model was an adequate fit to the data based on comparison of the Fisher's C statistic to a chi-square distribution (C = 13.579, p = 0.481). This implies that the model reproduced well the data and there was no missing relationships among unconnected variables in the model. The tests of directed separation on each regression model in the SEM also indicated that there was no missing relationships in the model. Proportion of variance explained by each regression model ranged from 19% to 52% (Appendix 5). Detailed outputs from the SEM analysis are given in the Appendix 5.

The results of the piecewise SEM analysis are given in Figure 24. Being a member of a farmer's group or community-based organisation positively affected farmer's knowledge and understanding of climate change ($p < 0.001$). However, the richness of membership affected negatively climate change knowledge and understanding ($p < 0.05$), implying that the characteristics of the group matter. Being a member of a farmer's group or community-based organisation and the diversity of source of agricultural knowledge positively affected farmer's knowledge and understanding of climate change impacts on crop and livestock production ($p < 0.01$). Farmers' knowledge and perception of change in climate was significantly correlated to their knowledge and understanding of climate change impacts on crop and livestock production ($r = 0.34$, $p < 0.001$, Appendix 5). This correlation and the other correlation structure in the data were captured in the piecewise SEM (see Figure 24 and Appendix 5).

Being a member of a farmer's group or community-based organisation and the diversity of source of agricultural knowledge positively affected farmer's access to extension system ($p < 0.001$), while the richness of membership affected negatively access to extension system ($p < 0.001$). Farmers that received a training on agricultural practices in the past were more likely to have access to extension systems ($p < 0.001$).

Female farmers ($p < 0.001$) and farmers that were not native of Koutiala ($p < 0.05$,) were less likely to have an individual land or plot on their household land, while older farmers ($p < 0.05$) and those with larger total land ($p < 0.001$) were more likely to have an individual land or plot.

The number of adaptation strategies adopted was affected positively by gender, membership in a farmer's group or community-based organisation and diversity of source of agricultural knowledge, while it was affected negatively by farmers' knowledge and understanding of climate change impacts on crop and livestock production and the richness of membership (see Figure 24 and Appendix 5). Male farmers and farmers that belonged to a farmer's group or community-based organisation were more likely to adopt a higher number of adaptation practices ($p < 0.05$). Farmers with a diverse source of agricultural knowledge were more likely to adopt a high number of adaptation practices ($p < 0.001$), while farmers' belonging to a high number of a farmer's group or community-based organisation and farmers with a better knowledge and understanding of climate change impacts on crop and livestock production were less likely to adopt a high number of adaptation practices ($p < 0.05$).

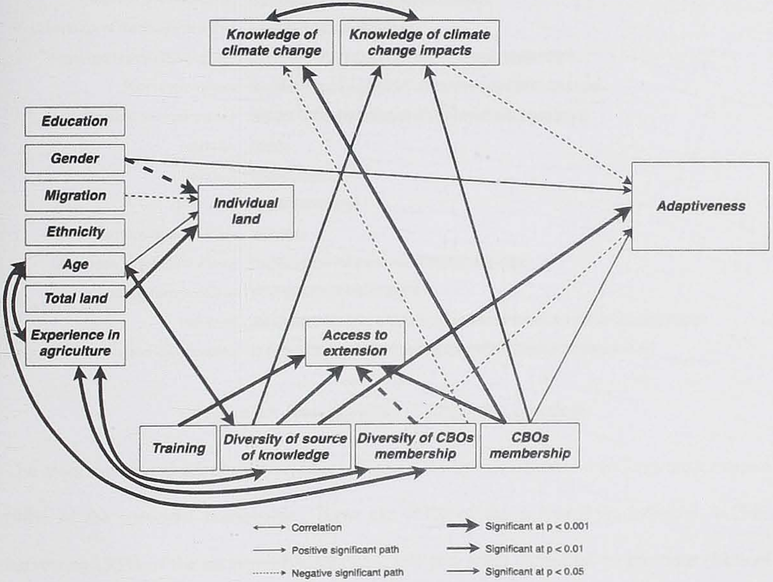

Figure 24. Structural equation models for adaptation practices by farmers in Koutiala

4.5.4 Household level adaptation strategies

At household level, adaptation responses to climatic and non-climatic risks were diverse (Figure 25). The number of adaptation practices per household ranged from 2 to 16, with a median numbers of 10 (mean of 9.49 ± 2.44). One and three quarters of the households used less than or equal to eight and 11 adaptation practices, respectively. Agrobiodiversity-based adaptation practices per household ranged from one to nine, with a median numbers of 7 (mean of 6.24 ± 1.73). One and three quarters of the households used less than or equal to five and eight agrobiodiversity-based adaptation practices, respectively.

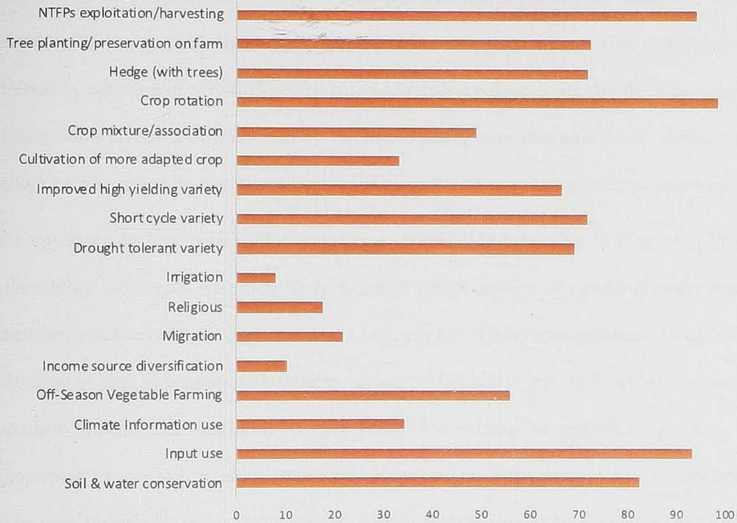

Figure 25. Household level adaptation practices

The most mentioned adaptation practices (Figure 25) by households were farm crop rotation (98% of the surveyed households), input use (93% of the surveyed households), NTFPs harvesting (93% of the surveyed households), soil and water conservation practices (82% of the surveyed households), agroforestry systems (planting or preserving trees on farm together with crop) (about 72% of the surveyed households), use of short cycle (about 71% of the surveyed households) and drought tolerant (about 68% of the surveyed households) varieties, and dry season vegetable production (about 56% of the surveyed households).

4.5.5 *Agrobiodiversity-based adaptation and household vulnerability*

The results of multinomial logistic regression testing the effect of adaptation and some co-variables on the probability that a household belongs to a given vulnerability archetypes is summarized in Table 8. Low vulnerability class (Vulnerability cluster 3, see Figure 19 and Table 7) was the reference category (or baseline) against which other vulnerability categories were compared. An analysis of Table 8 indicated that the probability of likelihood that a household belong to a vulnerability archetype or move to a given vulnerability archetype was affected by adoption of agrobiodiversity-based adaptation practices but also the total number of adaptation practices implemented by the household. It was also affected by institutional factors such as access to extension services and to credit, training on agricultural practices.

In comparison to low vulnerability archetypes, households belonging to high or medium vulnerability archetypes were less likely to adopt a high number of agrobiodiversity-based adaptation practices and less likely to adopt a high number of adaptation practices. Households belonging to high or medium vulnerability archetypes were also less likely to have access to extension systems and less likely to have received a training on agricultural practices in comparison to low vulnerability archetypes. However, in comparison to low vulnerability archetypes, households belonging to high or medium vulnerability archetypes were more likely to have household need satisfaction as their primary agricultural production objectives rather than market orientation.

Table 8. Results of multinomial logistic regressions of testing the effect of adaptation on household vulnerability patterns

	High		Medium	
	Coefficient (stand. error)	Odds ratio	Coefficient (stand. error)	Odds ratio
Agrobiodiversity-based adaptation practices	-0.178* (0.075)	0.837	-0.228** (0.072)	0.796
Adaptiveness	-0.170** (0.053)	0.844	-0.215*** (0.052)	0.807
Access to extension	-1.184*** (0.263)	0.306	-1.057*** (0.254)	0.348
Training on crop production	-1.386*** (0.318)	0.250	-0.931** (0.316)	0.394
Non-Market orientation	0.702* (0.301)	2.018	0.844** (0.291)	2.326
Age of HH	-0.010 (0.010)	0.990	-0.0004 (0.010)	1.000

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$; Standard error in brackets

CHAPTER FIVE: DISCUSSIONS

5.1 Climate variability and change

The study assessed climate change in study area by analysing trends in precipitation and temperature time series over a 35-year period (1981 to 2015). The findings showed that both minimum and maximum temperatures have significantly increased over the study period, albeit with decadal and interannual variability. It is worth noting that minimum temperature has increased faster than maximum temperature in the study area, with a figure (1.26°C over the 35-year period) close to global temperature increase since pre-industrial period. A similar observation has been reported by Kouressy et al. (2019). These findings were consistent with previous studies that reported a gradual increase in temperature over the last 50 years in West Africa (Collins, 2011; Daron, 2014; Riede et al., 2016; Sylla et al., 2016b). It has been shown that in SARs of West Africa, temperature has been increasing faster than global warming (Klutse et al., 2018; Sarr, 2012; Sultan et al., 2014), and this was confirmed by this study.

