

BEYOND ADAPTATION:
EXPLORING TRANSFORMATIVE PATHWAYS TO SOCIO-ECOLOGICAL
RESILIENCE IN AGRICULTURAL SYSTEMS IN MALI

By

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ABSTRACT

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Between the 1960s and 1980s, a series of abrupt, ‘unprecedented’ droughts occurred in the Sahel region of Sub Saharan Africa which created a regime shift in the Sahel where the socio-ecological and livelihood systems transitioned from a high resilience/low sensitivity to a low resilience /high sensitivity state. Mali, a landlocked country in sub-Saharan Africa, experienced dramatic impacts on food security and social, environmental, and institutional systems triggered by the droughts. As a result, Malian agriculture underwent significant transformations initiated by the cereal liberalization policies in the 1990s. Cereal production almost doubled in the early 2000s, yet the number of people facing chronic and persistent food insecurity and malnutrition has been steadily increasing in the past decade and may continue to rise in the context of current climate projections for a drier and hotter Sahel.

This dissertation undertakes a closer investigation, beyond production, on the structural root causes and socio-ecological processes of food security and climate resilience in Mali using a mixed-method approach of process tracing, participatory game design, causal loop mapping, and system dynamics modeling. Paper 1, titled “**The Malian Past: A historical analysis of the adaptive cycles in Malian socio-ecological systems**”, outlines the main environmental, social, and institutional changes in Mali from 1960 to 2017 and situates these changes within the adaptive cycle framework. The paper challenges the existing narrative of Mali as a region that transitioned from a high resilience state to a low resilience state and suggests that Mali exhibited stages of high resilience during the collapse, reorganization and growth stages that followed the drought period in the 1960s and beyond. Paper 2

titled **“The Malian Present: A participatory game design approach to examine causal pathways of Barriers and opportunities for food security and climate adaptation in Southern Mali”** explores the current barriers of food security and climate adaptation faced by rural farming households in Southern Mali. The paper elucidates on the development and implementation of the ‘Food and Farm’ game that was used as a tool to assess farming decision making under climate uncertainty. Using causal loop diagramming, this paper identifies unavailability of formal credit sources especially for non-cotton and female farmers; inadequate access to crop inputs; inadequate land access and user rights for female farmers; unavailability of adequate water; low soil fertility; climate risks and cost of early maturing varieties as the key barriers in agricultural adaptation. Paper 3 titled **“The Malian Future: System Dynamics Modelling of Resilience of Malian Agriculture as a Socioecological System”** discusses the results from a system dynamics model that performs a series of future climate and adaptation scenario analyses to assess the scope of future resilience of agricultural systems in Mali. The model suggests that the key drivers influencing food security in Mali are change in temperature during sowing phase which influences crop yields as well as rainfall patterns in growing season. Further increase in global temperatures and interdecadal fluctuations in rainfall patterns in crop growing phase will likely lead Mali to another famine and food insecurity phase by 2030. Adaptation strategies such as enhanced crop management, land-use change, stabilization of internal migration and urbanization rates and cereal land expansion will, at best, help in delaying the effects of declining food security as projected for 2025-2060. This dissertation recommends Malian policy-makers to move beyond incremental adaptation support and enhance preparedness for future food insecurity through systemic transformations in land rights and land use, especially among female farmers in Mali and support the cultivation of climate-resilient crops such as sorghum and millet as opposed to maize and rice.

This dissertation is dedicated to the people I met in Mali who shared their stories and made this research possible.

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TABLE OF CONTENTS

LIST OF TABLES	ix
LIST OF FIGURES	x
INTRODUCTION	1
1. Research background & rationale	1
2. Research objectives	2
3. Research framework.....	3
3.1. The Malian Past: A historical analysis of the adaptive cycles in Malian socio-ecological systems	4
3.2. The Malian Present: A participatory game design approach to examine causal pathways of barriers and opportunities for food security and climate adaptation in Southern Mali	5
3.3. The Malian Future: System Dynamics Modelling of Resilience of Malian Agriculture as a Socioecological System	5
REFERENCES.....	7
CHAPTER 1:	9
THE MALIAN PAST: A HISTORICAL ANALYSIS OF THE ADAPTIVE CYCLES IN MALIAN SOCIO-ECOLOGICAL SYSTEMS.....	9
1. Introduction	9
2. Conceptual Framework: Resilience, Adaptive cycle, and Transformation	10
3. Methodology	16
4. Case Study: Mali.....	21
5. Data	24
6. Results	25
6.1. Past climatological and development trajectories in Mali:	25
6.1.1. Climatological trends (1901-2013)	25
6.1.2. Land and agricultural production trends:.....	26
6.1.3. Demographic trends.....	31
6.1.4. Food security and nutrition trends.....	33
6.1.5. Political and institutional trends	36
6.2. Analysis of adaptive cycle in Malian Agricultural SES	38
6.2.1. Phase 1: Time period (1960-1980) (Collapse).....	39
6.2.2. Phase 2: Time period (1981-1990) (Reorganization).....	40
6.2.3. Phase 3: Time period (1991-2000) (Growth).....	41
6.2.4. Phase 4: Time period (2001-2017) (Conservation/Collapse).....	42
6.3. Analysis of regime shift in Malian agricultural socio-ecological system.....	43
7. Conclusion.....	45
REFERENCES.....	48
CHAPTER 2:	54
THE MALIAN PRESENT: A PARTICIPATORY GAME DESIGN APPROACH TO EXAMINE CAUSAL PATHWAYS OF BARRIERS AND OPPORTUNITIES FOR FOOD SECURITY AND CLIMATE ADAPTATION IN SOUTHERN MALI.....	54

1. Introduction	54
2. Systems thinking and agricultural adaptation	57
3. Study Area	59
4. Data collection	60
5. Structure of ‘Food and Farm’ Participatory Simulation Game.....	61
6. Analysis framework.....	67
6.1. Qualitative analysis of game verbal protocols.....	67
6.2. Causal loop diagramming.....	69
7. Results	70
7.1. Financial barriers.....	71
7.2. Land related barriers	72
7.3. Climate barriers.	74
8. Discussion	76
9. Conclusion.....	78
APPENDIX	81
REFERENCES.....	92
 CHAPTER 3	 99
THE MALIAN FUTURE: SYSTEM DYNAMICS MODELING OF RESILIENCE OF MALIAN AGRICULTURE AS A SOCIOECOLOGICAL SYSTEM.....	99
1. Introduction	99
2. Conceptualization of MALI-SES system dynamics model	101
2.1. Definition of food security & scale of the model	101
2.2. Dynamic feedbacks within Malian SES	104
3. Causal loop diagram- Mali –SES model.....	105
3.1. Ecological dynamics	107
3.2. Social & institutional dynamics	108
3.3. Exogenous and endogenous variables	110
4. Methodology	111
4.1. Model construction.....	111
4.1.1. Climate module	112
4.1.2. Crop yield & climate variability	116
4.1.3. Crop yield and fertilizer use:	118
4.1.4. Land use and crop production.....	120
4.1.5. Livestock production and climate dynamics.....	121
4.1.6. Population dynamics	123
4.1.7. Food consumption and demand	124
4.2. Model validation: Observed vs: Simulated data.....	125
4.3. Modeling Scenarios.....	125
4.3.1. Climate Scenarios A & B:	126
4.3.2. Adaptation Scenarios 1-5.....	127
4.4. Sensitivity analysis	128
5. Results and Discussion	129
5.1. Model validation results	129
5.2. Model simulation results	132
5.2.1. Scenario A: 1.5 °C warming with diminished rainfall.....	132
5.2.2. Scenario B: 1.5 °C warming with rainfall increasingly slightly	133
5.2.3. Comparison of adaptation Scenarios within climate scenarios A & B	135

5.2.4. Food security projections: Comparison for scenarios A 1-5 and B 1-5	145
5.3. Sensitivity analysis results.....	147
6. Conclusion.....	152
REFERENCES.....	156
CONCLUSION.....	160
REFERENCES.....	166

LIST OF TABLES

Table 1.1. Adaptive Cycle Heuristics	20
Table 1.2. Data sources	24
Table 1.3. Timeline of political and institutional trends in Mali (1960-2016)	38
Table 2.1. Demographic characteristics of game participants.....	61
Table 2.2. Climate event cards and their impacts.....	64
Table 2.3. Dice roll and its impact on the game.....	64
Table 2.4. Decision rubric codes and their definitions.....	68
Table 3.1. Sen's slope and Mann-Kendall trend test results for climate variables from 1961-2015.	114
Table 3.2. Results of multivariate regressions between climate variables and crop yield (1960-1990)	117
Table 3.3. Results of multivariate regressions between climate variables and livestock production variables (1960-2010).....	122

LIST OF FIGURES

Figure 1.1. Dissertation framework.....	4
Figure 1.2. Illustration of phases of the Adaptive Cycle.....	13
Figure 1.3. Transitions in the phases of the Adaptive Cycle	14
Figure 1.4. Map of the livelihood zones in Mali (adapted from USAID-FEWSNET map (2010))	22
Figure 1.5. a) Average Annual temperature trends (1901- 2015).....	25
Figure 1.5. b) Average annual precipitation trends (1901-2015).....	25
Figure 1.6. Agricultural land (ha) (1960-2016).....	26
Figure 1.7. Forest area trends (1960-2016).....	27
Figure. 1.8. Millet production and harvested area trends (1960-2016)	28
Figure. 1.9. Sorghum production and harvested area trends (1960-2016)	29
Figure. 1.10. Maize production and harvested area trends (1960-2016).....	29
Figure. 1.11. Rice production and harvested area trends (1960-2016).....	30
Figure. 1.12. Cotton production trends (1960-2016).....	30
Figure. 1.13. Livestock population trends (1960-2017).....	31
Figure. 1.14. Population growth (1960-2016)	32
Figure. 1.15. Percentages of urban and rural population (1960-2016).....	32
Figure. 1.16. Population trends in the largest city (1960-2016).....	33
Figure. 1.17. Food availability per capita (1960-2017).....	33
Figure. 1.18. Percentage of food insecure people by region (2013-2017)	35
Figure. 1.19. Nutritional status of children (1987-2015)	35
Figure. 1.20. Food import-export trends (1961-2016)	36
Figure. 1.21. Stacked area graph of agricultural production (1960-2016).....	44

Figure. 1.22. Stacked area graph of livestock production (1960-2009)	44
Figure 2.1. Map of Southern Mali	60
Figure 2.2. Structure of the ‘Food and Farm’ game.....	63
Figure 2.3. Participant drawing crop plots on the gaming grid.....	65
Figure 2.4. Participant deciding on crop inputs.....	65
Figure 2.5. Participant drawing climate card.....	66
Figure 2.6. Participant drawing coins.....	66
Figure 2.7. Collective causal loop diagram for food security and climate adaptation of farmers in Koutiala	71
Figure 2.8. Example of crop allocation on a gridded plot.....	86
Figure 3.1. Panarchy in the Mali-SES model	103
Figure3.2. Model structure of Mali-SES model.....	105
Figure 3.3. Causal loop diagram Mali-SES model.....	106
Figure 3.4. Ecological dynamics in Mali-SES model	108
Figure 3.5. Social and institutional dynamics in Mali-SES model.....	110
Figure 3.6. National temperature trends (sowing, growing and maturing phase) (1960-2015)	113
Figure 3.7. National precipitation trends (sowing, growing and maturing phase) (1960-2015)	113
Figure 3.8. Average precipitation during growth phase (1901-2015).....	115
Figure 3.9. Simulated and observed trends in temperature and precipitation during sowing, growing and maturing phases (1961-2015).....	129
Figure 3.10. Simulated and observed trends in cereal crop yield (1961-2015).....	130
Figure 3.11. Simulated and observed trends in crop production (1961-2015).....	131
Figure 3.12. Simulated and observed trends in rural, urban and total population (1961-2015)	131
Figure 3.13. Scenario A: Temperature and precipitation in sowing, growing and maturing phases (1960-2060)	132

Figure 3.14. Scenario B: Temperature and precipitation in sowing, growing and maturing phases (1960-2060)	134
Figure 3.15. Population projections (1961-2060)	134
Figure 3.16. Scenario A1- Crop acreage for maize, sorghum, millet and rice crops (1961-2060)....	135
Figure 3.17. Scenario B1: Crop acreage for maize, sorghum, millet and rice crops (1961-2060)	136
Figure 3.18. Scenario A1- Production amount for maize, sorghum, millet and rice crops (1961-2060)	136
Figure 3.19. Scenario B1- Production amount for maize, sorghum, millet and rice crops (1961-2060)	136
Figure 3.20. Scenario A2- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060) ...	137
Figure 3.21. Scenario B2- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)....	138
Figure 3.22. Scenario A2- Crop production for maize, sorghum, millet and rice crops (1961-2060)	138
Figure 3.23. Scenario B2- Crop production for maize, sorghum, millet and rice crops (1961-2060)	138
Figure 3.24. Scenario A3- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060) ...	139
Figure 3.25. Scenario B3- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)....	140
Figure 3.26. Scenario A3- Crop production for maize, sorghum, millet and rice crops (1961-2060)	140
Figure 3.27. Scenario B3- Crop production for maize, sorghum, millet and rice crops (1961-2060)	140
Figure 3.28. Scenario A4- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060) ...	141
Figure 3.29. Scenario B4- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)....	141
Figure 3.30. Scenario A4- Crop production for maize, sorghum, millet and rice crops (1961-2060)	142
Figure 3.31. Scenario B4- Crop production for maize, sorghum, millet and rice crops (1961-2060)	142
Figure 3.32. Scenario A & B 1-4- Food supply and demand (1961-2060)	143
Figure 3.33. Scenario A5- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060) ...	144

Figure 3.34. Scenario B5- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)....	144
Figure 3.35. Scenario A5- Crop production for maize, sorghum, millet and rice crops (1961-2060)	144
Figure 3.36. Scenario B5- Crop production for maize, sorghum, millet and rice crops (1961-2060)	145
Figure 3.37. Comparison of food security under Climate Adaptation Scenarios (A1-5) (1961-2060)	146
Figure 3.38. Comparison of food security under Climate Adaptation Scenarios (B1-5) (1961-2060)	146
Figure 3.39. Sensitivity runs for rate of change in sowing temperature.....	148
Figure 3.40. Sensitivity runs for rate of change in growing temperature.....	148
Figure 3.41. Sensitivity runs for rate of change in maturing temperature	149
Figure 3.42. Sensitivity runs for rate of change in sowing season precipitation.....	149
Figure 3.43. Sensitivity runs for rate of change in growing season precipitation	150
Figure 3.44: Sensitivity runs for rate of change in maturing season precipitation	150
Figure 3.45. Sensitivity runs for urbanization rates.....	151
Figure 3.46. Sensitivity runs for cereal extensification rates	151

INTRODUCTION

“It’s better to help a man when he is standing up than help a man who is down.”

–Mousaka Sonogo, Research participant, Mali (2016)

1. Research background & rationale

Climate change and its physical, economic, social, and political impacts have been a topic of wide discussion and deliberation since the late 1980s. The assessment reports by the U.N. Intergovernmental Panel on Climate Change (IPCC) in 1990 (AR1), 1995 (AR2), 2001 (AR4), 2007 (AR5) and 2014 (AR6) have been instrumental in synthesizing the scientific knowledge on social and biophysical impacts of climate change and developing policy recommendations and guidelines for countries to cope with these impacts. While the early AR reports focused on mitigation efforts to reduce carbon emissions, it wasn’t until the early 2000s that that climate adaptation was brought to the forefront as strategies which enabled “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC, 2001; pg. 72 AR3). In subsequent reports, scholars and practitioners increasingly acknowledged that the impact of and response to climate change are not evenly distributed across locations, gender, age, ethnicity, income and other socio-economic characteristics and that rural population in least-developed and developing countries were generally at greater risk due to both higher sensitivity¹ and lower adaptive capacity² to cope with the adverse effects of climate change (IPCC 2007c).

The latest AR report reveals an integrated approach of combining both adaptation and mitigation measures for development trajectories which are embedded within broader sustainable development

¹ Sensitivity is the degree to which the system is modified or affected by the hazard

² Adaptive capacity is the ability of the system to cope with, deal or accommodate the hazard/ climatic events (Adger, Arnell, and Tompkins 2005; Fussler and Klein 2006)

goals. This approach focuses on developing “climate-resilient pathways” that are “iterative, continually evolving processes for managing change within complex socio-ecological systems” (AR7, Denton, et al, 2014, pg 1106). As reflected by the AR7 report, scholarship increasingly acknowledges that complex environmental problems such as climate change, food security, land degradation, and population growth fall within the intersection of social and ecological systems and require an integrative and interdisciplinary approach for scientific inquiry (Binder et al. 2013; Salvia and Quaranta 2015; Sterk, van de Leemput, and Peeters 2017). It is no longer sufficient to study biophysical risks and exposure, climate sensitivity, vulnerabilities and adaptive capacities of populations in disciplinary silos but to explore socio-ecological systems as an integrated complex system where there is a scope for a range of adaptation and resilient outcomes to emerge. In other words, the development of climate-resilient pathways needs to be context-specific and cognizant of the past and future development trajectories that differ between regions and nations. Efforts along these adaptation pathways need to shift from an analysis of the role of individual actors and their capabilities towards an enhanced focus on the contexts, feedbacks, and interconnectedness of the components of the socio-ecological system (Berkes et al., 2003).

2. Research objectives

This dissertation is an attempt towards understanding the complex interdependencies and feedbacks between human decision making, food production, climate adaptation, and agricultural policies that impact the resilience of agricultural socio-ecological systems in Mali, West Africa. Mali serves as an interesting case study due to its unique historical transitions in social, environmental and institutional systems as a result of abrupt, ‘unprecedented’ droughts between the 1960s and 1980s in the Sahel region of Sub-Saharan Africa. These climate-induced droughts are seen to have created a regime shift in the Sahel where the socio-ecological and livelihood systems transitioned from a high resilience-low sensitivity state to a low resilience -high sensitivity state (Davies, 2016). In undertaking a detailed

contextual analysis of the interconnected social, economic, institutional and biophysical trajectories in the Malian socio-ecological systems I explore the complex ways in which the historical droughts in the Sahel impacted Mali and how these effects have introduced path dependency for the future of Mali.

The key objectives of this research are:

- To strengthen the conceptualization of social, behavioral, institutional and ecological processes of climate adaptation and food security as a complex socio-ecological process
- To strengthen the conceptualization of resilience of farmers within an adaptive cycle and system dynamic modeling framework
- To enhance the understanding of the household-level decision-making process behind food production, consumption, and climate change adaptation among farmers in Mali.
- To identify leverage points that can increase future farmers resilience to climate stressors

3. Research framework

The research framework for this study involves a mixed methodology of process tracing, participatory game design, causal mapping and system dynamics modeling where resilience is defined as “*the capacity of a system to either absorb, transition from or transform to alternate states and still exist*” (Miller et al. 2010). This dissertation is organized into three research papers in an hourglass structure both in terms of geographical and temporal scale of analysis (see Figure 1). Paper 1 assesses the past transitions in agricultural socio-ecological systems in Mali at the national scale; Paper 2 streamlines the analysis of the present status of agricultural socio-ecological systems at the household scale while Paper 3 projects the analysis of the future status of agricultural socio-ecological systems at the national scale.

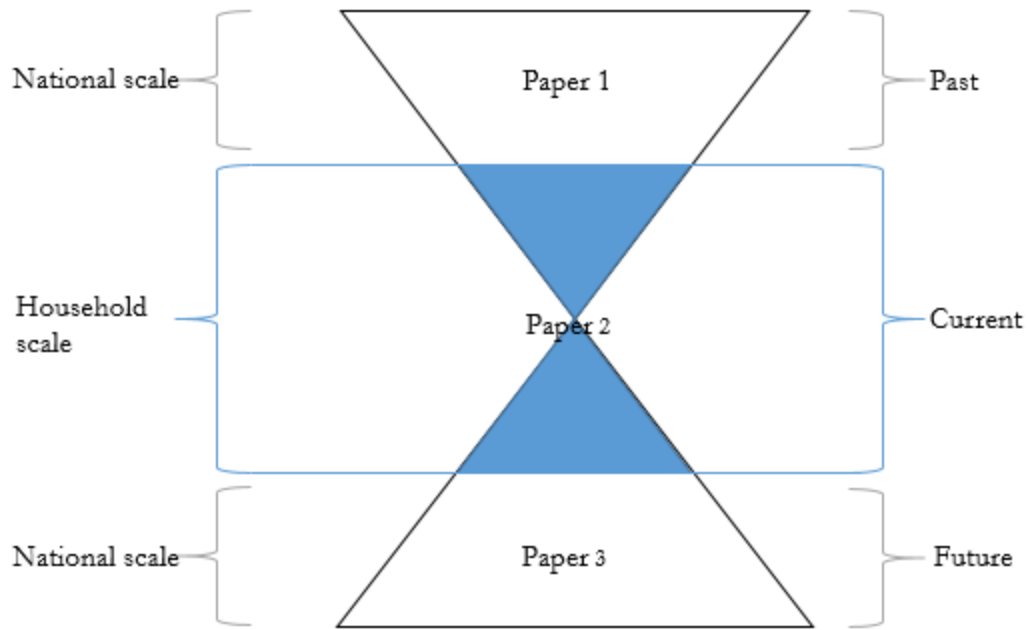


Figure 1.1. Dissertation framework

3.1. The Malian Past: A historical analysis of the adaptive cycles in Malian socio-ecological systems

The first paper presents a case study of agricultural socio-ecological systems in Mali - a region in the West African Sahel where persistent droughts, famines, high levels of poverty and political and social conflicts have created conditions of severe food insecurity in the region. Titled “The Malian Past: A historical analysis of the adaptive cycles in Malian socio-ecological systems”, this paper explores if the predominant narrative that the Sahelian droughts from the 1960-1980s decreased the resilience of Malian socio-ecological systems is true. I apply a systems approach to identify the main environmental, social and institutional changes in Mali from 1960 to 2017 through historical process tracing of time series data in climate, demographic and agricultural production and situate these temporal changes within the adaptive cycle framework. This paper challenges the existing narrative of Mali as a region that transitioned from a high resilience state to a low resilience state during the Sahelian droughts and shows that the Malian agricultural socio-ecological system exhibited cyclical stages of collapse,

reorganization and growth instead. The paper also highlights the key processes such as social capital, food sharing, investment in irrigation structures and improved production technologies that allowed the system to transition to reorganization and growth stages.

3.2. The Malian Present: A participatory game design approach to examine causal pathways of barriers and opportunities for food security and climate adaptation in Southern Mali

The second paper explores the structural root causes and ‘barriers’ that inhibit farmers from achieving food security and adapt to climatic stressors in the breadbasket region of Koutiala in Southern Mali. Using a mixed approach of participatory simulation game design and qualitative causal loop diagramming, I explore causal mechanisms and processes in agricultural decision-making and creation these barriers within the system and identify key leverage points (Meadows, 1999) and solutions that can channel the conversion of ‘barriers’ into opportunities to improve food security and adaptive capacity of farmers in the region. By synthesizing the various interlinked aspects of social, environmental and institutional aspects of agricultural food production, this paper lays a strong background for a comprehensive assessment of barriers of food security and climate adaptation in the region and provides relevant insights for regions beyond Mali and elsewhere in the Global South.

3.3. The Malian Future: System Dynamics Modelling of Resilience of Malian Agriculture as a Socioecological System

In the third paper, titled “The Malian Future: System Dynamics Modelling of Resilience of Malian Agriculture as a Socioecological System”, I elaborate on the system dynamics model that conceptualizes the agricultural systems of Mali as a socio-ecological system and performs a series of climate and adaptation scenario analysis to assess the future resilience of food systems in Mali. This paper conceptualizes and functionalizes the agricultural system of Mali as a socio-ecological system where ecological dynamics within the system interact with social dynamics to impact food security within the country. The system dynamics model incorporates the feedbacks and relations within

biophysical, climatological and social aspects of the agricultural socio-ecological system including temperature and precipitation trends, agricultural production, livestock production, land-use change, population growth, migration, urbanization, poverty and food demand /supply. The model also explores combinations of two climate scenarios and five key adaptation scenarios including decline in rainfall in the future , rainfall remaining at the present trend, and adaptation such as improved fertilizer use for millet and sorghum, land allocation changes; stabilization of decline in pastoralism and internal migration and cereal land extensification. This paper highlights the fact that small incremental adaptive changes within the agroecological systems are likely to delay an eventual system collapse in the short term. Unless there is a transformative change in the system where we challenge the status quo of who adapts, how and in what way, the system cannot prepare itself to be resilient to impending changes. The paper recommends two key policy avenues for transformative change; one, creation of policies that provide women with farmland ownership and user rights and leverage their capacities as food producers and second, enhanced cultivation of climate-resilient crops such as sorghum and millet as opposed to maize and rice.

In summary, according to George et al (2005), a detailed examination of a historical episode often allows for the generation of testable hypotheses or explanations that may be generalizable to alternative contexts and situations. With this goal in mind, I hope that the knowledge generated from this dissertation, both in terms of insights on past and future resilience of Sahelian socio-ecological systems as well as embedding local knowledge, experiences and perspectives first and foremost in analytical and methodological frameworks will prove to be useful for further explorations in developing climate-resilient futures.

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CHAPTER 1: THE MALIAN PAST: A HISTORICAL ANALYSIS OF THE ADAPTIVE CYCLES IN MALIAN SOCIO-ECOLOGICAL SYSTEMS

1. Introduction

The Sahel region of Sub Saharan Africa experienced a series of abrupt, ‘unprecedented’ droughts (Simpkins, 2018) between the 1960s and 1980s (Nicholson et al 1998) that created wide-spread poverty, famine, displacement and geopolitical conflicts in the region (Brooks, 2004; Nicholson et al 1998)). It is estimated that the droughts killed almost 100,000 people, left 750,000 people dependent on food aid, and affected most of the Sahel's 50 million people (UNEP, 2002). According to Davies (1996), the droughts created a regime shift in the Sahel where the socio-ecological and livelihood systems declined from a high resilience/low sensitivity to a low resilience /high sensitivity state. There are numerous studies that highlight the vulnerability of Africa to climate change impacts (Nick Brooks, Adger, and Kelly 2005; Thornton et al. 2008; Tschakert 2007); most echoing the sentiments of Sokona and Denton (2001) highlighting the *“inability of the continent and its people to grapple with environmental degradation due to a lack of institutional, economic and financial capacity to support such actions.”* (p. 118). Mortimore (2010), however, challenges such a despondent view of Africa as a victim of climate change with limited adaptive capacity and argued that despite the droughts in the 1960s and 1980s, farming systems in the Sahel persisted. 25 years post the droughts, population in Sahelian countries was either stable or increasing, agricultural production intensified and livelihoods became more diverse (M. Mortimore 2010). Scholars like Hulme (2001) and Mortimore & Adams (2001) provided an alternate perspective from the vulnerable Sahel to an ‘unstable but resilient’ Sahel where the Sahelian social-ecological systems exist in a fluctuating environment with multiple equilibrium states and where ‘normal’ is variability in rainfall at different time scales (Hulme 2001; Traoré et al. 2007).

Using a case study methodology to study past resilience of Mali, a country in the Sahelian Sub Saharan Africa, this paper aims to address two key questions: first, did the Sahelian droughts change the

agricultural socio-ecological landscape of Mali? Second, what were the impacts of the Sahelian droughts on the resilience of the Malian agricultural socio-ecological system? To answer the first question, I conduct a historical a process-tracing of changes in national-level trends in climatological and development indicators in Mali and juxtapose it with incidences of droughts that occurred between the period 1960-2017. I then use inductive reasoning to test if drought incidences in the 1960s-1980s caused changes in the agricultural landscape of Mali. To answer the second question, I use the ‘adaptive cycle’ heuristic, which has been used to identify the social and ecological resilience of a system (Antoni et al. 2019), as a diagnostic approach or lens to trace the resilience of dynamic Malian agricultural landscapes over time. Finally, I identify the key drivers that led to the resilience (or not) of agricultural socioecological systems in Mali. In what follows, Section 2 outlines the conceptual framework of resilience, adaptive cycles, and transformation that I use in this paper. Section 3 presents the case study for Mali followed by the methodology used for analyzing the adaptive cycles in Mali (Section 4). Section 5 elaborates on the description of the data used for the study (Section 4). Section 6 presents the results followed by discussion (Section 7) and the conclusion (Section 8).

2. Conceptual Framework: Resilience, Adaptive cycle, and Transformation

Vulnerability, resilience, and adaptation are central for studying maintenance, transitions, and transformations of complex socio-ecological systems; especially in the context of global environmental change. Vulnerability is seen as the degree to which a system is likely to experience harm due to exposure to a hazard or stress (Adger 2006) and has been conceptualized as a function of exposure and sensitivity of the system to external stressors and the ability or capacity of the system to adapt to such stressors (Smit and Wandel 2006). Resilience, on the other hand, has been defined as the capacity of a system to either absorb, transition from, or transform to alternate states and still exist (Miller et al. 2010). The concept of resilience originated in ecology (Holling 1973) as the *“measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between*

populations or state variables” (p 14). In other words, resilience was viewed as the capacity of a system to absorb disturbance and retain essentially the same function, structure, identity, and feedbacks (Brian Walker et al. 2004b). This conceptualization focused more on processes and nonlinear dynamics of system’s responses within which ecological systems could exist at multiple equilibrium (or stable) states³ and thresholds (Folke et al., 2010; Walker et al., 2006; Gunderson and Holling, 2002). Central to this concept is the visualization of ‘basins of attraction’ (Brian Walker et al. 2004a) which is the region or combination of state spaces where the system tends to remain in the absence of strong perturbations (Gallopín 2006). Measurement of ecological resilience as a function of the “magnitude of perturbations that can be absorbed before the state of the system fell outside its domain of attraction” (Gallopín, 2006, p. 299).

An alternative view proposed by Pimm (1984) defined resilience as the ability of a system to resist disturbance which could be measured by the rate at which the system bounced back to equilibrium (Holling and Meffe 1996). Often termed as ‘engineering resilience’, this definition assumed that that systems exist in a single steady-state and would eventually rebound or return to its equilibrium. (Holling and Meffe 1996). Based on this definition, failure to return to equilibrium would lead to a system collapse. Both these competing perspectives of ecological and engineering resilience, despite having different consequences in evaluation and management of natural resource management issues, have been used to model system change; often single equilibrium centered perspective dominating the analytical framework due to its mathematical tractability (Holling and Meffe 1996). However, Walker and Salt (2006) note that it is important to consider the crucial difference between a systems ability to “bounce back” and to “retain the ability to get back” (p.63); the former visualization of resilience does

³ State of a system is defined as the ‘set of values adopted by all the variables of the system at a given time’ (Gallopín, 2006, p. 297)

not consider the ability of systems to transform itself or maintain thresholds within which a system holds a capacity to absorb disturbances and still retain its essential function.

Scholars have increasingly acknowledged that socio-ecological systems (SES) are complex adaptive systems where both ecological and social systems influence each other through non-linear dynamic feedbacks, interactions and adaptation (Darnhofer 2014; Holland 2006; Levin et al. 2013; Quinlan et al. 2016; Rogers 2017; Tompkins and Adger 2001; Tschakert and Dietrich 2010; Walker 2006). This conceptualization challenges the single stable equilibrium approach and focuses more on processes and nonlinear dynamics of system's responses within which socio-ecological systems can have multiple equilibrium (or stable) states, thresholds, and uncertainty (Folke 2006; Miller et al. 2010). This view of socio-ecological resilience allows the scope of adaptive capacity, transformability and adaptive governance of agent and actor groups within changing ecological, social and political environments (Folke et al. 2010) and brings into forefront the role of human agency in placing the role of actors and their capabilities central to adaptation within dynamic socio-ecological systems (Crane, Roncoli, and Hoogenboom 2011).

In this study, drawing from the works of Antoni et al. (2019) who study the cyclic nature of socio-ecological systems and assess how complex adaptive systems react to external or internal drivers (Antoni et al. 2019), I apply the adaptive cycle framework to trace the historical resilience of Mali to external perturbations such as droughts and severe global price fluctuations for a period of 1960 to 2017. The adaptive cycle framework is often used as a metaphor for understanding the temporal trajectories of a complex system.

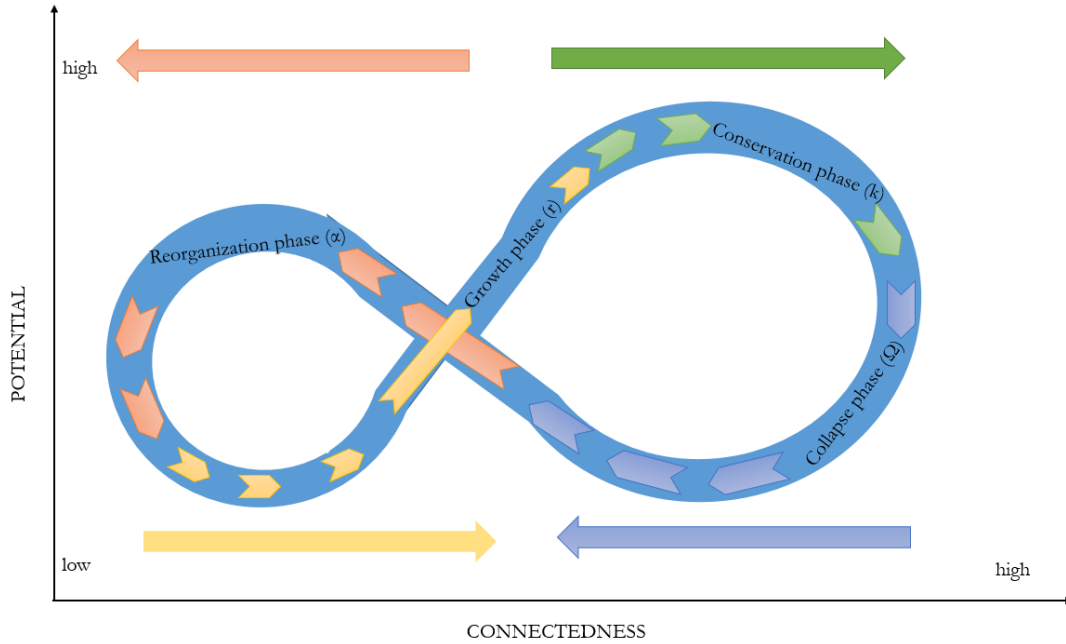


Figure 1.2. Illustration of phases of the Adaptive Cycle.

The arrow in yellow shows the growth phase (r) where potential (x axis) moves from low to high and connectedness (y axis) moves from low to high. The arrow in green shows conservation phase (k) where both connectedness is high and potential decreases. The arrow in purple shows collapse phase (Ω) where connectedness and potential decreases. The arrow in pink/peach shows the reorganization phase (α) where potential increases and connectedness decreases

The entire adaptive cycle, symbolized by an infinity loop (Figure 1.2), consists of four phases: rapid growth and exploitation (r), conservation (K), collapse or release (“creative destruction”, or Ω), and renewal or reorganization (α). The r phase is a slow phase that forms a cumulative forward loop where the dynamics of the system are easily predictable, and resilience begins to develop. The r phase launches the system into another new trajectory through the K phase where the resources become increasingly locked up and the system becomes less flexible and susceptible to external shocks. Ω and α are the brief periods where resilience peaks followed by a rapid collapse in the event of external perturbation. Reorganization occurs at the phase where resilience is low but novelty arises in the form of a new system state (e.g. species, institutions, rules, governance systems). (Davidson 2010; Brian Walker et al. 2004a). The Ω and α phases form an unpredictable back loop. The adaptive cycle is not fixed, and the systems can move between the phases interchangeably (Redman and Kinzig 2003).

Holling (2001) visualized the adaptive capacity cycle as existing in a three-dimensional space where the X-axis represents the “connectedness” of the system and the Y-axis represents the “potential” of a system and the Z-axis represents the ‘resilience’ of the system. The potential is a measure of the range of social, economic, and physical resources and capital within a system and “can be thought of, loosely, as the ‘wealth’ of a system” (Holling 2001:pg 394). Connectedness refers to the “the internal controllability of a system; that is the degree of connectedness between internal controlling variables and processes, a measure that reflects the degree of flexibility or rigidity of such controls, such as their sensitivity or not to perturbations” (Holling 2001:394). According to the adaptive cycle heuristic, the degree of connectedness and the potential differ throughout the cycle. At the growth phase, the resilience of a system is high, and the system’s connectedness and potential increases. At the conservation phase, the system has a high potential and the system increases its connectedness; the resilience of the system declines. At the collapse phase, the system has a low potential and resilience and the system’s connectedness declines. Finally, at the re-organization phase, the system’s connectedness declines and potential and resilience increases (Figure 1.3).