Our findings also demonstrated the strong interannual and spatial variability, rather than a clear significant change in total precipitation over the study period. The 80s and early 2000 (1999-2002, 2004-2005) experienced below normal precipitation while rainfall seemed to be recovering after 2005, though with year to year variability. Some areas experienced an increasing rainfall trend while other recorded a decreasing rainfall trend, with very few areas experiencing significant trends. This implied that rainfall pattern has become more variable over the study period. The strong interannual and spatial variability, rather than a clear change in precipitation reported in this study is in line with previous findings (Riede et al., 2016; Sylla et al., 2016b). Indeed, clear trend of mean precipitation change over West Africa is less evident and mean precipitation change generally varies between −10 and 10 %(Sylla et al., 2016b). There has been a substantial spatial and temporal variability in rainfall patterns in the semiarid parts of West Africa (Biasutti, 2019; Daron, 2014; Nicholson, 2013; Sarr, 2012). After the

1970s and 1980s severe drought episodes until today, the Sahel has slightly recovered, though the precipitation quantity is yet to reach the pre-drought level (Biasutti, 2019; Bichet & Diedhiou, 2018; Druyan, 2011; Nicholson et al., 2018; Panthou et al., 2018; Riede et al., 2016; Sanogo et al., 2015; Sylla et al., 2016b). The recovery is, however, characterized by new rainfall features including false start and early cessation of rainy seasons, increased frequency of rainy days along with increased precipitation intensity, more frequent dry spells, increasing number of hot nights and warm days and a decreasing trend in diurnal temperature range (Biasutti, 2019; Salack et al., 2016; Salack et al., 2015; Sanogo et al., 2015). Rather than a rainfall recovery, the Sahel is experiencing a new era of climate extremes (Biasutti, 2019; Panthou et al., 2018).

5.2 Drivers of vegetation cover dynamics

By combining coarse and moderate resolution NDVI time series, our findings illustrated the strong spatial heterogeneity in vegetation cover dynamics. Our results confirmed the overall greening trends observed in the region, particularly after the severe droughts of the 1970s and 80s, and extensively reported in the literature (Bégué et al., 2011; Brandt et al., 2014a; Brandt et al., 2014b; Dardel et al., 2014; Herrmann et al., 2005; Herrmann et al., 2014; Kaptué et al., 2015; Knauer et al., 2014; Mbow et al., 2015; Mbow et al., 2014; Olsson et al., 2005). However, the general greening trends must be nuanced. While post-droughts greening emerged, this trend was not homogenous or uniform and some areas experienced browning or degradation. Our findings highlighted the strong spatial variability in vegetation cover trends, corroborating previous findings that has suggested a nuanced interpretation of vegetation cover dynamics (Brandt et al., 2017b; Brandt et al., 2014b; Dardel et al., 2014; Kaptué et al., 2015). Both browning and greening was identified within the same area at both coarse and fine scale resolution. The observed spatio-temporal dynamics contrasts with the simplified labels of "greening" or "degradation" (Brandt et al., 2017b; Brandt et al., 2014b).

Possible drivers of vegetation cover dynamics includes climate variability and change, and agricultural intensification and expansion. Previous studies have shown that rainfall emerges as a dominant driver of vegetation dynamics in semiarid areas of West Africa, including in semiarid areas of Mali. Trends in vegetation have shown to be explained by changes in rainfall (Brandt et al., 2015; Brandt et al., 2017b; Herrmann et al., 2005; Leroux et al., 2017; Olsson et al., 2005; Zhang et al., 2018). Indeed, rainfall has emerged as a dominant causative factor for the positive NDVI trend (Brandt et al., 2015; Brandt et al., 2014b; Herrmann et al., 2005; Leroux et al., 2017; Olsson et al., 2005) and increases in woody vegetation (Anchang et al., 2019; Brandt et al., 2019; Brandt et al., 2017a). The positive NDVI (or greening) trends is reflected in vegetation impoverishment rather than improvement of vegetation conditions. Indeed, the greening trend in SARs of West Africa is reflected in increase in woody biomass, changes in vegetation composition and in reduction in woody species richness and diversity (Brandt et al., 2016; Brandt et al., 2019; Brandt et al., 2015; Brandt et al., 2017a; Brandt et al., 2014b; Hänke et al., 2016; Herrmann & Tappan, 2013; Spiekermann et al., 2015). This impoverishment of the vegetation is characterized by loss of large trees, an increasing dominance of shrubs and woody vegetation over herbaceous vegetation, and a shift towards more arid-tolerant species (Brandt et al., 2019; Brandt et al., 2015; Hänke et al., 2016; Herrmann et al., 2014; Herrmann & Tappan, 2013; Spiekermann et al., 2015).

However, rainfall is not the only causative factor explaining vegetation trends; other anthropogenic factors also play a role in vegetation trends (Brandt et al., 2014a; Herrmann & Tappan, 2013; Tong et al., 2017; West et al., 2017). For instance, cropland changes and expansion, land use transformation, migration and population density have been shown to explain greening trends (Bégué et al., 2011; Brandt et al., 2014a; Olsson et al., 2005; Spiekermann et al., 2015; Tong et al., 2017) and positive woody vegetation cover trends

(Brandt et al., 2016; Brandt et al., 2018). Therefore, explanations for trends cannot be generalized, but are rather heterogeneous and site-specific (Brandt et al., 2014a).

In the study region, cultivated areas has increased between 1994 and 2006 (Laris et al., 2015). Land use change analysis conducted in an area adjacent to Koutiala (our study site) has showed that agricultural land has expanded gradually together with intensification of land use from 1975 to 2010 (Laris et al., 2015). Cotton production has increased tremendously through varying periods of intensification and expansion of the cultivated areas (Benjaminsen, 2001; Benjaminsen et al., 2010; Laris et al., 2015). Cotton yields in the study region increased steadily during the early 1990s before beginning a gradual decline reflecting the national trend (Laris et al., 2015). Rapid expansion of cotton fields has occurred until the early 2000s, driven by attractive cotton prices in the 1990s (Benjaminsen et al., 2010; Laris et al., 2015). This has led to environmental transformation in the cotton zone, with bush and woodlands converted to agricultural parklands (Benjaminsen, 2001; Benjaminsen et al., 2010).

Key cereal crop (maize, sorghum, pearl millet and rice) production has also significantly increased in the study region (Kouressy et al., 2019; Laris et al., 2015). Maize yields and production, in particular, has steadily increased until present (Laris et al., 2015). A combination of factors including increased fertilizer usage and changes in agricultural technology such as new seed varieties, herbicides, and increased access to animal traction likely fuelled the long term rise in maize and other cereals crop production and yields in Mali (Laris & Foltz, 2014; Laris et al., 2015).

This illustrates that agricultural expansion and intensification has occurred simultaneously and in a complex manner (Laris et al., 2015). While the area in agriculture expanded slowly during the study period, the major agricultural change characterizing the period was a shift away from extensively farmed traditional grain crops, to one of intensive cotton and maize production (Laris et al., 2015).

Intensification of livestock production might also have played a role in vegetation cover trends. Indeed, a large fraction of rural households in the semiarid agro-ecological zones of West Africa rely on livestock as part of their livelihood strategies (Turner et al., 2014; Zougmoré et al., 2016). For both crop farmers and pastoralists, livestock serve as a productive asset to generate income, and form a key element in food security strategies in many countries of West Africa (Zougmoré et al., 2016). Following the 1970s severe droughts, there has been an intensification and expansion of livestock ownership across ethnicities and caste, due to lower production risk, compared to crop farming (i.e., livestock can be moved to where rainfall occurs) (Turner et al., 2014). High local spatiotemporal variability of rainfall and resulting vegetative growth has been one of the main drivers of livestock mobility and extensification of herding or extensification of local grazing management in the semiarid West Africa and (Turner & Hiernaux, 2008; Turner et al., 2014).

Future research avenues in analysing vegetation dynamics are related to how to document the underlying factors coherently (Leroux et al., 2017). Few studies have, however, attempted to link vegetation trends to causative factors, as it is usually done in land use and land cover change (LULCC) studies at finer resolution (Leroux et al., 2017). Local assessments at a higher spatial resolution are needed to verify the medium- to coarse-resolution results and investigate the reasons for greening or degradation as well as the interactions among drivers of trends (Knauer et al., 2014; Mbow et al., 2015).

An additional approach to disentangle the influence of non-climatic factors in NDVI trends might be the Residual Trend Analysis (RESTREND). RESTREND is based on the assumption that since biomass production is greatly controlled by inter-annual rainfall variability in semi-arid environments, the trends in NDVI contain a significant rainfall signal (Herrmann et al., 2005; Leroux et al., 2017). To separate rainfall-induced changes from changes induced by other drivers, the rainfall component must be removed from the NDVI trends (Leroux et al., 2017).

RESTREND is one of the most reliable trend analysis technique for disentangling the effects of climate from human-induced (Ibrahim et al., 2015).

5.3 Drivers of farmers' knowledge of climate change and its impacts

Our findings showed that respondents' social network characteristics were the main drivers of knowledge of climate change and its impacts. While CBOs membership improved farmer's knowledge and understanding of climate change, the diversity of CBOs membership affected negatively climate change knowledge and understanding. This implied that the characteristics of the group matter and that climate information and knowledge is not acquired through all types of CBOs. In addition to CBOs membership, the diversity of source of agricultural knowledge improve farmer's knowledge and understanding of climate change impacts on crop and livestock production. This indicated that farmers that belonged to a farmer's group or community-based organisation or that obtained or acquired agricultural knowledge and information from a wide range of source were more likely to have a better understanding and knowledge of climate change impacts on crop and livestock production.

These findings provide strong support to the social network theory-derived hypothesis of social network as driver of local ecological knowledge dynamics (Gaoue et al., 2017). Accordingly, the knowledge of an individual is influenced/shaped by the individual's position in their social network and the collective knowledge of that network; thus, individuals who are more connected will have greater knowledge (Gaoue et al., 2017).