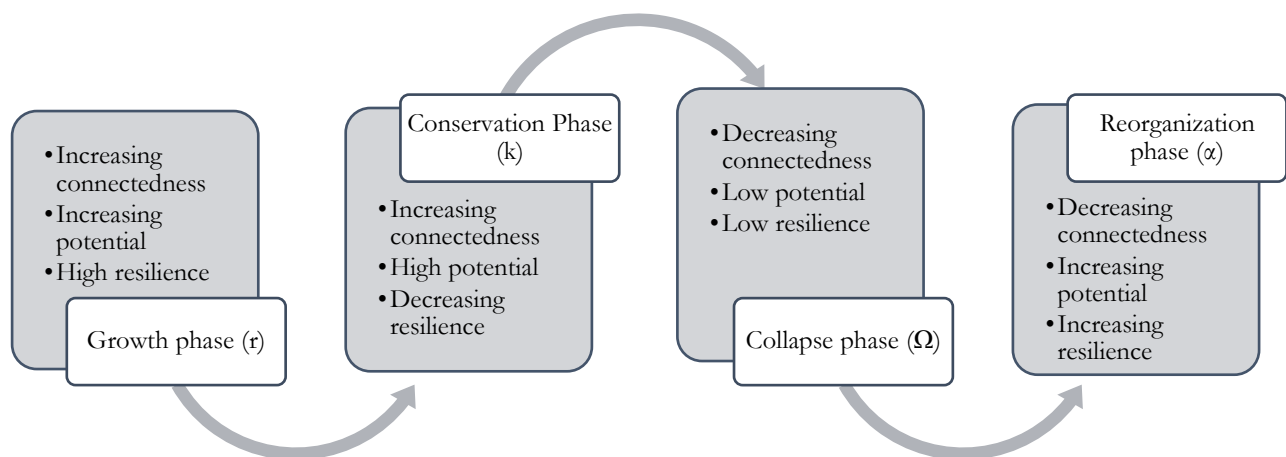


Figure 1.3. Transitions in the phases of the Adaptive Cycle

The transitions in the adaptive cycle can lead to three possible outcomes in a socio-ecological system:

(a) The system reorganizes and falls back into the same ‘structural regime’ and state spaces (b) the

system adapts and shifts to a different state with possible shifts in feedback processes and the scales at which these processes operate. (c) the system transforms into a new regime (Davidson 2010).

In the recent decade, the adaptive cycle approach has been applied to various case studies to understand the temporal dynamics and behavior of socio-ecological systems. According to Carpenter et al. (2001), while the adaptive cycle is primarily a metaphor and not a scientifically testable hypothesis; the utility of the adaptive cycle is in generating testable explanations of socio-ecological dynamics. Scholars have used the adaptive cycle approach to assess why and how do systems change and the underlying processes that control the ability of complex socio-ecological systems to adapt to these changes. For example, Beier, Lovcraft, and Chapin (2009) assess the growth and collapse of forest systems in Alaska, namely “Tongass National Forest” between 1908 to 2008 and showed how federal policies along with global market changes drove transformative change in both forest and forest management. The authors showed how policies such as lease contracts stabilized the system for a certain time period, it introduced rigidity in the system leading to a severe system collapse and emergence of social traps. Rasmussen and Reenberg (2012) analyzed the dynamics in Sahelian agro-pastoral systems in Burkina Faso between 1975 and 2004 and showed that scenarios based on sudden events, such as a drop in millet prices or a total stop in circular migration, have a more pronounced impact on the system than other more long term alterations such as increased rainfall variability. Allison and Hobbs (2004) studied the dynamics of an agricultural socio-ecological system; food production and livestock in Western Australia between 1889 and 2000 and showed that despite numerous policies directed at controlling natural resource degradation, sustainable natural resource management was not achieved due to disparities between the scale and complexity of the problem, the design of management policies, and region's history. Antoni et al. (2019) assessed the dynamics of forest systems in Mexico between 1940 to 2017 and integrated knowledge on the historical development of a 70-year old social-ecological system (SES) to inform a more nuanced understanding

of the vulnerability, resilience, and adaptability of land and people (livelihoods) to current diverse external and endogenous drivers. Drawing from these studies, in the following section, I present the methodology for the analysis of the case study from Mali and the adaptive cycle from 1960-2017.

3. Methodology

A case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (Yin, 2003, p. 13). Case studies are particularly useful when the contextual analysis of a complex phenomenon is critical to answering the “how” and “why” questions of the phenomenon. Yin (1994) describes three types of case studies: exploratory case studies where data informs theory building for the case, causal case studies where cause and effect relationships are assessed to develop explanatory theories for the case and descriptive case studies where theory is first developed and then tested on data. This paper falls under the causal case study category where I explore if the Sahelian droughts caused changes in the socio-ecological resilience of Malian agricultural systems after the 1960s.

According to Gerring (2004), “all empirical evidence of causal relationships is covariational in nature” (Pg 342). Thus, in attributing a causal relationship between $X \rightarrow Y$, there should be a covariate association between X and Y. While statistical analysis of causal effects estimate the probability of effect on Y given a change in X, taking into account all confounding factors in the error term and random variation; case study analysis offer a comparative advantage by supporting the insights of the covariation between X and Y through a deeper analysis of the causal mechanisms that cause the covariation between X and Y. These causal mechanisms are hypothesized by supporting insights from existing literature or theories. In this paper, I use the process-tracing method to infer causal effects and “historical explanation” of sequences in response to rare or unique exogenous events (Bennett and Elman 2006; Gerring 2004; Mahoney 2015). Process tracing involves two stages: theory construction and theory testing (Mahoney 2015). Theory construction involves the identification of

the variables Xs that influence Y in a case Z and can be undertaken in two ways: a counterfactual analysis where the potential causal factors Xs can be identified by asking whether a historical event's absence would have changed the outcome Y; or, through inductive discovery, the potential causal factors can be identified by drawing on existing theory literature. Theory testing involves assessing if X indeed cased Y in a case Z. According to Mahoney (2015), theory testing can be conducted in three different ways: One, attributing X as a necessary factor for Y in case Z. For example, the Sahelian droughts was a necessary condition to create a change in socio-ecological resilience in Mali. Second, attributing X as a contributing factor for Y in case Z. For example, the Sahelian droughts was a contributing factor in changing the socio-ecological resilience in Mali. Third, attributing X as an essential component of the factors that caused Y in case Z. That is, the Sahelian droughts were an essential factor in changing the socio-ecological resilience in Mali.

The period chosen for this study was 1960-2017 for two reasons: first, the literature points out to the drought incidences in the 1960s-1980s as the key factors that brought changes in socio-ecological dynamics in Mali and, second, longitudinal data for social demographics, land use, and agricultural production is available for years post-1960s and scant for the years prior. The national-level longitudinal data for this study was compiled from various sources such as the World Bank, the Emergency Events Database, the World Food Program, and Food and Agriculture Organization data repositories. An initial exploratory analysis of the trends in socio-ecological change in Mali from 1960-2017 was carried out by tracking macro changes in population, nutrition status, infant mortality, per capita income, crop production (for major food and cash crops), land-use change, livestock counts, food import and export trends, crop price fluctuations, urbanization trends etc. These trends were then juxtaposed with incidences of droughts that occurred between a period of 1960-2017 to construct theories for the observed trends. The testing of these theories was conducted through inductive discovery and substantiated with findings from existing literature.

Here, the national agriculture-livestock system of Mali is conceptualized as a macro-level socio-ecological system. Following Pretty et al. (2011) who conceptualize agriculture as a socio-ecological system with interlinked components of agroecosystem composed of the social subsystem such as undernourishment, rural poverty, livelihoods, rural migration, human health and agrobiodiversity and the ecological system and the ecological subsystem such as climate change, water resources, land, ecosystem health, landscapes and agrobiodiversity. These two subsystems are interconnected dynamically and have feedback structures, the strength of which is determined by governance structures within the socioecological system. In the Malian agricultural socio-ecological system, the social subsystem is assessed through macro-level indicators of demographic trends, food and nutrition trends, agricultural technology, food import and export, migration trends, education, and the natural subsystem is assessed through indicators such as climatological trends (temperature and precipitation), crop diversity, livestock diversity and agricultural land and crop production.

The analysis of the phases of the adaptive cycle in the SES was carried out by tracing the three interconnected dimensions of potential, connectedness, and resilience of the system over time (see Figure 1.2). In this study, capitals are used as indicators for the potential of the system. Abel, Cumming, and Anderies (2006) highlight that in socio-ecological systems both potential and connectedness can be captured in terms of social, human, natural, physical and financial capitals; where social capital refers to the social networks, formal and informal institutions and levels of trust, reciprocity, and interaction between the members of the system (McGinnis and Ostrom, 2014; Putnam, 2000.). Natural capital is the ecosystem services available to humans (Berkes & Folke, 1998). Human capital is the knowledge, skills, and attributes of individuals that contribute to their well-being. Physical capital is access to technology and infrastructure while financial capital is access to money (Abel, Cumming, and Anderies 2006). Connectedness, on the other hand, has been defined as the

“ability of the system to internally control its own destiny” (Abel, Cumming, and Anderies 2006). This definition is hard to quantify or assess.

The assessment of the change in resilience of the Malian SES is done through the adaptive cycle heuristics (Table 1.1) where the potential of a system is indicated through the levels of natural, social, financial and social capital in the system and the connectedness of a system is indicated through the local scale interactions and systems sensitivity to global changes. Levels of natural capital at the national level are measured as the total annual crop production (including sorghum, millet, maize, and rice), annual livestock production (cattle, sheep, and goats), and annual food availability per capita. Levels of physical capital are estimated as the agricultural infrastructure development in the country (such as irrigation structure), total agricultural machinery. Financial capital is measured as the per capita income levels at the national level and total annual production of cash crops i.e. cotton. Human capital is estimated through the levels of internal displacement and migration patterns, livelihood diversity, education, and nutrition status. Social capital, at the national level, is hard to estimate quantitatively and is assessed through anecdotal references in past studies assessed the levels of food sharing and social bonds in the country during these time frames and the levels of active participation of farmers in forming collectives, cooperatives, and village associations. The connectedness of a system is often measured as the levels of local-scale interactions and systems sensitivity to global-scale changes. This definition quite falls close to the definition of connectivity or social capital of the system. To avoid confusion, I specifically use the definition of connectedness as the ability of a system to control its destiny (Gunderson & Holling, 2002) which can be indicated through the sensitivity to global market price fluctuations and externally driven agricultural policy change, with the assumption that global market prices and donor-driven conditionalities are external influences to the Malian agriculture that likely reduce the ability of the Malian agricultural system to controls its destiny or

pathway.

	Indicator	<i>Growth phase</i>	<i>Conservation phase</i>	<i>Release/ Collapse phase</i>	<i>Reorganization phase</i>
Potential	Natural capital	Increasing	Increasing	Low	Increasing
	Social capital				
	Human capital				
	Financial capital				
	Physical capital				
Connectedness	System's ability to control its' destiny	Increasing	High	Decreasing	Decreasing
Resilience		High	Decreasing	Low	Increasing

Table 1.1. Adaptive Cycle Heuristics

A word of caution that is necessary to highlight here is that the assessment of the adaptive cycle should be taken as a metaphor and not a testable scientific hypothesis (Grimm & Calabrese, 2011). Hence, the aforementioned indicators and their measures are considered as general guides assessing the levels of potential, connectedness, and resilience of the system at a particular point as high, low, increasing or decreasing. For example, if the system had increasing levels of both potential and connectedness, the resilience of the system is high and the system is placed within the growth phase in the adaptive cycle. If the system has increasing levels of potential and high connectedness, the resilience of the system is decreasing and the system is placed in the conservation phase. Similarly, low potential and decreasing connectedness indicate low levels of resilience and the system is placed in the release or collapse phase. Increasing levels of potential, decreasing levels of connectedness and increasing levels of resilience place the system in the reorganization phase.

4. Case Study: Mali

Mali, a landlocked country that spans the Sudano, Sahelian, and Saharan zones of West Africa, has a population of around 14 million (Mali census 2009) and a land area of around 480,000 sq. mi which makes it the 8th largest country in the African subcontinent. Mali, which forms a transition zone from the extremely arid sandy deserts in the North to the more tropical savanna regions in the South and is particularly sensitive to climate shocks because of high poverty levels, low resource endowments and primarily rain-fed livelihoods (Sultan and Gaetani 2016, Davies, 2016). The special report by USAID's Famine Early Warning Systems Network FEWS-NET (2010) conceptualized as 12 distinct livelihood zones in Mali based on key livelihoods and annual precipitation patterns outlined below (Figure 1. 4). These 12 zones can be collapsed the distinct 12 zones into three main livelihood -based zones: **Pastoralism** (Zone 1, 2); **Agro-pastoralism** (Zone 3, 4, 6, 8; transhumance livestock rearing and rice, millet and sorghum cultivation, fishing) and **Agriculture** (Zones 5, 7, 9, 10, 11, 12); millet, sorghum, cotton, maize, fruits, shallots, wild foods, rice).

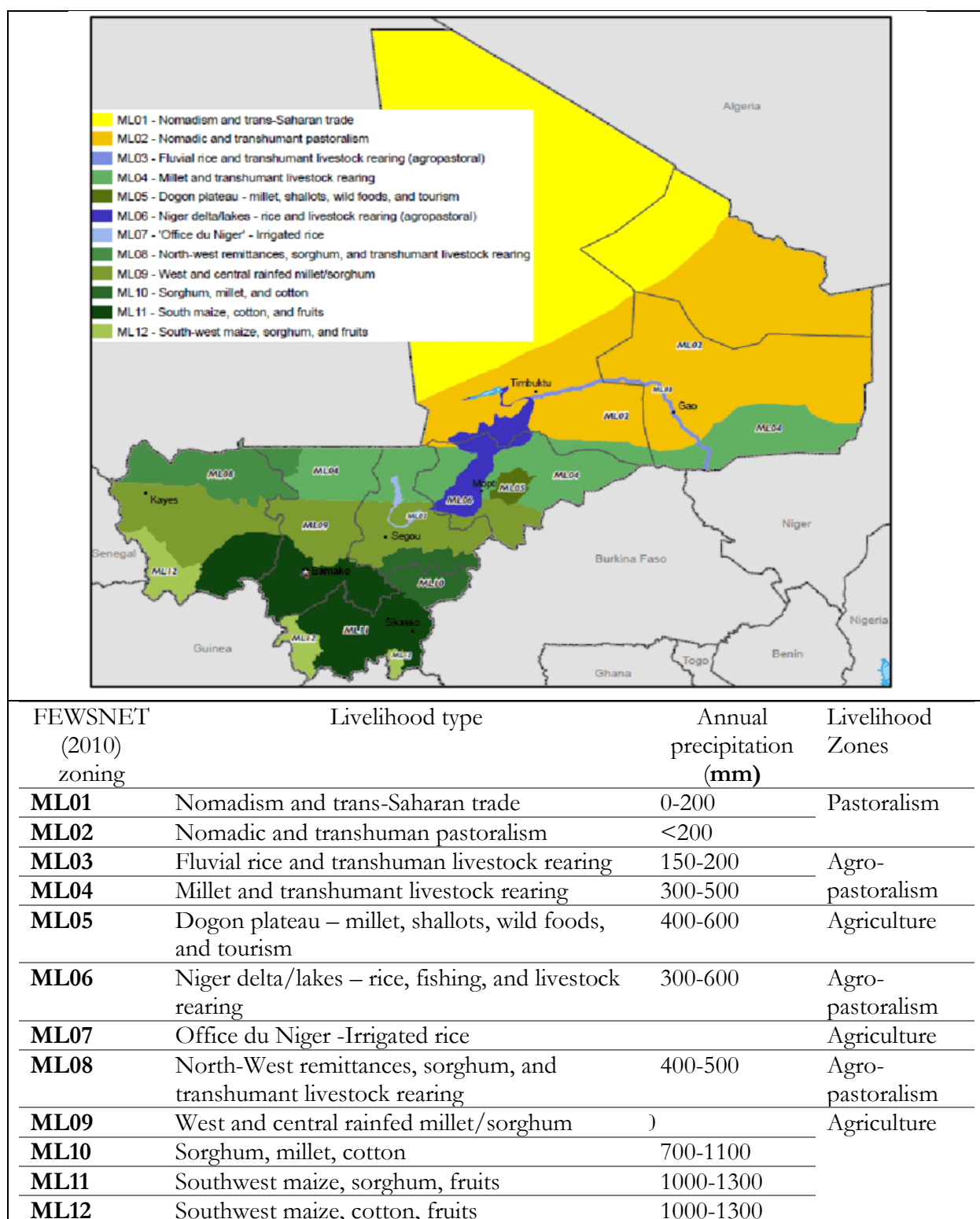


Figure 1.4. Map of the livelihood zones in Mali (adapted from USAID-FEWSNET map (2010))

Environmental impacts: Rainfall records for the past century have shown that after the droughts in the 1970s, rainfall patterns in the Sahel shifted from an interannual scale to an interdecadal scale (Nicholson, Tucker, and Ba 1998). In Mali, between 1970 and 2010, the average temperature increased by 0.6 to 0.8 degree Celsius with increased frequency and severity of extreme rainfall events, driven by changes in worldwide sea surface temperatures (Biassuti et al. ,2008), and reinforced by increase in population, agricultural intensification and land-use change (Taylor et al. 2002).

Social impact: The annual change in population of Mali increased from 1.3% in 1964 to around 2.1% in 1983. Further, there is evidence that the droughts led to high rates of migration both within and outside the country, especially within the transgender populations in the north to the agricultural lands in the South spurring land-use conflicts between pastoralists and farmers (Bassett & Turner, 2007). Mali, which was a lead exporter of cattle and cereals in the Sahel in the early 1960s, was left with a declining per capita food availability after the droughts until the 1990s (Davies, 2016). After a series of technical adaptation efforts in the 1990s by the government of Mali, cereal production grew at an average annual growth rate of 4.6% (Staatz et al, 2011). However, despite increased food production, the number of people under significant and extreme food insecurity in Mali is on the rise and is projected to continue to rise due to structural wealth inequalities and lack of access to resources (Davies, 2016).

Institutional impact: The droughts initiated a series of political and economic reforms in the country (Batterburry and Warren, 2001). The sustainability and efficacy of these reforms remain contentious. According to some scholars, the conditionalities imposed by various aid sponsors such as World Bank, International Monetary Fund (IMF) etc.; such as decentralization and privatization of the cotton industry; inhibited the strengthening of existing governance structures in post-colonial Mali and created an environment where corruption and geo-political conflicts fostered(Nielsen et al. 2016). The conflicts Northern Mali and growing discontentment of people with corruption in the government

eventually led to a military coup in 2012 that further destabilized the country and spurred a large population displacement and migration both within the country and to neighboring countries such as Burkina Faso, Mauritania, and Niger

5. Data

Various sources of time-series national /regional data aggregated for Mali country profile were obtained from the World Bank development series catalog, Food and Agriculture Organization of the United Nations statistics (FAOSTAT), Emergency Food Security Assessment (EFSA) (See Table 1.2.). These sources are publicly available and open-sourced.

Variables	Period	Source
Historic temperature and precipitation in Mali	1901-2016	The World Bank Data Catalog (Climate Change Knowledge Portal) https://climateknowledgeportal.worldbank.org/
Drought incidences	1900-2019	EM-DAT: The Emergency Events Database - Universite catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be , Brussels, Belgium
Crop production patterns	1961-2016	FAOSTAT data: Mali Food and Agriculture Organization of the United Nations
Population changes	1961-2016	World Bank Development indicators data (2018)
Deforestation rates	1961-2016	World Bank Development indicators data (2018)
Livestock /herd population changes	1961-2016	FAO stat data: Mali (2018)
Agricultural land conversion rates	1961-2016	FAO stat data: Mali (2018)
Nutritional data	1987-2016	United Nations International Children's Emergency Fund UNICEF 2018
Food security status data	2013-2017	Emergency Food Security Assessment (EFSA) and Enquête Nationale de la Sécurité Alimentaire (ENSA) reports by the World Food Program (WFP) 2018
Global food prices change (for cotton)		Global Food Prices Database (WFP) - Humanitarian Data Exchange
Food import and export	1960-2016	World Bank development indicators (2018)

Table 1.2. Data sources

6. Results

6.1. Past climatological and development trajectories in Mali:

6.1.1. Climatological trends (1901-2013)

According to Masih, Maskey, Mussá, & Trambauer (2014), from 1900-2013 Mali suffered from 11 drought events in 1910, 1940, 1966, 1976, 1980, 1991, 2001, 2005, 2006, 2010 and 2011 affecting almost 7 million people. Changes in worldwide sea surface temperatures, especially the Atlantic and the Indian Ocean, have been known to play a key role in the increase in frequency and intensity of droughts in the 1960's and the 1970's (Biasutti & Sobel, 2009; Brooks, 2004; Giannini, Biasutti, & Verstraete, 2008).

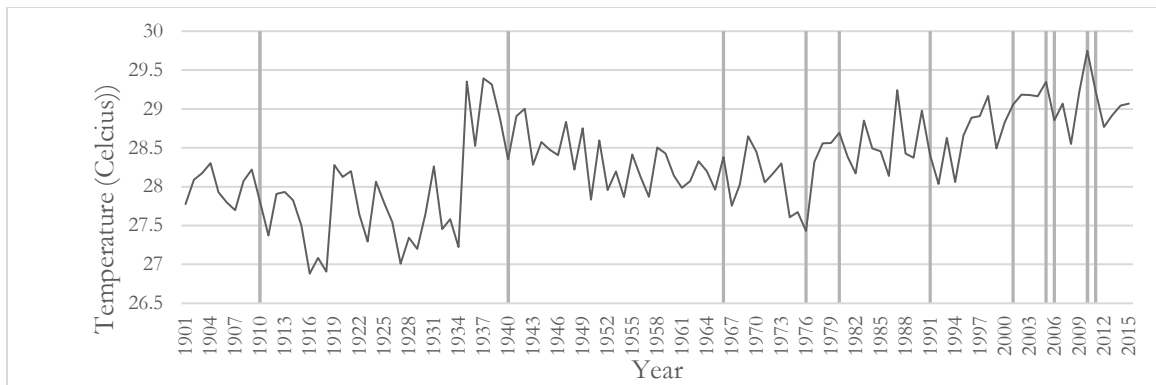


Figure 1.5. a) Average Annual temperature trends (1901-2015)

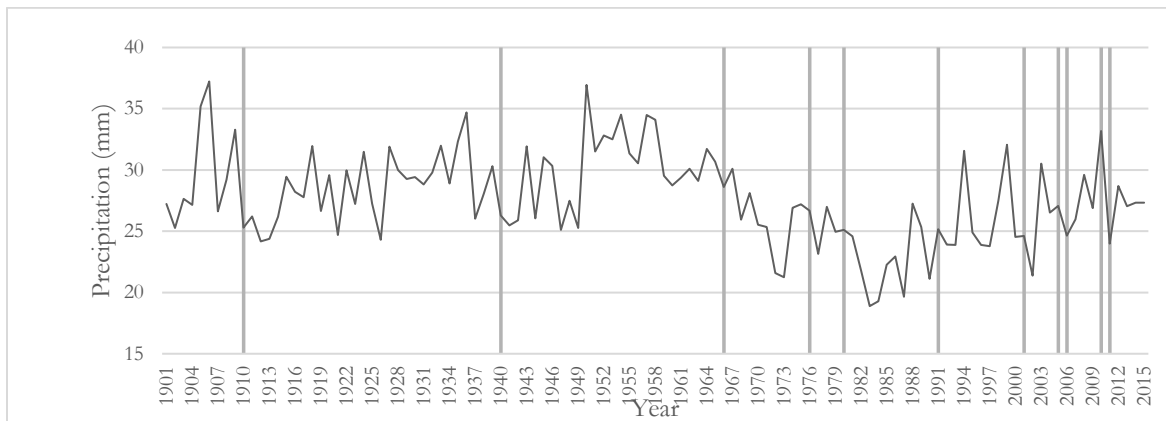


Figure 1.5. b) Average annual precipitation trends (1901-2015)

Global climate models (GCM) have been able to reproduce most of the variability in rainfall in the Sahel due to changes in global sea surface temperatures from 1930 to 2000, thus proving that the

major forcing of droughts in the Sahel is primarily due to tropical sea surface temperature (Giannini et al. 2008; Nicholson et al. 1998). As we see in Figure 1.5 (a) and 1.5 (b), variability in yearly precipitation from 1901-1936 gave way to a decreasing trend in rainfall and temperature from 1937-1977 punctuated with three drought incidences in 1941, 1966 and 1977. Between 1978 – 2013 temperature and rainfall increased as the number of drought incidences almost doubled to 7 incidences (1980, 1991, 2001, 2005, 2006, 2010, 2011). The period between 1978-2013 witnessed an increasing trend in the average annual rainfall and temperature.

6.1.2. Land and agricultural production trends:

Land use data from the World Bank development indicators dataset indicates that Mali experienced a rapid expansion of agricultural land area after 1991. The average yearly growth rate in the agricultural land area was 0.05% from 1961 to 1990 and increased by almost twenty times to 0.98% average yearly growth rate from the years 1990 to 2016 (Figure 1.6). Forest land coverage has decreased consistently between 1990 to 2016 at the rate of 1.4% per year (Figure 1.7)

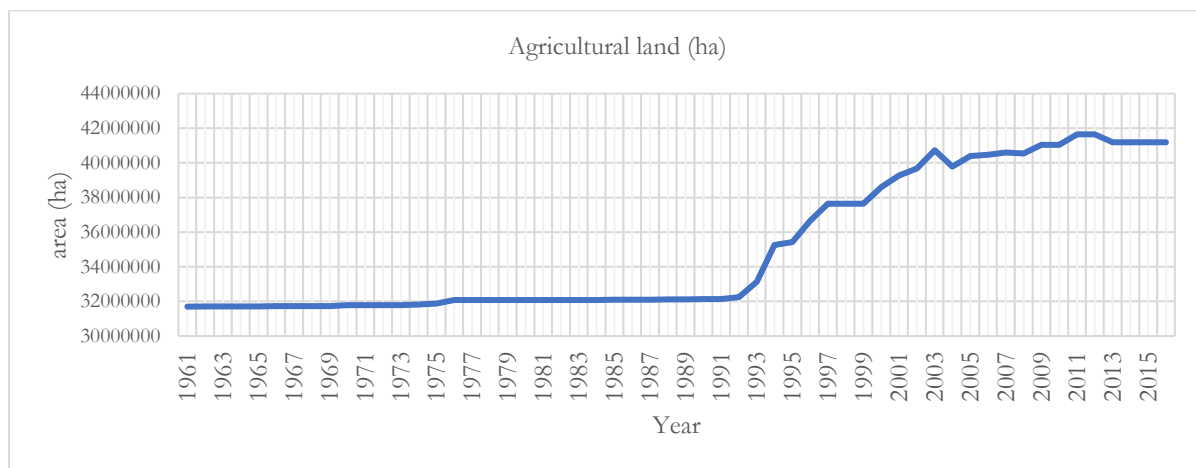


Figure 1.6. Agricultural land (ha) (1960-2016)

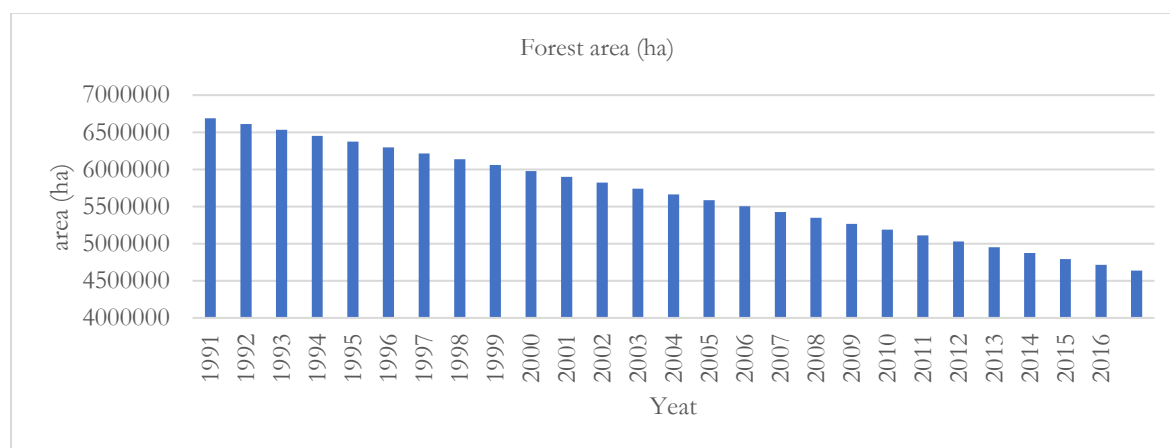


Figure 1.7. Forest area trends (1960-2016)

Researchers attribute the rapid expansion of agricultural land in the 1990s to agricultural intensification coupled with deforestation and other land use changes (Taylor et al. 2002), as well as external drivers such as human population growth (rural and urban), livestock population, rainfall, cereals imports, and rural farming systems (Stéphenne and Lambin 2001). Consistent with the rise in agricultural land expansion in 1990s, production of cereal crops also increased during the same time frame. The average annual growth rate of cultivated area for millet rose from 2.6% in the period between 1961 to 1990 to 4.5% in the period between 1991-2016. Production of millet rose from 3.3% annual growth in the period between 1961 to 1990 to 4.3% in the period between 1991-2016. Similarly, the average annual growth rate of cultivated area for sorghum rose from 3.4% in the period between 1961 to 1990 to 4.5% in the period between 1991-2016. Production of sorghum rose from 2.7% annual growth in the period between 1961 to 1990 to 3.9% in the period between 1991-2016. The production growth of sorghum and millet is correlated with growth in cultivated area with a high inter annual variability in production. (Figure 1.8 & 1.9). Growth in rice and maize production, on the other hand show exponential growth. The annual growth rate in maize production and harvested area grew from 10.1% and 8.4% respectively in the time period between 1961 to 1990 to 13.9 % and 12.2% respectively between 1991-2016 (Figure 1.10). Similarly, the annual growth rate in rice production and harvested

area grew from 5.6% and 4.8% respectively in the time period between 1961 to 1990 to 9.8% and 5.4% respectively between 1991-2016 (Figure 1.11). According to Staatz et al. (2011) the growth of rice and maize production in the country since the 1990s was driven liberalization of the cereal market which incentivized improved irrigation infrastructure, seed varieties and availability of fertilizers (Staatz et al, 2011). The average annual production growth rate of cotton declined from 12.66% between 1961-1990 to 10.11% between 1991-2016. The sharp declines in cotton production in years 1986, 2001 and 2008-2009 coincides with the sharp fall in global cotton prices in 2001 and 2009 (Figure 1. 12).

Mali was a lead exporter of cattle in the Sahel in the early 1960s (Davies, 2016), but the droughts in the 1970s impacted mortality rates and livestock production. The decline in livestock counts, especially cattle, coincides with the drought period in the 1970s and 1980s (Figure. 1.13).

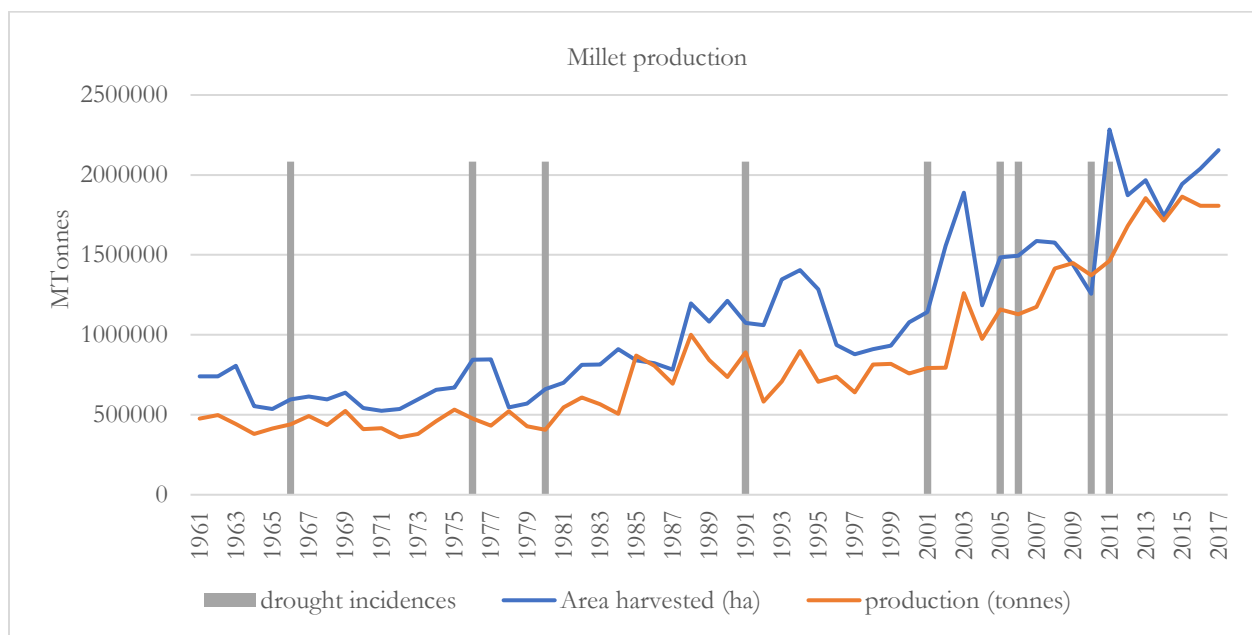


Figure. 1.8. Millet production and harvested area trends (1960-2016)

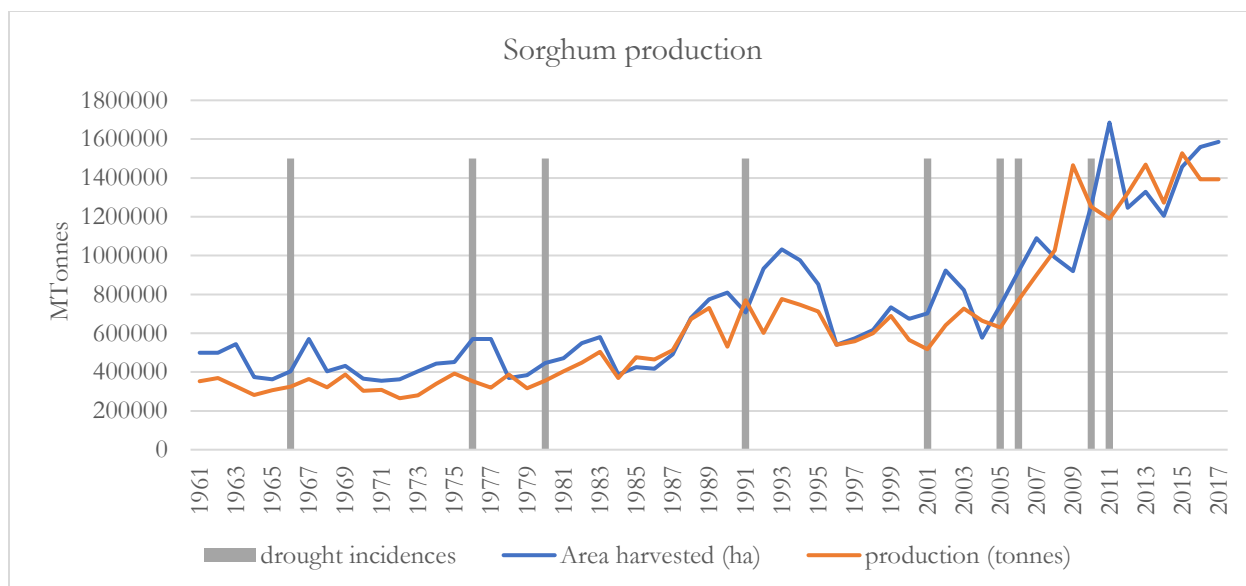


Figure. 1.9. Sorghum production and harvested area trends (1960-2016)

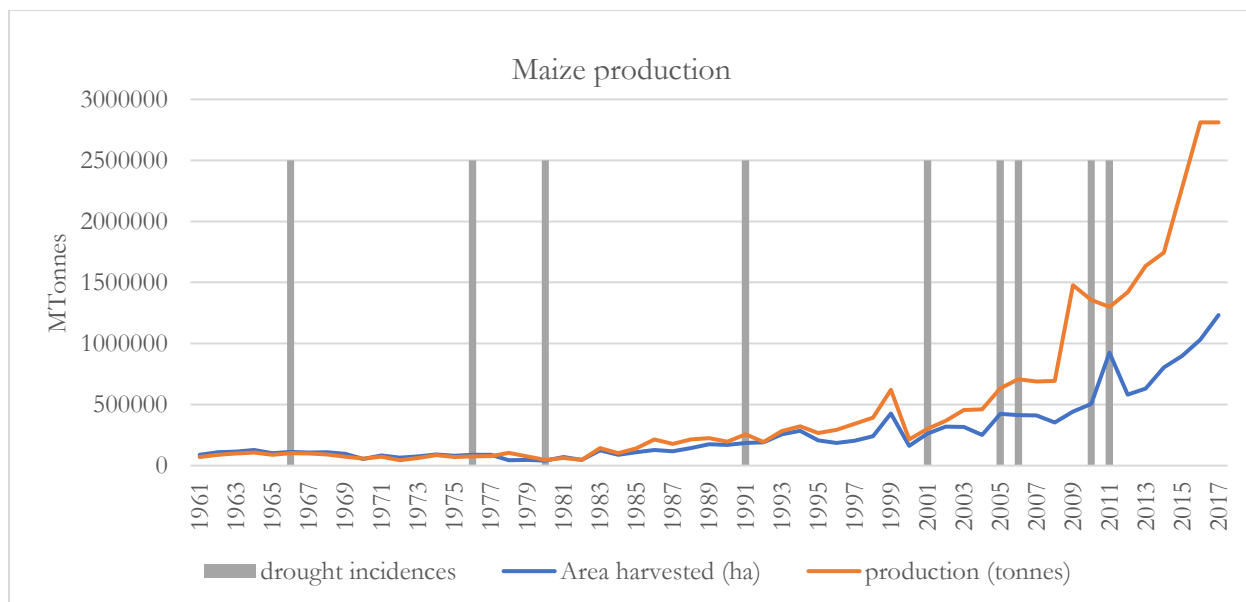


Figure. 1.10. Maize production and harvested area trends (1960-2016)

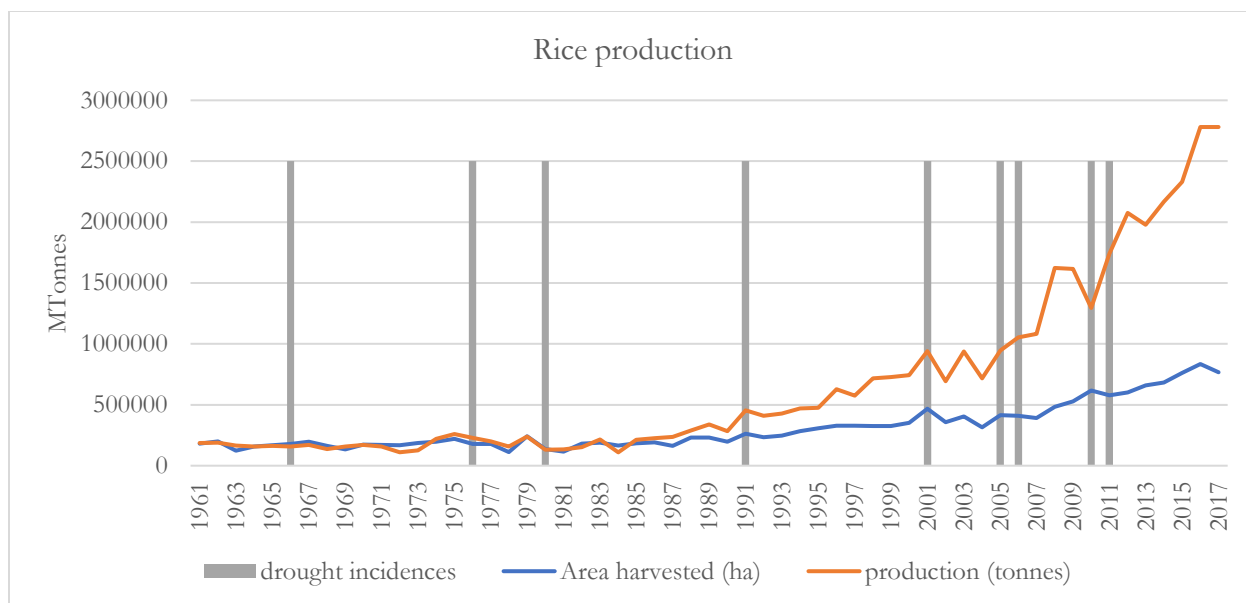


Figure. 1.11. Rice production and harvested area trends (1960-2016)

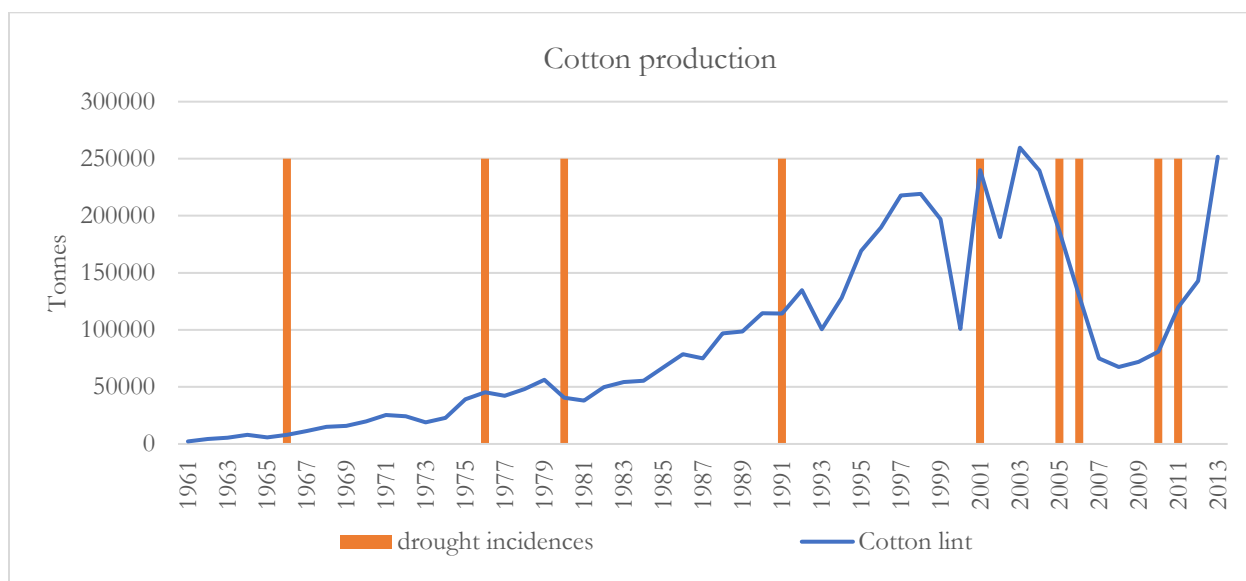


Figure. 1.12. Cotton production trends (1960-2016)

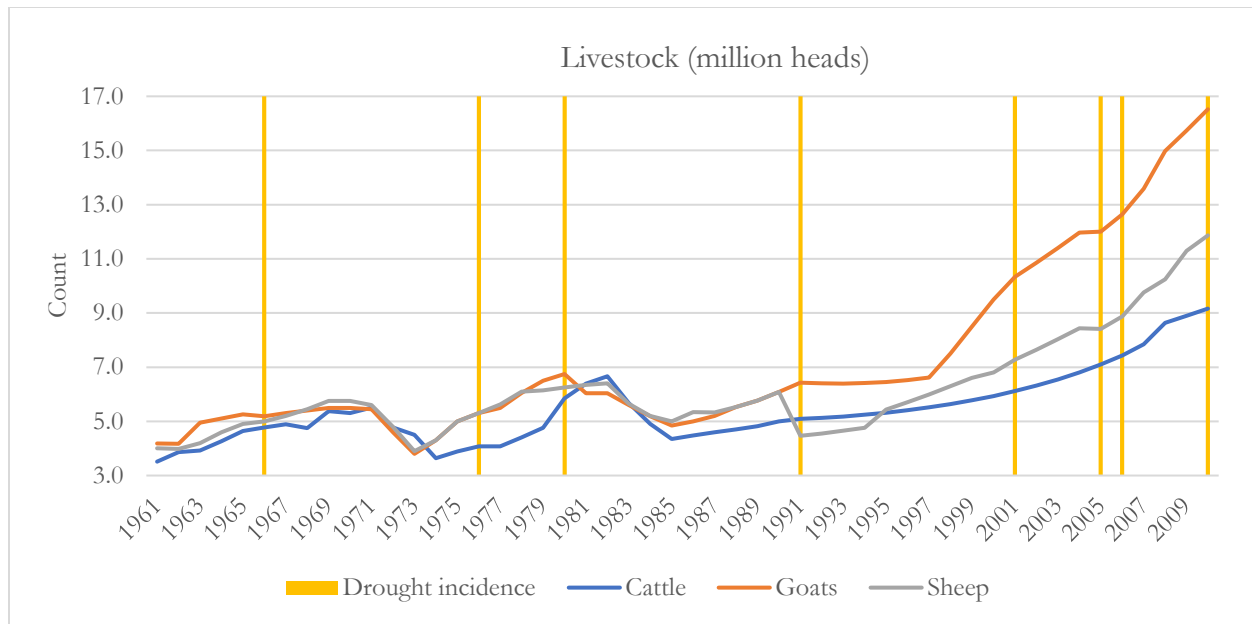


Figure. 1.13. Livestock population trends (1960-2017)

6.1.3. Demographic trends

Mali's population has increased exponential since independence from the French in 1960, from around 5.2 million in 1960 to more than 18 million in 2017 (Figure 1.14). Mali is and has been predominantly a rural population, but the percentage of the rural population has decreased from almost 90 percent in 1960 to around 60 percent in 2016; the percentage of urban population has increased from 10 percent in 1960 to 40 percent in 2016 (Figure 1. 15). According to the 2009 census, roughly 1.8 million people lived in the capital city of Bamako which is the largest city in Mali and seven other cities with over 100,000 inhabitants (CIA, 2009). The population trends in the largest city (the capital city of Bamako) show interesting dynamics in population trends (Figure 1.16): population in Bamako increased immediately after the drought in 1966 and peaks in 1976 followed by a period of population decline after 1991. This supports findings from other studies that high rates of migration of pastoralists from the severely affected areas in Northern Mali to the agro-pastoralism and agriculture-based areas in central and southern Mali were spurred by the droughts in the 1960s. This can be seen as a phase where transherdsmen and their families reached a tipping point in their livelihoods and responded to

droughts by migrating to the inner Niger delta or increasing production of domestic livestock such as goats and sheep instead of cattle (Bassett & Turner, 2007).

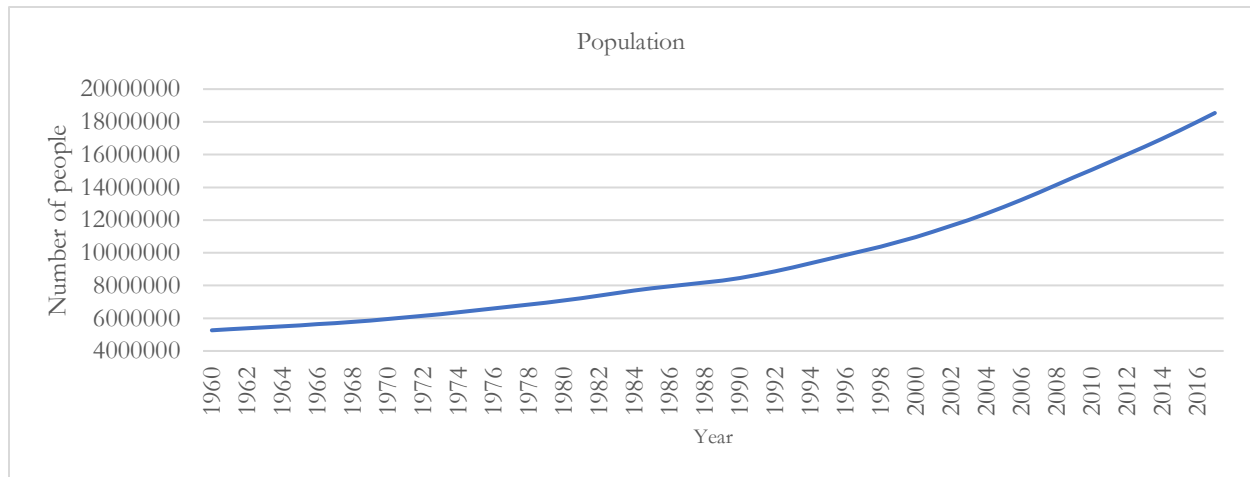


Figure. 1.14. Population growth (1960-2016)

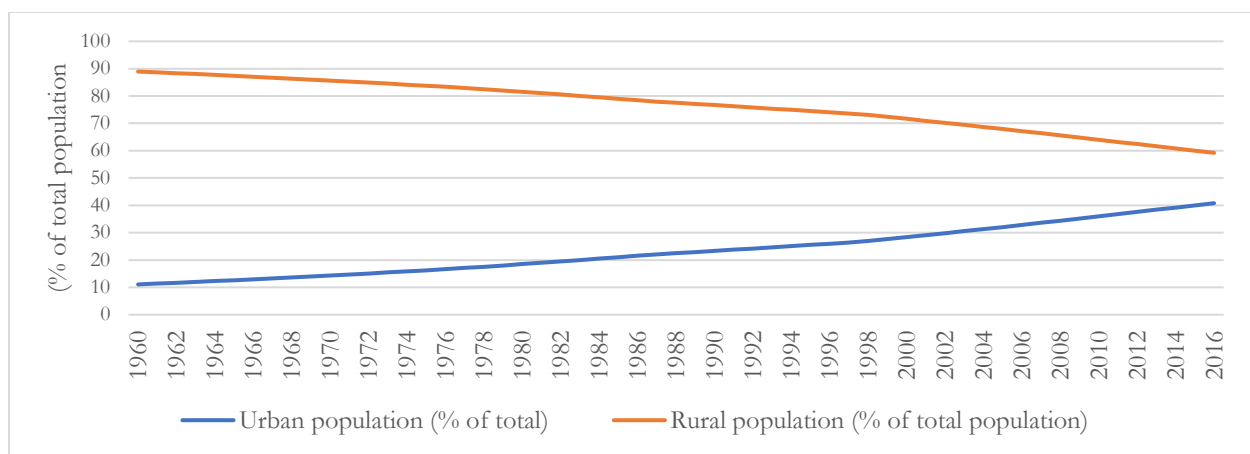


Figure. 1.15. Percentages of urban and rural population (1960-2016)

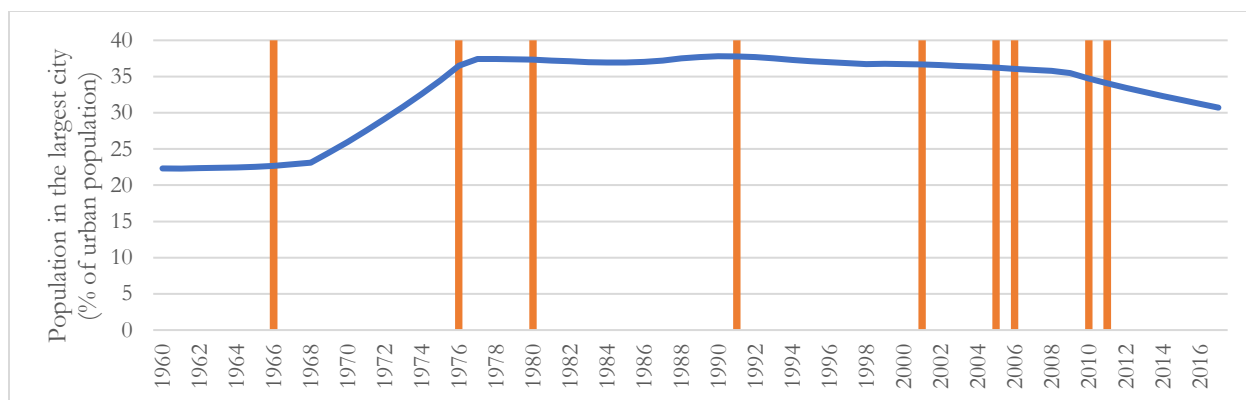


Figure. 1.16. Population trends in the largest city (1960-2016)

6.1.4. Food security and nutrition trends

Despite increased food production in Mali between 1991-2016, the number of people under significant and extreme food insecurity in Mali is on the rise. While there is an increase in food availability per capita for rice and maize since the 1960s; the availability of millet and sorghum (the staple food of Malians) has not shown any significant change over time (Figure 1.17). According to a study by Me-Nsope (2014), the average per capita consumption of millet, sorghum in West Africa has decreased over time while maize and rice consumption has increased.

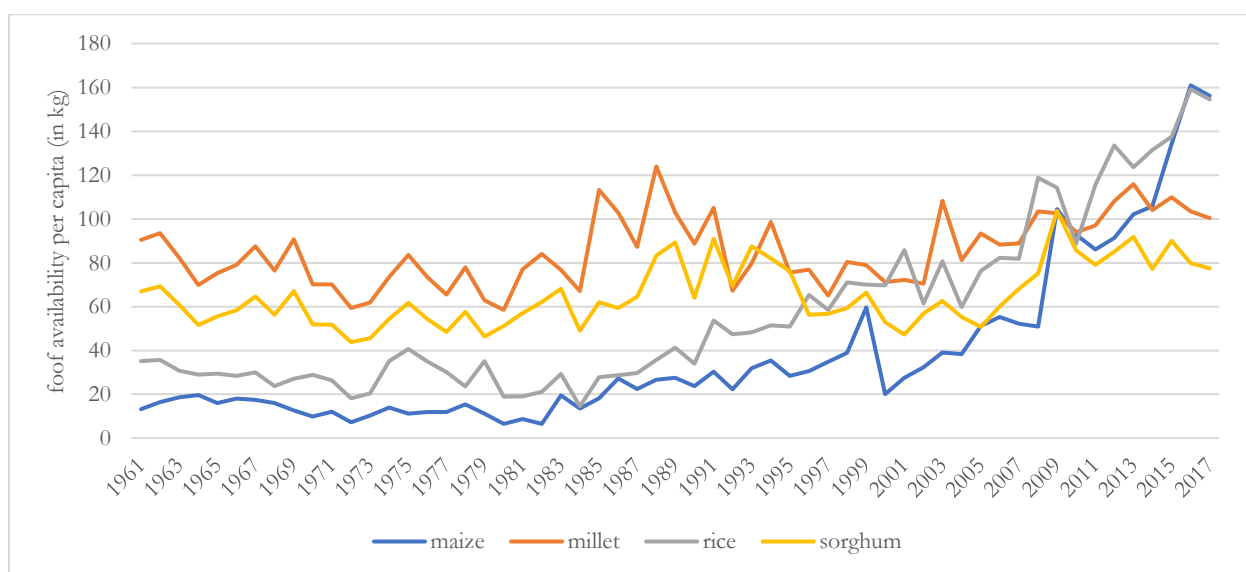


Figure. 1.17. Food availability per capita (1960-2017)

The Cercle-wise data from Emergency Food Security Assessment (EFSA) and *Enquête Nationale de la Sécurité Alimentaire* (ENSA) reports by the World Food Program (WFP) (2018) shows the percentage of food-insecure people in the pastoralist regions in North Mali (Gao, Kidal, and Tombouctou) is higher than agro-pastoralists who practice both sorghum and millet cultivation as well as livestock rearing in central (Koulikoro and Mopti) and southern agricultural regions (Kayes, Segou, and Sikasso). However, recent trends show that between 2013-2017, despite a higher overall percentage of food insecure people among northern pastoralist zones than central agro-pastoralists and southern agriculturists, there is a declining trend in food insecurity in the pastoralist regions and an increasing trend in overall food insecurity in the agro-pastoralist and agriculturist regions (Figure 1.18). Further, the percentage of children who are either stunted⁴, underweight⁵, wasted⁶ and severely wasted⁷ has not changed significantly over the period from 1987 to 2015 (Figure 1.19).

⁴ Stunting –Percentage of children under 5 who are below minus two standard deviations from median height-for-age of the WHO Child Growth Standards

⁵ Underweight –Percentage of children under 5 who are below minus two standard deviations from median weight-for-age of the World Health Organization (WHO) Child Growth Standards.

⁶ Wasting –Percentage of children under 5 who are below minus two standard deviations from median weight-for-height of the WHO Child Growth Standards.

⁷ Severe Wasting: Percentage of children under 5 who are below minus three standard deviations from median weight-for-height of the WHO Child Growth Standards.

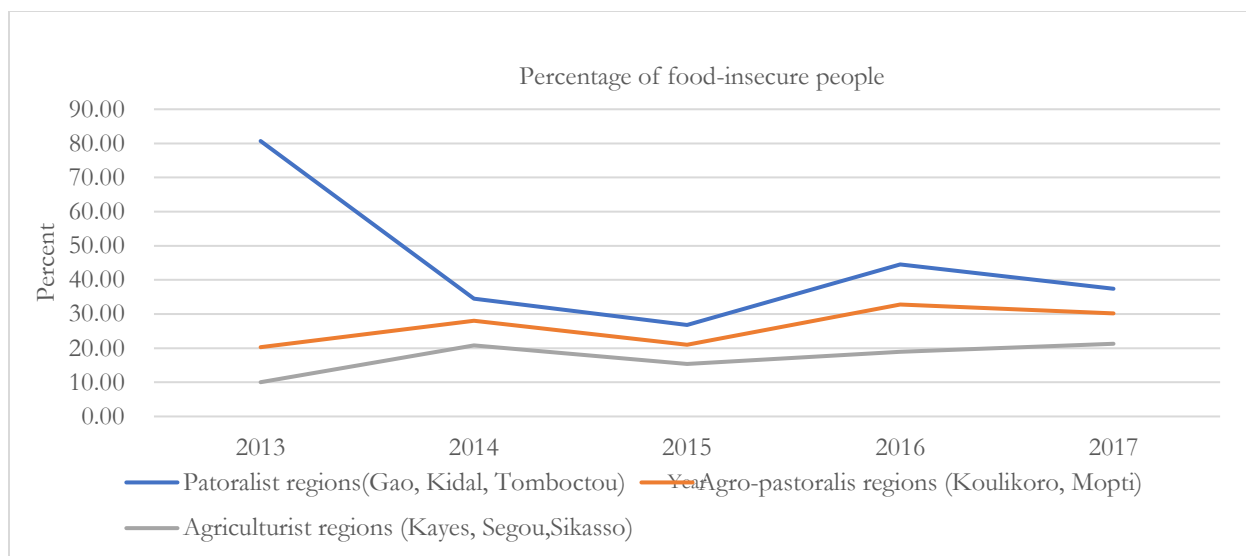


Figure. 1.18. Percentage of food insecure people by region (2013-2017)

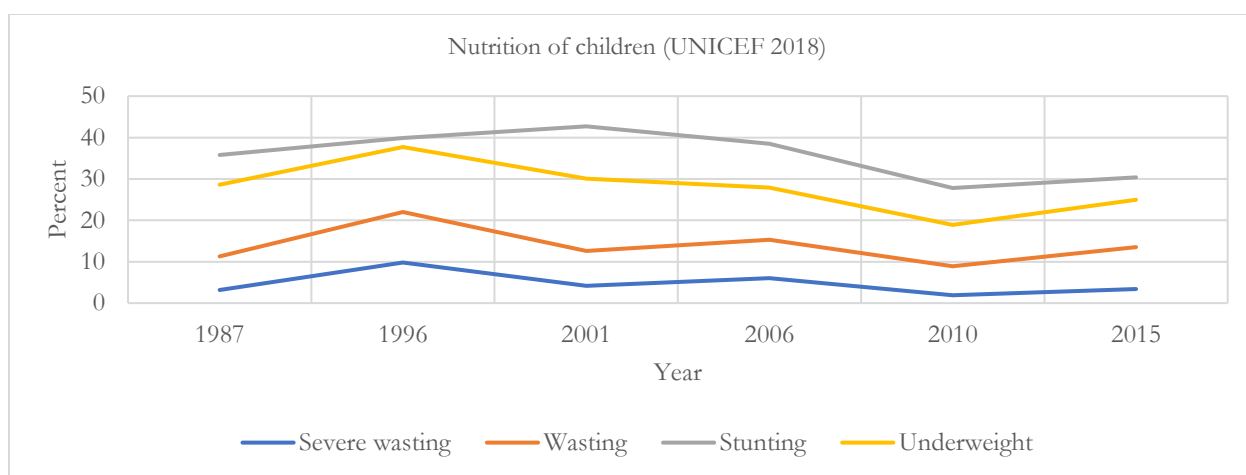


Figure. 1.19. Nutritional status of children (1987-2015)

Data from World Bank development indicators (2018), shows that food exports from 1960-2016 have declined over time. Trends in food imports show that during the 1970s and 1980s spiked in relation to the Sahelian droughts. Food imports including commodities such as food grains (primarily rice), live animals, beverages and tobacco, oilseeds, oil nuts, and oil kernels during 1995-2003 exceeded food exports (primarily cotton and livestock) including suggesting low national food sufficiency during that

phase (Figure 1.20). These trends in food export correlate with the incidences of droughts where export decline after each drought incidence in 1966, 1976, 1980, 1990, 2001, and 2010-2011.

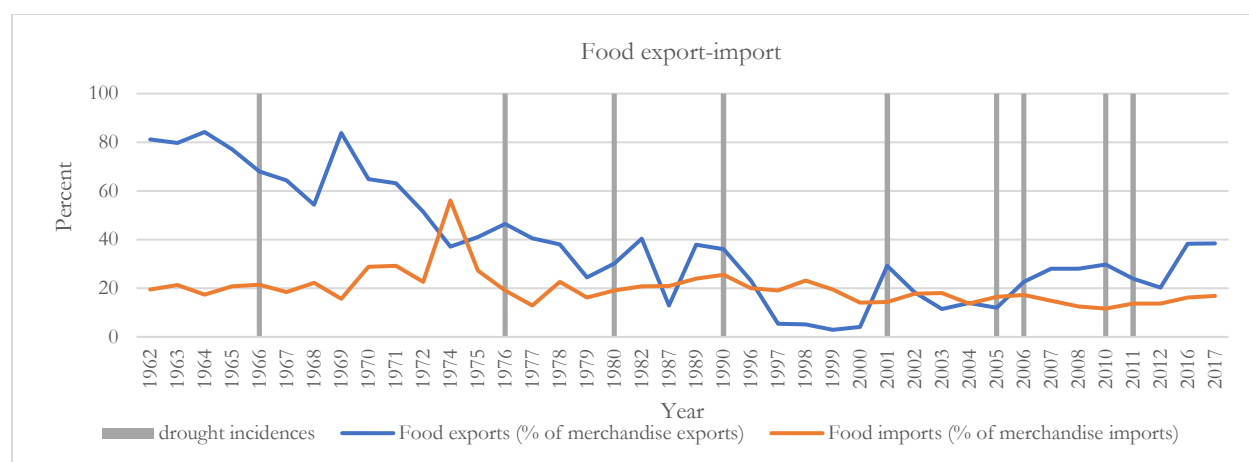


Figure. 1.20. Food import-export trends (1961-2016)

6.1.5. Political and institutional trends

Mali gained independence in 1960 from French colonization and has since undergone several political and institutional changes as a result of complex interlinked factors triggered by droughts, geopolitical conflicts, structural economic reforms, and global trade patterns. While a comprehensive review of all institutional changes that occurred between 1960 to 2017 is out of the scope of this paper, I highlight a timeline of the key institutional changes that influenced the livelihoods of Malians in terms of agricultural production (Table 1.2). There is evidence that the Sahelian droughts had an indirect influence in the geopolitical conflicts in Northern Mali where individuals from Tuareg tribes, already fighting for an independent state, migrated to neighboring countries such as Algeria and Libya and returned with arms and training supported by Al Qaeda by the early 2000s (Benjaminsen, 2016). The conflicts in the North and growing discontentment of people with corruption in the government eventually led to a series of military coups in 1968, 1991 and 2012 that further destabilized the country, especially in the Northern regions. Further, the droughts in the 1960s also rendered Mali heavily dependent on external foreign aid as the largest source of government revenue (R. A. Nielsen et al.

2016) and initiated a series of economic reforms in the country in the 1990s (Batterbury and Warren 2001). The cotton industry holds an important position in the nation's economy as it has been involved not only in export and economic rent to the elites but also as a source of livelihood to 1/4th of the Malian population. According to some scholars, the conditionalities imposed by various aid sponsors such as World Bank, IMF, etc. such as decentralization, privatization of the cotton industry, etc. inhibited the strengthening of existing governance structures in post-colonial Mali and created an environment where corruption fostered (Sidibe et al. 2018).

To address farmers' lack of financial resources and credit system, in the mid-1980s to mid-1990s, an interlocked credit cotton-input system was introduced. Improved access to inputs was one of the main reasons for the increase in cotton yield. In the 1980s, national cotton company CMDT started incurring state debt due to the fall in international cotton prices. This led to growing discontent among farmers against corruption and lack of transparency within CMDT, and in 1991 farmers organized a series of large-scale cotton boycott and protests. The strike coincided with the toppling of the military regime in Mali and the democratic movement in March 1991. Farmers demanded policy reforms that were accompanied by a larger shift in the institutional environment in the country from a military-led regime to a democracy. By the early 2000s, the Malian government also implemented several institutional reforms by converting above 7000 village associations into cotton producer cooperatives *Sociétés coopératives des Producteurs du Coton*, SCPCS. The SCPCS were a part of a five-level pyramid structure of cooperatives where members were democratically chosen, and the benefits and risks were shared within the cooperatives. Producers could form their own groups and could legally exclude high risk, indebted farmers from membership. However, in reality, only some of the existing village associations split in smaller SCPCS because of traditional social norms, kinship and a sense of solidarity among village members who did not want to exclude other poorer, indebted farmers from their group. As a result, most cooperatives still struggle to maintain their credit (Theriault and Sterns, 2012).

1960	Mali gains independence from France. Mobido Keita becomes the country's first president.
1962	Mali establishes its own currency, the Malian Franc.
1962-64	First Tuareg Rebellion led by separatist Nomadic Tuareg peoples in the north of Mali
1968	A coup led by Moussa Traore overthrows Mobido Keita's regime.
1968-74	Mali suffers from a major drought
1974	Malian government nationalized the cotton sector and created a new company CMDT
mid-1980s to mid-1990s	An interlocked credit cotton-input system was introduced ; a series of structural adjustment programs that opened trade to the private sector
1990-95	Second Tuareg Rebellion begins in June 1990
1990s	International donors such as World Bank and IMF pushed for privatization and liberalization of cotton sector in Mali
1991	Farmer within various village associations organized a second large scale cotton boycott due to corruption and lack of transparency within CMDT
1992	First democratic elections Alpha Konare is elected president, and then re-elected in 1997
1998	Implementation of Malian decentralization reform
2001	Several institutional reforms by converting above 7000 village associations into cotton producer cooperatives <i>Sociétés coopératives des Producteurs du Coton</i> , SCPCs
2002	Amadou Toumani Toure, who led the 1991 coup overthrowing Traore, is elected president
2005	World Food Programme warns of severe food shortages, the result of drought and locust infestations in 2004
2007	Cotton crises due to fall in global cotton prices
2012	A new government is formed under Prime Minister Cheick Modibo Diarra

Table 1.3. Timeline of political and institutional trends in Mali (1960-2016)

6.2. Analysis of adaptive cycle in Malian Agricultural SES

In this section, I present an analysis of the adaptive heuristics of country-level Malian agricultural SES from 1960-2017, divided into four phases viz. phase 1 (1960-1980); phase 2 (1981-1990); phase 3 (1991-2000) and phase 4 (2001-2017). The system's potential and connectedness are assessed

based on insights from the environmental, agricultural production, demographics and institutional trends described in the previous section.

6.2.1. Phase 1: Time period (1960-1980) (Collapse)

During this phase, the total annual production of food crops such as millet, sorghum, maize, and rice show an interannual variability in response to annual temperature and precipitation, however, overall production levels remained stable over time. Cotton production increased slightly. However, the annual food availability per capita declined in this period where millet availability declined by 1.2 kg per year per person; sorghum availability declined by 0.7 kg per year per person; maize production declined by 0.4 kg per year per person and rice availability declined by 0.2 kg per person per year. During this phase, livestock production declined in the 1970s and increase to its previous levels around 1980. This, it can be inferred that the country-level natural capital declined during this phase.

Through analysis of historical famines in various regions of the world, Dirks et al. (1980) identified three phases of social and economic behavior as food insecurity intensifies. In the 'alarm phase', or the early stages of shortage, as food insecurity increases social and economic activities also increase (such as buying and sharing of food). Social bonds, reciprocity, and kinship ties intensify and people share their resources with one another. According to (Adams 1993), this trend certainly held true for rural households in Mali during the famines that occurred between 1960-1980 where food sharing provided “a vital (but not exclusive) means of minimizing risk in an uncertain environment”. Based on this argument, social capital levels can be considered high during this phase. Further, high levels of internal displacement and migration patterns of people from rural to urban areas show a decline in human capital during this period. Data from the World Bank on per capita income levels and count of agricultural machinery show that financial and physical capital remained low. The connectedness

of the system in this phase as a measure of the ability of the system to control⁸ its destiny can be seen as decreasing externally driven patterns of climate patterns governed food production and scarcity. Low levels of natural, physical, human and financial capital in the system suggest an overall low potential of the system which when combined with decreasing levels of connectedness, suggests that during this phase, the resilience of the system was low and Malian agricultural SES existed in the collapse phase.

6.2.2. Phase 2: Time period (1981-1990) (Reorganization)

During this phase, the production of food crops such as millet, sorghum, maize, and rice as well as cash crops such as cotton increased. The annual food availability per capita increased as well where millet availability increased by 3.9 kg per year per person; sorghum availability increased by 2.4 kg per year per person; maize availability increased 2.19 kg per year per person and rice availability increased by 2.03 kg per person per year. During this phase, livestock production declined. Natural capital increased as did other forms of social capital in the form of formal and informal village associations and cooperatives. An interlocked credit cotton-input system was introduced by the cotton company CMDT to help farmers access crop inputs such as fertilizers and seeds on credit, increasing the financial capital of the system. Physical infrastructure in the form of irrigation structures built by the Office du Niger, increased the physical capital. Human capital increased as erstwhile pastoralists and herdsmen started adapting by adopting farming livelihoods stabilizing the high rates of internal migration. Overall, the potential of the system increased during this phase.

With the privatization of the cotton company, the connectedness of the system decreased as external players such as the World Bank and IMF and the global market prices played an increasing role in the cotton market through market liberalization. Increasing levels of potential and decreasing

⁸ Connectedness of a system is often confused with the connectivity or social capital of the system. In this paper, I make a distinction of connectedness as the ability of a system to control its destiny. Social capital and levels of connectivity within the actors in the social capital is seen as a component of the potential of the system in the form of human capital.

connectedness of the system suggest that during this phase the resilience of the system increased and the Malian SES transitioned into the reorganization phase.

6.2.3. Phase 3: Time period (1991-2000) (Growth)

During this phase, the total annual production of food crops such as maize and rice as well as cotton increased. The rate of increase in maize production was lower than rice and maize production experienced a sharp decline in 2000. The production of millet and sorghum showed an interannual variability in response to the variability in temperature and rainfall. Overall, the production levels in this period neither increased nor decreased. Correspondingly, the per capita maize availability increased by 1.2 kg per person per year and rice availability increased by 2.7 kg per person per year. The availability of millet and sorghum decreased by 1.9 kg per person per year and 3.6 kg per person per year respectively. Livestock production increased during this phase with the rate of increase in goat and sheep production higher than cattle. Hence, natural capital increased.

Social capital increased as evidenced by the organization of large-scale national boycott of cotton production by farmers in existing village organizations organized to protest corruption and lack of transparency within the cotton company. Physical capital indicated by the number of agricultural machineries increased during this phase. According to World Bank data [2018], the number of agricultural machineries in the mid-1990s was 25 times as much as the numbers in the 1960s. Human capital increased as literacy rates doubled from 9.4% in 1976 to 19% in 1998 [World Bank 2018].

Thus, there is evidence of increase in potential of the system during this phase. This phase also coincided with the national level cereal liberalization policies and hence the connectedness of the system also increased. Increasing levels of potential and increasing connectedness of the system suggest that during this phase the resilience of the system increased and the Malian SES transitioned into a growth phase.

6.2.4. Phase 4: Time period (2001-2017) (Conservation/Collapse)

During this phase, the total annual production of food crops including millet, sorghum, maize, and rice increased sharply. The rate of increase in maize and rice production was significantly higher than millet and sorghum due to improved crop varieties and irrigation facilities. The per capita maize availability increased by 8 kg per person per year and rice availability increased by 5.6 kg per person per year. The availability of millet and sorghum decreased by 1.8 kg per person per year and 2.3 kg per person per year respectively. Livestock production, especially for goats, increased sharply during this phase along with sheep and cattle. This suggests an overall increase in the natural capital of the agricultural system.

In this phase, several institutional reforms were implemented with the aim of converting village associations into cotton producer cooperatives *Sociétés coopératives des Producteurs du Coton*, SCPCs. The SCPCS were a part of the 5-level pyramid structure of cooperatives at the village level, commune level, sectoral level, and regional level unions. The government also established the National Alliance of Cotton Cooperatives (*Union National des Sociétés Coopératives des Producteurs du Coton*, UN-SCPCs in 2007 which composed of the four regional unions. UN-SCPCs were responsible for negotiating, purchasing and distributing inputs at the beginning of growing season along with setting the cotton prices. Unlike the village, SCPCs had legal status and were financially autonomous and could make transactions and have contracts with financial institutions independently. Members were democratically chosen, and the benefits and risks were shared within the cooperatives. Producers could form their own groups and could legally exclude high risk, indebted farmers from membership. However, in reality, only some of the existing VAs split in smaller SCPCs because of traditional social norms, kinship and a sense of solidarity among village members who did not want to exclude other poorer, indebted farmers from their group. As a result, most cooperatives still struggle to maintain their credit. This is indicative of the high levels of social capital among the farmers.

Cotton production declined sharply during 2008 and 2011 in response to the decline in global cotton prices. This also suggested a decline in the connectedness of the system where agricultural systems in Mali were highly tied to global and national market fluctuations. The system's ability to "internally control its own destiny" decreased.

The increasing potential and decreasing connectedness of the system suggest another decline in the resilience of the system, placing the system at the intersection between conservation -collapse phase.

6.3. Analysis of regime shift in Malian agricultural socio-ecological system

These changes are highlighted in the 100% stacked area charts of proportional changes in agricultural and livestock production systems in Mali from 1960-2017. Figure 1.21 shows how the constituent parts, that is, crop production of cotton, millet, sorghum, maize and rice within the total agricultural production system have changed over time. The y-axis represents the percentage proportion of the production of each crop type in the production system at any given time (x-axis). The area within each color represents the proportion of production of each crop within total agricultural production over the period 1961-2017 (Figure 1.22). Figure 18 shows how the proportion of cattle, sheep and goat production changed over time.