However, contrary to expectations, the findings didn't support the hypothesis of socio-cultural and demographic traits (such as gender, age, religion, ethnicity, and education level) as drivers of local ecological knowledge (Gaoue et al., 2017; Segnon et al., 2015). Similarly to Segnon et al. (2015), the study did not find significant support for age-dependent agroecological knowledge. Our findings contrasted with a previous study by Sanogo et al. (2017), which reported age, education level, and gender as the main factors influencing farmers' perception of climate change in Koutiala. Discrepancies between our results and findings by Sanogo et al. (2017) could be explained by differences in study design and methodological approaches. First, farmers' perception of climate change was measured by Sanogo et al. (2017) as a series of categorical variables with three categories ("increase", "decrease" and "no change"). This approach failed to capture respondents' knowledge and perception of the seasonal, temporal and spatial heterogeneity in climate variables, especially rainfall patterns. Indeed, previous studies on farmers' perception in semiarid West African regions have shown that local people perception of change (either decrease or increase) in the amount of rainfall was inconsistent with observed meteorological data and it was their knowledge of changes and variability in distribution, frequency and intensity of rainfall patterns (Barbier et al., 2009; Kosmowski et al., 2016; Mertz et al., 2012; Ouédraogo et al., 2010; Tambo & Abdoulaye, 2013; Traore et al., 2015) that were consistent with the new era of climate extremes from observations (Biasutti, 2019; Kosmowski et al., 2016; Panthou et al., 2018). Therefore, assessing farmers' knowledge should not focus on whether total amount of rain increased or decreased but rather on changes and variability in rainfall patterns (distribution, intensity, frequency).

To address this gap, we adopted a different approach in designing our study: our study questionnaire was composed of a number of items and categorized into constructs. The items were identified from an extensive literature review on climate change and variability, climate change impacts on socioecological in semi-arid areas of West Africa (see Sections 2.1-2.3) and insights from the FGDs conducted in each village. Each item was presented as a statement, and participants were asked to indicate their level of agreement using a 5-point Likert scale, ranging from strongly disagree to strongly agree (Babbie, 2013; Segnon et al., 2015). By converting 5-point Likert scale into score (ranging from one to five), a quantitative variable of knowledge score can be obtained. Cronbach's α coefficient ranged from 0.70 to 0.87, indicating a good reliability of the multiple item constructs in our study questionnaire.

Second, Sanogo et al. (2017) performed a series of individual multinomial logit regressions to identify the main determinants of farmers' perception of climate change (a categorical variable with more than two categories). Our study used a structural equation modelling approach to simultaneously model multiple predictor and response variables in a single causal network (Lefcheck, 2016). Since farmers' perception variable was composed of scores obtained by converting 5-point Likert scale into score (ranging from one to five), we performed generalized linear regressions with Poisson error structure (Crawley, 2013), instead of multinomial logit regressions like Sanogo et al. (2017).

Third, our study sample size was more than twice as larger than in the study by Sanogo et al. (2017) (501 vs. 240 respondents); a large sample size allows to a minimize the sampling error and gives better statistical reliability for estimates. Fourth, Sanogo et al. (2017)'s individual comparable models R-squared ranged from 0.04 to 0.13, while our knowledge models R-squared were 0.19 and 0.23. This implied that our models explained more variation in farmers' knowledge and perception of climate change compared to Sanogo et al. (2017)'s models.

The inconsistencies of our findings with the hypothesis of socio-cultural and demographic traits as drivers of local ecological knowledge (Gaoue et al., 2017) could be explained by the fact the study focused only one socio-professional group (farmers) that was involved in climate-sensitive economic activities. Previous research in the region has shown that being involved in climate-sensitive economic activities (or not) also affects perception of climate change (Kosmowski et al., 2016), with smallholder farmers, pastoralists and sedentary agro-pastoralists having a higher level of awareness of rainfall changes than other inhabitants. Knowledge and perception of these groups were more consensual and more closely related to observed changes (Kosmowski et al., 2016). Thus, a heterogeneity could have observed in our findings if we have included other socio-professional groups.

The non-significant effects of socio-cultural and demographic attributes on climate change knowledge dynamics in the study area might also be explained by the awareness raising and capacity building efforts by both local and international NGOs and non-state actors, and Research for Development programmes and projects in the region following the 1970s and 1980s severe drought. Indeed, in addition to parents, social network and learning by doing, external actors such NGOs, Research for Development (R&D) projects or programmes, extension services and inputs suppliers were the key sources of agricultural knowledge mentioned by the respondents in the study area. Moreover, CBOs were also source of knowledge as most of the respondents belonged to at least one farmer- or community-based organisations. Actually, CBOs and diversity of source of agricultural knowledge the only factors that affected respondents' knowledge and perception of climate change and its impacts.

NGOs and other non-state actors have been very active in communities resilience building in the regions and increasingly acting as brokers, and sometimes producers, of climate services and dissemination of climate and weather information across scales in sub-Saharan Africa (Harvey et al., 2019). Currently, there is evidence of generalization of access and utilization of weather and climate information services for agricultural production and adaptation decision making in West Africa, especially by crop farmers (Carr & Onzere, 2018; Ouedraogo et al., 2018; Vaughan et al., 2019). For instance, weather and climate information services use in Koutiala is the highest (although declining) in Southern Mali (Carr & Onzere, 2018). This could have contributed to the homogenization of knowledge and perception of climate change and its impacts on crop and livestock production systems. Indeed, a review of literature supplemented by interviews with experts conducted by Singh et al. (2018) suggests that externally provided weather and climate information has an important role in building on local knowledge to shape understanding of climate risks and guide decision-making across scales.

While recognising that many factors can affect knowledge dynamics, future research investigating simultaneously how the characteristics of a social network and socio-cultural and demographic attributes affect the understanding and knowledge of climate change and its impacts can further the mechanistic understanding of climate change knowledge dynamics (Gaoue et al., 2017).

5.4 Heterogeneity in household vulnerability in semi-arid areas

Our findings highlighted the diversity of stressors or risks driving household vulnerability in the study area. While climatic stressor, namely drought, was the most mentioned stressors, there was a diversity of stressors that drove household vulnerability. Climatic stressors or risks were just one among many challenges. Indeed, a recent systematic review of climatic stressors in the semiarid Sahel has shown that while climatic drivers are dominant, there is however an increasing attribution to non-climatic stressors and drivers (Epule et al., 2018). Our findings emphasise the interconnections between climatic and non-climatic factors driving human vulnerability (Räsänen et al., 2016) and contributes to the increasing and growing 'multiple stressors' studies in sub-Saharan Africa (Nyantakyi-Frimpong & Bezner-Kerr, 2015; Räsänen et al., 2016; Tonmoy et al., 2014; Williams et al., 2018). Multiple non-climatic stressors operating at different scales drive vulnerability (Räsänen et al., 2016) and climate change is just one among many socio-ecological challenges facing smallholder farmers in semiarid regions (Jost et al., 2016; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Ouédraogo et al., 2016).

Drought was the most mentioned stressors in the study area, confirming previous studies which have reported drought as the most important climatic stressors in semiarid regions of West Africa (Epule et al., 2018; Gautier et al., 2016). The second most mentioned stressor was food insecurity. This is consistent with previous studies highlighting the association between food insecurity with high vulnerability in Africa (McDowell et al., 2016; Williams et al., 2018).

Indicator-based vulnerability assessments typically use aggregation methods to compute a composite index at community level (Hahn et al., 2009; Hinkel, 2011; Panthi et al., 2016; Simane et al., 2016; Tonmoy et al., 2014), failing to capture intra- or within community differential vulnerability. Here, we assessed vulnerability patterns at household level within community and constructed vulnerability archetypes. Our findings illustrated the heterogeneity in household vulnerability patterns within and across communities. Households are not uniform or homogeneous in terms of vulnerability to both climatic and non-climatic risks. It is worth noting that all the three vulnerability archetypes were represented in all the 10 study communities.

Our findings indicated that key determinants of household vulnerability patterns were socio-demographic status, livelihood strategies, household resources, food security, water security, social network, physical accessibility, and health and sanitation. Environmental and socio-economic shocks or stressors were not discriminant. This implied that household vulnerability patterns in the study area were mainly shaped by household adaptive capacity and sensitivity. The non-association between vulnerability clusters and stressors (both environmental and socio-economic stressors) implied that household exposure to stressors did not vary and was similar. These findings confirmed that differential vulnerability can be explain by not just by difference in exposure to climate-related and environmental hazards but largely by social and economic processes (Thomas et al., 2019). Following the four broad themes (resource access, governance, culture, and knowledge) identified by Thomas et al. (2019) as useful in explaining differential local-scale vulnerability, resource access and knowledge were key determinants of differential vulnerability patterns. Access to resources is one crucial factor that shapes people's ability to plan for and respond to climate change impacts (Thomas et al., 2019). Access to resources influences vulnerability by reducing or increasing exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). Social processes of marginalization and deprivation stemming from social stratification play key roles in creating patterns of unequal access to resources, which in turn drives differential sensitivity to climate impacts and capacity to respond (Thomas et al., 2019). Knowledge and information interact with vulnerability to climate change in various ways, directly and indirectly shaping peoples' adaptive capacity, exposure, and sensitivity (Thomas et al., 2019). Different types and sources of information and modes of knowledge transmission affect how people understand, perceive, and act on information (Thomas et al., 2019). While information is necessary, it is not alone sufficient for reducing vulnerability (Thomas et al., 2019).

In addition to resource access and knowledge, socio-demographic status, livelihood strategies, food security and water security, physical accessibility, and health and sanitation were also key determining factors of household vulnerability patterns in the study area. Household socio-demographic indicators such household size or number of productive household members (in this study) determined household ability to respond to various socioecological stressors or challenges such as labour availability, ability to produce enough food (in terms of diversity and quantity) to ensure food security, household members' sickness or death. In fact, family labour, especially child labour, is still playing an important role in West African farming systems, and elsewhere in Africa. Indeed, according to the 2016 Global Estimates of Child Labour, the agriculture sector accounts 85% of all child labour in Africa (ILO, 2017). For instance, one of the main drivers of farmers' decisions to adopt, as well as to intensify the use of soil and water conservation practices to adapt to climate change in semiarid dryland of West Africa are the presence of children in the household (Kpadonou et al., 2017). The numbers of household labour is one the key drivers of adoption of climate-smart technologies and practices in southern Mali (Ouédraogo et al., 2019). These highlight how crucial household size and labour is for household adaptive capacity in the region.