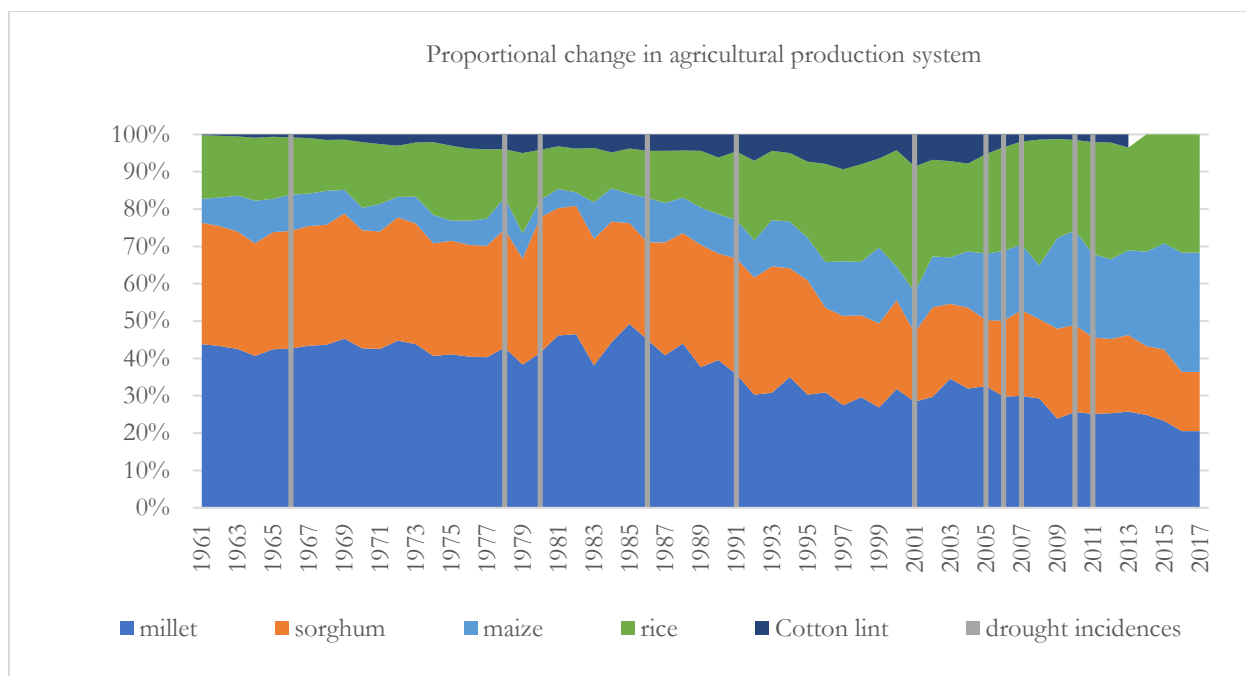


Figure. 1.21. Stacked area graph of agricultural production (1960-2016)

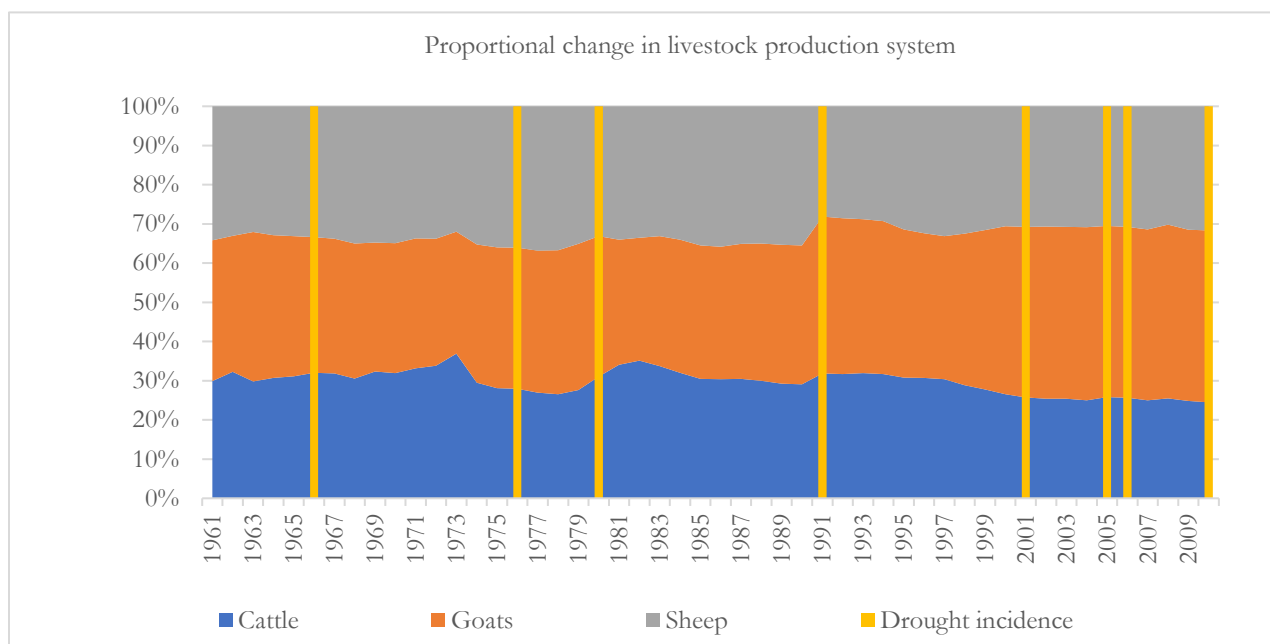


Figure. 1.22. Stacked area graph of livestock production (1960-2009)

The proportional changes in agricultural and livestock production from 1960-2017 show that between 1960-1990 (Figure 1.21 & 1.22), millet and sorghum dominated the agricultural production system; similarly, cattle production dominated the livestock production system. The period between 1991-2017 shows a shift in the agricultural and livestock regime where maize and rice production dominated agricultural production instead of sorghum and millet. Cattle dominated livestock production system shifted to a goat and sheep dominated production system.

As I posited in the introduction section, the Malian agricultural socio-ecological system has shown resilience despite the droughts in the 1960s to the 1980s. Historical process tracing of the Malian SES shows that the frequency of drought incidences has doubled from the 1960-1980s to the 1980s - present. Despite these changes, agricultural production in Mali has increased over time. However, the droughts in the 1960s did indeed bring about a regime shift in the Malian SES.

7. Conclusion

In the book “Adaptation to Climate Change: From resilience to transformation”, Pelling (2011) argued that adaptation is much more than a technical response but a “social and political act”. Despite a narrative of sub-Saharan Africa as a region with high vulnerability and low resilience; this chapter highlights a historical perspective of the changes in Malian agricultural SES within the adaptive cycle framework and suggests that Mali exhibited stages of high resilience during the collapse, reorganization and growth stages that followed the 1960s and beyond.

While complex socio-ecological systems function through the interaction of a multitude endogenous and exogenous factors (Roe, 1998); the key processes that guide the behavior of the socio-ecological system are dependent on a smaller set of “critical controlling factors or variables” that enable the system to self-organize and transform during the “evolutionary process of social development” (Holling 2001: 392). An assessment of the past development trajectories between 1961 -2017 as elucidated in the results section shows that the Malian production systems in agriculture and livestock,

as well as urbanization trends, exhibit two distinctive patterns; one between 1960-1990 and another between 1991-2017. Between 1960-1989, the production of both agriculture and livestock was primarily driven by drought incidences and variability in annual temperature and precipitation. Between 1990-2017, agriculture and livestock production were driven by environmental changes including increased frequency of droughts, increase in temperature and decline in precipitation over time as well as institutional changes such as the reforms in the cotton sector, cereal market liberalization and fluctuation in global cotton prices. As we observe from the adaptive cycle heuristics, the Malian agricultural SES underwent a collapse phase in 1960-1980 to reorganization phase (1981-1990) to growth (1991-2000) and is presently at a cusp of growth and conservation phase (2001-present). Within each of these phases, the Malian agriculture SES has shown an ability to persist and transform itself to external environmental and non-environmental stressors. Within these changes, the role of ‘human agency’ of Malians in adapting to such changes by leveraging their social capital both within their households and within their communities have often been undervalued. For example, Adams (1993) highlights the role of ‘moral economy’ in helping Malians cope with periods of severe food security where gift giving, non-market credit and labor exchange provided almost 50 percent of food during the food shortage period in 1988. In fact, during the agricultural season of 1988 when food insecurity was widespread, 27 percent of households received food gifts compared to 13 per cent during the mild shortage of 1989 (Adams, 1993). Further, competitive market- based structural reforms in Mali, such as the promotion of farmers associations that enable farmers to organize themselves based on competitive advantages, have been rejected by some farmers who leaned towards helping weaker farmers due to pre-existing social ties within the village (Staatz et al., 2011). The strength of informal social institutions in Mali are quite strong and have developed over time due to people’s need to bank on each other during hard periods of famine and droughts.

High levels of social capital combined with technical agricultural reforms and land expansion enabled Mali to transition from a collapse phase and reorganize itself to another agricultural regime where maize, rice and smaller livestock production became dominant components of the agricultural production system. However, this shift has also led to an enhanced sensitivity of Malian agricultural landscape to external climate and non-climate drivers such as global market price fluctuations. Further, the overall decline in the proportion of staple food crops such as millet and sorghum production has important repercussions on the overall food security of households in Mali. According to Traoré et al. (2007), traditional crops such as millet and sorghum are already highly adapted to variability in rainfall and are less affected by an increase in temperature (Sultan and Gaetani 2016). Maize and rice are more sensitive to fluctuations in temperature and precipitation (Sultan and Gaetani 2016). This, combined with future climate projections of a warmer Sahel and higher variability in rainfall, positions Mali into the precipice of another possible collapse and make Mali more vulnerable to the effects of climate change, in particular, changes in temperature and rainfall patterns.

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CHAPTER 2:
THE MALIAN PRESENT: A PARTICIPATORY GAME DESIGN APPROACH TO
EXAMINE CAUSAL PATHWAYS OF BARRIERS AND OPPORTUNITIES FOR FOOD
SECURITY AND CLIMATE ADAPTATION IN SOUTHERN MALI

1. Introduction

Persistent droughts, dependence on rainfed agriculture, high levels of poverty, population growth and political and social conflicts have rendered West Africa extremely vulnerable to food and livelihood insecurities (Brown, Hintermann, & Higgins, 2009; Grist & Nicholson, 2001; Nicholson, Some, & Kone, 2000; Thornton et al., 2008, Sissoko et al., 2011). Mali, a landlocked country in West Africa, with a population of around 14 million (Mali census 2009) and a majority 66 percent (in 2006) of its population involved in subsistence agriculture (World Bank, 2015), is emblematic of the struggles of food insecurity and climate vulnerability in the West African region. According to the Global Report on Food Crises (2017), in 2016, around 2.1 million people in Mali were considered food insecure, with more than 200,000 individuals facing conditions of extreme food crisis, emergency, and famine (WFP, 2017). The Malian government has been investing considerable amount of resources in developing its agricultural sector and related technologies to combat food insecurity and hunger in the region including the appropriate technologies, information systems, institutional support and market opportunities to enhance the capacity of farmers to improve food security in the country (Andrieu et al. 2017; Bingen 1998). However, even though the production of staple and cereal crops has steadily increased since the 1970s (Giannini et al, 2017), the number of people facing chronic and persistent food insecurity and malnutrition has been steadily increasing in the past decade and may continue to rise in the context of current climate projections for a drier and hotter Sahel (Sultan and Gaetani 2016; Traore et al. 2013, 2015; Traoré et al. 2007). This warrants a closer investigation, beyond food production, on the structural root causes and ‘barriers’ that inhibit farmers from achieving food security for their households and adapt to climatic stressors.

Barriers have been defined in adaptation literature as *‘challenges, obstacles, constraints or hurdles that impede adaptation’* (Eisenack et al., 2014 p. 867) and are different than ‘limits’ to adaptation in their ability to be surmountable (Eisenack et al., 2014, Adger, 2008, Laube et al. 2012; Hulme et al. 2007; Dow, 2013). In the past decade, there have been various assessments of barriers to climate change adaptation (Antwi-agyei, Dougill, & Stringer, 2015; Barnett et al., 2015; Biesbroek, Klostermann, Termeer, & Kabat, 2013; Eisenack, 2012; Matasci, Kruse, Barawid, & Thalmann, 2014; Moser & Ekstrom, 2010; Nielsen & Reenberg, 2010b, 2010a; Shackleton, Ziervogel, Sallu, Gill, & Tschakert, 2015; Spires & Shackleton, 2017; Uittenbroek, Janssen-Jansen, & Runhaar, 2013). At a theoretical level, such studies either categorize barriers as financial, technological, cognitive, cultural and institutional (Eakin and Luers 2006)(Adger et al, 2007, Field et al. 2010) or more broadly as natural (including physical and ecological barriers), human (including informational, knowledge, technological and economical barriers) and social (including cognitive, normative and institutional barriers) (Jones and Boyd 2011). Moser & Eckstrom (2010) take a more intersectional approach towards classifying barriers in adaptation planning within leadership, resources, communication, information, values and belief categories. However, most assessments of barriers have followed a normative “structural-functional logic’ where barriers are viewed as static impediments that need to be ‘overcome’ for adaptation to take place (Biesbroek et al. 2013). While it is important to identify and isolate the factors that function as barriers to adaptation in a system, such static view precludes a more nuanced understanding of the causal mechanisms and the interactions of the elements within the realm of adaptation decision-making and thereby create these barriers in the first place (Biesbroek et al., 2013; Eisenack et al, 2014). In particular, Shackleton et al. (2015) who conducted an extensive literature review of the state-of-knowledge on the barriers of agricultural adaptation in sub-Saharan Africa, *“few [of the] studies ask why these barriers emerge, and most pay little attention to the underlying political-economic and structural factors that create the constraints mentioned and that makes farmers vulnerable in the first place.”* (p. 329). Shackleton et al. (2015)

and other scholars (Biesbroek et al. 2013; Eisenack et al, 2014) have called for further research in addressing gaps in understanding the mechanisms or pathways of creation of barriers with a focus on the developing decision-centered approaches for analysis of adaptation barriers (Eakin et al. 2016; Wise et al. 2014).

In this paper, we address the research gaps in the ‘barriers’ of adaptation literature in two ways: first, we step away from the view of barriers as static impediments and adopt a system thinking approach (Barry 1993) that focuses on the dynamic feedbacks and interaction of the elements within a system. Second, the participatory nature of our approach ensures that we explicitly incorporate the experiential knowledge of farmers on the various factors that influence their decisions on agricultural production and climate adaptation. This paper has three main objectives: (i) to introduce an innovative methodology of participatory simulation game design that identifies the decision-making factors that influence food cultivation and climate change adaptation among rural farmers in Southern Mali; (ii) to conduct a systems analysis of the causal pathways or mechanisms of barriers of food security and climate adaptation and (iii) to identify and elucidate key leverage points (Meadows, 1999) and solutions that can channel the conversion of ‘barriers’ into opportunities to improve food security and adaptive capacity of farmers in the region. We identify and elucidate key leverage points (Meadows, 1999) and solutions that can channel the conversion of ‘barriers’ into opportunities to improve food security and adaptive capacity of farmers in the region. In the following sections, we highlight the main theoretical background for this study (**Section 2**), before elaborating on the methodology, design, and analysis of the ‘Food and Farm’ simulation game and systems analysis of barriers to food security and adaptation (**Section 3-4**). We discuss the results in **Section 5** and conclude with specific policy recommendations in **Section 6**.

2. Systems thinking and agricultural adaptation

In this paper, assessment of barriers in agricultural adaptation follows a system thinking approach where to answer any question of “what causes what effect?” the focus is on a deeper understanding of the underlying structure of the causal factors in a system. (Risbey et al. 1999). System thinking was initially coined in the 1900s by Barry Richmond (1987) and later developed by scholars such as Senge (1990) and Sweeney & Sterman (2000) as a discipline or framework that focuses on interactions and feedbacks within the elements of a system that lead to a dynamic behavior of the system over time. Drawing from the principles of systems thinking approach, we apply two diagnostic methodologies to assess the elements of the system and the causal mechanisms that operate within the system. First, we applied the participatory game design approach to assess the factors that guide agricultural decisions and actions and second, we use causal loop diagramming to assess the feedbacks and interactions of the elements within the system.

According to Schiere et al (2004), a systemic approach to assessing agricultural systems utilizes methodologies where the observer of the system is a part of or is embedded within the system as opposed to a positivist measurement of facts and observations where the observer is an outsider. The systemic approach recognizes that the functionality and operationalization of the system are subject to interpretive subjectivity and constructivism based on the observation lens. Such analysis then necessitates the participation of agriculturists in enhancing the understanding of not only the system’s structure and behavior but also the decision-making contexts of the agents within the system. Assessing the decision-making context is particularly important because our knowledge of the decision-making ‘processes’ through which farmers adapt to various climate and non-climate stressors is limited (Edwards-Jones 2006). Here, adaptation is defined as the “*process of maintaining various farming objectives (such as yield, basic survival, and aversion of hunger, profitability) in the face of changes in external conditions*” (Risbey et al, 1999 pg 138). Crane, Roncoli, and Hoogenboom (2011) and others argue that agricultural

adaptation are more than technical responses to biophysical changes but are dynamic and embedded within the social, institutional and cultural contexts in which they are placed Paul Richard's (2002) conceptualized agriculture as a 'performance' where farmers enact agricultural decisions with 'some degree of informed spontaneity' as opposed to a calculated deliberation to reach a decision. Following an inductive approach of understanding the *performative* processes of how farmers grow food and the decision-making process of agricultural adaptation, the participatory simulation game design approach situates players as performers of agricultural adaptation where players co-design the rules of the game that matches their experiential knowledge and allows them to make '*sequential adjustments to unpredictable conditions*' (Richards 1992, pg 67). The participatory decision-centric approach also allows for the identification of the causal mechanisms that influence food security and climate adaptation among farmers. These mechanisms are illustrated in a causal loop diagrams or stock and flow processes where researchers/ modelers articulate a problem and develop dynamic hypothesis of how the system functions.

Unlike linear modelling approaches, where the assumption is that the causal factors are independent of each other and contribute to a linear effect on an outcome, system dynamics modelling approach focuses on the interactions between the causal factors where factor A influences factor B which influences factor C which in turn influence factor A, leading to system behavior which is more than the sum of its individual parts (Barry 1993). These circular processes are called feedback processes and may either stabilize a system's behavior over time (balancing or negative feedback) or may reinforce a system's behavior (reinforcing or positive feedback) (Barry 1993; Feola and Binder 2010). In short, creation of the causal loop diagrams centers around identification of key variables or causal factors in a system and formalized by breaking down the system into individual steps of identifying the key resources (also known as stocks) and the forces which "control, drive or transfer" these resources (Coyle 2000; Wolstenholme and Coyle 1983). The feedback loops are then superimposed

or connected with each other to create a collective diagram which form the basis of a qualitative or quantitative analysis of system behavior over time (Coyle 2000). While construction of causal loop diagrams is often considered a precursor for the quantitative calibration and simulation of the model. However, scholars have highlighted that qualitative assessment of the feedback structures in a causal loop diagram can itself can reveal important insights into a problem that does not necessitate the formalizing of the models into quantitative system dynamics models. (Coyle 2000; Luna-Reyes and Andersen 2003; Wolstenholme and Coyle 1983). In this paper, we mainly focus on the qualitative assessment of causal loop diagrams generated through the analysis of participatory simulation game where the three decision factors isolated from the qualitative assessment of the games are developed in to feedback structures which are then superimposed to construct a collective ‘causal loop diagram’ that illustrates the barriers to food security and climate change adaptation of households.

3. Study Area

The study area for this research is the Koutiala district in the cotton zone of Sikasso region in Southern Mali (Figure 2.1). Koutiala has a Sudanian climate characterized by an alternation of a dry season and a rainy season that lasts about six months each. The agricultural system in Koutiala is mainly a rainfed with cotton as the main cash crop along with food crops such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), maize (*Zea mays*), rice (*Oryza sativa*), groundnuts (*Arachis hypogaea*), and cowpeas (*Vigna unguiculate*) (Traore et al., 2013). Sikasso region provides an interesting context for the study due to the ‘agricultural paradox’ in the region where despite higher land fertility and higher annual rainfall than the rest of the country, it’s one of the poorest regions in Mali with high incidences of malnutrition and food insecurity (Delarue et al, 2009; Dury & Bocoum, 2012; Cooper & West, 2017). Scholars attribute this paradox to agricultural policies related to cotton production and market reforms in the area that led to price fluctuations (Cooper and West 2017; Delarue et al. 2008) as well as climate risks such as increase in temperature, uncertainty in rainfall patterns and increase in extreme weather

events have led to a decline in the yield of cotton and maize (Staatz et al, 2011). There is evidence that increased incidences of pests and diseases in agriculture have had immediate impacts on food production, distribution, livelihoods, health and socio-economic status of humans in the entire food chain (McCarl et al, 2013).

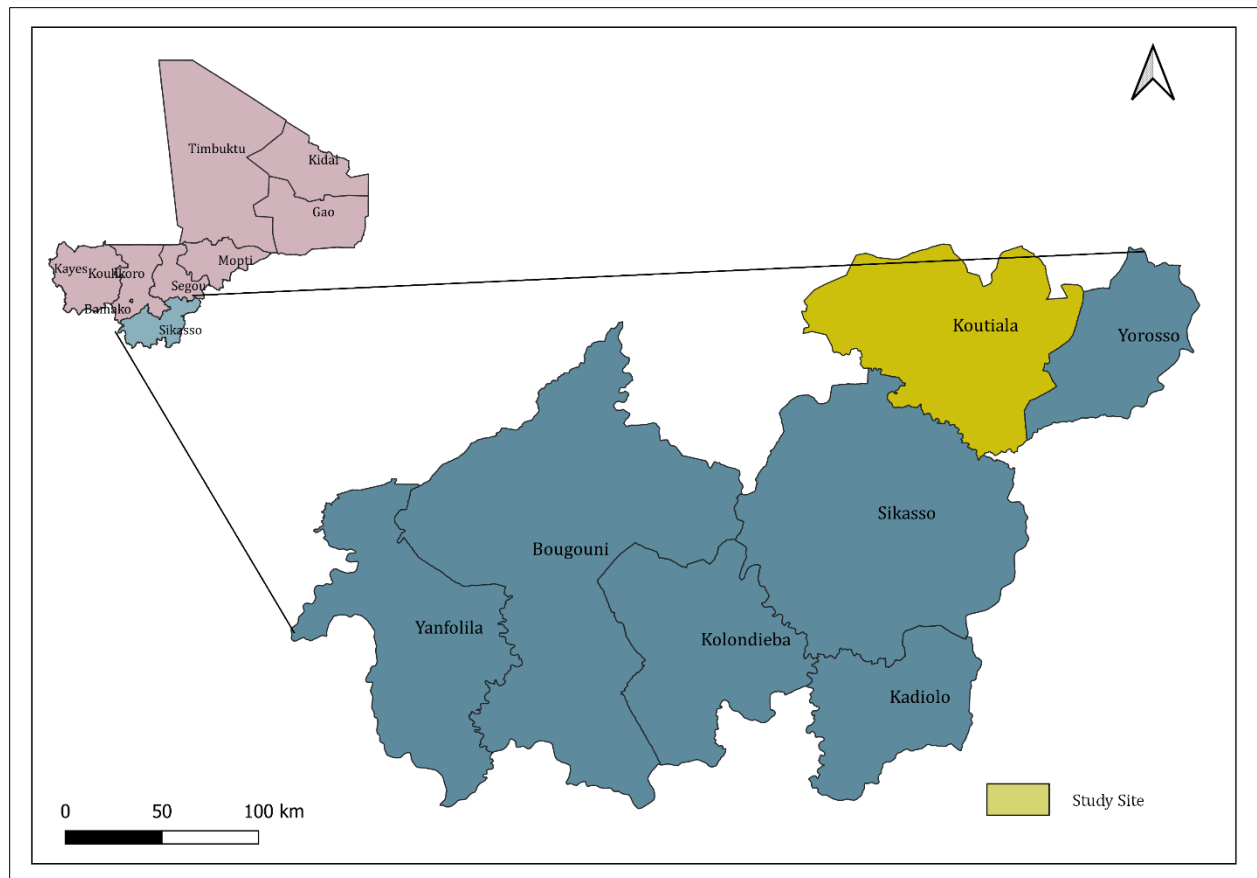


Figure 2.1. Map of Southern Mali

4. Data collection

The game was implemented in seven villages in Koutiala among 16 (8 male and 8 female) farmers which were within a 50 km radius of the main Koutiala city center. These villages were chosen due to their ongoing relationship with ICRISAT research scientists and researchers which facilitated entry into the village and participation of the village members. In Malian society, men hold primary rights of access to and control of land and decide which parts, if any, women can farm. At the household

level the allocation of land use between the collective and individual members lie with the head of household and this responsibility generally passes to the next oldest male family member. In such a system, individual plots are usually allocated to married women within the household who are often expected to participate in labor work collective plot which decreases their ability to give time and labor to their individual plots (Becker, 1990). Thus, decision-making is contingent on age and gender of the farmers within the farming household.

The game participants were selected through purposive snowballing sampling technique based on two criteria; age and gender. In each village, the chief of the village was contacted who guided us to respondents who fit the criteria of being either the elder member of the household (men and women) and younger members of the household (men and women). Demographic information about the gaming participants such as gender, age, education level, land size and number of people in the household are summarized in **Table 2.1**.

		number of players	average age of player category (in years)	average land size of player category (in hectares)	average number of plots of player category	average household size of player category
elder	men	3	71	43	6	47
(large/small land)		1	70	6	4	16
younger men		1	44	36	6	53
(large /small land)		3	49	8	4	17
elder women		5	51	0.8	2	28
younger women		3	30	1	2.5	28

Table 2.1. Demographic characteristics of game participants

5. Structure of ‘Food and Farm’ Participatory Simulation Game

‘Food and Farm’ was a one player (plus game master) game where the players played to feed themselves and their family that aims to understand the individual decision-making process of players

under climate uncertainty. Each round in the game signified one cropping season in a year. The main objective of the game was for the player to either : a) maximize the amount of food available for consumption and/or b) maximize income from farming. **Figure 2.2** illustrates the main structure of the game which consists of eight consecutive phases within the food production cycle in a season namely financial resource access, plot allocation, crop selection, seed selection, fertilizer/pesticide application, labor investment, harvesting, and grain allocation respectively. Elements in the game (denoted by dashed --- arrows in **Figure 2.2**); namely selection of climate cards, dice roll and coin selection along with setting of seed prices in the game were pre-constructed and common for all game players. For other elements in the game; players were given the agency to systematically construct and add relevant elements of the game that matched their social and institutional ground realities. For example, in financial resource access (phase 1), players determined the credit source, amount and interest rate of the financial resources they would need to play the game (this information was cross checked with the local agricultural officers for consistency); in plot allocation (phase 2), players constructed their own farming plots on a gridded sheet board (see Figure 2.3); in crop selection (phase 3), players selected the type of crops they would grow ; in seed selection (phase 4) players selected the source and varieties of seeds for their selected crops ; in fertilizer/ pesticide application (phase 5), players selected the source of inputs and the rules for payment for these inputs (credit or cash; interest rate etc.) (See figure 2.4). Similarly, in labor use (phase 6) for sowing, weeding and ploughing players selected the source of labor and rules for payment of labor. In harvesting (phase 7), players determine the sequence of harvesting their crops. In the final phase 8, players determine grain allocation for consumption and selling for the entire season. The information on crop seed /input and labor prices in the games were cross-checked with local prices to ensure consistency and prevent inflation of prices in the game..

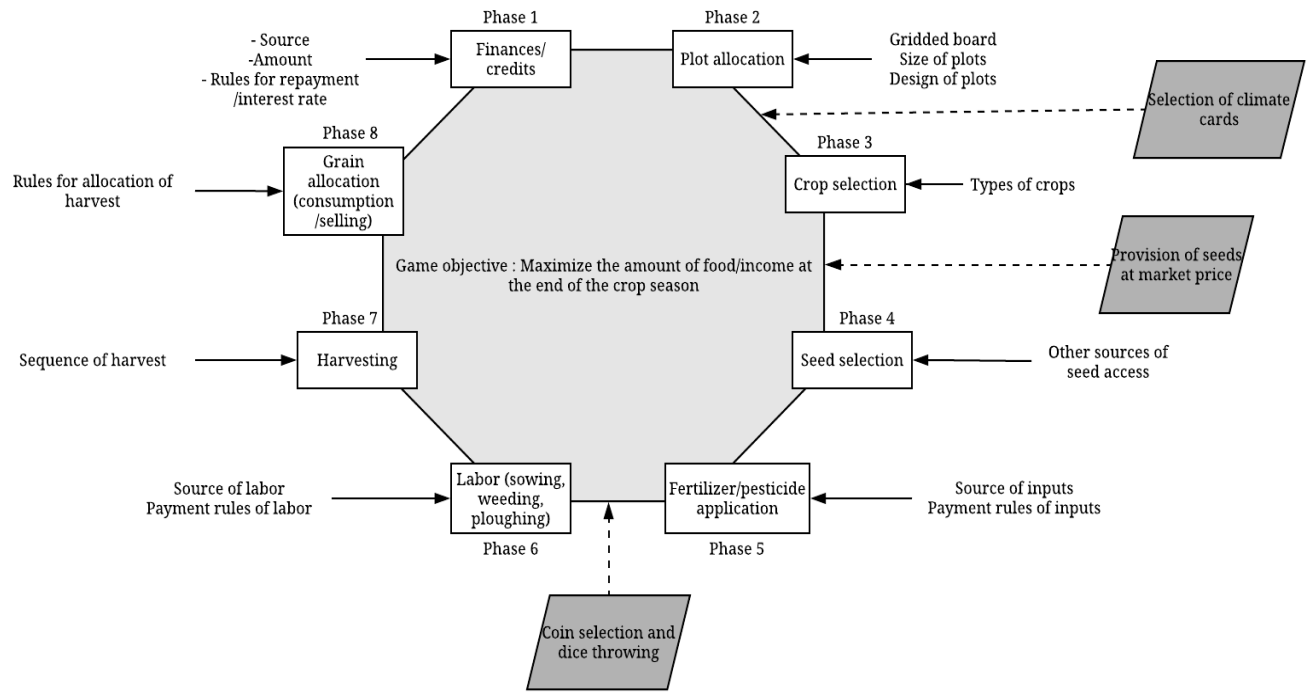


Figure 2.2. Structure of the 'Food and Farm' game

Climate uncertainty is incorporated in the game in the form of climate cards which were randomly selected by the player between phase 2 and 3, i.e. plot allocation and crop selection (see Figure 2.5). The climate cards represent the 5 climate events that can occur during a cropping season and impact crop production (**Table 2.2**). The climate event cards, impact and time of impact was determined based on prior discussions with agronomists in the region. Coin selection and dice roll represented the probability and severity of the climate card event. At the phase corresponding to the time of impact of climate event card drawn by the player (see **Table 2.3**), the players drew a coin from a bag of black and white coins that determined whether the event occurred or not (**Figure 2.6**). If they drew a black coin, the climate event card *would* occur, and the player would roll a dice. The number of the dice roll represented severity of the climatic event. For example, if they draw 'Late rains' and the dice roll was '5': 8 of every 10 'food grain' tokens that they made the end of the season would be lost. **Table 2.3**

outlines the dice rolls and severity of impact of the climate event. At the end of every game, the player estimates the total amount of income from selling their harvest and the total food in their granaries.

<i>Climate risk event cards</i>	<i>Impact</i>	<i>Time of impact</i>
Early drought	Difficulty in crop establishment	Right after sowing phase
Mid-season drought	Reduced grain yield	During weeding phase
Terminal drought	Poor grain filling	During harvesting phase
Late rains	Shorter rainy season	During weeding phase
Excessive rainfall	Mildew / pests /waterlogging	During sowing/weeding/harvesting phase

Table 2.2. Climate event cards and their impacts

A detailed explanation of the steps in the game can be found in the ‘Food and Farm’ rule book in

Appendix A

<i>Dice roll</i>	<i>Severity</i>	<i>Effect on yield</i>	<i>Impact on the grain tokens</i>
1	None	No effect in yield	None of the grain tokens are lost by player
2	Very low severity	10 % loss in yield	1 of every 10 ‘food grain’ tokens are lost by player
3	Low severity	30 % loss in yield	3 of every 10 ‘food grain’ tokens are lost by player
4	Medium severity	50% loss in yield	5 of every 10 ‘food grain’ tokens are lost by player
5	High severity	80% loss in yield	8 of every 10 ‘food grain’ tokens are lost by player
6	Very high severity	100 % loss in yield	10 of every 10 ‘food grain’ tokens are lost by player

Table 2.3. Dice roll and its impact on the game



Figure 2.3. Participant drawing crop plots on the gaming grid



Figure 2.4. Participant deciding on crop inputs



Figure 2.5. Participant drawing climate card



Figure 2.6. Participant drawing coins

The administration of the game was conducted in the local language Bambara by a local field assistant who played the role of the game-master and interacted with the player throughout the game. During each step of the game, the farmers were asked the rationale or ‘verbal protocol’ for their decision-making and actions within each step. The end of the game also led to a reflection/discussion with the individual players on the additional adaptation steps they could have taken but did not take. The field assistant translated the verbal protocols of the player to the lead author of this paper in English at each step of the game play which were captured in the game data matrix sheets (See **Appendix for** sample of game data matrix sheets). The game rounds were audio recorded to capture any missing details in the verbal protocol.

6. Analysis framework

The systems analysis of barriers of climate adaptation and food security followed two procedural steps where first, we performed a qualitative analysis of the verbal protocols from the games to identify the decision factors that influences agricultural production and climate adaptation, and second, we constructed a causal loop diagram to identify barriers of food security and climate adaptation. These two procedures are elaborated below:

6.1. Qualitative analysis of game verbal protocols

Verbal protocols from the game data were coded and analyzed using NVivo content analysis software (Version 11) based on a coding rubric that consisted of nine decision aspects with the game corresponding to the eight game phases. The coding rubric developed from the games and their definitions are outlined in **Table 2.4**.

Code rubrics	Definition
Financial decision	Decisions made about sources of credit and amount of financial resources borrowed to cultivate in the game round
Plot allocation decision	Decisions made about size and number of plots allocated for game round
Crop selection decision	Decisions made about selection of crops to grown on the plots of land constructed in the game
Seed decision	Decisions made about sources of seed, variety and quantity of seeds for crop cultivation in the game
Crop input decision	Decisions made about source, quantity and price of inputs to use on different crops such as fertilizers, compost and pesticides
Labor decision	Decisions made about the source, quantity and price of labor used for ploughing, sowing, weeding activities for specific crops
Harvesting decision	Decisions made about the harvest of grains
Grain allocation decision	Decisions about selling and saving of grains for future consumption
Climate adaptation decision	Decisions made about adaptation to climate event cards as it occurred in the game round

Table 2.4. Decision rubric codes and their definitions

As an illustration, consider the following verbal protocols (VP) for selected players on crop selection decision aspects of game play:

VP 1: *“Cotton and peanut is for selling. Maize, millet and sorghum is for consumption but if I made enough benefit...I would sell them.”*

VP 2: *“I love growing rice...for consumption. If the man will leave me [to cultivate] from collective farm, I will first start to grow rice for consumption. Children like to eat rice ..to change menu. I will use peanuts to make sauce. For sesame, I will make seasoned sweet....add sugar , cook it and sell it in the market ..from the money I will buy goods for her children...children like to eat conpea....if I cook conpea and tob ..all the children will eat conpea and not tob⁹ usually the chief [of the family] grows sesame for my family.”*

VP 3: *“[Sorghum was initially chosen for 3 ha] the soil is not fertile, the rest lands is more fertile. Usually I do grow cotton because of late rains (but once the climate card was selected as normal production year decided to grow cotton)”*

VP 4: *“Even if the event [drought climate card] happens, I will not change the size of cotton [plot] because I will use a lot of fertilizer here and next year he will grow cereal in this plot. So, if I knows this event will happen, that will have*

⁹ Tob is a pudding like dish made from pounded millet.

an effect on sorghum plot because when the drought happens, there are some insects who eat the leaves of sorghum. So, I will reduce the size of sorghum plot.”

In particular, the player chooses to grow sorghum because it survives climate risks such as late rain and low soil fertility but changes his decision to produce cotton when assured of a normal production season without any climate risks. It can be inferred from these verbal protocols that the choice of crop that farmers select to grow in their plots depend on (among several factors) the utility provided by the crop (consumption/selling) as demonstrated by VP1 and VP 2; soil fertility as demonstrated by VP 3 and type of climate risk as demonstrated by VP 4 where the decision to grow cotton is influenced by soil fertility and climate risks such as late rains such that an increase in soil fertility increases land allocated to cotton production but an increase in climate risks such as late rains, decreases the land allocated to cotton production. All verbal protocols were coded and analyzed to isolate factors that influence decisions making across the agricultural production phase as highlighted in the decision rubric codes.