Previous research have shown that vulnerability in semi-arid regions of Africa is gendered differentiated (Rao et al., 2019). As female-headed households were rare in our study area context, our analysis was unable to reveal gender differentiated vulnerability patterns. A replication of our approach in a context where female-headed households are culturally accepted and common might provide a better insights regarding gender and vulnerability patterns.

Consistently with previous studies highlighting the association between food insecurity with high vulnerability in Africa (McDowell et al., 2016; Williams et al., 2018), our findings also showed that food insecurity was a key determinant of vulnerability patterns.

Our analysis highlighted the diversity in household vulnerability and the context-specific nature of driving forces of vulnerability in SARs of West Africa. Failing to account for this diversity and nuanced understanding in adaptation planning might result in a mismatch between adaptation needs and interventions and poor impacts of adaptation interventions.

5.5 Diversity in adaptation responses

To respond to climatic and non-climatic risks, local communities in the study area relied on a wide range strategies and practices at both individual and household levels. They also relied on a diversity of agrobiodiversity-based adaptation practices. These findings indicated that farmers in SARs relied on a portfolio of strategies to respond to risks/shocks and this is consistent with Modern Portfolio Theory for risks management (Markowitz, 1991, 2010; Paut et al., 2019). According to the Modern Portfolio Theory, asset diversification in a portfolio can reduce the global risk of the financial portfolio. Risk reduction based on asset diversification is a well-studied mechanism in economics and finance (Markowitz, 1991, 2010; Paut et al., 2019). Future research quantifying risk reduction potentials of adopting a diversity adaptation practices at different scales will provide better insights and understanding on the importance of diversity for risk reduction.

Our findings showed that adoption of agrobiodiversity-based adaptation practices affected household vulnerability. Our results indicated that in comparison to low vulnerability archetypes, households belonging to high or medium vulnerability archetypes were less likely to adopt a high number of agrobiodiversity-based adaptation practices. However, other factors also influenced household vulnerability patterns. The total number of adaptation practices adopted by household also affected household vulnerability patterns, with households belonging to high or medium vulnerability archetypes less likely to adopt a high number of adaptation practices in comparison to low vulnerability archetypes. Institutional factors such as access to extension services and to credit, training on agricultural practices also affected household vulnerability patterns.

These findings implied that the dichotomy agrobiodiversity-based (or ecosystem-based) vs. other adaptation practices/strategies in relation to vulnerability reduction might be misleading and not tell the full story on the ground. Our analysis rather indicated a complementarity between agrobiodiversity (ecosystem)-based and non-agrobiodiversity-based adaptation strategies in reducing household vulnerability. In fact, more than 94% of the respondents adopted at least one agrobiodiversity-based adaptation practices. Agrobiodiversity-based adaptation practices per household ranged from one to nine, with a median number of 7 (mean of 6.24 ± 1.73). One and three quarters of the households used less than or equal to five and eight agrobiodiversity-based adaptation practices, respectively (i.e., 25th percentile = 5 and 75th percentile = 8). Moreover, all respondents who adopted agrobiodiversity-based adaptation practices also relied on other adaptation practices. Our findings, therefore, suggest that adaptation should be conceptualised or promoted as part of a more holistic development approach or process which take into account climatic risks as well as development needs and aspiration to build sustainable and resilient livelihood systems.

Avenues for future research might aim to address synergies and trade-offs among multiple climate change adaptation strategies and practices at different scales, from plot to farming systems and household levels. Key questions are: what are the synergies and trade-offs among agrobiodiversity-based adaptation practices, and agrobiodiversity-based practices and other strategies? How to take stock on synergies and limit trade-offs to build resilience? Will adoption of a given practice result in adoption and benefits of another practices?

The very few research on joint adoption and synergies among adaptation practices in the semi-arid region provides a starting point to build on. The scanty available literature showed, for instance, that many soil and water conservation practices are interdependent either as complementary or substitutable (Kpadonou et al., 2017). Household members migration, as an adaptation strategy, intensified the use of soil and water conservation practices for climate change adaptation, but this happened only when it was in line with the household's land endowment and labour needs for farm activities (Kpadonou et al., 2017). It was shown that positive complementarity linkages exist between manure use and adoption of modern seeds, suggesting that organic fertilizer can serve as an enabling factor for greater adoption of modern seeds, especially in less favourable climate areas of West African drylands (Kpadonou et al., 2019). At plot level, combining soil and water conservation practices with (organic or chemical) fertilizer application can synergistically result in soil erosion reduction, cereal crop increase and substantial economic benefits in semiarid areas of West Africa (Zougmoré et al., 2011).

Advancing the understanding the synergies and trade-offs in adoption of agrobiodiversity-based adaptation practices (and more generally multiple climate-smart practices and strategies) can provide critical inputs and insights to inform policy decisions for building resilience and upscaling climate-resilient livelihood systems in semiarid areas of West Africa.

5.6 Drivers of adaptation practices and strategies

Our findings showed that gender, knowledge of climate change impacts rather than perception of changes in climate, and diversity of source of agricultural knowledge and social networks indicators such as CBOs membership and number of CBOs membership explained the diversity of adaptation responses. These findings indicated that demographic and socioeconomic factors which define *"who a respondent is"* (gender in this study), *"what he/she knows"* (knowledge of climate change impacts on livelihoods), and *"where his/her knowledge comes from"* (CBOs membership and number of CBOs membership) drive *"what he/she does"* (the diversity of adaptation strategies implemented/used).

Our findings are consistent with previous studies analysing factors affecting farmers' adaptation to climate change across different contexts and ecologies (Dang et al., 2019). Demographic and socioeconomic factors (such as age, gender, ethnicity, caste, education, household size, household income and assets) which represented the status and economic condition of farm households have been shown to have an important impact on farmers' adaptation (Dang et al., 2019, Harmer & Rahman, 2014; Ouédraogo et al., 2010; Ouédraogo et al., 2019; Ouédraogo et al., 2016; Thomas et al., 2019). This was also shown in this study, albeit not all household characteristics had statistically significant effects on adaptation. Farm household characteristics contribute to whether farmers are willing to and adjust their farming practices, or what adaptive measures they would probably undertake (Dang et al., 2019; Harmer & Rahman, 2014).

Our findings showed that gender was a key driver of adaptation, with women more likely to have a fewer number of adaptation practices. This corroborates previous findings that has demonstrated how adaptation is gender differentiated in farming context in rural areas (Carr & Onzere, 2018; Dang et al., 2019; Jost et al., 2016).

Current literature shows that women appear to be less adaptive compared to men (Carr & Onzere, 2018; Carr & Thompson, 2014; Gumucio et al., 2019; Jost et al., 2016). This can be explained by the gender-differentiated access to technological, natural and human resources prevalent in most agricultural communities across sub-Saharan Africa (Carr & Onzere, 2018; Carr & Thompson, 2014; Jost et al., 2016; Peterman et al., 2014). Indeed, we found in this study that women farmers were less likely to have an individual or personal land and tended to work on household land. In fact, because of customary tenure systems and religious barriers, very few women (about 3%) in agriculture in Mali hold land (Lastarria-Cornhiel et al., 2014). Across southern Mali (where we conducted this study), women's production is seen as secondary to men's role as subsistence providers, and therefore women generally cannot own land (Carr & Onzere, 2018). Women's insecure land tenure serves as a disincentive for planting long-term tree crops or undertaking other improvements to the land, and ultimately hinders planning for and implementation of adaptation actions (Carr & Onzere, 2018; Carr & Thompson, 2014).

There are also gender-based differences in access, use and benefits from climate services (Gumucio et al., 2019). Differential access to group processes and to Information and Communications Technologies can significantly limit women's access to weather and climate information (Gumucio et al., 2019). Moreover, socio-cultural norms that define women's and men's labour roles can also influence the resources and decisions under women's and men's control, affecting their differing climate information needs and demand (Gumucio et al., 2019).

These gendered access gaps, mediated through socio-cultural norms, are responsible for observed productivity differences, but also differential adaptive capacity between men and women (Carr & Onzere, 2018; Carr & Thompson, 2014; Jost et al., 2016; Kpéra et al., 2017; Peterman et al., 2014)

While cultural dimensions have been shown to influence farmers' adaptation (Adger et al., 2013; Dang et al., 2019; Nielsen & Reenberg, 2010; Thomas et al., 2019), our findings didn't find supports to cultural differentiated effects on adaptation strategies in the study area. However, we do acknowledge that culture informs perceptions of risk and, thus, affects the adaptive capacity of those exposed and help to explain differences in responses across populations to the same environmental risks (Adger et al., 2013; Thomas et al., 2019). Our findings could be explained by the low variation or diversity in sociocultural groups represented in our sample. In fact, our sample was composed of more than 87% of respondents from Minanka ethnic group, the native and dominant ethnic group in the study area. A replication of our analysis in an area with a more diverse ethnic composition might highlight (or not) the social differentiation of climate change adaptation.

Our findings, however, confirmed that social networking can increase the capacity to cope with a threat, as network members share access to information, transportation, or other resources (Thomas et al., 2019). Access to information through social networks was a key driver of adaptation, as it has already been shown in previous studies (Dang et al., 2019; Harmer & Rahman, 2014; Ouédraogo et al., 2010; Ouédraogo et al., 2016; Tambo & Abdoulaye, 2013; Thomas et al., 2019). Our analysis highlighted that the characteristics of social networks were important as belonging to more groups reduced the number adaptation practices or strategies adopted.

The extent to which farmers awareness of climate change is linked to adaptation action is still a debated issue in the literature (Harmer & Rahman, 2014; Mertz et al., 2010). In this study, we showed that farmers' knowledge of climate change impacts on crop and livestock production rather than their perception of changes in climate affected the diversity of climate change adaptation used by farmers. This finding is in line with previous studies indicating that farmers who had concerns about the impacts of climate change on agriculture had a more positive adaptation attitude (Dang et al., 2019; Ouédraogo et al., 2010). Contrary to previous research that has highlighted the role of farmers' climate risk perception on adaptation intention (Dang et al., 2014, 2019), we showed in this study that knowledge and understanding of climate change impacts affect actual adaptation practices not adaptation intention. This confirmed that local knowledge played an important part in adaptation decisions, though this contribution depended on interactions with other types of knowledge and institutions (Naess, 2013).