6.2. Causal loop diagramming

After all the decision factors were isolate from the decision protocols d through the qualitative analysis, causal loop diagrams were developed to highlight the mechanisms of how those decision factors influenced crop production and climate adaptation. These diagrams were then superimposed with each other to construct a composite causal map where the key barriers to food security and climate adaptation were highlighted and elaborated. While food security encompasses all four aspects of food including availability, access, stability and utilization; in this analysis we only focus on food security as crop production in a season. We do this because of two reasons: 1. Most farmers in Koutiala practice subsistence agriculture with little or no surplus trade except cotton; hence food availability, access and stability depend on crop production and income generation within the household and 2. The main season for cereal production for the entire year occurs in the wet season from July-October, hence a

game play for a cropping season effectively covers the food production related decisions for the household in a year. The unit for analysis for the causal loop diagram is a household with food security decisions spanning a year. The following section elaborates on the results from the qualitative assessment of the games and the causal maps.

7. Results

Figure 2.7 illustrates the collective causal loop diagram for the decision factors and actions that influence food security and climate adaptation of farmers in Koutiala. The red arrows in the causal map highlight the barriers in food production and climate adaptation decisions identified in the Nvivo analysis. The causal loop diagram highlights the mechanisms through which farmers make financial decisions such as loans and credits, plot and crop allocation decisions, input use decisions such as seed procurement, fertilizer and pesticide access and application, labor decisions, and harvest allocation decisions such as income generation and food consumptions along with climate risks and adaptation decisions.

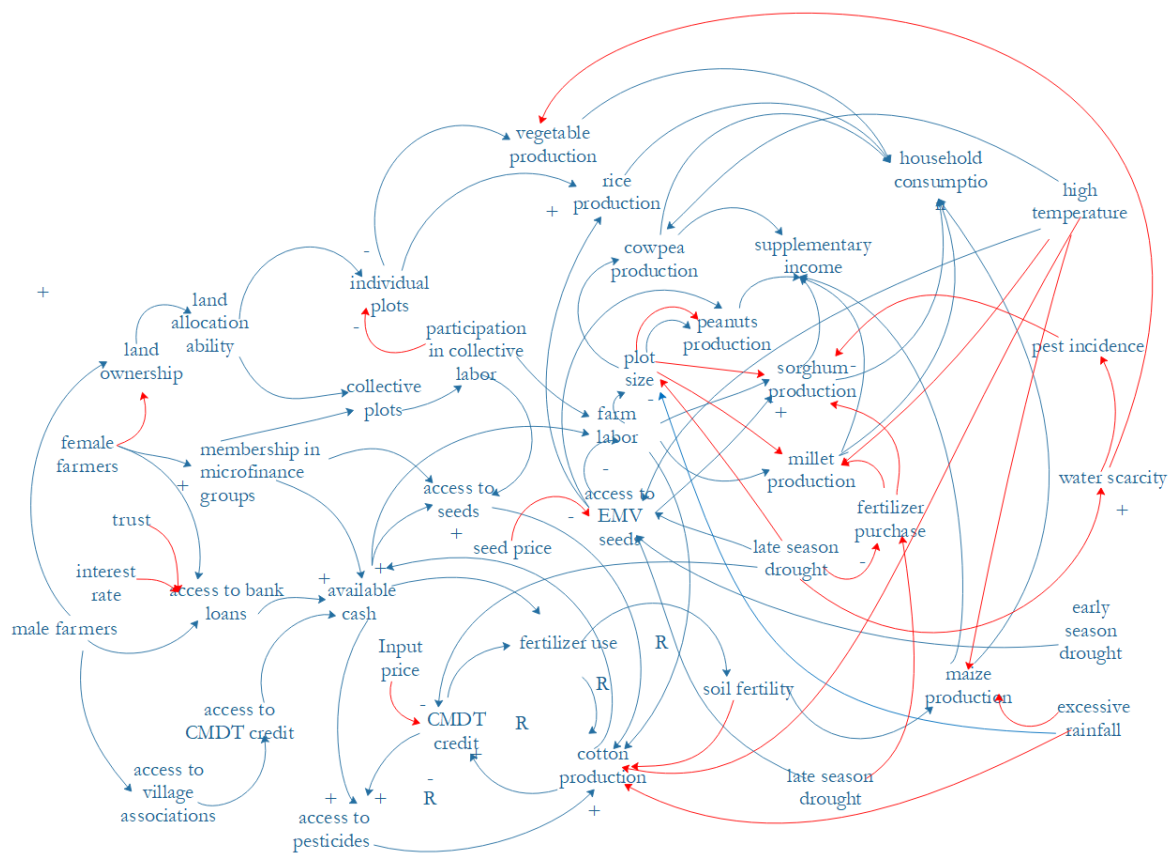


Figure 2.7. Collective causal loop diagram for food security and climate adaptation of farmers in Koutiala.

7.1. Financial barriers

Unavailability of formal credit sources especially for non-cotton and women farmers

Analysis of the verbal protocols show that financial decisions within a cropping season are influenced by the gender of the farmer, the types of crops grown, access to formal and informal credit sources and membership to micro-finance institutions. Male farmers, notably cotton growers, have membership with village association which organizes sale and credit transactions for cotton cultivation the cotton company *Compagnie malienne pour le développement du textile* (CMDT). Members of the Village Associations (VA) have better access to credit from the CMDT which allows cotton farmers to purchase fertilizers and pesticides. Despite a higher credit price of fertilizers (12000 CFA) and pesticides compared to market price of fertilizers (11675 CFA); farmers often chose to avail credit

from CMDT due to unavailability of cash in the beginning of the season to buy inputs in the market. Hence, high credit price and unavailability of cash in the beginning of a cultivation season, both act as financial barriers in crop cultivation.

For female farmers, membership with micro finance groups enables them to increase cash availability for purchase of seeds and crop inputs through loans from women's savings groups and other informal sources such as friends and family. Membership with micro-finance groups also increases access to seeds, particularly rice and vegetable seeds such as okra and shallots.

While farmers also have the choice to borrow from local banks, high interest rate and low levels of trust decrease farmers willingness to access loans from banks. Both male and female farmers stated a preference for informal loans from friends and neighbors as well as remittances from family members as additional sources for cash in the beginning of a season. Lack of liquid cash available to the farmer in the beginning of a season acts as a barrier to purchasing fertilizers and pesticides in a season.

As we see in the CLD, access to CMDT credit allows farmers to increase their fertilizer use for cotton production; which further increases cotton production which in turn increases access to CMDT credit (reinforcing feedback). Overall, access to CMDT credits enables male cotton farmers to purchase inputs for cotton and maize and improve soil fertility which further increases crop production for cotton and maize. Such facilities are not available for other food crops such as millet, sorghum, cowpea, peanuts, rice or vegetables. Since cotton is primarily grown by male farmers in collective plots, women are involuntarily excluded from accessing formal credit.

7.2. Land related barriers

Inadequate land access rights; time and labor constraints in collective vs individual plots for female farmers

Decisions on plot allocation and selection of crops to grow are also largely influenced by gender, which influence the land ownership and land use rights of farmers. These gender dynamics were

evident in the way the games were played by male and female participants. Female players constructed individual plots of land (~1 ha) and cultivated crops such as rice, shallots, cowpea, peanuts and vegetables while men constructed the collective plots for crop cultivation and grew crops such as cotton, maize, sorghum, millet, cowpea and peanuts.

As we see in the CLD, male farmers had higher land ownership which increases their ability for allocation into collective and individual plots for the household. Collective plots are plots where the extended household, including the chief of the household, his wives, sons (along with their wives and children) and unmarried grows food collectively for the entire family. Individual plots are small plots of land where a single family member can cultivate crops for themselves. While male farmers, who have higher land ownership of collective plots and a higher ability for plot allocation, increase the size of plots for collective farming and decrease the size of plots for individual plots for female farmers. The larger collective plots lead to increased cultivation of cotton, maize, sorghum, millet and peanuts; smaller collective plots lead to higher cultivation of rice, vegetables and cowpea for the household. In the game plays, male farmers decided to grow cotton mainly for profit and to access credit for cotton seeds and fertilizers and pesticides at subsidized prices. Other crops such as maize, millet and sorghum were grown primarily for household consumption. Peanuts and cowpea were versatile and grown for household consumption, cash from selling as well as feed for cattle especially among female farmers. Female participants mainly chose to grow rice for household consumption during festivities and special occasions. Except for shallots and vegetables, all crops were grown once a year in the rainy season that lasts from June to October. Soil type and fertility also played a role in the selection of crops in the farm plots. Cotton and maize were usually allocated to less sandy, more fertile plots which receive additional inputs such as synthetic fertilizers.

Older women who did have access to individual plots reported having only small plots of land (~1 ha) for crop cultivation. Lack of adequate land in addition to lack of financial resources to buy crop

inputs and seeds prevented women from growing cash crops such as cotton as they chose to allocate their small plots to cultivation of vegetables or rice, or sorghum or millet or cowpea. Lack of access to land and expected participation in collective plots, thus, acts as a barrier to cultivation of desired crops by female farmers. Women, particularly younger game participants, highlighted that their expected responsibility towards labor contribution in collective plots inhibited them from gaining access to individual plots and the labor commitments in collective plots managed by the male members of the household inhibited them from investing time in working on their individual plots, thereby, acting as a barrier for female farmers to cultivate food of their choice.

7.3. Climate barriers

Climate risks such as early and late season droughts, high temperature and excessive rainfall, water scarcity, pest incidences

Various climatic risks such as early and late season droughts, water scarcity, excessive rainfall, and high temperatures were reported to influence crop production for maize, cotton, millet, sorghum and peanuts. Peanuts were reported to be susceptible to terminal droughts; hence given the possibility of late season drought, farmers reduced the land allocated for peanuts. Late season droughts were reported to affect sorghum mainly through increased water scarcity which increases pest incidences, lowering sorghum production. As coping strategies, increase in incidences of late season droughts leads to decisions to reduce plot size for sorghum and millet. Farmers also limit fertilizer purchase for sorghum and millet crops which further decreases production. Farmers reported adapting to early and late season drought by purchasing earl maturing seed varieties, which also reduces efforts in farm labor and prevents yield loss later in the season.

Excessive rainfall was reported to negatively influence maize and cotton production by limiting conformation in maize and imparting a reddish tinge in cotton produce, lowering its market price. Faced with a possibility of excessive rainfall, farmers also report changing crop type to peanut and cowpea

instead of sorghum and millet because cowpea leaves and peanuts can be sold in the market and their production costs are lower than sorghum or millet.

Extremely high temperatures were reported to decrease the production of cotton, maize and millet crops. High temperatures also lead to water scarcity which decreases vegetable production. Farmers adapt to extremely high temperature by changing crop type increasing cowpea production as it matures in 2 months and decreasing the plot allocation to maize and millet crops.

In the games, farmers changed decisions from planting traditional varieties of crops to buying early-maturing varieties when faced with possibility of adverse climatic conditions such as droughts and extreme high temperatures. However, for most farmers, the purchase of early maturing or hybrid varieties of crops is inhibited by the lack of available cash for the purchase of these seeds. High price of early maturing varieties is often a barrier for adaptation.

In summary, faced with climate risks in the form of climate cards, game participants implemented three main adaptation actions; change in plot allocation, change in crop type and use of early maturing varieties. Most farmers decided to grow traditional varieties of sorghum and millet as they are already adapted to variability in rainfall. Indeed, research shows that traditional varieties of sorghum and millet are already adapted to variability in rainfall due to their ability to allow flowering of plants at the end of the rainy season for a variety of planting dates and are also less affected by temperature increase (Sultan et al., 2013; Dingkuhn et al. 2006). Research also shows that maize and cotton yields are more susceptible to increase in temperature and rainfall variability (Ebi et al, 2011; Traore` et al. 2013). Vegetable gardening, while primarily conducted by women to provide nutritional supplements for household consumption, was also an option for some farmers during high temperature events. When access to water was limited, however, large scale vegetable production (in larger plots) was inhibited. Additionally, water scarcity for vegetable cultivation during dry season also was a factor that inhibited

farmers from growing vegetables that would likely enhance the nutritional value of their food consumption.

8. Discussion

In their review paper, Shackleton et al. (2015) emphasize the need for studies to explore the heterogeneous impacts different farmer types (e.g., gender, age, class and ethnicity) face from similar barriers. In this study, we were able to explicitly highlight the intersectionality within decision-making contexts, especially with respect to gender and cropping system (cash crop vs food crop cultivation). The analysis of the games is embedded within a systems methodology approach to highlight interaction of the various factors which influenced decision-making and identified the dynamic pathways through which barriers function. In particular, our analysis led to the identification of three key high level structural and institutional barriers that created cascading effects at the local and individual levels: (i) lack of financial credit for female and non-cotton farmers; (ii) lack of land access and user rights for younger female farmers, particularly younger women and (iii) climate risks such as early and late season droughts, high temperature and excessive rainfall, water scarcity, pest incidences. First, while the dominance of interlocked credit cotton-input system through CMDT (Theriault and Sterns, 2012) provides opportunities for access to crop inputs for cotton farmers, it also acts as barriers for smaller farmers and female farmers who lack access to land and labor payment. Research also shows that lack of personal loans to farmers, crop loss, delay in payment to farmers, high input prices and low cotton prices have led to an increase financial indebtedness among farmers (Theriault and Sterns, 2012). This has farmers trust and willingness to borrow financial loans from banks. Second, there exists a high degree of uncertainty about land rights in Mali. Land tenure and use exists within coexistence of various alternative systems (customary laws usually under Islamic law influence) or state laws (Delville, 1998). Policy interventions which target effective land security and rights will enable farmers, to have better access and control over farm land area; and thereby allowing land to be

used as collateral for loan and improving farmers' access to financial capital. Land ownership and user rights for female farmers within a household is furthermore contentious and dependent on the discretion of the male head of the household who holds primary rights of access to and control over land and decide which parts, if any, women can farm. This limits women's agency to cultivate desired crops and access seed, labor and inputs in their fields to enhance food security within their household or to grow cash crops such as groundnuts, sesame or cowpea for economic benefits. Policy interventions which enhance land ownership and user rights for women may increase their agency in decision making and allow them to bargain with the collective to farm on her own land and thereby reduce labor and time obligations in the collective field.

Third, and last, in the games, climate information was constructed in the game design using climate cards and rolled dices. However, post-game discussions on the role of climate information in farmers' decision-making revealed that most of the weather forecast information is received through radio. Most farmers reported the information being useful which enables farmers to plan for the cropping season. Climate risks such as droughts, excessive rainfall, extremely high temperatures, water scarcity and pest incidences lead farmers to grow crops such as cowpea and peanuts which provide supplementary income rather than allocate land to production of food crops such as sorghum, millet and maize. This has repercussions in household food stability and availability across the year. Most of extension services efforts in Mali that provide technical trainings and support for input use and crop management, focus on vertical information dissemination, particularly for cotton producers and to a lesser extent, other cereal crops. Outreach towards women farmers and non-cotton farmers has been low. These services also target farm production, which is male dominated, than marketing and processing which has a higher participation from women farmers (Staatz et al., 2011). Farmer cooperatives have often excluded women from membership in cooperatives due to gender biases in marketing as well as production systems (Harriss-White, 2005; Boserup and Kanji, 2007). Technical

assistance to farmers in terms of nutrient management, irrigation services, seed varieties and farm advisory services needs to be expanded to both women and non-cotton farmers to make information and price of early maturing varieties affordable to farmers. While numerous climate smart agriculture technologies such as conservation agriculture, use of climate-tolerant varieties, water conservation, integrated nutrient management practices have been promoted in the West African region (see Zougmore et al. (2016) for a review), yet the outreach of these technologies has been low. Policy interventions which focus on farm-to-farm knowledge exchange and community-to-community learning can leverage on the existing social networks, trust and social capital among villages and lead to a ‘contagion’ effect of technical information and knowledge exchange which equitably targets both men and women.

Additionally, farmers reported an absence of adequate crop insurance and nonpayment of claims as one of the factors that acts as a barrier for investing in crops that require purchase of seeds and inputs. Expansion of financial loan and credit portfolios for farmers growing other food crops and development of crop insurance schemes will likely enhance farmers’ capacity to undertake activities that increase food production within the household.

9. Conclusion

To summarize, a key contribution of this study is the use of a simulation game called ‘food and farm’ which was co-designed and played by farmers to assess decisions regarding food production as well as climate adaptation. Simulation games offer certain methodological advantages for assessing the contexts and rationales behind agricultural adaptation decisions undertaken by farmers ; first , following the principles of participatory game design which involves the direct involvement of stakeholders in the design of the game and the set of rules that govern the game play (Brandt, 2006; Schuler & Namioka, 1993), participation of at-risk populations and related stakeholders in simulation games lead to a shared learning experience and knowledge generation of the social, economic,

institutional and environmental aspects of decision-making be explicitly included in our analysis. Second, the game play encourages a real-time discussion and dialogue between the players and the researchers where players which forms a rich database for qualitative assessment of the how these factors are related with each other as well as reasoning behind player choices and decisions

By using a simulation game design approach, this study assessed the various factors that influence farmers' decisions to cultivate food and adapt to a rapidly changing and unpredictable climate. The game enabled the participants to co-design and simulate sequential crop production in a season and respond to random climate events and was a useful tool to assess individual adaptation decision-making of farmers. However, the game was a single player game and, hence was unable to explore the collective decision-making and negotiation processes in collective farming by households. While a multi-player game exploring collective decision-making on farming and food security would generate interesting insights, development of such a game was unfeasible due to unwillingness of participants to question or counter the decision of elders even in a game setting. It was important to maintain cultural sensitivity and respect towards the research participants, and hence the game was kept as a single player game. Results from the game analysis show that decision-making among rural farmers is complex and dependent on a multitude of factors including gender, access to land, type of crops grown, type of climate risks, access to credit and crop inputs, access to labor, efficacy of crop inputs, food preference and nutritional quality of food etc. The study also highlights the key drivers that lead to creation of barriers as identified in our results section, namely; unavailability of formal credit sources especially for non-cotton and female farmers; inadequate access to crop inputs for food crops; inadequate land access and user rights for female farmers; unavailability of adequate water for vegetable production during dry season; low soil fertility; climate risks; cost of early maturing varieties. Barriers, as the word suggests, have been described in literature as inherently undesirable, with the assumption that once such barriers are 'overcome' adaptation will follow. However, in our opinion

and as evidenced in this paper, this follows a reductionist, linear approach towards a problem which is inherently complex in nature. As demonstrated by our results, factors such as availability of interlocked credit-input systems for cotton production may act as enablers of adaptation for cotton farmers but become barriers for non-cotton and female farmers by way of market dominance. Similarly, land access and user rights for male farmers act as barriers for female farmers by way of intra-household land allocation dynamics. Climate adaptation and food security are closely interlinked and complex in nature which require a systems approach where the focus is on understanding pathways, feedbacks and heterogeneity in decision-making and contexts.

APPENDIX

APPENDIX

Food and Farm rule book

Dumuni ni sènè (Food & Farm)

The Food Security and Climate Adaptation Board Game

Objective of the game:

The “Food & Farm” board game was used to understand the decision making process behind food production, food consumption and climate change adaptation among farmers in Mali. The game simulates farming experience of smallholder farmers from food production to allocation to consumption. The game also simulates random climatic risk events that occur during a cropping season that influence the yield of crops and also the food security status of the farmer and his/her family. Through the game, the farmers also play out adaptation strategies to these random climatic events. The purpose of the game is to calibrate their decision structures which can be used for the parameterization of the system dynamics model.

Rulebook & Instructions

(for 1 player)

Introduction

In the “***Dumuni ni sènè***” game of food and farming strategy, you are playing to feed yourself and your family. To play, you must implement farming strategies to accomplish the following objectives:

1. **Maximize the amount of good and nutritious food** available to you and your family for consumption.
2. **Maximize your income** from farming.

You will try to implement strategies which are as close to your real farming life from food production which involves land preparation, buying seeds and fertilizers, sowing, weeding, harvesting and threshing as well as food consumption which involves food allocation to the people who cook, food

processing (pounding miller) and food preparation (deciding menu, buying condiments, cooking etc.). However, just as in real life, you can't control everything that happens in your farm. There can be risks in climate over which you have no control! You may invest in a crop which you hope will give a good yield at the end of the season but it may not rain on time or there may be a drought and all your planted seeds may die! In case they occur, you must create innovative strategies which enable you to remain protected from these climatic risks.

In each round of the game, use your strategies to obtain maximum number of grains and income from the game to be able to feed your family in every round. Let's play!

Setting up the game

The game can be played by the player over 5 rounds. Each of the 4 rounds goes through six phases, which are played one after another.

1. Field preparation phase:
2. Sowing phase:
3. Weeding phase:
4. Harvesting phase:
5. Food allocation phase:
6. Food preparation phase:

Game Equipment

1 gridded farm game board
1 rolling Dice
Deck of 5 climate risk cards
Deck of 5 crop cards along with price cards of the crop
150 'money' tokens (**1 money token represents 10,000 CFA*)
20 labor tokens
100 yellow "millet" seed tokens
100 green "rice" seed tokens
100 blue "vegetable" seed tokens
100 purple "sorghum" seed tokens
100 orange "maize" seed tokens
100 brown "cotton" seed tokens

50 yellow “millet” grain tokens
50 green “rice” grain tokens
50 blue “vegetable” grain tokens
50 purple “sorghum” grain tokens
50 orange “maize” grain tokens
50 brown “cotton” grain tokens
1 crop calendar timer

Setup of the game

Players Roles:

1. **Farmer:** The farmer is the main player in the game who will make the cropping/ food allocation decisions.
2. **Game master:** The game master who administers the game with the player plays the role of a credit source, money lender, input (seed and fertilizer) seller, grain seller/buyer and labor and machineries provider (on rent). The player interacts with the game master for any inputs he/she needs as well as to sell the produce in exchange of money tokens.

Place the money, labor, seed and grain tokens (with price tags) in front of the game master where the player can see them.

Place the farm board in front of the farmer and provide a pen to draw the plots on.

Place the crop cards face up in front of the farmer along with the price of the seeds of each crop.

Shuffle the deck of climate risk cards and place it face down on the side of the board.

Course of play:

Round 1(Normal production season): The first round of each game is the ‘normal production season’ round. In this round, there are no climate risks to your farm and you will produce in your farm the way you usually do.

Strategy:

(Note: ask the farmers these questions and give them time to think and wait for their answer)

Think of the total agricultural land size than you manage; What is the total agriculture land size that you manage?

How many plots do you have?

What are the size of the largest of these plots, the second largest...? (*and so on until the player tells you all the plots sizes*)

Now starting from the largest plot, draw all the plots in this board with a pen. (*allow the farmer to draw the plots*)

Step 1: Preparing for the season of farming.

1. Calculate the amount of money you usually need to start farming in this season. You can borrow the amount from the game master on credit. At the end of the game, you will return that money to the game master. (Note: after the farmer has decided, ask the player the reason of his/her choice)
2. Select the type of crops you want to grow in your plots. You may also leave plots empty/fallow if you don't want to grow anything this season. Place the crop card on top of each of the plots. (Note: after the farmer has decided, ask the player the reason of his/her choice)

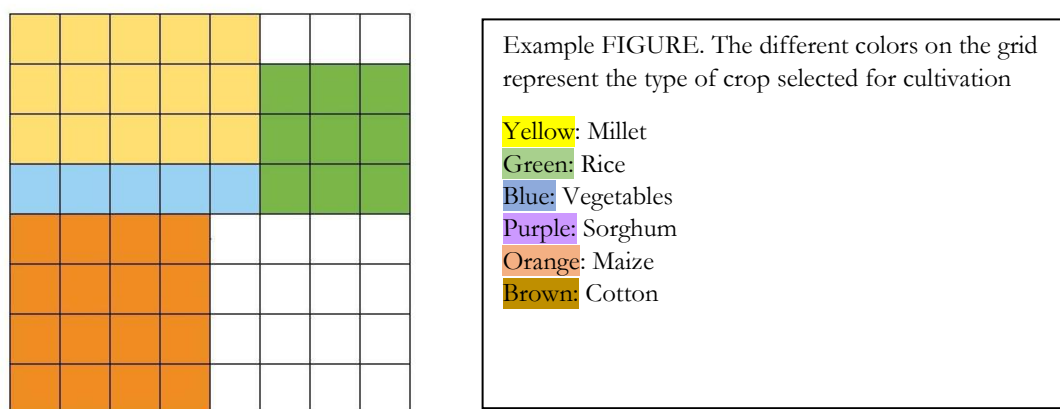


Figure 2.8. Example of crop allocation on a gridded plot

3. Now calculate the amount of seed you need for each crop you decided to cultivate and tell the game master what you need to buy. The game master will tell you the price of each of the crops and the total amount you need to pay. Decide whether you want to go ahead with your choice and buy the seeds from the game master. (Note: if the player decided to change his decision, ask the player the reason of his/her change in decision)
4. Calculate the amount of fertilizer you need for your crops. The game master will tell you the total price of fertilizers. Decide whether you want to go ahead with your choice and buy the seeds from the game master. (Note: if the player decided to change his decision, ask the player the reason of his/her change in decision)

Step 2.: Crop production

1. Now the game master starts the crop calendar timer. The crop cycle timer moves each month from the months of June – January (wet/mango season) and January- May (dry season). Set the timer to June and begin the crop production phase.
2. You now have the seeds and fertilizers to start the cropping. But you would need to prepare the field for sowing first, you perhaps would need to hire additional labor apart from your family members. If you usually hire labors you can buy labor at 1000 CFA per day. Estimate the number of additional labor you need for field preparation, if any. (Note after the farmer has decided, ask the player the reason of his/her choice)
3. The game master will tell you the total price of each labor. Buy additional labor that you need for field preparation. Game master will update the phase in the crop timer.
4. Now you need to start sowing, estimate the number of laborers (family and paid laborers) and machineries for sowing of each crop. Pay for additional laborers. Game master will update the phase in the crop timer.

5. Now you need to start weeding, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.
6. Now the crop has started to ripen, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.
7. After harvesting, it's time for threshing, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.

Now is the time to reap your harvest!

Based on the amount of seeds you planted, you will get an exchange your seed tokens with grain tokens of that crop.

Step 3: Food allocation and consumption

1. Now you need to decide on how much of collected grain tokens you want to set aside for the household consumption and how much you want to sell in the market for additional money tokens. (Note: after the farmer has decided, ask the player the reason of his/her choice)
2. You can take your grain tokens set aside for selling to the game master to exchange the tokens with money tokens.

The remaining grain tokens will be deposited into the family grain bank for future consumption during the year. The grain amount in the bank will decrease by half by the end of the next season around.

ROUND 2 and onwards:

Step 1: Preparing for the season of farming.

Keeping in mind that you have to produce enough food to feed your family for the entire year and also make some money for household expenses;

1. The starting money from this round will be the money tokens you have from the first season round.
2. We now introduce the climate risk cards. You know that each season, we have no control over the climate risks and it may happen at any time. We have five climate cards here (Game master shows 5 climate cards to the farmer and shuffles them. She explains each card to the farmer. (Note : Ask the farmers which crops do each of these climate event affect the most, and why?))
3. You will select one card from this deck of cards, whichever card you draw, that event **MAY** happen in the following season. Whether that happens or not, you will get to know after you sow your crops. You will draw from this bag of two tokens (Note shows bag with two tokens). If you draw black token, it will happen, if you draw yellow token, it will not happen.
4. Select the type of crops you want to grow in your plots. You may also leave plots empty/fallow if you don't want to grow anything this season. Place the crop card on top of each of the plots. (Note: after the farmer has decided, ask the player the reason of his/her choice)
5. Now calculate the amount of seed you need for each crop you decided to cultivate and tell the game master what you need to buy. The game master will tell you the price of each of the crops and the total amount you need to pay. Decide whether you want to go ahead with your choice and buy the seeds from the game master. (Note: if the player decided to change his decision, ask the player the reason of his/her change in decision)
6. Calculate the amount of fertilizer you need for your crops. The game master will tell you the total price of fertilizers. Decide whether you want to go ahead with your choice and buy the seeds from the game master. (Note: if the player decided to change his decision, ask the player the reason of his/her change in decision)

Step 2.: Crop production

1. Now the game master starts the crop calendar timer. The crop cycle timer moves each month from the months of June – January (wet/mango season) and January- May (dry season). Set the timer to June and begin the crop production phase.
2. (Only at the specific time that the climate card represents) Now the player draws the black/white token from the bag. If it is yellow, there is no effect. If it is black, the event will happen at a specified time in the seasonal calendar.
3. (Only if the player draws black) Now that you know that the event will happen, roll this dice. The number of the dice represents how severe the effect of that climate event going to be. For example, if you drew 'Late rains' and the dice roll was '5': 8 of every 10 'food grain' tokens that you make in the end of the season will be lost player
4. You now have the seeds and fertilizers to start the cropping. But you would need to prepare the field for sowing first, you perhaps would need to hire additional labor apart from your family members. If you usually hire labors, you can buy labor at 1000 CFA per day. Estimate the number of additional labor you need for field preparation, if any. (Note: after the farmer has decided, ask the player the reason of his/her choice)
5. The game master will tell you the total price of each labor. Buy additional labor that you need for field preparation. Game master will update the phase in the crop timer.
6. Now you need to start sowing, estimate the number of laborers (family and paid laborers) and machineries for sowing of each crop. Pay for additional laborers. Game master will update the phase in the crop timer.
7. Now you need to start weeding, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.

8. Now the crop has started to ripen, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.
9. After harvesting, it's time for threshing, estimate the number of laborers (family and paid laborers) for each crop. Pay for additional laborers. Game master will update the phase in the crop timer.

Now is the time to reap your harvest!

Based on the amount of seeds you planted, you will get an exchange your seed tokens with grain tokens of that crop. This is the amount you would have received if there was no climate event but since you had a climate event, based on the climate card intensity of the dice you will lose the grain tokens you received. Game master takes away respective amount of grain tokens.

Step 3: Food allocation and consumption

3. Now you need to decide on how much of collected grain tokens you want to set aside for the household consumption and how much you want to sell in the market for additional money tokens. (Note: after the farmer has decided, ask the player the reason of his/her choice)
4. You can take your grain tokens set aside for selling to the game master to exchange the tokens with money tokens.

The remaining grain tokens will be deposited into the family grain bank for future consumption during the year. The grain amount in the bank will decrease by half by the end of the next season around.

Now that you have seen the effects of climate events, you need to strategize to deal with these events. You may make changes on your decision on which crops to grow, allocate seed amount and variety from the seed dealer, changes in labor allocation during the crop cycle timer, amounts for selling and purchasing etc. You may implement these strategies in the next rounds.

Be resourceful! Come up with innovative solutions and strategies! You may discuss with other players on a common strategy and introduce new aspects into the game as well.

Enjoy!

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CHAPTER 3
THE MALIAN FUTURE: SYSTEM DYNAMICS MODELING OF RESILIENCE OF
MALIAN AGRICULTURE AS A SOCIOECOLOGICAL SYSTEM

1. Introduction

Climate change poses a huge challenge for farmers across the world and threatens the food security of billions of people. Increase in temperature, uncertainty in rainfall patterns and higher frequency of extreme weather events has immediate impacts on agricultural food production, distribution, livelihoods, and socio-economic status of humans in the entire food chain (Chen et al, 2017). Sub-Saharan Africa is particularly sensitive to climate change-induced food security due to its high dependence on rainfed agriculture. According to the General Circulation Model (GCM) predictions, by the end of the 21st century, the average temperature in sub-Saharan Africa will increase by almost 3.3 degrees (Traore et al, 2013). Most GCM models have been unable to reach a consensus on future projections in rainfall, mainly due to high uncertainty and complexity in incorporating the multiple physical mechanisms and feedbacks influencing Sahelian rainfall (Druyan, 2010; Biassutti and Giannini, 2006; Cook and Vizi, 2006, Patricola and Cook, 2009). Some climate model projections predict a drier Sahel while the other models project wetter conditions in the future (Giannini et al, 2008). According to Taylor et al (2002), increase in population and agricultural intensification may create positive or negative feedbacks in climate forcing which may trigger another period of extreme droughts, famine and food insecurity in the region. Understanding the dynamics that drive the food insecurity in the region in response to ecological, climatological and socio-political dynamics within the system requires an integrated approach which includes an exploration of how the systems are interconnected.

System dynamics modeling is a technique that allows researchers to investigate the dynamics of a complex system with both social and ecological components. System dynamics models have been used

in a wide variety of fields including climate science to build tools for supporting policy decisions that are simpler than the large scale physically-based global climate models but retain the essential characteristics and behavior of the original models (Sterman et al. 2013). Often, large physical models on environment change focus on the development of future scenarios to inform policymaking: yet the high levels of uncertainty and complexity associated with such models, often lead to gridlocks within decision making spaces (Lemos & Rood, 2010). The modeling philosophy behind systems dynamics focuses on the ability of “powerful small models’ (Forrester, 2007) to capture important key feedbacks and dynamics within the system instead of replicating the physical ‘reality’ of a system in order to identify the key leverage points that can bring desirable change and transformation. Such small models have the added advantage of higher tractability, flexibility and better communicability with policymakers, interventionists, and stakeholders.

In the past decade, there has been an increasing number of quantitative system dynamics models representing food security in Sub-Saharan Africa (Oyo, 2016). For example, Kopainsky et al (2012) assessed the effectiveness of social dynamics such as trust influencing the adoption of improved crop varieties among farmers and the scope of transformation from subsistence farming to small scale commercial agriculture. Oyo (2013) developed a farmer level system dynamics model of food security and livelihoods in Uganda. Stephens et al (2012) explored the dynamic feedbacks between household decision-making and long-term soil fertility through a system dynamics model of poverty and food insecurity in Kenya. I take a similar approach here, incorporating essential dynamics from biophysical, climatological and social aspects of temperature and precipitation trends, agricultural production, livestock production, land-use change, population growth, migration, urbanization, poverty and food demand /supply dynamics into a simplified but integrated system dynamics model of food security in Mali. The model, henceforth Mali-SES model, conceptualizes the agricultural systems of Mali as a socio-ecological system where ecological dynamics within the system interact with social dynamics to

impact the food security of the country. I conduct a scenario analysis of various adaptation strategies to assess the resilience of food systems in Mali based on future adaptation policies that can be implemented in Mali at the national scale. This chapter is organized in the following manner: Section 2 outlines the conceptualization of MALI-SES as a socio-ecological system dynamics model. Section 3 outlines the detailed methodology for model construction, validation, and adaptation scenario development and assessment. Section 4 discusses the model results and scenario assessment followed by the conclusion in section 5.

2. Conceptualization of MALI-SES system dynamics model

2.1. Definition of food security & scale of the model

The term ‘food security’ first originated in the World Food Conference (1974) where it was defined as: *“Availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices”*. This definition encompassed adequate food availability in terms of food supply and price stability at national and international levels. In the mid-1980’s, the United Nations Food and Agricultural Organization expanded this definition to include food access and defined it as: *“Ensuring that all people at all times have both physical and economic access to the basic food that they need”* (FAO, 1983). This implied that the definition of food security also covered food access at the individual and household levels. Later, a World Bank report on Poverty and Hunger (1986) introduced temporal dynamics of food security and stressed the causal factors of hunger and food insecurity (Clay, 2002). In 1996, the World Food Summit outlined a multidimensional and comprehensive definition of food security: *“Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”*. This definition introduced aspects of food utilization (*‘safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life’*) along with food availability (*all people*), food stability (*at all times*) and food access (*physical and economic access*).

The analysis of food security can be conducted at various scales. According to Thompson & Metz (1998), food security at the national scale is the balance between food demand and supply at reasonable prices. At the household scale, food security exists if the entitlements possessed by the household are sufficient to satisfy the household food needs. At the individual level, food security exists if a person's food consumption is greater than their needs. In this model, I assess the food availability and stability aspects of food security instead of food access and utilization for two reasons: one, assessment of food utilization and access at the national level has often been derived from strong assumptions on “undernourishment estimates” by the Food and Agriculture Organization (FAO) ; and often masks the intranational heterogeneity within the country, further such estimates are unable to capture aspects of household and seasonal food preference across the region (Barrett 2010). The primary scale of analysis of agricultural socio-ecological systems was kept at the national scale. While a disaggregated sub-national or household level analysis of food security would have allowed more precision in terms of climate patterns, household food requirements and preferences as well as patterns of income and allocation to food resources, such detailed disaggregated level data for the time scale between 1960-2017 was unavailable. Second, the inclusion of food access and food utilization dynamics in the model would have introduced more complexity in the model as well as reduced the tractability of the model. However, in order to incorporate heterogeneity at the sub-national scales, primarily at the main livelihood zones, where it has been demonstrated that there are differences in livelihood patterns, socio-economic characteristics and food production across the north-south agro-ecological gradient in Mali, the Mali-SES model explicitly incorporated the concept of panarchy in its structure (Figure 3.1).

Panarchy implies that complex social-ecological systems do not exist in isolation; rather they are composed of multiple subsystems operating at different scales across both space and time where feedbacks and interactions at one scale influence the feedbacks at another scale (Gunderson & Holling,

2002). Such panarchical relationships suggest both top-down and bottom-up interactions where micro-scale dynamics and macro-scale dynamics influence each other. Agricultural systems can be conceptualized as a social-ecological system composed to two interdependent and interlinked subsystems each operating at different scales with interdependent social and biophysical dynamics (Norgaard, 1984; Woodhill and Röling, 1998; Matthews and Selman, 2006; Thompson et al., 2007; Darnhofer et al., 2008; Feola & Binder, 2010). In the Mali agricultural SES model, climate patterns, crop yield, land use, population change, poverty rates, crop yield, and food consumption patterns are considered to be operating at the national scale. These patterns, in turn, affect livelihoods at the sub-national scale (eg. pastoralism, agro-pastoralism and agriculture), urbanization, migration and input prices at the sub-national level. Adaptation actions at the household level, such as change in cropland allocation, use of crop inputs, etc. are influenced by the sub-national and national scale dynamics and when aggregated, further influence dynamics at the national level (eg. crop yield, poverty rates, land use, etc.) (See Figure 3.1).