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study aimed to contribute to the growing and evolving knowledge on ecosystem-based adaptation using the lens of agrobiodiversity-based adaptation with a focus on semiarid areas of Mali, West Africa. Using vegetation/land cover and NDVI as a spatially-explicit proxy of biodiversity and ES (de Araujo Barbosa et al., 2015; Feng et al., 2010), the study assessed climate trends and vegetation dynamics at different scales from 1982 to 2015 in Koutiala, a semiarid area in Southwestern part of Mali, West Africa. It drawn from available knowledge in the study region to unpack the climatic and non-climatic driving forces of vegetation dynamics in semi-arid areas of Mali. Second, it assessed farmers' knowledge of climate change and its impacts on agroecosystems and analysed adaptation practices using an integrated and holistic framework. Third, the study documented agrobiodiversity-based adaptation practices and analysed how these practices influenced household vulnerability patterns.

The study showed that both minimum and maximum temperature have significantly increased over the study period, albeit with decadal and interannual variability. It is worth noting that minimum temperature has increased faster than maximum temperature in the study area, with a figure close to global temperature increase since pre-industrial period. The findings also demonstrated the strong interannual and spatial variability, rather than a clear significant change in total precipitation over the study period. By combining coarse and moderate resolution NDVI time series, our findings illustrated the strong spatial heterogeneity in vegetation cover dynamics. While greening trends was dominant, this trend must be nuanced as it was not homogenous or uniform and some areas experienced browning or degradation as well. Current knowledge and available literature indicated that climate variability and change has strongly impacted on vegetation dynamics in SARs of West Africa. In addition to climate, anthropogenic factors also drive vegetation dynamics in SARs of West Africa. In our study region, agricultural intensification and expansion and to some extent livestock production intensification were the key anthropogenic drivers of vegetation dynamics.

Our findings showed that respondents' social network characteristics such as CBOs membership, diversity of CBOs membership and diversity of source of agricultural knowledge were the main drivers of knowledge of climate change and its impacts. The findings revealed that the characteristics of the group matter and that climate information and knowledge is not acquired through all types of CBOs.

Our findings highlighted the diversity of environmental and socioeconomic stressors or risks driving household vulnerability in the study area. Climatic risks were just one among many challenges. Drought and food insecurity were the most mentioned stressors in the study area. Vulnerability patterns analysis indicated three vulnerability archetypes, which cut across all the study communities, illustrating the heterogeneity, within and across communities, in household vulnerability patterns to climatic and non-climatic risks.

Key determinants of household vulnerability patterns were socio-demographic status, livelihood strategies, household resources, food security, water security, social network, physical accessibility, and health and sanitation. Environmental and socio-economic shocks or stressors were not discriminant, implying that household vulnerability patterns in the study area were mainly shaped by household adaptive capacity and sensitivity and that household exposure to risks was similar. The non-association between vulnerability clusters and stressors (both environmental and socio-economic stressors) implied that household exposure to stressors did not vary and was similar.

To respond to climatic and non-climatic risks, local communities in the study area relied on a wide range strategies and practices, including a diversity of agrobiodiversity-based practices, at both individual and household levels. The study found that demographic and socioeconomic factors which define *"who a respondent is"* (gender in this study), *"what he/she knows"* (knowledge of climate change impacts on livelihoods rather that perception of change in climate), and *"where his/her knowledge comes from"* (CBOs membership and number of CBOs membership) drive *"what he/she does"* (the diversity of adaptation strategies implemented/used).

Our analysis indicated there was rather a complementarity between agrobiodiversity (ecosystem)-based and non-agrobiodiversity-based adaptation strategies in reducing household vulnerability. More than 94% of the respondents adopted at least one agrobiodiversity-based adaptation practices. Moreover, all respondents who adopted agrobiodiversity-based adaptation practices also relied on other adaptation practices. The study revealed that not only adoption of agrobiodiversity-based adaptation practices, but also the number of adaptation practices adopted by household affected household vulnerability patterns. Households in low vulnerability archetypes relied on a high number of agrobiodiversity-based adaptation practices and were more likely to have a higher number of total adaptation practices. In comparison to low vulnerability archetypes, households belonging to high or medium vulnerability archetypes were less likely to adopt a high number of agrobiodiversity-based adaptation practices and less likely to adopt a high number of adaptation practices. This implied a synergistic effect rather than mutually exclusive impacts on household vulnerability. In addition, institutional factors such as access to extension services and to credit, training on agricultural practices also influenced household vulnerability patterns.

6.2 Recommendations

Based on the findings, the study outlines the following implications and recommendations for both research and policy and practices.

To quantitatively disentangle the effects of both climatic and non-climatic factors on vegetation dynamics, a residual trend analysis might provide additional insights. As vegetation production is principally controlled by inter-annual rainfall variability in semi-arid ecosystems (Herrmann et al., 2005; Leroux et al., 2017), to separate rainfall-induced changes from changes induced by other factors, the rainfall component must be removed from the vegetation cover trends (Leroux et al., 2017). Local assessments at a higher spatial resolution are also needed to verify the medium- to coarse-resolution results and investigate the reasons of greening or degradation as well as the interactions among drivers of trends (Knauer et al., 2014; Mbow et al., 2015).

While recognising that many factors can affect knowledge dynamics, future research investigating simultaneously how the characteristics of a social network and socio-cultural and demographic attributes affect the understanding and knowledge of climate change and its impacts can further the mechanistic understanding of climate change knowledge dynamics (Gaoue et al., 2017).

Previous research have shown that vulnerability in SARs of Africa is gendered differentiated (Rao et al., 2019). As female-headed households were rare in our study area context, a replication of our approach in a context where female-headed households are culturally common might provide a better insights regarding gender and vulnerability patterns. In addition, as sociocultural group diversity was low in our study area and sample, a replication of our analysis in an area with a more diverse ethnic composition might highlight (or not) the social differentiation of climate change adaptation.

Our analysis highlighted the diversity in household vulnerability and the context-specific nature of driving forces of vulnerability. Failing to account for this diversity and nuanced understanding in adaptation planning might result in a mismatch between adaptation needs and interventions and poor impacts of adaptation interventions.

Dichotomy agrobiodiversity-based (or ecosystem-based) vs. other adaptation practices/strategies in relation to vulnerability reduction might be misleading and not tell the full story on the ground. There is a complementarity between agrobiodiversity (ecosystem)-based and non-agrobiodiversity-based adaptation strategies in reducing household vulnerability. Adaptation should be conceptualised or promoted as part of a more holistic development approach or process which take into account climatic risks as well as development needs and aspiration to build sustainable and resilient livelihood systems.

Future research quantifying risk reduction potentials of adopting a diversity adaptation practices at different scales will provide better insights and understanding on the importance of diversity for risk reduction. Avenues for future research might also aim to address synergies and trade-offs among multiple climate change adaptation strategies and practices at different scales, from plot to farming systems and household levels. Key questions are: what are the synergies and trade-offs among agrobiodiversity-based adaptation practices, and agrobiodiversity-based practices and other strategies? How to take stock on synergies and limit trade-offs to build resilience? Will adoption of a given practice result in adoption and benefits of another practices? Advancing the understanding the synergies and trade-offs in adoption of agrobiodiversity-based adaptation practices (and more generally multiple climate-smart practices and strategies) can provide critical inputs and insights to inform policy decisions for building resilience and upscaling climate-resilient livelihood systems in semiarid areas of West Africa.

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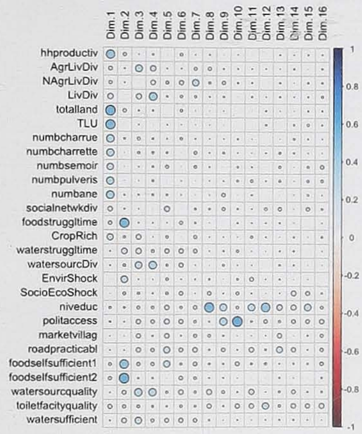
APPENDICES

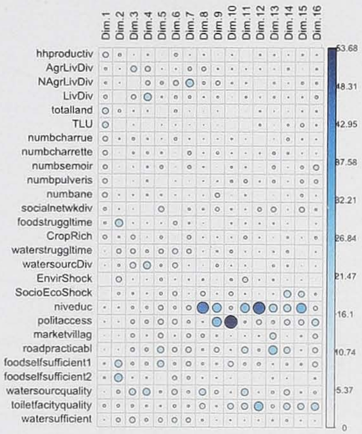
Appendix 1. Summary of the results of FAMD analysis in R software

```
Call:
FAMD(base = final_datachp4, nep = 16, sup.var = 28:35)


Eigenvalues
                 Dim.1 Dim.2 Dim.3 Dim.4 Dim.5 Dim.6 Dim.7 Dim.8 Dim.9 Dim.10
Dim.11
Variance          4.398 2.781 2.523 2.103 1.774 1.425 1.339 1.252 1.196 1.145 1.079
% of var.        12.217 7.724 7.008 5.842 4.928 3.957 3.719 3.478 3.322 3.181 2.997
Cumulative % of var. 12.217 19.941 26.949 32.791 37.719 41.676 45.395 48.873 52.195
55.376 58.373
                 Dim.12 Dim.13 Dim.14 Dim.15 Dim.16
Variance          1.016 0.980 0.958 0.917 0.894
% of var.         2.822 2.723 2.661 2.548 2.484
Cumulative % of var. 61.195 63.918 66.578 69.127 71.611

Individuals (the 10 first)
                  Dist   Dim.1   ctr  cos2   Dim.2   ctr  cos2   Dim.3   ctr  cos2
1               |  5.716 |  0.306 0.004 0.003 |  1.793 0.231 0.098 | -0.539 0.023 0.009 |
2               |  7.100 |  1.466 0.098 0.043 |  0.641 0.030 0.008 | -2.785 0.614 0.154 |
3               |  4.642 | -0.222 0.002 0.002 |  0.881 0.056 0.036 |  0.891 0.063 0.037 |
4               |  6.865 | -0.219 0.002 0.001 | -1.144 0.094 0.028 | -0.017 0.000 0.000 |
5               |  5.072 | -1.575 0.113 0.096 | -0.713 0.036 0.020 | -1.384 0.152 0.075 |
6               | 11.274 | -2.477 0.278 0.048 |  0.760 0.041 0.005 | -1.679 0.223 0.022 |
7               |  6.144 | -2.023 0.186 0.108 | -0.378 0.010 0.004 | -0.741 0.043 0.015 |
8               |  8.882 |  4.796 1.044 0.292 | -1.214 0.106 0.019 | -1.229 0.119 0.019 |
9               |  6.677 |  1.383 0.087 0.043 | -3.460 0.859 0.269 |  0.149 0.002 0.000 |
10              |  3.584 | -0.745 0.025 0.043 | -0.411 0.012 0.013 |  0.138 0.002 0.001 |

Continuous variables (the 10 first)
                 Dim.1   ctr   cos2   Dim.2   ctr  cos2    Dim.3    ctr  cos2
hhproductiv     |  0.669 10.180 0.448 |  0.271 2.634 0.073 | -0.046  0.085 0.002 |
AgrLivDiv       |  0.314  2.238 0.098 | -0.077 0.212 0.006 |  0.549 11.944 0.301 |
NAgrLivDiv      |  0.267  1.626 0.071 |  0.076 0.208 0.006 | -0.004  0.001 0.000 |
LivDiv          |  0.441  4.425 0.195 | -0.006 0.001 0.000 |  0.431  7.377 0.186 |
totalland       |  0.759 13.101 0.576 |  0.271 2.639 0.073 | -0.101  0.408 0.010 |
TLU             |  0.739 12.415 0.546 | -0.009 0.003 0.000 | -0.062  0.151 0.004 |
numbcharrue     |  0.606  8.338 0.367 |  0.147 0.780 0.022 | -0.244  2.370 0.060 |
numbcharrette   |  0.585  7.788 0.343 | -0.026 0.025 0.001 | -0.194  1.492 0.038 |
numbsemoir      |  0.518  6.105 0.268 | -0.026 0.025 0.001 | -0.064  0.161 0.004 |
numbpulveris    |  0.579  7.609 0.335 |  0.018 0.012 0.000 |  0.042  0.068 0.002 |

Supplementary continuous variables
                 Dim.1  cos2   Dim.2  cos2   Dim.3  cos2
dependratio     | -0.130 0.017 | -0.041 0.002 | -0.049 0.002 |
```

```
DivLivstock       | 0.513  0.263 | -0.001  0.000 | 0.111  0.012 |
numboxen          | 0.728  0.529 | 0.006  0.000 | -0.124  0.015 |
healthfacilitytime | -0.098  0.010 | 0.109  0.012 | 0.046  0.002 |
healthcasenumb    | 0.195  0.038 | 0.030  0.001 | -0.184  0.034 |
TotalChronic      | 0.092  0.008 | 0.112  0.013 | -0.083  0.007 |

Categories (the 10 first)
                Dim.1   ctr   cos2 v.test   Dim.2   ctr   cos2 v.test   Dim.3   ctr   cos2
Coranic         | -0.291  0.048  0.010 -1.088 | -0.656  0.611  0.049 -3.090 | -0.573  0.567
0.037
Literacy        | 0.496  0.368  0.089  3.373 | 0.029  0.003  0.000  0.246 | -0.030  0.004  0.000
NoEducation      | -0.421  0.313  0.080 -3.230 | 0.126  0.070  0.007  1.219 | 0.459  1.129
0.095
Primary         | 0.031  0.001  0.000  0.170 | 0.088  0.021  0.002  0.606 | -0.427  0.600
0.043
Secondary        | 0.513  0.068  0.013  1.254 | 0.044  0.001  0.000  0.135 | 0.090  0.006
0.000
Easy            | -0.041  0.005  0.002 -0.560 | 0.039  0.012  0.002  0.659 | -0.310  0.937  0.134
FairlyEasy       | -0.986  0.180  0.033 -2.029 | -0.197  0.018  0.001 -0.509 | -1.185  0.792
0.048
NotEasy          | -1.102  0.063  0.011 -1.179 | 0.943  0.115  0.008  1.269 | -1.880  0.554
0.032
VeryEasy         | 0.215  0.080  0.019  1.625 | -0.078  0.027  0.002 -0.745 | 0.756  3.009
0.233
Mrkt            | -0.077  0.019  0.007 -1.012 | -0.050  0.019  0.003 -0.816 | -0.450  1.915  0.245
              v.test
Coranic         -2.833 |
Literacy        -0.270 |
NoEducation      4.650 |
Primary         -3.094 |
Secondary        0.289 |
Easy            -5.568 |
FairlyEasy      -3.220 |
NotEasy         -2.658 |
VeryEasy         7.557 |
Mrkt            -7.779 |

Supplementary categories
                 Dist   Dim.1   cos2 v.test   Dim.2   cos2 v.test   Dim.3   cos2 v.test
Health_F         | 0.381 | -0.001  0.000 -0.031 | -0.076  0.040 -2.048 | -0.131  0.119 -3.728 |
N_Health_F        | 1.545 | 0.006  0.000  0.031 | 0.308  0.040  2.048 | 0.534  0.119  3.728 |
Mbership         | 0.211 | 0.152  0.521  6.551 | 0.040  0.036  2.154 | 0.022  0.011  1.266 |
N_Mbership        | 3.434 | -2.479  0.521 -6.551 | -0.648  0.036 -2.154 | -0.363  0.011 -1.266 |
```

Appendix 2. Correlation and contribution of initial variables with principal components





Appendix 3. Description of the vulnerability clusters by the indicator variables

```
Link between the cluster variable and the categorical variables (chi-square test)
=================================================================================
                          p.value  df
watersourcquality    5.238863e-82  4
toiletfacityquality  2.725583e-07  4
foodselfsufficient1  1.935302e-06  4
foodselfsufficient2  4.572843e-05  2
niveduc              1.431163e-04  8
watersufficient      7.985113e-04  2
roadpracticabl       1.496629e-02  4
membership           4.134056e-02  2

Description of each cluster by the categories
=============================================
$`1`
                                   Cla/Mod   Mod/Cla    Global      p.value     v.test
watersourcquality=N_Improv_WS     78.26087 74.654378 41.317365 6.969882e-42  13.559405
watersourcquality=Improv_WS       77.46479 25.345622 14.171657 3.481907e-10   6.275644
politaccess=FairlyEasy            77.77778  6.451613  3.592814 3.236991e-03   2.944288
roadpracticabl=NotPracti          66.66667 10.138249  6.586826 5.940894e-03   2.751026
foodselfsufficient1=Own_BuyHigh   28.07018  7.373272 11.377246 1.303900e-02  -2.482702
watersourcquality=Both_WS          0.00000  0.000000 44.510978 7.391475e-86 -19.637524

$`2`
                                   Cla/Mod   Mod/Cla    Global      p.value     v.test
watersourcquality=Both_WS        78.026906 98.863636 44.510978 5.952462e-86  19.648519
niveduc=NoEducation              49.707602 48.295455 34.131737 1.176727e-06   4.859517
foodselfsufficient1=Own_BuyHigh  57.894737 18.750000 11.377246 2.150379e-04   3.700662
watersufficient=W_Selfsuf        44.339623 53.409091 42.315369 2.374345e-04   3.675446
foodselfsufficient2=N_F_Selfsuf  39.669421 81.818182 72.455090 4.603838e-04   3.502806
```

```
toiletfacityquality=N_Improv_TF 40.131579 69.318182 60.678643 3.486445e-03   2.921237
roadpracticabl=YearRound       38.529412 74.431818 67.864271 2.013109e-02   2.323896
marketvillag=N_Mrkt           41.000000 46.590909 39.920160 2.586534e-02   2.228228
niveduc=Literacy             28.275862 23.295455 28.942116 3.973454e-02  -2.056498
marketvillag=Mrkt             31.229236 53.409091 60.079840 2.586534e-02  -2.228228
roadpracticabl=NotPracti       12.121212  2.272727  6.586826 2.661972e-03  -3.004295
niveduc=Primary              22.857143 13.636364 20.958084 2.597224e-03  -3.011778
foodselfsufficient2=F_Selfsuf   23.188406 18.181818 27.544910 4.603838e-04  -3.502806
toiletfacityquality=Both_TF     11.363636  2.840909  8.782435 2.486735e-04  -3.663622
watersufficient=N_W_Selfsuf     28.373702 46.590909 57.684631 2.374345e-04  -3.675446
foodselfsufficient1=OwnProd     18.897638 13.636364 25.349301 5.151385e-06  -4.558526
watersourcquality=Improv_WS      2.816901  1.136364 14.171657 2.704147e-12  -6.992301
watersourcquality=N_Improv_WS    0.000000  0.000000 41.317365 1.146941e-55 -15.717538

$`3`
                                 Cla/Mod    Mod/Cla    Global      p.value     v.test
toiletfacityquality=Both_TF     47.727273 19.4444444  8.782435 5.634366e-05  4.027623
foodselfsufficient2=F_Selfsuf   33.333333 42.5925926 27.544910 1.339787e-04  3.819028
foodselfsufficient1=OwnProd     32.283465 37.9629630 25.349301 1.012874e-03  3.286926
membership=Mbership            22.669492 99.0740741 94.211577 7.336781e-03  2.681158
toiletfacityquality=Improv_TF   28.758170 40.7407407 30.538922 1.098889e-02  2.543052
niveduc=Literacy               28.275862 37.9629630 28.942116 2.235560e-02  2.284271
watersufficient=N_W_Selfsuf     24.913495 66.6666667 57.684631 3.271347e-02  2.135582
foodselfsufficient1=Own_BuyLow  18.611987 54.6296296 63.273453 3.789344e-02 -2.076006
watersufficient=W_Selfsuf       16.981132 33.3333333 42.315369 3.271347e-02 -2.135582
membership=N_Mbership            3.448276  0.9259259  5.788423 7.336781e-03 -2.681158
niveduc=NoEducation            12.865497 20.3703704 34.131737 4.944015e-04 -3.483771
foodselfsufficient2=N_F_Selfsuf 17.079890 57.4074074 72.455090 1.339787e-04 -3.819028
toiletfacityquality=N_Improv_TF 14.144737 39.8148148 60.678643 7.998195e-07 -4.935411
```