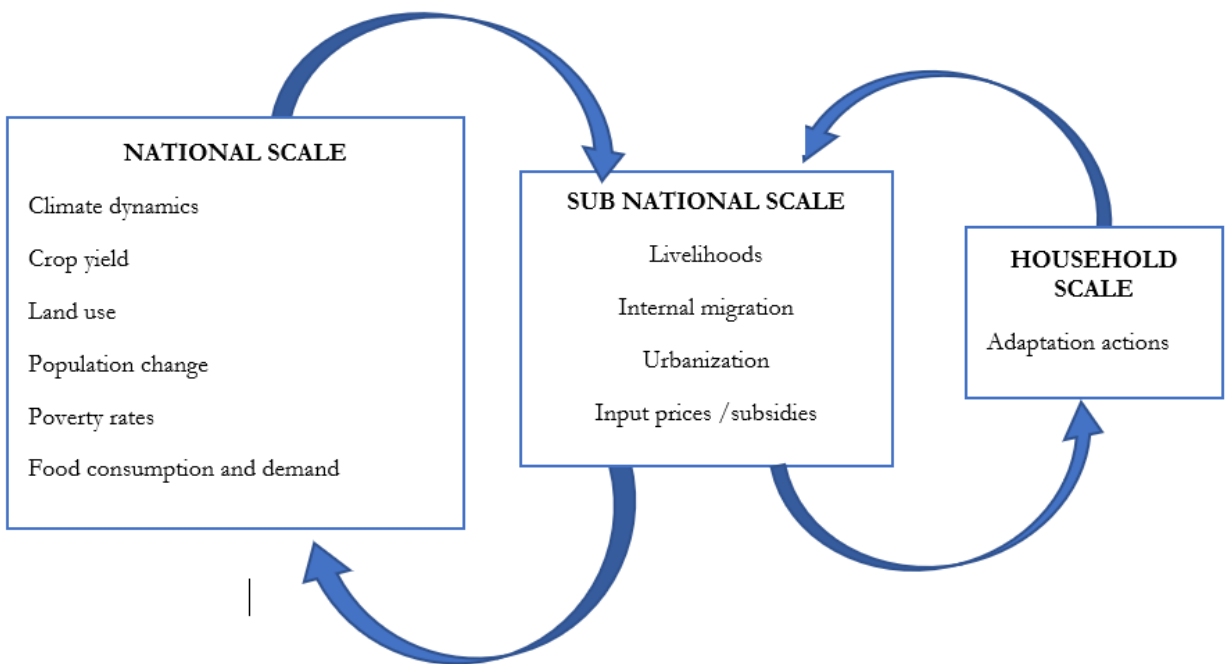


Figure 3.1. Panarchy in the Mali-SES model

2.2. Dynamic feedbacks within Malian SES

The Mali-SES model consisted of several modules where the dynamics within each module influence other modules. The climate and land-use module influences the crop yield module which influences the cereal production module which in turn influences the food security module. Changes in temperature and precipitation changes, fertilizer use, and irrigation management influence crop yield. Increase in crop yield and land acreage leads to an increase in crop production, which increases food supply and therefore, food security. The climate module also influences the livestock production module which influences poverty and urbanization modules, which in turn influences the cereal consumption module. Increase in temperature and decline in precipitation changes leads to decrease in pastoralism which increases urbanization rates which, in turn, increases the urban population and decreases the rural population. The poverty and urbanization module influences the livelihoods module where increased urbanization decreases the proportion of pastoralists and increases the proportion of agro-pastoralists and agriculturalists. The population module also influences the cereal consumption module which in turn influences the food security module which further influences the land use module, hence, closing the model loop (Figure 3.2). Increase in agriculturalists increases land acreage for crop cultivation which in turn increases food production and food supply (B1 balancing feedback).

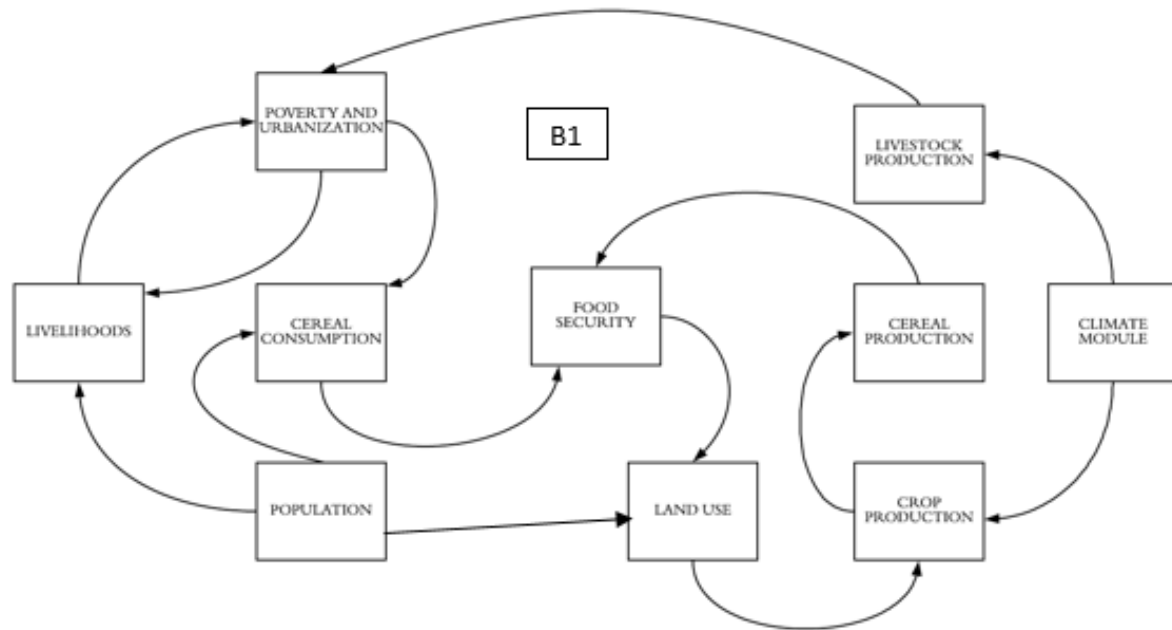


Figure3.2. Model structure of Mali-SES model

3. Causal loop diagram- Mali –SES model

This section explains the causal loop diagram (CLD) for the structure of the MALI-SES system dynamics model (Figure 3.3). CLDs are a diagrammatic representation of the key variables within a system where the arrows represent the causal relationships between the variables. As opposed to static models, causal loop diagrams describe the relationships and feedbacks between the system variables over a period of time where feedbacks are *“any reciprocal flow of influence”* (Haraldsson, 2000).

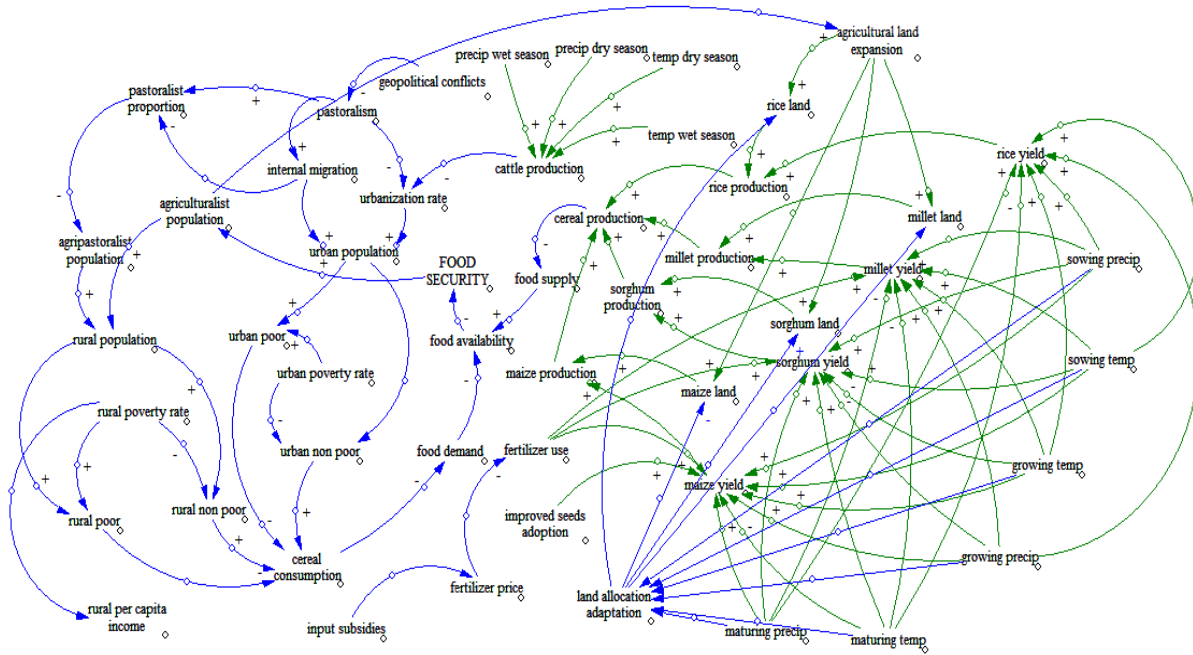


Figure 3.3. Causal loop diagram Mali-SES model

In Mali-SES model, various social, environmental and institutional processes influence food security at the national level. Food security forms the main variable of the model which depends on ‘food availability’ stock which in turn, depends on inflow and outflow of national scale food supply and food demand at a particular time step. The outflow of food demand depends on social dynamics of livelihood and population change, geopolitical conflicts, internal migration, urbanization trends, poverty rates, food consumption patterns as well as institutional dynamics of agricultural land expansion, adaptation actions on land-use change, development of irrigation structures and agricultural input use such as fertilizer subsidies and fertilizer use. The inflow of food supply depends on the environmental/ecological dynamics of cereal production which depends on crop yield and land under production. Crop yield is influenced by temperature and precipitation at various development stages of the crop as well as crop management practices such as the use of fertilizers, irrigation, and improved seed varieties. Temperature and precipitation during dry and wet seasons also influence cattle production which leads to changes in pastoral livelihoods and internal migration within the

country. This impacts the change in rural-urban population dynamics over time and food demand and consumption. These dynamics are elucidated in detail in the following sections; where I describe the ecological and social dynamics within the causal loop diagram in more detail.

3.1. Ecological dynamics

The ecological dynamics in the Mali-SES model (Figure 3.4) incorporate the increase in the agricultural land expansion which increases rice, millet, maize and sorghum land area (positive relation). Increase in agricultural land also increases land under irrigation which is also influenced by the increase in urban non-poor population (positive relation). Increase in precipitation at the sowing season increases rice, millet, sorghum and maize yield (positive relation). Increase in temperature in the sowing phase increases rice, millet, sorghum and maize yield (positive relation). Increase in temperature during the growing phase increases rice, millet, and maize yields (positive feedback) and decreases sorghum yield (negative relation). Increase in precipitation during the growing phase increases rice, millet, sorghum yield (positive relation) and decreases maize yield (negative relation). Increase in temperature during the maturing phase decreases rice, millet and maize yield (negative relation) and increases sorghum yield (positive relation). Increase in precipitation during the maturing phase increases rice, sorghum and maize yield (positive relation) and decreases millet yield (negative relation). Increase in improved seed varieties increases maize yield (positive relation). Increase in fertilizer use also increases maize, millet and sorghum yield (positive relation). Increase in rice, maize, millet, and sorghum yield, as well as increase in rice, maize, millet and sorghum land area, increases crop production (positive relation). Similarly, an increase in average temperature and precipitation during dry and wet season increases cattle production (positive relation). Temperature and precipitation in sowing, growing and maturing crop phases also influence adaptation actions on land use and acreage where climate effects reduce land allocation to maize and rice and increase the land allocation to sorghum and millet.

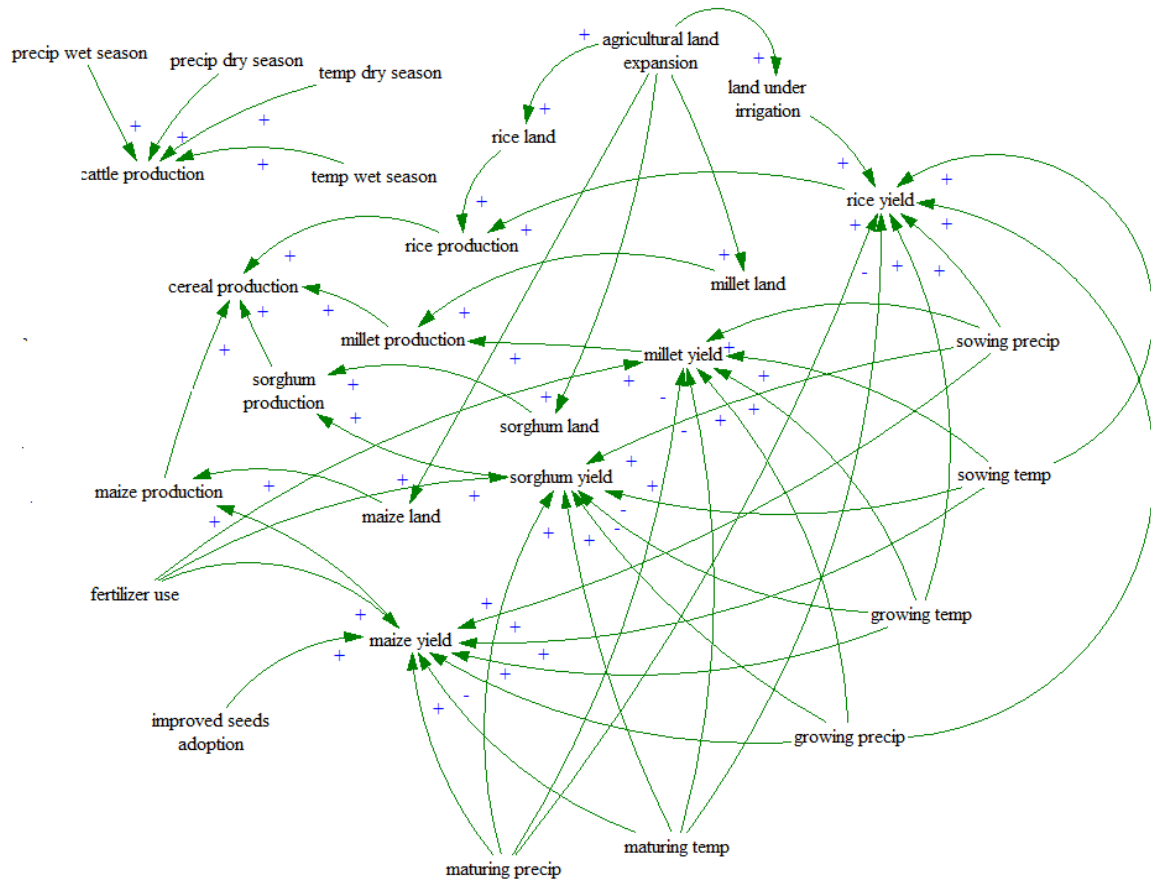


Figure 3.4. Ecological dynamics in Mali-SES model

3.2. Social & institutional dynamics

As mentioned in Chapter 1, Mali can be broadly divided into three livelihood zones, the pastoralist zone in the North, the agro-pastoralist zone in central Mali and the agriculturalist zone in the South. The heterogeneity in livelihood patterns and population changes at the sub-national level are explicitly incorporated in the model (Figure 3.5); Migration is influenced by dry, hot years which increases livestock mortality, which increases migration rates of people in the North and population of the central and southern regions increases. Increase in temperature and precipitation in both dry and wet seasons causes a decline in cattle production and increases the urbanization rate (negative relation)

which in turn increases the urban population (negative relation). Decline in cattle production as well as the increase in geopolitical conflicts, especially in Northern Mali, causes a decline in pastoralism (positive and negative relation respectively). Decline in pastoralism causes a decline in the pastoralist population (positive relation) and an increase in internal migration (negative relation). Increase in internal migration and urbanization rate increases the urban population (positive relation). Increase in internal migration also causes a decrease in the pastoralist population (negative relation) which in turn leads to an increase in the agro-pastoralist population (negative relation). Increase in the agriculturalist population and agro-pastoralism increases the rural population (positive relation). Increase in rural poverty rates within the rural population increases the rural poor population (positive relation) and decreases the rural non-poor population (negative relation). Increase in the rural poor population causes a decline in overall cereal consumption (negative relation). Increase in rural non-poor populations causes an increase in overall cereal consumption (positive relation). Similar dynamics manifest within the urban population where increase in urban poverty rates increases urban poor and decreases non-urban poor populations. Increase in urban poor population decreases overall cereal consumption (negative relation) and increase in urban non-poor increases overall cereal consumption (positive relation). Increase in overall cereal consumption increases food demand (positive relation k); increase in food demand decreases food availability (negative relation). Decrease in food availability leads to a decline in food security (positive relation). As an adaptation measure to climate change and food security decline, adaptation actions such as increased use of fertilizers, land use and acreage change and stabilization of urbanization rates increase crop production and decreases urban food demand and improve food security (balancing feedback).

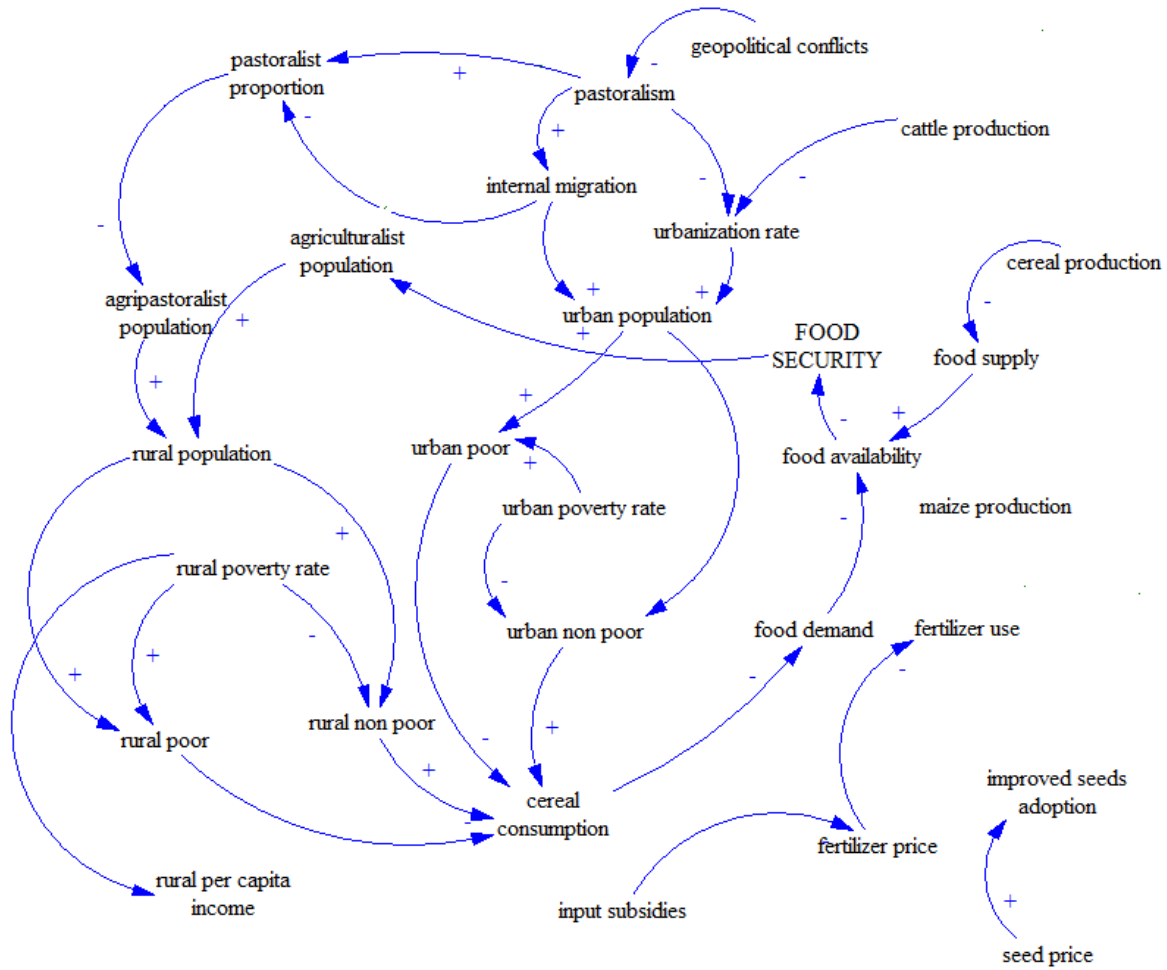


Figure 3.5. Social and institutional dynamics in Mali-SES model

3.3. Exogenous and endogenous variables

The Mali-SES model contains both endogenous and exogenous feedbacks which are either explicitly or implicitly represented in the model. The endogenous feedbacks within the model are interactions that are influenced by the variables within the model while exogenous feedbacks are not specifically stated within the model but function outside the system boundaries to influence the behavior of the system. In this model, climate variables such as changes in temperature and precipitation at different crop growth stages and seasons, influence of geopolitical conflicts on changes in pastoralism livelihoods, poverty rate (for both rural and urban populations) as well as institutional changes with crop subsidies and irrigation use are treated as exogenous feedbacks. Changes in population,

urbanization rate, food consumption, food demand, crop yield, cereal production, and food supply are treated as endogenous feedbacks and dynamics within the model.

4. Methodology

4.1. Model construction

The model was constructed in two main phases: Phase 1 involved the calibration of the various modules in the baseline Mali-SES model using data from 1960-2015 (55 years). The baseline model was calibrated using observed empirical data for land use and climate variables in the model in a graphical format and simulated historical trends in population growth, urbanization, livestock production and crop yield and production of the four cereal crops in Mali.

There exists a high temperature and precipitation gradient across Mali, with the annual precipitation ranging from 100 to 1700 mm across the North -South gradient respectively. The rainy season in the South lasts up to six months and decreases to up to two months in the North. Most of the agriculture production including maize, rice and sorghum and millet is produced in the Southern regions spanning the Sudanian and Sudanian- Guinean eco-climatic zones. Due to limitations in accessibility of time series data of monthly temperature and precipitation from 1901s to 2017 disaggregated by ecoclimatic zones, I chose to incorporate nationally aggregated monthly temperature and precipitation data available at the World Bank's Climate Knowledge Portal and produced by the Climatic Research Unit (CRU) of University of East Anglia (UEA). Average monthly precipitation and temperature was further aggregated according to phases in the crop cycle for rainy season (sowing, growing and maturing phases) of millet, sorghum, rice and maize crops. The sowing phase of crops; maize, millet, sorghum occurs during May, June & July; growth season occurs during August and maturing occurs during September, October, and November. Thus, the temperature and precipitation variables were aggregated and averaged for the respective sowing, growing and maturing phases for maize, millet and sorghum crops. The sowing phase for rainfed rice occurs during June, July; the growth phase occurs

during August, September, October while the maturing phase occurs between November and December. The average temperature and precipitation data were aggregated and averaged accordingly for rainfed rice.

Trends in population birth rate, death rate, urban and rural poverty rates were obtained from national-level data sourced from the World Bank Open data (2018). Data for land expansion rates and proportion of land under cereal consumption for rice, sorghum, millet and maize crops were obtained from FAO statistics (2017). This phase was a key step in developing confidence in the model to accurately represent the key dynamics that influence food production and food consumption in the region. The model was validated by comparing simulated data with observed data where the goodness of fit of the model was estimated based on the correlation coefficients between the simulated and observed data.

Phase 2 involved replacing the observed data in the input parameters and calibrating the model using differential equations. This phase focused on developing the simulation Mali-SES model which included future scenarios for climate trends in temperature and precipitation, land expansion, enhanced fertilizer use and improved seed varieties from 1960 to 2060.

4.1.1. *Climate module*

Data on past climatic trends in Mali during crop growth phases from 1961-2015 show a linear growth trend for average temperature during sowing, growing and maturing phases (Figure 3.6). Average precipitation during sowing and maturing phases also show a linear trend while the average precipitation during the maturing phase shows a decreasing trend in rainfall until 1985 followed by an increasing trend from the late 1980s until 2015 (Figure 3.7). The slope of trends of temperature and precipitation during crop cycle phases from 1961-2015 were analyzed using Sen's Slope and Mann-Kendall methods (**Table 3.2**). The Mann–Kendall trend test is a nonparametric rank-based procedure that is used to assess the existence of trends in non-normally distributed time-series data. In the testing

process, the null hypothesis (H_0) is that there is no trend in the population from which the dataset is drawn. The alternate hypothesis (H_1) is that there is a trend in the population. The H_0 was rejected if $p \leq 0.05$ (confidence level: 95%) Similarly, the trend was quantified using Sen's slope method. Sen's slope was used to quantify the trend using the nonparametric procedure developed by Sen (Sen, 1968).

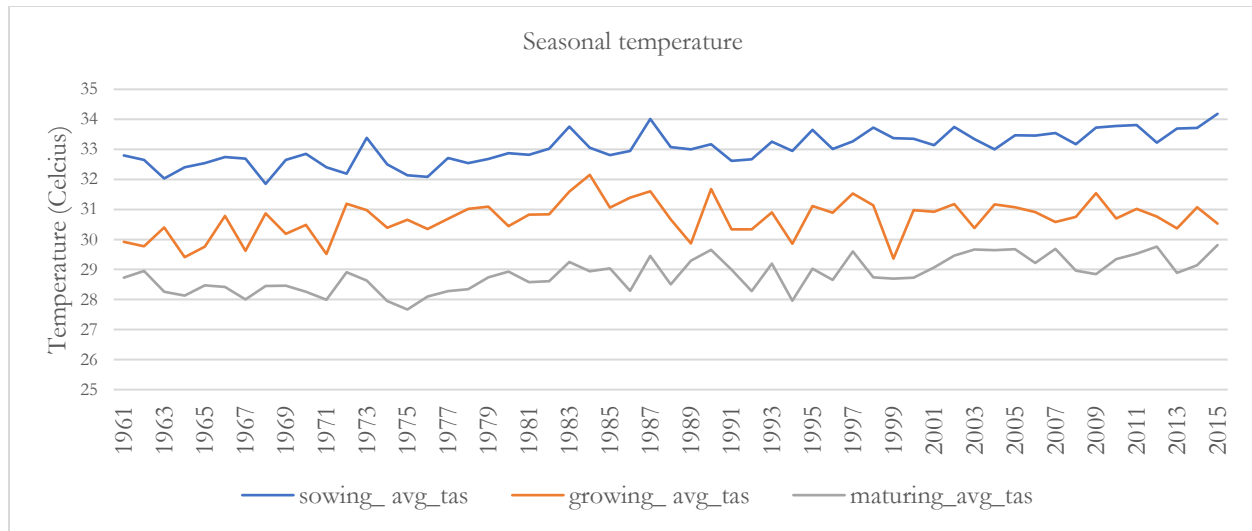


Figure 3.6. National temperature trends (sowing, growing and maturing phase) (1960-2015)

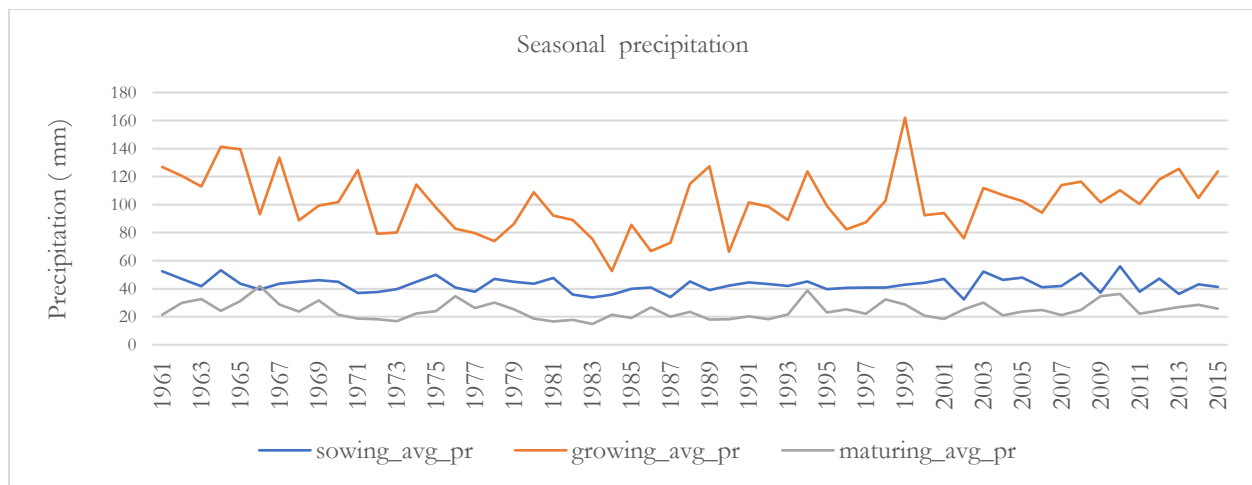


Figure 3.7. National precipitation trends (sowing, growing and maturing phase) (1960-2015)

Time series	First year	Last year	Test z	Significance (95% confidence interval)	Q (slope)
Sowing _{temp}	1961	2015	6.42	***	0.026
Sowing _{precip}	1961	2015	-0.41		-0.016
Growing _{temp}	1961	2015	2.40	*	0.011
Growing _{precip}	1961	2015	0.60		0.105
Maturing _{temp}	1961	2015	5.24	***	0.023
Maturing _{precip}	1961	2015	0.57		0.030

Table 3.1. Sen's slope and Mann-Kendall trend test results for climate variables from 1961-2015

Results of Sen's slope and Mann-Kendall trend test for temperature and precipitation variables showed significant positive trends in temperature in sowing, growth and maturing phases (Table 3.1.). Average precipitation during the sowing and maturing phase showed a statistically non-significant negative and positive slope respectively (Table 3.1.). The average precipitation during growth phase, on the other hand, showed a non-linear trend where rainfall declined from 1960-1985 and increased from 1985-2015. When the pattern in rainfall trends during crop maturing phase is scaled back from 1901-2015, these interannual and interdecadal trends of alternate increase and decrease of rainfall are clearly evident where an increase in rainfall is observed from 1901-1960 followed by a decline in rainfall from 1960-1985 and a subsequent increase in rainfall from 1985-2015 (Figure 3.8). These trends were consistent with other findings which show that regions in the Sahel (including Mali) experience alternating wet and dry spells in annual and decadal time periods (Brooks, 2004; Foley et al., 2003; Hulme, 2001) and increasing trend in both maximum and minimum temperatures in all three Sudanian, Sahelian and Sahelian-Saharan ecological zones in the West African Sahel as well as a period of wet years from 1950-1969 followed by a period of dry years from 1970-1993 (Halimatou et. al, 2017). Brooks (2004) and Foley et al. (2003) attribute global warming as the driver for the 'regime shift' in the climate from an interannual to a decadal-scale variability in rainfall patterns after the Sahelian droughts in the 1960s.

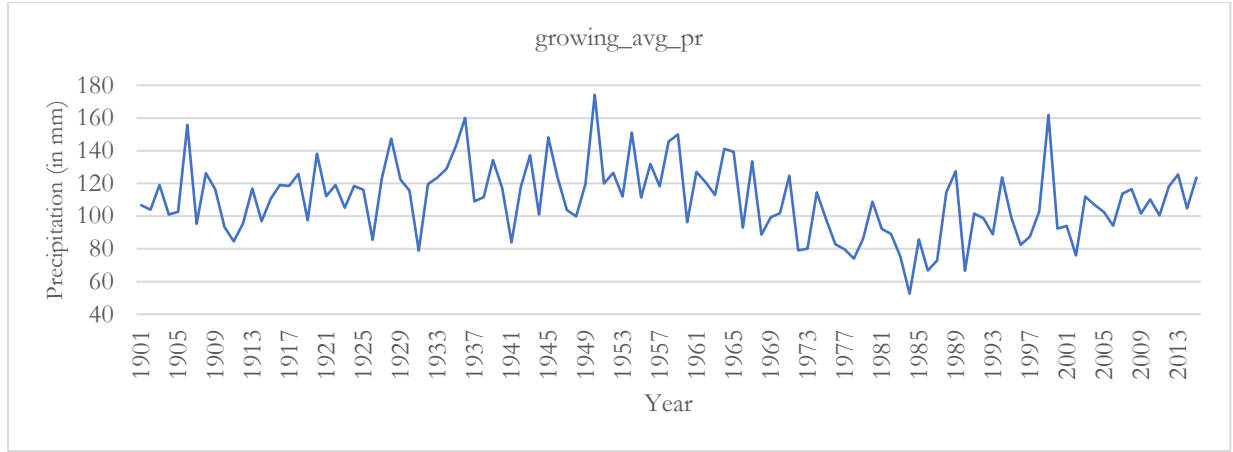


Figure 3.8. Average precipitation during growth phase (1901-2015)

The Mali-SES model functionalized climate variables using linear equations for temperature at sowing, growing and maturing phases as well as precipitation at sowing and maturing phases where

$$y = mx + c \quad (1)$$

Where y is the temperature at sowing, growing and maturing and precipitation at sowing and maturing; m is the Sen's slope, x is time that iterates with time step of a year and c is the intercept that is random number generated between the average minimum and maximum for observed climate parameters.

This function is calibrated in the model using time series data from 1960-2015 as:

$$Temp_{sowing} = (0.026 * TIME) + RANDOM(31.7, 32.7) \quad (2)$$

$$Temp_{growing} = (0.011 * TIME) + RANDOM(29.86, 31.06) \quad (3)$$

$$Temp_{maturing} = (0.023 * TIME) + RANDOM(27.64, 28.84) \quad (4)$$

$$Precip_{sowing} = (-0.016 * TIME) + RANDOM(38.45, 48.55) \quad (5)$$

$$Precip_{maturing} = (0.03 * TIME) + RANDOM(17.03, 29.03) \quad (6)$$

Precipitation during growth phase is functionalized using a sinusoidal equation

$$y = A \sin\left(\frac{2\pi}{B}(x - C)\right) + D \quad (7)$$

where A is the amplitude which is the difference between mid-line or average precipitation at growth phase and the highest value of precipitation in the curve, B is the time period within which a sine curve repeats itself, C is the phase shift or shift along the x-axis or the number of time steps and D is the shift along the vertical axis (average precipitation). This function is calibrated in the model using the time series data from 1960-2015 as

$$Precip_{growing} = 25 \sin\left(\frac{2\pi}{70}(TIME - 25)\right) + 100 + RANDOM(-20,20) \quad (8)$$

The random function introduces variability in precipitation.

Similarly, trends in precipitation and temperature in relation to livestock production were estimated by aggregating monthly temperature and precipitation into dry and wet seasons. The temperature and precipitation at the wet season were averaged for the months of June, July, August, September, October, and November while temperature and precipitation at dry season were averaged for the months of December, January, February, March, April, and May.

Trends in temperature during dry and wet season were functionalized as:

$$Temp_{dry} = 0.0224*TIME + RANDOM(29, 32) \quad (9)$$

and

$$Temp_{wet} = (0.0222*TIME^2) - (1.1604*TIME) + RANDOM(40, 65) \quad (10)$$

Trends in precipitation during dry season and wet season were functionalized as

$$Precip_{dry} = (-0.0083*TIME) + RANDOM(0,4) \quad (11)$$

and

$$Precip_{wet} = (0.0272*TIME) + RANDOM(23, 26) \quad (12)$$

4.1.2. Crop yield & climate variability

The relationship between temperature and precipitation at sowing, growing and maturing phases and average crop yields of rice, maize, sorghum, and millet crops were functionalized and calibrated using a series of multivariate regression analyses from crop yield and climate data from 1961-1990 (FAO,

2017). The relationship between climate variables and crop yield is isolated by regressing climate variables and crop yield between 1960-1990 as crop yields for maize, rice, sorghum, and millet show a high correlation with average temperature and precipitation trends at sowing, growing and maturing phases. The effects of cereal liberalization and increase in the use of crop inputs such as fertilizers and improved irrigation that subsequently came into effect for maize, sorghum, millet, and rice crops after 1990 (Staatz et al, 2011) were introduced separately within the model as elaborated in sections below.

1. The four regression models for maize, sorghum, millet, and rice yields were conducted using SPSS version 15 statistical software. The simple multivariate regression equation can be expressed as

$$Y_{crop} = c + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \gamma_1 Z_1 + \gamma_2 Z_2 + \gamma_3 Z_3 \quad (13)$$

where Y_{crop} is the dependent variable i.e. crop yield for maize, sorghum, millet, and rice respectively, c is the intercept, X and Z represent the independent variables i.e. temperature and precipitation respectively where $i=1$ represents sowing phase, $i=2$ represents growing phase, $i=3$ represents maturing phase. β_i is the mean increase in Y_{crop} given an increase in X_i while other X_i 's are kept fixed and γ_i is the mean increase in Y_{crop} given an increase in Z_i while other Z_i 's are kept fixed. **Table 3.2** shows the results of the regression equations.