Link between the cluster variable and the quantitative variables

```
===============================================================================
                        Eta2      P-value
watersourcDiv    0.63752689 1.818332e-110
totalland        0.40496098 7.274705e-57
TLU              0.38349002 4.955508e-53
numboxen         0.34612043 1.145368e-46
hhproductiv      0.30217328 1.239229e-39
numbane          0.26980410 9.917634e-35
numbcharrette    0.24987922 8.084782e-32
numbcharrue      0.24520259 3.799875e-31
numbpulveris     0.18723985 3.807485e-23
numbsemoir       0.16395020 4.323198e-20
CropRich         0.12968294 9.543269e-16
DivLivstock      0.07886987 1.305948e-09
LivDiv           0.06187140 1.239744e-07
socialnetwkdiv   0.05679667 4.750358e-07
NAgrLivDiv       0.05255204 1.453069e-06
foodstruggltime  0.05211807 1.628573e-06
healthcasenumb   0.03337155 2.136161e-04
healthfacilitytime 0.01872638 9.031108e-03
AgrLivDiv        0.01504871 2.292312e-02

Description of each cluster by quantitative variables
=================================================================
$`1`
                      v.test Mean in category Overall mean sd in category Overall sd      p.value
healthfacilitytime -2.003365       13.2718894   14.6067864     11.4704506 13.0239712 4.513815e-02
AgrLivDiv          -2.055814        1.9078341    1.9860279      0.7124847  0.7434373 3.980040e-02
LivDiv             -2.268028        2.6774194    2.7864271      0.8835917  0.9394309 2.332750e-02
DivLivstock        -2.666003        3.0276498    3.2175649      1.4333649  1.3923697 7.675902e-03
socialnetwkdiv     -2.901730        1.1059908    1.1896208      0.4921607  0.5633271 3.711078e-03
numbsemoir         -4.520093        0.4700461    0.6007984      0.5172388  0.5654025 6.181248e-06
```

```
numbcharrue        -4.768203     1.8571429  2.2115768    1.0745730  1.4529019 1.858760e-06
numbcharrette      -4.787198     1.0368664  1.2015968    0.3573138  0.6725866 1.691260e-06
numbane            -5.113768     1.2165899  1.4750499    0.6252014  0.9878889 3.157953e-07
TLU                -5.572413     4.3800000  6.3196407    4.1784056  6.8035201 2.512345e-08
numboxen           -5.731368     2.2857143  2.7944112    1.2522527  1.7348284 9.962405e-09
numbpulveris       -5.854299     0.5207373  0.7245509    0.5521499  0.6804777 4.790270e-09
hhproductiv        -6.383655     6.8847926  9.0139721    3.5819053  6.5192640 1.729106e-10
CropRich           -6.404777     9.2211982 10.4151697    2.9287881  3.6437256 1.505895e-10
totalland          -6.964318     9.4019355 11.5529641    3.6573401  6.0370290 3.299973e-12
watersourcDiv     -16.486211     1.0368664  1.5209581    0.1884336  0.5739347 4.609665e-61

$`2`
                     v.test Mean in category Overall mean sd in category Overall sd      p.value
watersourcDiv      15.852147     2.0738636  1.5209581    0.2615488  0.5739347 1.358582e-56
foodstruggltime     4.222974     2.3920455  1.9700599    1.7088487  1.6442915 2.410991e-05
healthfacilitytime  3.059586    17.0284091 14.6067864   14.7742209 13.0239712 2.216430e-03
numbpulveris       -2.132513     0.6363636  0.7245509    0.6602654  0.6804777 3.296473e-02
LivDiv             -2.429466     2.6477273  2.7864271    0.8665471  0.9394309 1.512107e-02
DivLivstock        -2.638336     2.9943182  3.2175649    1.4713057  1.3923697 8.331398e-03
numbsemoir         -3.098924     0.4943182  0.6007984    0.5112058  0.5654025 1.942251e-03
NAgrLivDiv         -3.293528     0.6647727  0.8003992    0.6361353  0.6776146 9.893842e-04
healthcasenumb     -3.902190     1.4488636  1.9900200    1.7573543  2.2819915 9.532643e-05
hhproductiv        -3.936099     7.4545455  9.0139721    4.2182210  6.5192640 8.281678e-05
numbcharrue        -4.584157     1.8068182  2.2115768    1.0751105  1.4529019 4.558207e-06
numbcharrette      -4.654121     1.0113636  1.2015968    0.3533707  0.6725866 3.253651e-06
numbane            -4.695020     1.1931818  1.4750499    0.8306344  0.9878889 2.665803e-06
totalland          -5.020948     9.7108807 11.5529641    4.4925443  6.0370290 5.141720e-07
numboxen           -5.379380     2.2272727  2.7944112    1.3545149  1.7348284 7.474274e-08
TLU                -6.121240     3.7887500  6.3196407    3.7486740  6.8035201 9.285018e-10
```

```
$`3`
                  v.test Mean in category Overall mean sd in category Overall sd      p.value
totalland      14.220636       18.8768519   11.5529641      6.3902250  6.0370290 6.822979e-46
TLU            13.820729       14.3412963    6.3196407      8.6255112  6.8035201 1.911251e-43
numboxen       13.151051        4.7407407    2.7944112      1.7286816  1.7348284 1.678248e-39
hhproductiv    12.261560       15.8333333    9.0139721      9.0997558  6.5192640 1.456678e-34
numbane        11.612390        2.4537037    1.4750499      1.1815265  0.9878889 3.565102e-31
numbcharrette  11.171400        1.8425926    1.2015968      1.0555149  0.6725866 5.628692e-29
numbcharrue    11.067291        3.5833333    2.2115768      1.7853571  1.4529019 1.807825e-28
numbpulveris    9.529935        1.2777778    0.7245509      0.6502611  0.6804777 1.573811e-21
numbsemoir      9.044134        1.0370370    0.6007984      0.5257433  0.5654025 1.508560e-19
CropRich        7.272918       12.6759259   10.4151697      3.5481573  3.6437256 3.518040e-13
DivLivstock     6.275297        3.9629630    3.2175649      0.7926272  1.3923697 3.489668e-10
LivDiv          5.553270        3.2314815    2.7864271      1.0238497  0.9394309 2.803739e-08
socialnetwkdiv  5.302489        1.4444444    1.1896208      0.5983516  0.5633271 1.142343e-07
NAgrLivDiv      4.894442        1.0833333    0.8003992      0.7216878  0.6776146 9.858494e-07
healthcasenumb  2.619629        2.5000000    1.9900200      2.7971546  2.2819915 8.802552e-03
AgrLivDiv       2.556192        2.1481481    1.9860279      0.8029438  0.7434373 1.058248e-02
TotalChronic    2.019606        0.4907407    0.3712575      0.8107538  0.6934914 4.342432e-02
foodstruggltime -4.275119       1.3703704    1.9700599      1.4375429  1.6442915 1.910348e-05
```

Appendix 4. Descriptive statistics of vulnerability indicators

Dimensions	Components	Indicators	Percentage (%)	Mean (Stand. dev.)	Median (min-max)
Adaptive capacity	Socio-demographic status	Gender of HH head			
		Male	98.40		
		Female	1.60		
		Age of HH head		48.33 (12.28)	48 (19 – 84)
		Ethnic groups			
		Minianka	86.62		
		Peulh	4.19		
		Others	6.19		
		Education			
		None	34.13		
		Islamic/Koranic	10.98		
		Literacy	28.94		
		Primary	20.96		
		Secondary	4.99		
		Religion			
		Muslim	95.80		
		Traditional	3		
		Christian	1.2		
		Household productive members		9.01 (6.52)	7 (1 – 58)
		Dependency ratio (suppl.)		1.42 (0.79)	1.25 (0.167 – 6.5)
	Livelihood strategies	Agricultural livelihood diversity		1.99 (0.74)	2 (1 – 4)
		Non-agricultural livelihood diversity		0.80 (0.68)	1 (0 – 3)
		Livelihood diversity		2.79 (0.94)	3 (1 – 6)
	Resources	Agricultural land		11.55 (6.04)	10.27 (1 – 41.80)
		Livestock (TLU)		6.32 (6.80)	4.20 (0 – 54.70)
		Diversity of livestock type		3.22 (1.39)	4 (0 – 5)
		Number of plough		2.21 (1.45)	2 (0 – 9)
		Number of draught animal		2.79 (1.73)	2 (0 – 12)
		Number of donkey		1.48 (0.99)	1 (0 – 6)

		Number of cart		1.20 (0.67)	1 (0 – 8)
		Number of pesticide sprayer		0.72 (0.68)	1 (0 – 3)
		Number of seed drill		0.60 (0.57)	1 (0 – 2)
	Social networks	CBOs membership			
		Yes	94.21		
		No	5.79		
		Diversity of CBOs membership		1.19 (0.56)	1 (0 – 4)
		Political access			
		Very easy	33.53		
		Easy	61.88		
		Fairly easy	3.59		
		Not easy	1.00		
	Physical accessibility	Market			
		Available in the village	60.08		
		No market	39.92		
		Road practicability			
		Not practicable year round	6.59		
		Practicable year round	67.86		
		Fairly practicable	25.55		
Sensitivity	Food security	Source of household food			
		Own + Buying High	11.38		
		Own Production	25.35		
		Own + Buying Low	63.27		
		Food self-sufficiency			
		Not food self-sufficient	72.46		
		Food self-sufficient	27.54		
		Number of month with insufficient food		1.97 (1.64)	2 (0 – 8)
		Crop diversity		10.42 (3.64)	10 (2 – 22)
	Health & Sanitation	Drinking water quality			
		Improved	14.17		
		Not Improved	41.32		
		Both	44.51		

		Toilet facility quality			
		Not Improved	60.68		
		Improved	30.54		
		Both	8.78		
		Illness (Health case number)		1.99 (2.28)	1 (0 – 15)
		Household member with chronic illness		0.37 (0.69)	0 (0 – 6)
		Average time to closest health facility		14.61 (13.02)	10 (1 – 60)
		Availability of health facility in the village			
		Yes	80.24		
		No	19.76		
	Water security	Diversity of water source		1.52 (0.57)	1 (1 – 3)
		Water sufficiency			
		Water sufficient	42.32		
		Not water sufficient	57.68		
		Number of month with insufficient water		1.67 (1.80)	1 (0 – 9)
Exposure	Environmental shocks	Environmental shocks experienced over the past 12months		1.92 (0.83)	2 (0 – 5)
	Socio-economic shocks	Socio-economic shocks experienced over the past 12months		0.81 (0.93)	1 (0 – 5)

Appendix 5. Outcome of the Structural Equation Model in R software

```
Structural Equation Model of sem.final5

Call:
  KCC ~ Gender + Age + Ethnicgroup + OriginMigration + Experience + Membership +
NumMembership + AccessExtens + Trainingspeficagric + Divtecagricsourc
  KCCI ~ Gender + Age + Ethnicgroup + OriginMigration + Experience + Membership +
NumMembership + AccessExtens + Trainingspeficagric + Divtecagricsourc + totlandsiz2 +
landind
  Age ~~ Experience
  Age ~~ NumMembership
  Experience ~~ NumMembership
  Age ~~ Divtecagricsourc
  Experience ~~ Divtecagricsourc
  KCC ~~ KCCI
  AccessExtens ~ Gender + Age + Experience + Membership + NumMembership +
Divtecagricsourc + Ethnicgroup + OriginMigration + Trainingspeficagric + totlandsiz2 +
landind
  landind ~ Gender + Age + Experience + totlandsiz2 + OriginMigration
  adaptivtotal ~ KCC + KCCI + Gender + Age + Ethnicgroup + OriginMigration +
Experience + Membership + NumMembership + AccessExtens + Trainingspeficagric +
Divtecagricsourc + totlandsiz2 + landind

    AIC      BIC
 127.579  367.926

---
Tests of directed separation:

                        Independ.Claim Estimate Std.Error  DF Crit.Value P.Value
        landind ~  Ethnicgroup + ...  -0.3976    0.3666 494    -1.0844  0.2782
         landind ~  Membership + ...   0.2360    0.3346 494     0.7053  0.4806
      landind ~  NumMembership + ...   0.1366    0.1868 494     0.7312  0.4647
  landind ~  Trainingspeficagric + ... -0.4651    0.3437 494    -1.3534  0.1759
     landind ~  Divtecagricsourc + ...  0.1110    0.0943 494     1.1770  0.2392
             KCC  ~  totlandsiz2 + ...  -0.0004    0.0007 489    -0.5813  0.5610
                 KCC  ~  landind + ...   0.0038    0.0128 488     0.2961  0.7672

Global goodness-of-fit:

  Fisher's C = 13.579 with P-value = 0.481 and on 14 degrees of freedom

---
Coefficients:

     Response          Predictor Estimate Std.Error  DF Crit.Value P.Value Std.Estimate
         KCC             Gender  -0.0134    0.0154 490    -0.8713  0.3836          NA
         KCC                Age   0.0002    0.0008 490     0.2313  0.8171          NA
         KCC        Ethnicgroup  -0.0005    0.0146 490    -0.0368  0.9707          NA
```

```
        KCC    OriginMigration -0.0074   0.0128 490    -0.5776  0.5635          NA
        KCC       Experience  0.0003   0.0008 490     0.3770  0.7062          NA
        KCC       Membership  0.0597   0.0177 490     3.3724  0.0007          NA ***
        KCC     NumMembership -0.0220   0.0097 490    -2.2650  0.0235          NA  *
        KCC      AccessExtens  0.0066   0.0131 490     0.5055  0.6132          NA
        KCC Trainingspeficagric -0.0079   0.0137 490    -0.5814  0.5609          NA
        KCC   Divtecagricsourc -0.0037   0.0037 490    -0.9912  0.3216          NA
       KCCI           Gender -0.0135   0.0232 488   -0.5814  0.5610          NA
       KCCI              Age -0.0001   0.0011 488   -0.1259  0.8998          NA
       KCCI       Ethnicgroup  0.0029   0.0194 488    0.1496  0.8811          NA
       KCCI    OriginMigration -0.0167   0.0170 488    -0.9804  0.3269          NA
       KCCI        Experience  0.0000   0.0011 488   -0.0198  0.9842          NA
       KCCI        Membership  0.0724   0.0235 488    3.0864  0.0020          NA **
       KCCI     NumMembership -0.0156   0.0128 488    -1.2189  0.2229          NA
       KCCI       AccessExtens  0.0025   0.0174 488    0.1421  0.8870          NA
       KCCI Trainingspeficagric -0.0115   0.0182 488    -0.6322  0.5272          NA
       KCCI   Divtecagricsourc  0.0138   0.0049 488    2.8021  0.0051          NA **
       KCCI       totlandsiz2  0.0008   0.0010 488    0.8682  0.3853          NA
       KCCI          landind  0.0149   0.0170 488    0.8733  0.3825          NA
      ~~Age      ~~Experience  0.8638       NA 499   38.2917  0.0000      0.8638 ***
      ~~Age    ~~NumMembership  0.1879       NA 499    4.2732  0.0000      0.1879 ***
~~Experience    ~~NumMembership  0.2123       NA 499    4.8528  0.0000      0.2123***
      ~~Age ~~Divtecagricsourc  0.2802       NA 499    6.5208  0.0000      0.2802 ***
~~Experience ~~Divtecagricsourc  0.2370       NA 499    5.4499  0.0000      0.2370 ***
      ~~KCC           ~~KCCI  0.3369       NA 501    7.9855  0.0000      0.3369 ***
AccessExtens           Gender  0.5936   0.4582 489    1.2957  0.1951      0.1178
AccessExtens              Age  0.0107   0.0230 489    0.4663  0.6410      0.0491
AccessExtens       Experience  0.0071   0.0220 489    0.3211  0.7481      0.0337
AccessExtens       Membership  3.0945   0.4905 489    6.3094  0.0000      0.5884 ***
AccessExtens     NumMembership -1.9131   0.2898 489   -6.6024  0.0000     -0.6646***
AccessExtens  Divtecagricsourc  0.4704   0.0932 489    5.0481  0.0000      0.2629 ***
AccessExtens       Ethnicgroup -0.0939   0.3838 489   -0.2447  0.8067     -0.0124
AccessExtens    OriginMigration -0.2987   0.3578 489   -0.8347  0.4039     -0.0491
AccessExtens Trainingspeficagric  2.0880   0.3328 489    6.2737  0.0000      0.3632 ***
AccessExtens       totlandsiz2  0.0201   0.0184 489    1.0872  0.2770      0.0554
AccessExtens          landind  0.0462   0.3677 489    0.1256  0.9001      0.0091
    landind           Gender -3.4445   0.3196 495  -10.7770  0.0000     -0.6761 ***
    landind              Age  0.0505   0.0210 495    2.3999  0.0164      0.2290  *
    landind       Experience -0.0227   0.0207 495   -1.0992  0.2717     -0.1071
    landind       totlandsiz2  0.0899   0.0184 495    4.8896  0.0000      0.2458 ***
    landind    OriginMigration -0.6798   0.3065 495   -2.2179  0.0266     -0.1105  *
adaptivtotal              KCC -0.0032   0.0042 486   -0.7737  0.4391          NA
adaptivtotal             KCCI -0.0118   0.0052 486   -2.2778  0.0227          NA  *
adaptivtotal           Gender  0.1188   0.0594 486    1.9997  0.0455          NA  *
adaptivtotal              Age  0.0014   0.0029 486    0.4743  0.6353          NA
adaptivtotal       Ethnicgroup  0.0651   0.0497 486    1.3106  0.1900          NA
adaptivtotal    OriginMigration  0.0078   0.0453 486    0.1719  0.8635          NA
adaptivtotal       Experience  0.0039   0.0028 486    1.3916  0.1640          NA
adaptivtotal       Membership  0.1610   0.0646 486    2.4921  0.0127          NA  *
adaptivtotal     NumMembership -0.0826   0.0322 486   -2.5641  0.0103          NA  *
```

```
adaptivtotal      AccessExtens  0.0472   0.0425 486    1.1110  0.2666        NA
adaptivtotal Trainingspeficagric  0.0336   0.0434 486    0.7737  0.4391        NA
adaptivtotal  Divtecagricsourc  0.0696   0.0125 486    5.5517  0.0000        NA ***
adaptivtotal       totlandsiz2  -0.0030   0.0025 486   -1.2162  0.2239        NA
adaptivtotal            landind  -0.0461   0.0436 486   -1.0579  0.2901        NA

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05

Individual R-squared:

    Response     method R.squared
         KCC nagelkerke      0.19
        KCCI nagelkerke      0.23
AccessExtens nagelkerke      0.47
     landind nagelkerke      0.52
adaptivtotal nagelkerke      0.42
```