	Dependent variables			
Independent variables	Maize yield	Sorghum yield	Rice yield	Millet yield
Intercept	-14440.3	-4301.93	-1941.04	-5385.86
$Sowing_{temp}$	285.15	115.89	93.4	94.11
$Sowing_{precip}$	18.73	11.22	3.77	2.5
$Growing_{temp}$	212.39	-70.97	38.66	131.21
$Growing_{precip}$	-0.81	-2.3	0.73	2.09
$Maturing_{temp}$	-45.39	115.96	-63.48	-41.99
$Maturing_{precip}$	10.53	7.72	0.68	-0.04

Table 3.2. Results of multivariate regressions between climate variables and crop yield (1960-1990)

This relationship is functionalized and calibrated in the Mali-SES model as follows:

$$\begin{aligned} Yield_{maize} = & -1440.30 + 285.15 * sowing_{temp} + 18.73 * sowing_{pr} + \\ & 212.39 * growing_{temp} - 0.81 * growing_{pr} - 45.39 * \\ & maturing_{temp} + 10.53 * maturing_{prep} \end{aligned} \quad (14)$$

$$\begin{aligned} Yield_{sorghum} = & -4301.93 + 115.89 * sowing_{temp} + 11.22 * sowing_{pr} - \\ & 70.97 * growing_{temp} - 2.30 * growing_{pr} + 115.96 * maturing_{temp} + 7.72 * \\ & maturing_{prep} \end{aligned} \quad (15)$$

$$\begin{aligned} Yield_{millet} = & -5385.86 + 94.11 * sowing_{temp} + 2.50 * sowing_{pr} + \\ & 131.21 * growing_{temp} + 2.09 * growing_{pr} - 41.99 * maturing_{temp} - 0.04 * \\ & maturing_{prep} \end{aligned} \quad (16)$$

$$\begin{aligned} Yield_{rice} = & -1941.04 + 93.40 * sowing_{temp} + 3.77 * sowing_{pr} + \\ & 38.66 * growing_{temp} + 0.73 * growing_{pr} - 63.48 * maturing_{temp} + 0.68 * \\ & maturing_{prep} \end{aligned} \quad (17)$$

4.1.3. Crop yield and fertilizer use:

The effects of fertilizer application on maize, sorghum and millet crops and irrigation in rice crops are prominent after 1990. These dynamics are introduced using the dynamics of fertilizer agronomic efficiency for maize crops; fertilizer use for sorghum and millet crops and land under irrigation and irrigation efficiency for rice crops.

Maize (Fertilizer use, hybrid varieties):

The agronomic efficiency of nitrogen-based fertilizers AE [kg (kg N)⁻¹] has been defined as the increase in maize grain yield per unit of fertilizer N applied:

$$AE = \frac{Y_F - Y_C}{F_{appl}} \quad (18)$$

where Y_F and Y_C refers to grain yields [kg ha⁻¹] in the treatment where fertilizer N has been applied and in the control plots, respectively, and F_{appl} is the amount of fertilizer N applied [kg N/ha]. According to research by (Vanlauwe et al. 2011), the agronomic efficiency of nitrogen fertilizer use decreases as the fertilizer use is increased from 20 kg per hectare to 150 kg per hectare. Maize yield follows a linear increase from 1000 kg per ha to 6000 kg per ha with fertilizer application from 50 to

120 kg per hectare and stabilizes with further increase in fertilizer application. These dynamics are incorporated in the Mali-SES model using the Michaelis-Menten equation

$$Yield = \frac{Yieldmax + fertilizeramt}{Km + fertilizeramt} \quad (19)$$

where Yieldmax is the maximum yield achieved through fertilizer use and Km is a constant that represents the amount of fertilizer that would lead to production of Yieldmax/2. Based on research by Vanlauwe et al., 2011, the model assumes that the fertilizer amount of 120 kg/ha N leads to max yield of 6000 kg per ha for current varieties of maize in Mali, hence the value of Km is set to 60 kg/ha (for half of the maximum yield).

The effect of the use of hybrid varieties of maize is functionalized using insights from Vanlauwe et al. (2014) where the use of hybrid maize varieties increased AE values from 17 kg(kg N)⁻¹ (local varieties) to 26 kg(kg N)⁻¹. Mixing fertilizer with manure and compost further increases NAE values to 36 kg(kg N)⁻¹.

Sorghum and Millet (fertilizer use):

The effects of fertilizer use on sorghum and millet yields were calibrated using insights from Aune, Doumbia, and Berthe (2010) who found that yield of sorghum increased by 34% and 52% compared with the control after applying 0.3 g of fertilizer per land pocket (which is equivalent of 30 -75 kg/ha depending on location and soil quality) for the years 2000 and 2001 respectively. For pearl millet, the corresponding yield increase after applying 0.3 g per land pocket of fertilizer was 48% and 67% for 2001 and 2003 respectively. The model was calibrated as a yield increase of 50% for millet and 40% for sorghum. Fertilizer use is initiated from the year 2000 (time step= 40) onwards. Game data from this research revealed that farmers in general use fertilizers mainly for cotton and maize fertilizers. Hence, the initial parameterization of fertilizer use in sorghum and millet was kept at zero.

Rice (irrigation efficiency):

The dynamics of irrigation use and rice yields are introduced in the model by incorporating an irrigated land expansion for rice cultivation. Irrigation improves and stabilizes rice yield between 4000 to 6000 kg/ha by making rice production less dependent on annual rainfall (Guindo et al. 1999; Saito et al. 2015). The model uses the random function to simulate yields of irrigated rice between 4000 to 6000 kg per ha.

4.1.4. Land use and crop production

The dynamics of land use and expansion are introduced through exogenous variables such as land expansion rate which is based on data on the agricultural land area from World Bank data sources (2017). The agricultural land growth rate peaked between 1990-2000 to 2.5% and declined to 1% by 2010. These trends are introduced using the graphical function in Stella. The proportion of agricultural land allocated to cereal crop cultivation is functionalized through the cereal intensification variable using a regression function between yearly temperature and precipitation variables and the proportion of land allocated to cereal cultivation data from 1961-2015. The function is as follows:

$$\begin{aligned} \text{cereal}_{intesification} = & -0.9946 + 0.021 * \text{sowing}_{temp} + 0.00028 * \\ & \text{sowing}_{precip} + 0.012 * \text{maturing}_{temp} \end{aligned} \quad (20)$$

The proportion of land under cereal allocated to the four main cereal crops, namely maize, sorghum, millet, and rice individually are influenced by yearly temperature and precipitation patterns as well. This relationship was substantiated through the insights from the game data in Koutiala where farmers reported decreasing acreage of maize, sorghum, and millet in case of high temperatures and excessive rainfall (refer to Chapter 2). The relationship between climate trends and proportion of land allocated to respective cereal crops was functionalized by variables maize, sorghum, millet and rice allocation climate effect variables estimating the regression function of observed cereal crop acreage as a

proportion of land under cereal cultivation with the climate variables i.e. temperature and precipitation at sowing, growing and maturing phases.

$$Yield_{maize} = -1.5665 + 0.03 * sowing_{temp} + 0.0006 * sowing_{precip} + 0.02 * maturing_{temp} + 0.002 * maturing_{precip} \quad (21)$$

$$Yield_{sorghum} = 1.6791 - 0.042 * growing_{temp} - 0.0009 * growing_{pr} \quad (22)$$

$$Yield_{millet} = 1.2121 - 0.02 * sowing_{temp} - 0.001 * growing_{precip} \quad (23)$$

$$Yield_{rice} = -0.7 + 0.024 * growing_{temp} + 0.0008 * growing_{precip} \quad (24)$$

Crop production for each of the four crops was calculated by multiplying the land under the specific crop cultivation and the respective crop yield.

4.1.5. *Livestock production and climate dynamics*

The relationship between average temperature and precipitation at dry and wet seasons and livestock production (cattle, goat and sheep) in Mali was functionalized and calibrated using results from a series of three multivariate regressions of cattle, goat and sheep production and climate data (precipitation and temperature for wet and dry seasons) from 1961-2010 (FAO, 2017). The results of the regression models showed that cattle production was significantly and positively correlated with temperature and precipitation at dry season and precipitation at the wet season (**Table 3.3**). Goat production was significantly and positively correlated with the temperature in the dry season and temperature and precipitation in the wet season. Sheep production was found to be positively and significantly correlated with temperature and precipitation during both wet and dry seasons. This finding is supported by the study by Wilson & Sayer (1987) who found that most conceptions for livestock in central Mali occur during the hot dry season.

Independent variables	Dependent Variables		
	Cattle production	Goat production	Sheep production
Intercept	-71.37	-186.97	-99.46
<i>Temp dry</i>	0.07 ***	0.23****	0.10***
<i>Precip dry</i>	0.45*	0.95	0.68**
<i>Temp wet</i>	0.45	1.22*	0.77*
<i>Precip wet</i>	1.94***	4.75***	2.52***

Table 3.3. Results of multivariate regressions between climate variables and livestock production variables (1960-2010)

This relationship was functionalized and calibrated in the Mali-SES model as follows:

$$Cattle_{production} = -71.37 + 0.07 * temp_{dry} + 0.45 * precip_{dry} + 0.45 * temp_{wet} + 1.94 * precip_{wet} \quad (25)$$

$$Goat_{production} = -186.97 + 0.23 * temp_{dry} + 0.95 * precip_{dry} + 1.22 * temp_{wet} + 4.7 * precip_{wet} \quad (26)$$

$$Sheep_{production} = -99.46 + 0.10 * temp_{dry} + 0.68 * precip_{dry} + 0.77 * temp_{wet} + 2.52 * precip_{wet} \quad (27)$$

Effect on pastoralism (predominantly in Northern Mali) is caused by a decline in cattle production and increase in geo-political conflicts. Note that the mathematical functionalization of effect on pastoralism and geopolitical conflicts are qualitative variables which are harder to observe directly or multidimensional. System dynamics models allow (even encourage!) the incorporation of such fuzzy qualitative variables into the model through structural verification and subsequent formulation (Luna-Reyes et al., 2003). The inverse relationship of cattle production with pastoralism and the direct relationship with geopolitical conflicts was introduced in the model by functionalizing pastoralism as

$$effect\ on\ pastoralism = 1 - \left(\frac{1}{cattle_{production}} + geopolitical\ conflicts \right) \quad (28)$$

where geopolitical conflicts were represented by a graphical function that follows an S-curve, where effects of conflicts are low between 1960-1980 and increased exponentially between 1990- 2020 before stabilizing between 2030 -2060.

4.1.6. *Population dynamics*

The population dynamics in Mali are represented through a stock-flow diagram where birth rate determines inflow of growth in population each year through a reinforcing loop; death rate determines the outflow of decline in population each year through a balancing loop. The birth rate and death rate were calibrated for Mali using a graphical function that represents data from the World Bank Indicators (2016) for yearly birth rate and birth rate from 1960-2015 where both birth and death rates are declining over time.

The total population of Mali was disaggregated into livelihood-based populations; namely pastoralists, agro-pastoralists, and agriculturalists. The ‘effect of pastoralism’ as a function of livestock production and geopolitical conflicts, directly influenced the proportion of pastoralists in the Mali- SES. Changes in the agriculturist population in the country were represented by a graphical function which shows historical trends in the decline of the proportion of agriculturalists in Mali from 1960-1990 followed by a recovery trend from 2000- present. The proportion of the pastoralist population is influenced by the decline in pastoralism variable and functionalized as:

$$\text{pastoralist population proportion} = \frac{(1-\text{decline in pastoralism})}{12} \quad (29)$$

The proportion of the agro-pastoralist population in Mali was represented as a function of the proportion of pastoralist and agriculturalist population as follows:

$$\text{agro-pastoralist population} = [1-(\text{agriculturalist_proportion} + \text{pastoralist_proportion})] * \text{population} \quad (30)$$

The population was also disaggregated into rural and urban populations through the urbanization rate converter. The urbanization rate in Mali is found to be inversely related to the pastoralist population

where the decline in pastoralists increases the urbanization rate due to internal migration in the country. This relationship is represented using the following function:

$$\text{Urbanization rate} = 1 / \text{pastoralist proportion} \quad (29)$$

Further, the total population was disaggregated into rural and urban populations based on trends in rural and urban poverty rates, which were calibrated using poverty distribution estimation data from the World Bank titled “Geography of poverty in Mali” (2015). According to the report, urban poverty rates in Mali declined from 22.9 percent to 14.3 and 13.7 percent for the years 2001, 2006 and 2010 respectively. The rural poverty rates in Mali declined from 60.3 percent to 50.6 and 48.9 percent for the years 2001, 2006 and 2010 respectively. These patterns were plotted as graphical functions in the Mali-SES model with the assumption that urban and rural poverty rates are likely to continue declining in the future.

4.1.7. *Food consumption and demand*

Food demand dynamics in the Mali-SES model were calibrated using insights from the study by the USAID report (2007) which used INSTAT Mali data (2006) and ENBC data (2007) to compute average quantities of cereal consumption in Mali by poverty status. According to the study, the average per capita consumption of millet, sorghum, maize and rice consumption for the urban non-poor populations is 90.183, 98.044, 104.212 and 48.905 kg, the per capita consumption for the urban poor is 49.86, 53.806, 58.041 and 25.595 kg. Similarly, the average annual per capita consumption of millet, sorghum, maize and rice consumption for the rural non-poor populations is 82.419 88.423, 91.84, and 44.424 kg, the per capita consumption for rural poor is 39.76, 44.01, 46.91, and 20.71 kg. The total demand for maize, millet, sorghum and rice crops was computed by using a summation function for rural and urban population cereal consumption. The food availability represented the stock of cereal food available in a particular year and was influenced by the inflow of cereal produced and outflow of cereal demand at a particular time step.

The variable ‘food security’ is a measure of food supply and demand and quantified as

$$food\ security = \frac{food\ supply}{food\ demand} \quad (30)$$

Values above 1 represent a food ‘secure’ status while values under 1 represent a food ‘insecure’ status. Deviation from the equilibrium (i.e. value 1) represents the severity of food insecurity or security in the country.

4.2. Model validation: Observed vs: Simulated data

By definition, a model is an abstract representation of a real-world system. Model validation is the process of assessment of the performance of the model where the goodness of the model is based on how accurately the model predicts the variables in a system in comparison to the actual observed behavior of the system. The validation of the Mali-SES model was performed by simulating the model for 55 time steps to represent the time period from 1961-2015. The simulated output was then compared with the observed data on climate trends, crop production, population change, urbanization and land use from 1961-2015 to estimate the goodness of fit of the model. Correlation coefficients between simulated and observed data were chosen as a measure of model performance.

4.3. Modeling Scenarios

Scenario analysis is a process of evaluating possible system trajectories or outcomes in a model by considering various feasible parameter spaces. It can be thought of as an in-silico experimentation of the model when it’s not possible to explore the outcomes through actual observations of the system such as events that could take place in the future. The Mali-SES model explored 10 scenarios which consisted of two key climate projection scenarios each of which explored a combination of five climate adaptation scenarios including fertilizer use for millet and sorghum, land allocation changes, stabilization of decline in pastoralism and cereal land expansion. In each of these scenarios, it is assumed that birth rate continues to decline with the current trajectory (5% in 1961, 3.9% in 2015 and

2.3% in 2060); death rate continues to decline with the current trajectory (3.6% in 1961, 1% in 2015 and 0.2% in 2060), urban poverty rates decline with the current trajectory (33% in 1961, 23% in 2015 and 11% in 2060) and rural poverty rates declines with the current trajectory (83% in 1961, 60% in 2015 and 36% in 2060).

4.3.1. *Climate Scenarios A & B:*

The Global Circular Model for West Africa projects continuous warming of 1.5 to 6.5 ° C and uncertain precipitation (-30 and 30%) for the Sahel region by end of the century (Sylla et al., 2016). Birkel & Mayewski (2015) who examined the historical climate and projected climate variability of Mali with historical data, reanalysis, general circulation model (CMIP5) and regional climate models show that climate projections are highly uncertain, especially accounting for spatial heterogeneity within the region. According to their analysis, in the case of GCM, simulated temperature and precipitation failed to validate against historical observations and had a significant cool temperature bias and precipitation deficit. The authors suggest caution on using the GCM rainfall projections across Western Sahel region for Mali and offer the following plausible climate projection scenarios for the country for 2030-2050:

- Standard CMIP5 projection of 2 °C warming with slight rainfall decline.
- Annual temperature rise > 1 °C with rainfall remaining at present norm, or increased slightly.
- Annual temperature rise > 1 °C with diminished rainfall or drought
- Annual temperature rise > 1 °C with the onset of severe drought
- Abrupt climate shift in response to the collapse of summer Arctic sea ice, wherein any of the scenarios above could develop within a decade.

In the Mali-SES model, I incorporated only the first three moderate climate scenarios from 2020-2060 and leave out the extreme scenarios of severe drought and abrupt climate shift to form two climate scenarios:

Scenario A: 1.5 °C warming with diminished rainfall

Scenario B: 1.5 °C warming with rainfall remaining at present norm | increasingly slightly.

Under each of these two climate scenarios: a series of five adaption scenarios were tested including: no adaptation: business as usual; increased fertilizer use for sorghum and millet crops; increase in land allocated to sorghum and millet; stabilization of decline in pastoralism; and increased cereal extensification.

4.3.2. *Adaptation Scenarios 1-5*

Adaptation Scenario 1 Business as usual

The Business as Usual scenario represented a reference or a baseline for exploring food security projections if the agricultural socio-ecological systems in Mali behaved in the same manner as the current trends. This implied the following assumptions for this scenario:

- Land expansion occurs from 1990-2000 to a maximum of 3% followed by no expansion between 2000-2060
- Low fertilizer use for sorghum and millet crops

Adaptation Scenario 2: Fertilizer use for millet and sorghum crops

Adaptation scenario 2 built on the business as usual scenario by including fertilizer use for sorghum and millet cultivation (60 kg/ha) for millet and sorghum use from 2016 to 2060.

Adaptation Scenario 3: Fertilizer use + Land allocation effect

Adaptation scenario 3 built on adaptation scenario 2 with an incremental increase in land allocated to millet and sorghum and the corresponding decline in land allocated for maize and rice crops from 2016- 2060.

Adaptation Scenario 4: Fertilizer use + land allocation effect+ Stabilization of decline in pastoralism

Adaptation Scenario 4 built on scenario 3 by introducing a stabilization effect on the decline of pastoralism and rural to urban migration.

Adaptation Scenario 5: Fertilizer use + land allocation + stabilization in pastoralism decline + cereal land expansion

Scenario 5 built on Scenario 4 and introduces incremental land expansion under cereal cultivation from 2020 to 2060.

The model was simulated separately for each of the five adaptation scenarios within each climate scenario and the trend in food security projections was compared for all scenarios.

4.4. Sensitivity analysis

Sensitivity analysis is a simple yet powerful tool to assess the change in system outputs due to variations in the key parameters that affect the internal dynamics of the system (Gunawan, 2005). A parameter is considered highly sensitive if small variations in the parameter lead to drastic changes in the system behavior or performance (and vice versa). Hence, sensitivity analysis is often used to identify key driving mechanisms that influence the system. In this study, a sensitivity analysis was conducted with six key parameters to identify if they act as drivers of food security. These parameters were:

1. Rates of increase in sowing, growing, maturing season temperature respectively;
2. Rate of increase in overall precipitation
3. Rate of urbanization and
4. Rate of cereal extensification.

A series of 5 sensitivity runs were conducted for each parameter where the parameter values were set for an incremental increase with each run within a range that varied between their original parameterized values to three times their original value. For example, the rate of increase in

temperature at sowing season was tested from a range of 0.023 degree Celsius per year to 0.078 degrees Celsius per year.

5. Results and Discussion

5.1. Model validation results

5.1.1. *Climate trends:*

The R square value between simulated and observed temperature and precipitation data between the years 1961 (time =1) and 2015 (time = 55) are 0.69, 0.13, 0.47 for the temperature at sowing, growing and maturing phases respectively and -0.119, 0.54 and -0.007 for precipitation at sowing, growing and maturing phases respectively, suggesting good goodness of fit of the model with growing and maturing temperature and growing precipitation (Figure 3.9).

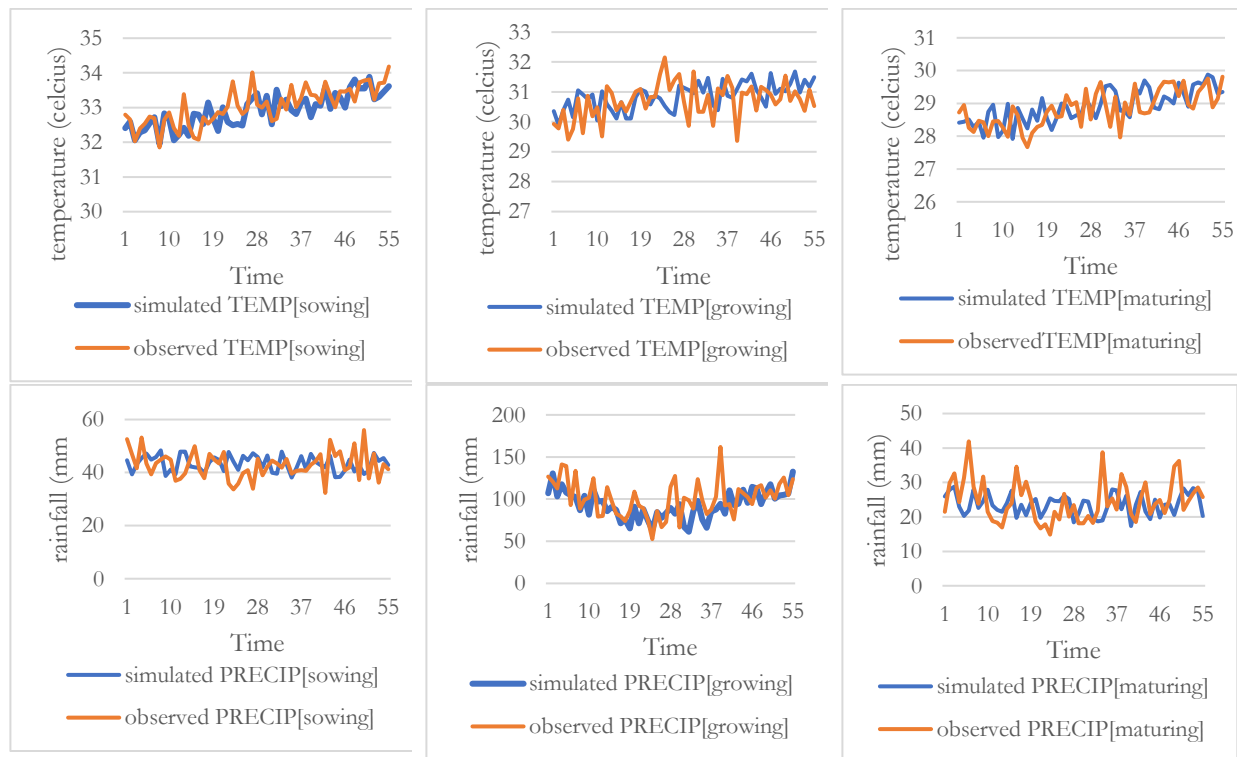


Figure 3.9. Simulated and observed trends in temperature and precipitation during sowing, growing and maturing phases (1961-2015)

5.1.2. Crop yield trends:

The R^2 value between simulated crop yield and observed crop yield between the years 1961 (time =1) and 2015 (time = 55) for maize, sorghum, millet, and rice crops are 0.73, 0.16, 0.25, 0.86 suggesting good goodness of fit of the model output with observed data for maize and rice yields (Figure 3.10).

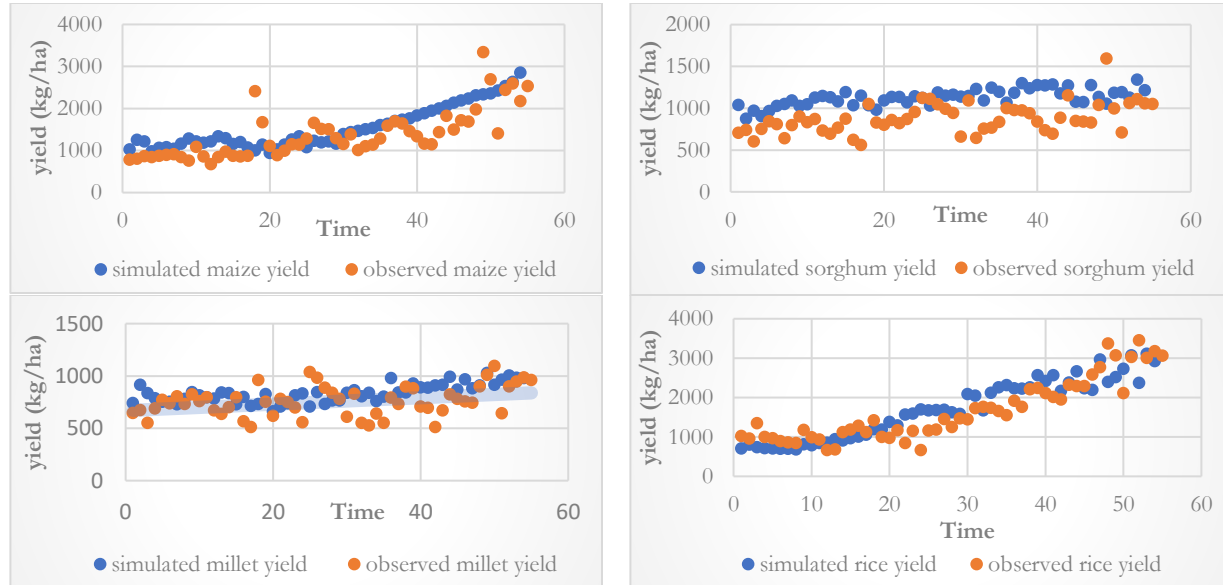


Figure 3.10. Simulated and observed trends in cereal crop yield (1961-2015)

5.1.3. Crop production trends:

The R^2 value between simulated and observed crop production between the years 1961 (time =1) and 2015 (time = 55) for maize, sorghum, millet, and rice crops are 0.92, 0.75, 0.84, 0.93 suggesting high goodness of fit of the model output with observed data (Figure 3.11).

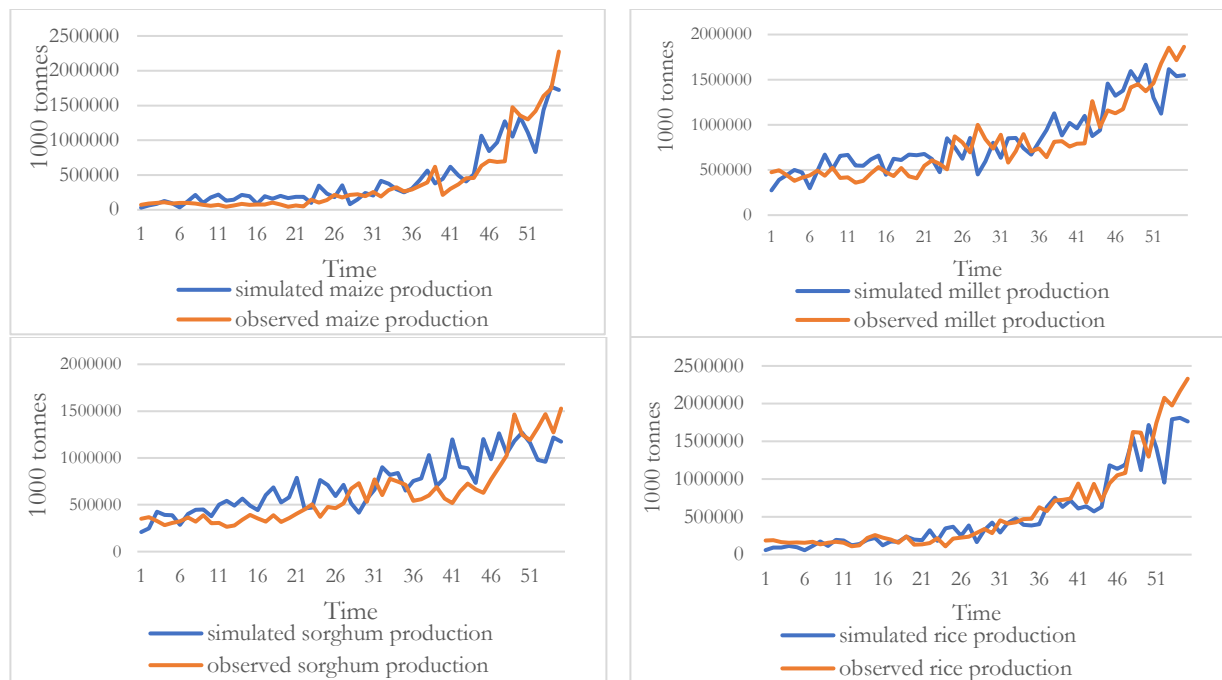


Figure 3.11. Simulated and observed trends in crop production (1961-2015)

5.1.4. Population and urbanization trends:

The R^2 value of simulated and observed population trends between the years 1961 (time =1) and 2015 (time = 55) is 0.99 suggesting high goodness of fit of the model output with observed data (Figure 3.12).

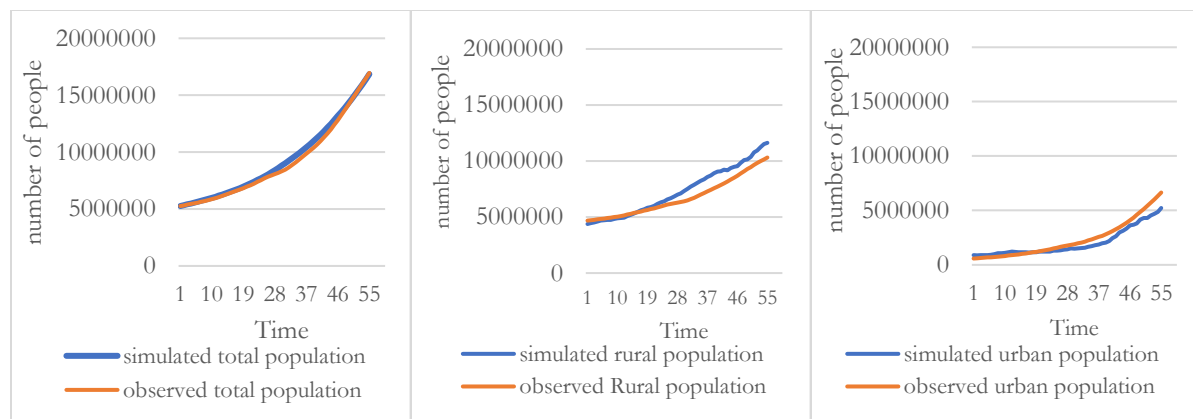


Figure 3.12. Simulated and observed trends in rural, urban and total population (1961-2015)

5.2. Model simulation results

This section outlines the results on future projections of climate and adaptation scenarios generated by the Mali-SES model as well as a detailed overview and comparison of the scenario runs conducted within the model.

5.2.1. Scenario A: 1.5 °C warming with diminished rainfall

The Mali-SES model shows an increasing trend in temperature for all crop sowing, growing, and maturing phases. This trend is consistent with the temperature projection scenarios by Birkel & Mayewski (2016). This scenario incorporated a declining trend in rainfall in growing phase precipitation from 2020- 2060 (Figure 3.13 b).

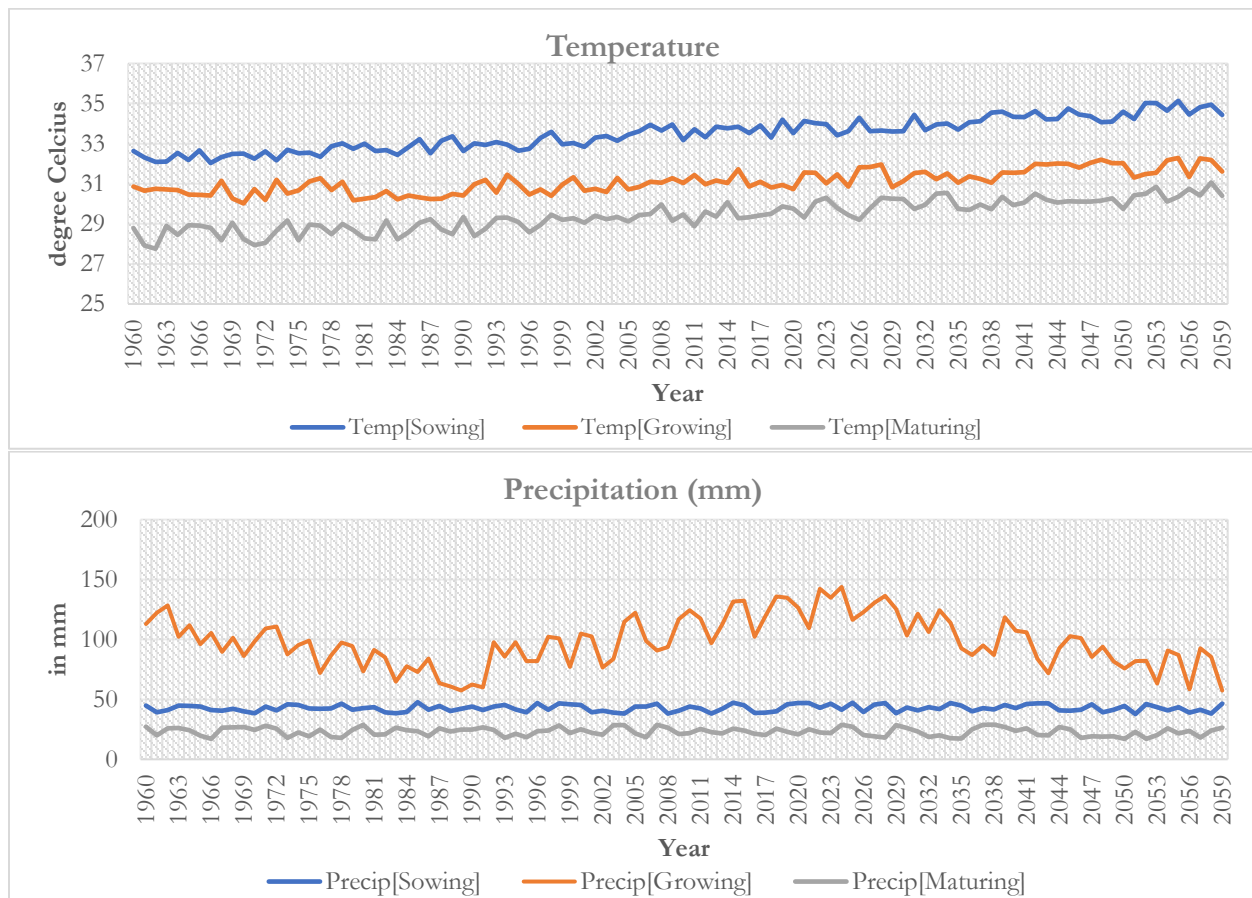


Figure 3.13. Scenario A: Temperature and precipitation in sowing, growing and maturing phases (1960-2060)

According to the model, the temperature in the sowing season increased at a rate of approximately 0.03 degrees Celsius per year and estimates an accumulative temperature increase of 1.5 Celsius between 1961-2019 and a projected increase of 1.04 degrees Celsius between 2020- 2060. The temperature in the growing season increased at a rate of 0.02 Celsius per year with an estimated accumulative temperature increase of 0.9 Celsius between 1961-2019 and a projected increase of 0.6 degrees Celsius between 2020- 2060. The temperature in the growing season increased at a rate of 0.02 Celsius per year with an accumulative temperature increase of 1.3 Celsius in 1961-2019 and a projected increase of 0.9 degrees Celsius between 2020- 2060.

Further, the model functionalizes the precipitation trends in the growing phase at a coarse national level scale using an estimated sinusoidal function. However, given the model validity tests which show a good fit of the MALI-SES model for growing phase precipitation trends during 1961-2015, we have a reasonable level of confidence in the Mali-SES model projections. In this scenario, the model simulates a declining trend in rainfall during the growing phase between 1961-1990 followed by an increasing trend between 1991-2020 and projects another decline in growing phase precipitation from 2025- 2060. The model also projects a slight increase in rainfall in the sowing phase at the rate of 0.005 mm per year and a slight decrease in the maturing phase at the rate of 0.02 mm per year.

5.2.2. *Scenario B: 1.5 °C warming with rainfall increasingly slightly*

Under this scenario, temperature change is the same as in Scenario A with an increasing trend in temperature for all crop sowing, growing, and maturing phases. However, the rainfall trends after 2020 are kept at the present norm / slightly increasing (Figure. 3.14).

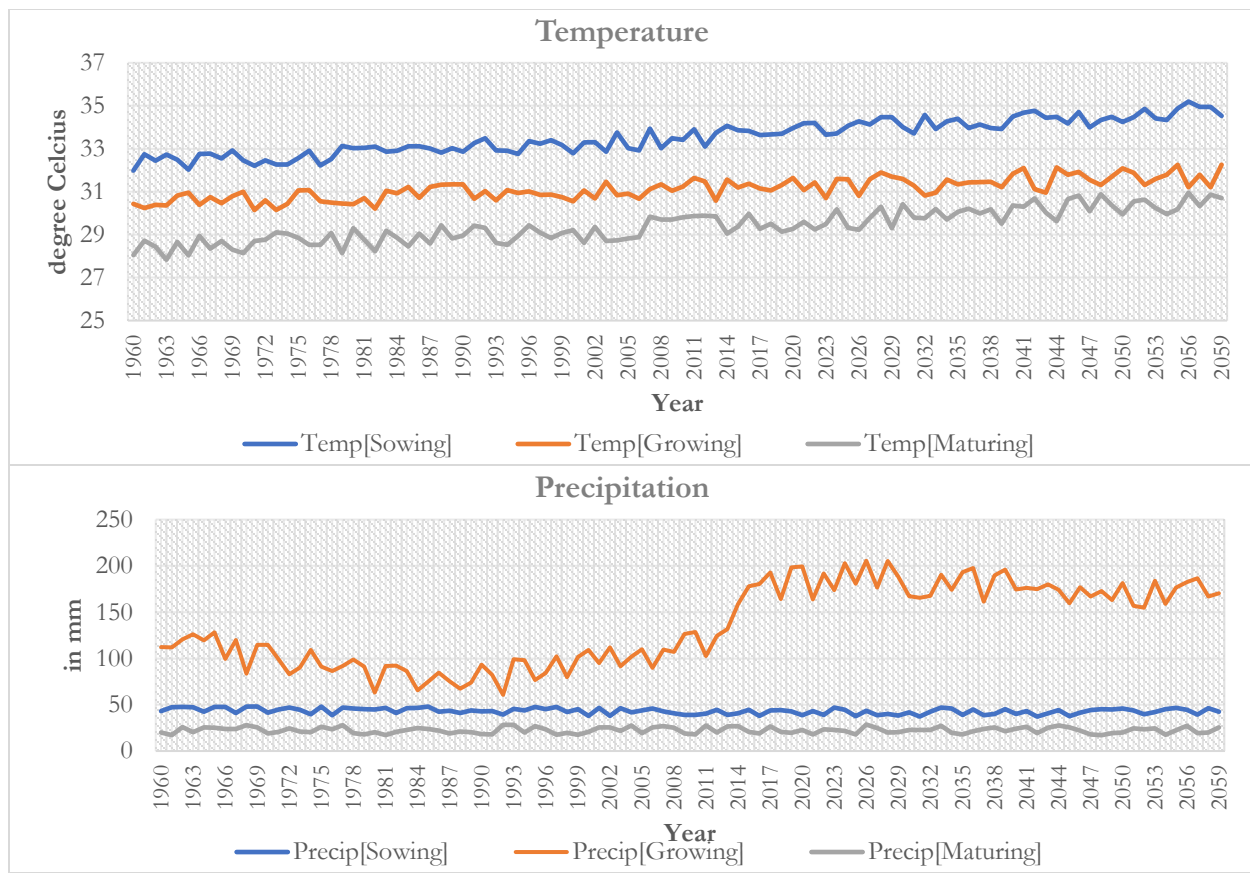


Figure 3.14. Scenario B: Temperature and precipitation in sowing, growing and maturing phases (1960-2060)

The model projects an exponential increase in population to around 52 million people by 2060, with a higher rate of increase in the agriculturalist population followed by agro-pastoralist population and a low rate of growth of the pastoralist population (Figure 3.15).

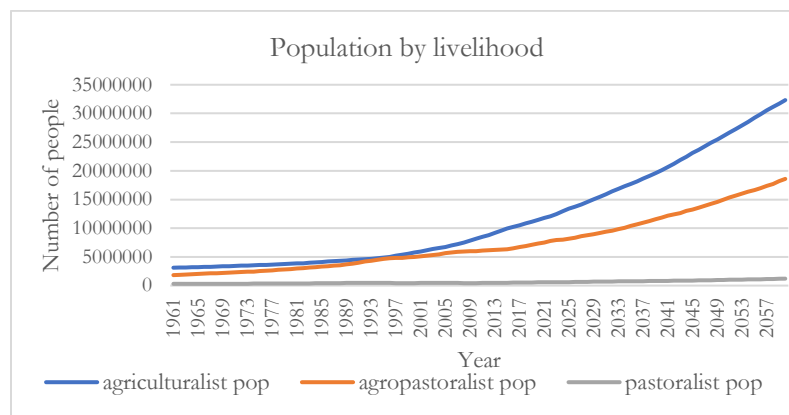


Figure 3.15. Population projections (1961-2060)

5.2.3. Comparison of adaptation Scenarios within climate scenarios A & B

5.2.3.1. Adaptation Scenario 1: No adaptation

Crop Acreage and production projections:

The model simulations for ‘no adaptation’ [A1] scenario under Climate scenario A suggests that crop acreage for millet and sorghum crops will continue to increase with time and the crop acreage for maize and rice will stabilize over time (Figure 3.16). This occurs as increasing temperature and decreases rainfall leads to a decrease in the cultivation of maize and rice and an increase in the cultivation of sorghum and millet. The model simulations for no adaptation scenario under Climate scenario B1 suggests that crop acreage for millet will continue to increase while the increase of crop acreage for sorghum will stabilize over time. The crop acreage for maize and rice crops will continue to increase slightly but at a much lower rate than that of millet (Figure 3.17). A comparison of model simulations for crop production under scenario A1 and B1 shows that millet and sorghum production remains unaffected by rainfall trends despite an increase in crop acreage for both crops while rice and maize production increases with increase in rainfall over time (Figure 3.18 and Figure 3.19).

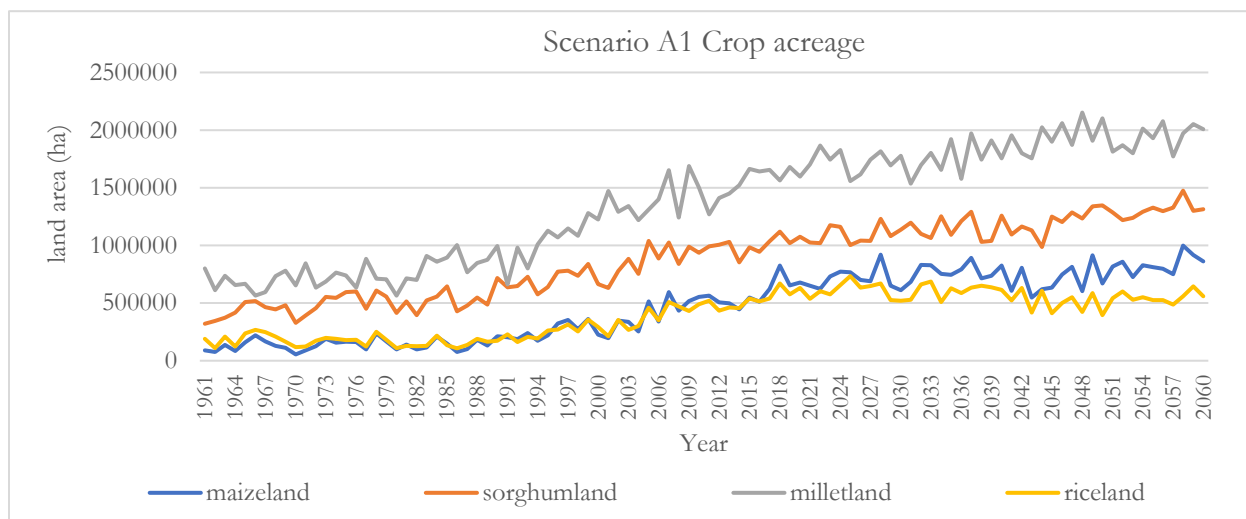


Figure 3.16. Scenario A1- Crop acreage for maize, sorghum, millet and rice crops (1961-2060)

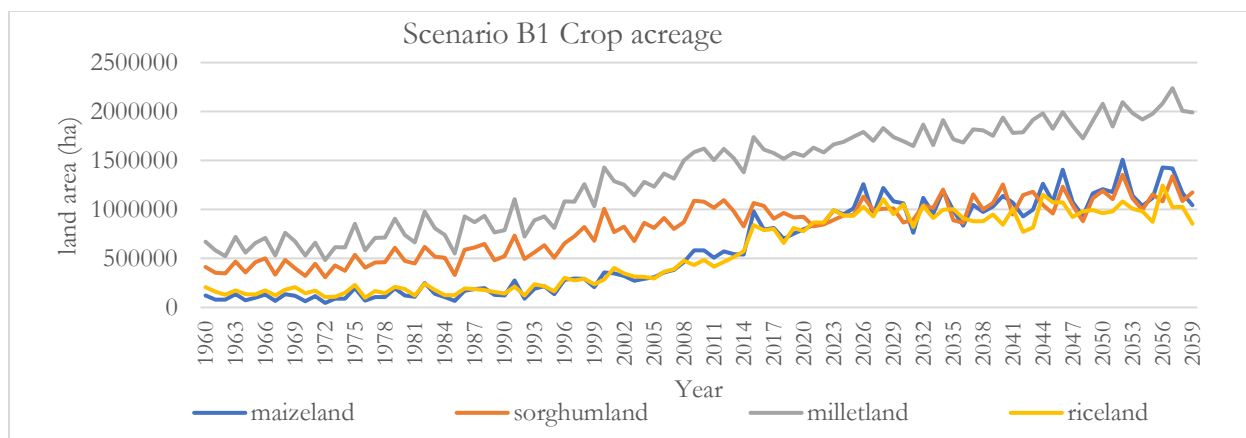


Figure 3.17. Scenario B1: Crop acreage for maize, sorghum, millet and rice crops (1961-2060)

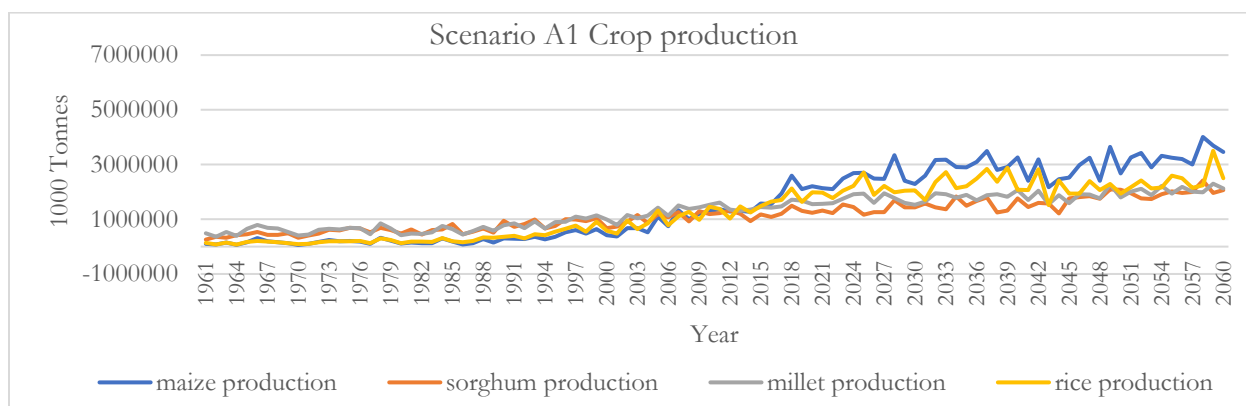


Figure 3.18. Scenario A1- Production amount for maize, sorghum, millet and rice crops (1961-2060)

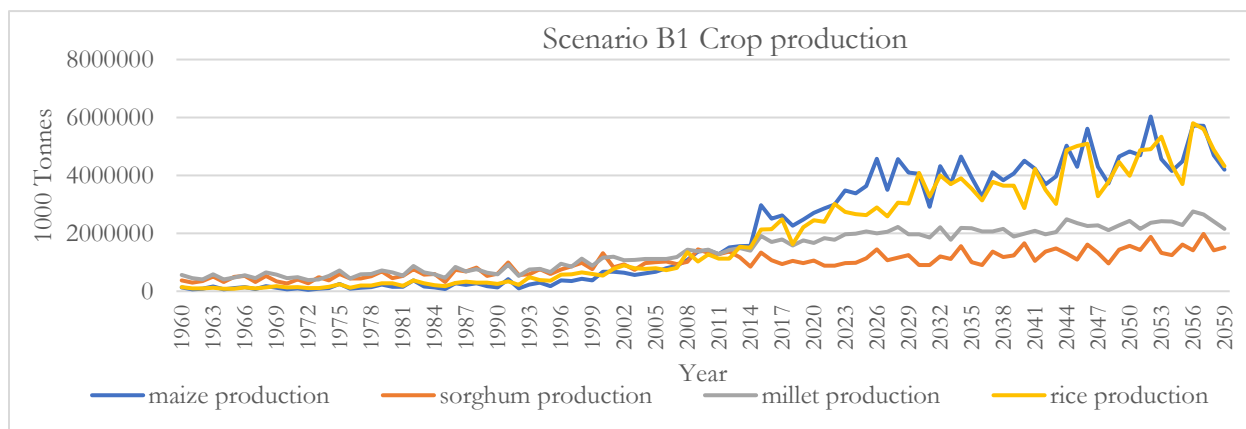


Figure 3.19. Scenario B1- Production amount for maize, sorghum, millet and rice crops (1961-2060)

5.2.3.2. Scenario A2: Fertilizer use

Crop acreage and production projections

The model simulations for the fertilizer use for sorghum and millet [A2] and [B2] under climate scenarios A and B show no change in crop acreage than scenario [A1] and [B1] (Figure 3.20 and 3.21). However, as expected the production of sorghum and millet increases due to improved fertilizer efficiency. The production amount of sorghum and millet increases correspondingly between 2020-2040 and becomes at par with maize and rice production amounts. All crops show stabilization in production growth rate between 2040-2060 and high interannual variability of crop production over time in response to increase in temperature and decline in rainfall during crop growing phase (Figure 3.22). Under Scenario B2, an increase in rainfall leads to a further increase in production levels of maize and rice. The production of maize and rice is almost double by 2060 as compared to the production levels at 2060 under climate scenario A2. The production levels of sorghum in scenario B2 is similar to the production levels at scenario A2 while production levels of millet is lower than scenario A2 (Figure 3.22 and 3.23).

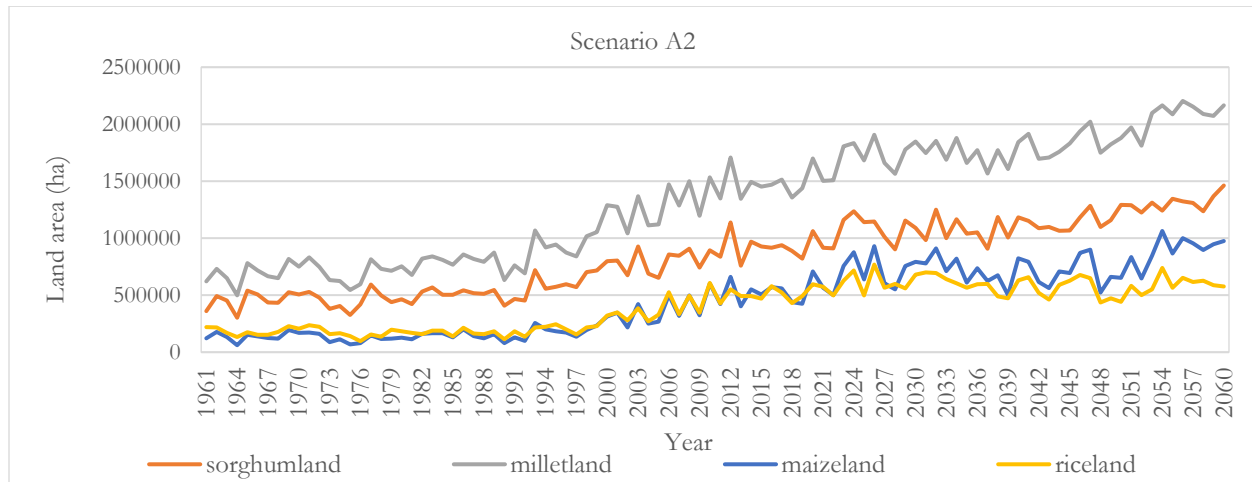


Figure 3.20. Scenario A2- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

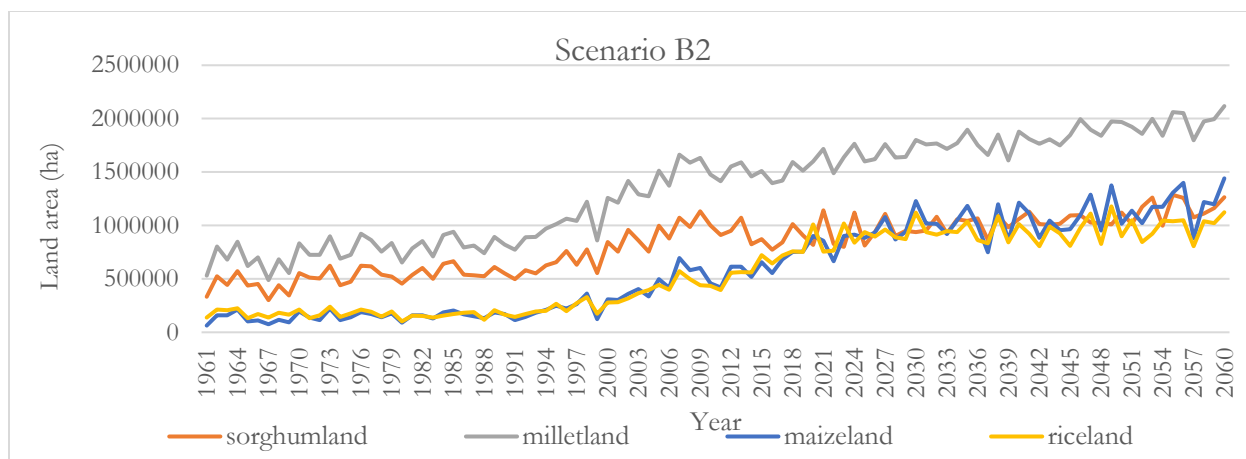


Figure 3.21. Scenario B2- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

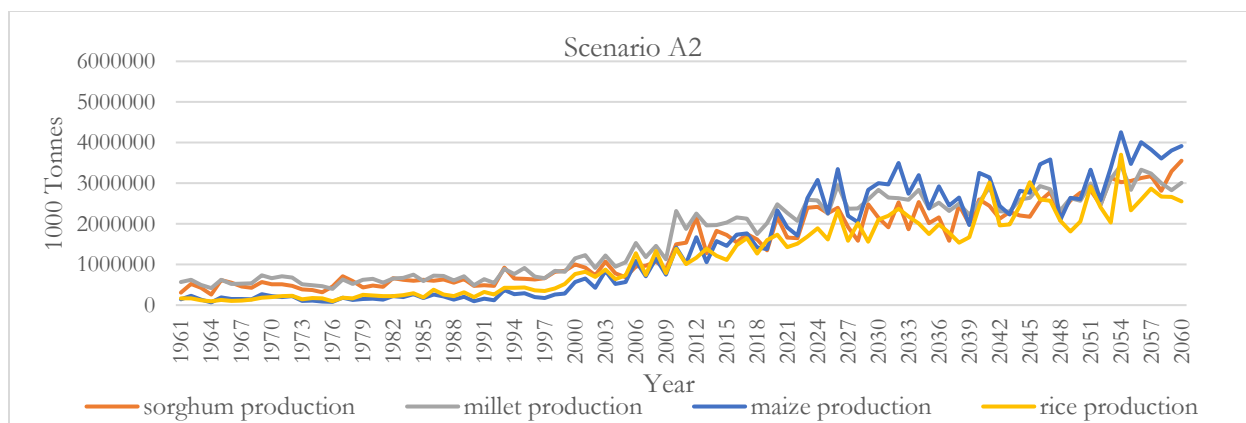


Figure 3.22. Scenario A2- Crop production for maize, sorghum, millet and rice crops (1961-2060)

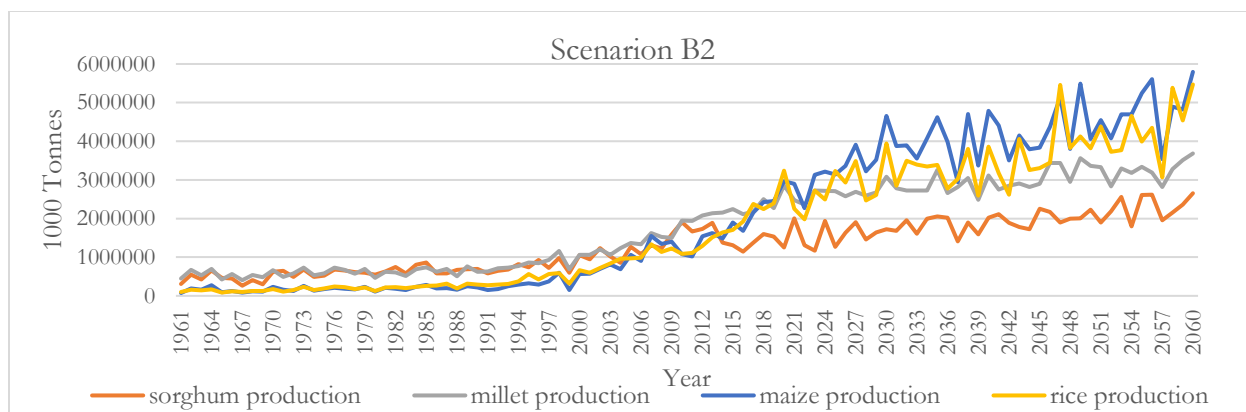


Figure 3.23. Scenario B2- Crop production for maize, sorghum, millet and rice crops (1961-2060)

5.2.3.3. Scenario A3: Fertilizer use + increased land allocation to sorghum and millet

Crop production and land use projections:

The model simulations for the adaptation scenario [3] under climate scenario A shows that an expected increase crop acreage for millet and sorghum crops due to increased land allocation to sorghum and millet. Crop acreage for maize subsequently stabilizes between 2020-2060 while crop acreage for rice decreases slightly due to a decrease in rainfall (Figure 3.24). Under climate scenario B, the growth rate for maize and rice crop acreage also increases slightly along with sorghum and millet crops (Figure 3.25).

Crop production of maize and rice under scenario A3 is lower than scenario A2 due to the decrease in crop acreage (Figure 3.26). Under scenario B3, Rice and maize production increases despite a decrease in crop acreage due to yield improvement due to an increase in rainfall in the growing phase (Figure. 3.27).

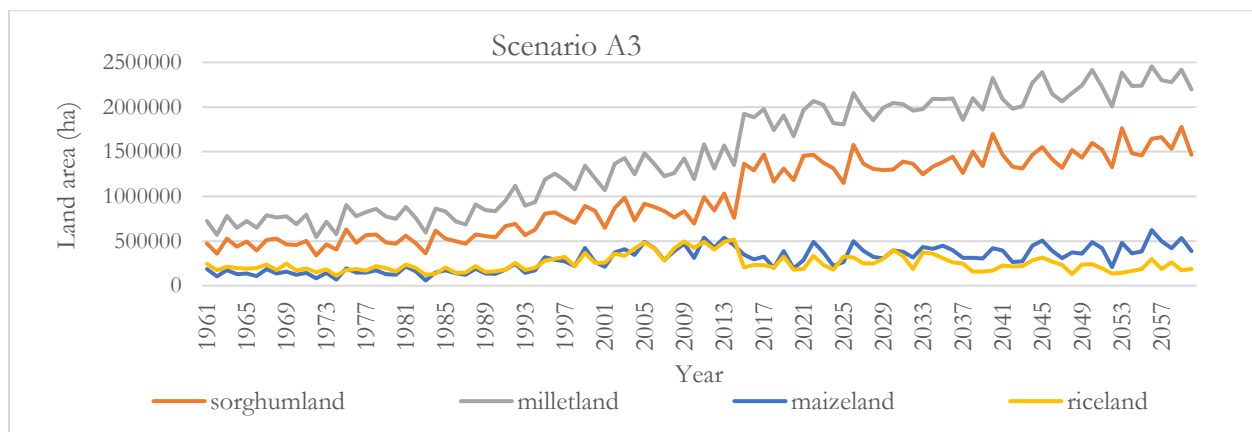


Figure 3.24. Scenario A3- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

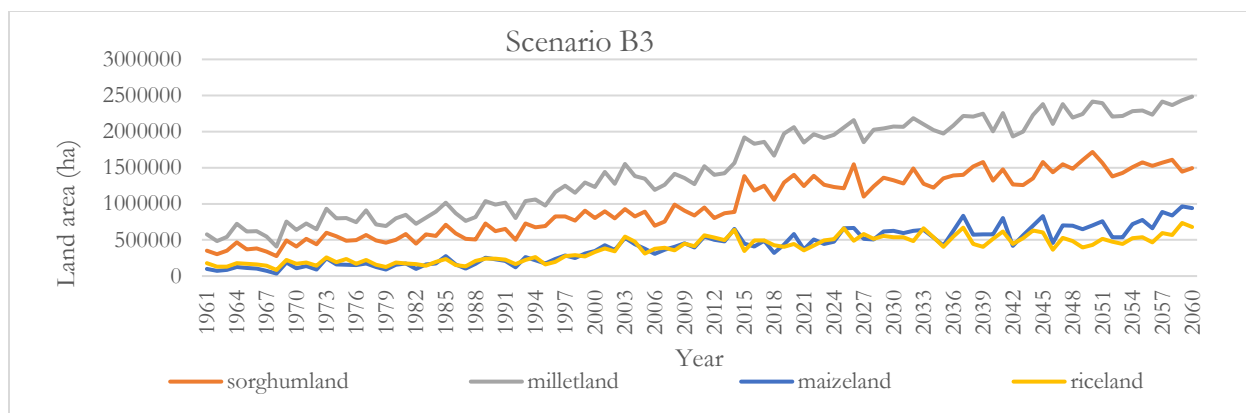


Figure 3.25. Scenario B3- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

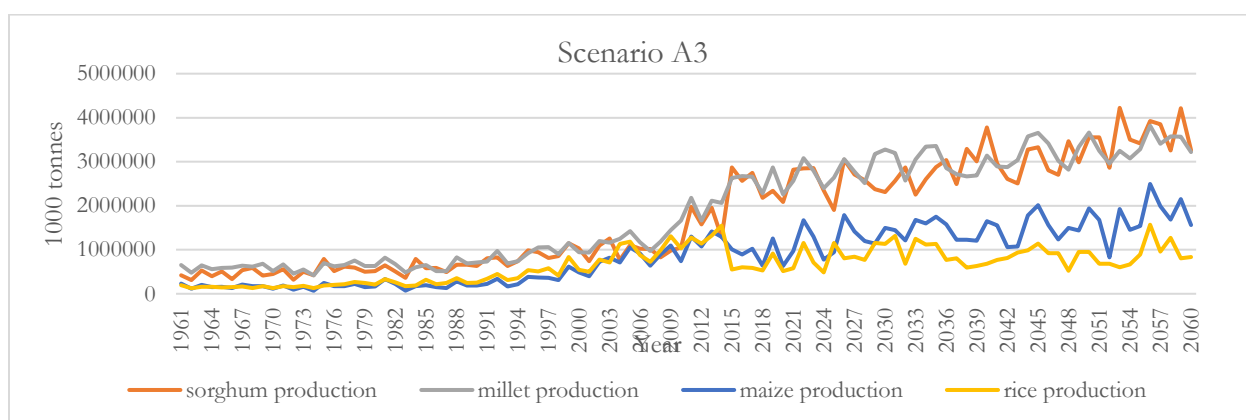


Figure 3.26. Scenario A3- Crop production for maize, sorghum, millet and rice crops (1961-2060)

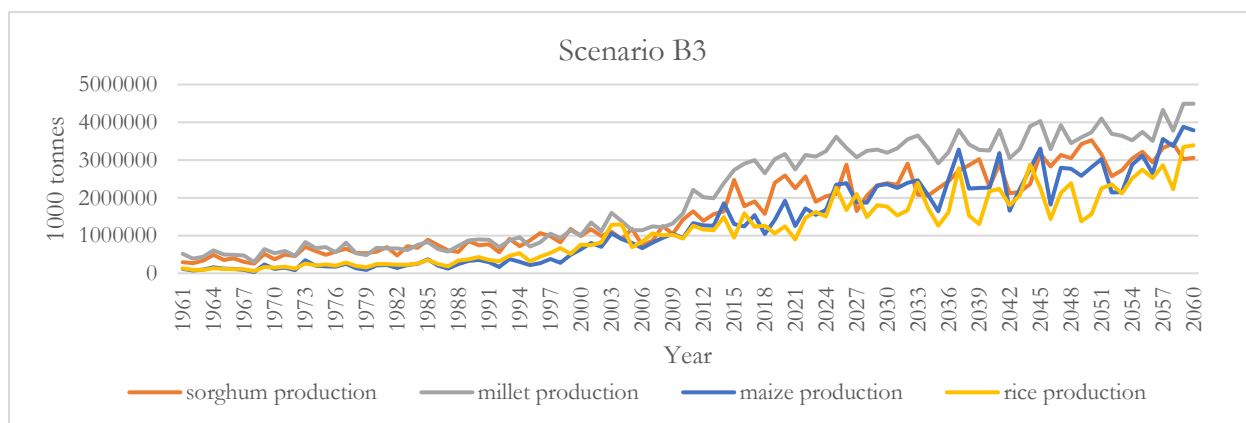


Figure 3.27. Scenario B3- Crop production for maize, sorghum, millet and rice crops (1961-2060)

5.2.3.4. Scenario A4: Fertilizer use + increased land allocation to sorghum and millet + stabilization in decline of pastoralism

The model simulations for adaptation scenario [A4] or [B4] shows no change in crop acreage (Figure. 3.28 and 3.29) or production (Figure. 3.30 and Figure 3.31) than scenario [A3] or [B3] as the adaptation strategy influence food demand rather than food supply.

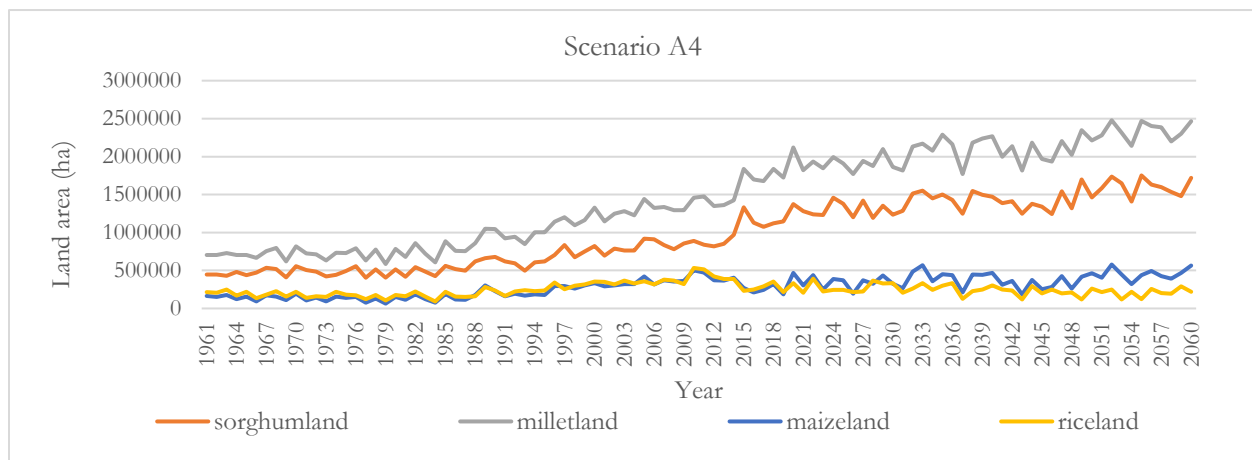


Figure 3.28. Scenario A4- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

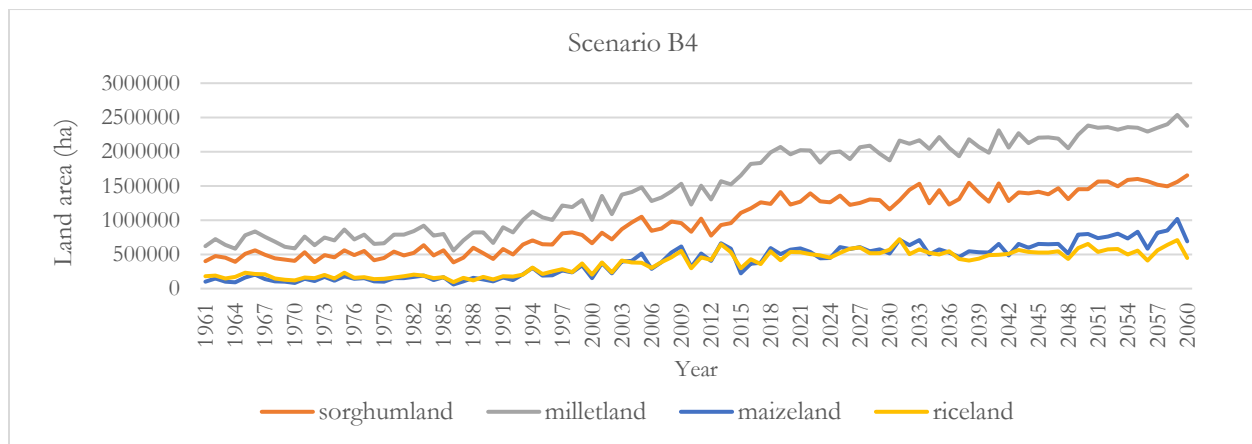


Figure 3.29. Scenario B4- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

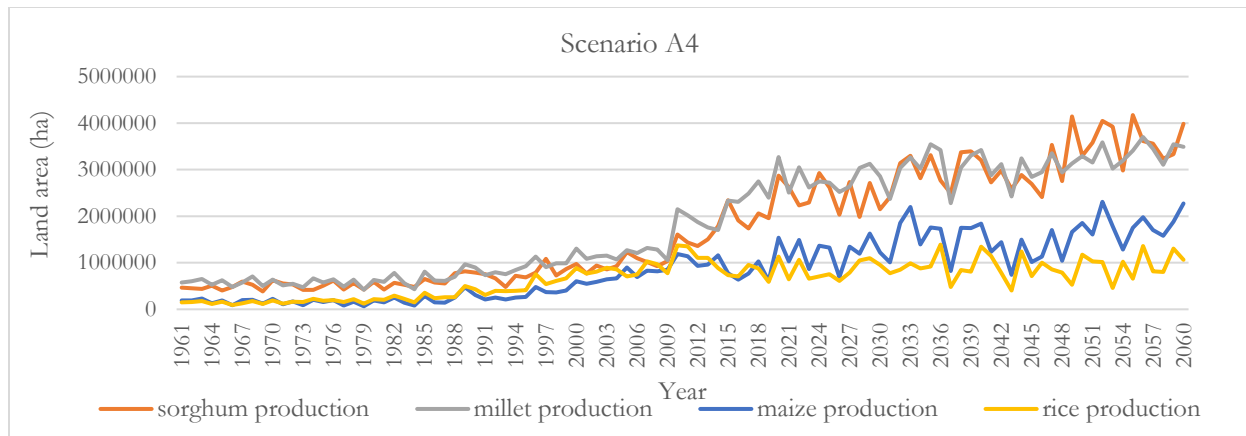


Figure 3.30. Scenario A4- Crop production for maize, sorghum, millet and rice crops (1961-2060)

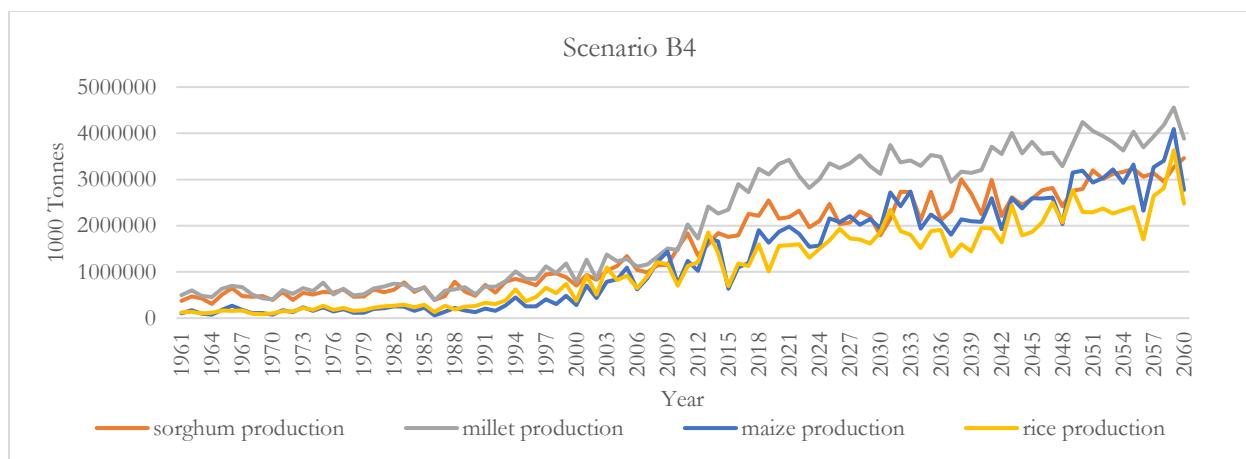


Figure 3.31. Scenario B4- Crop production for maize, sorghum, millet and rice crops (1961-2060)

A comparison of model simulations of yearly food supply and demand for climate scenarios A & B and adaptation scenarios 1-4 shows that under A4 and B4, crop demand is lower than other adaptation scenarios (Figure. 3.32). As decline in pastoralism stabilizes over time, urbanization rates decrease which reduces the urban population growth and subsequently reduces overall crop demand.

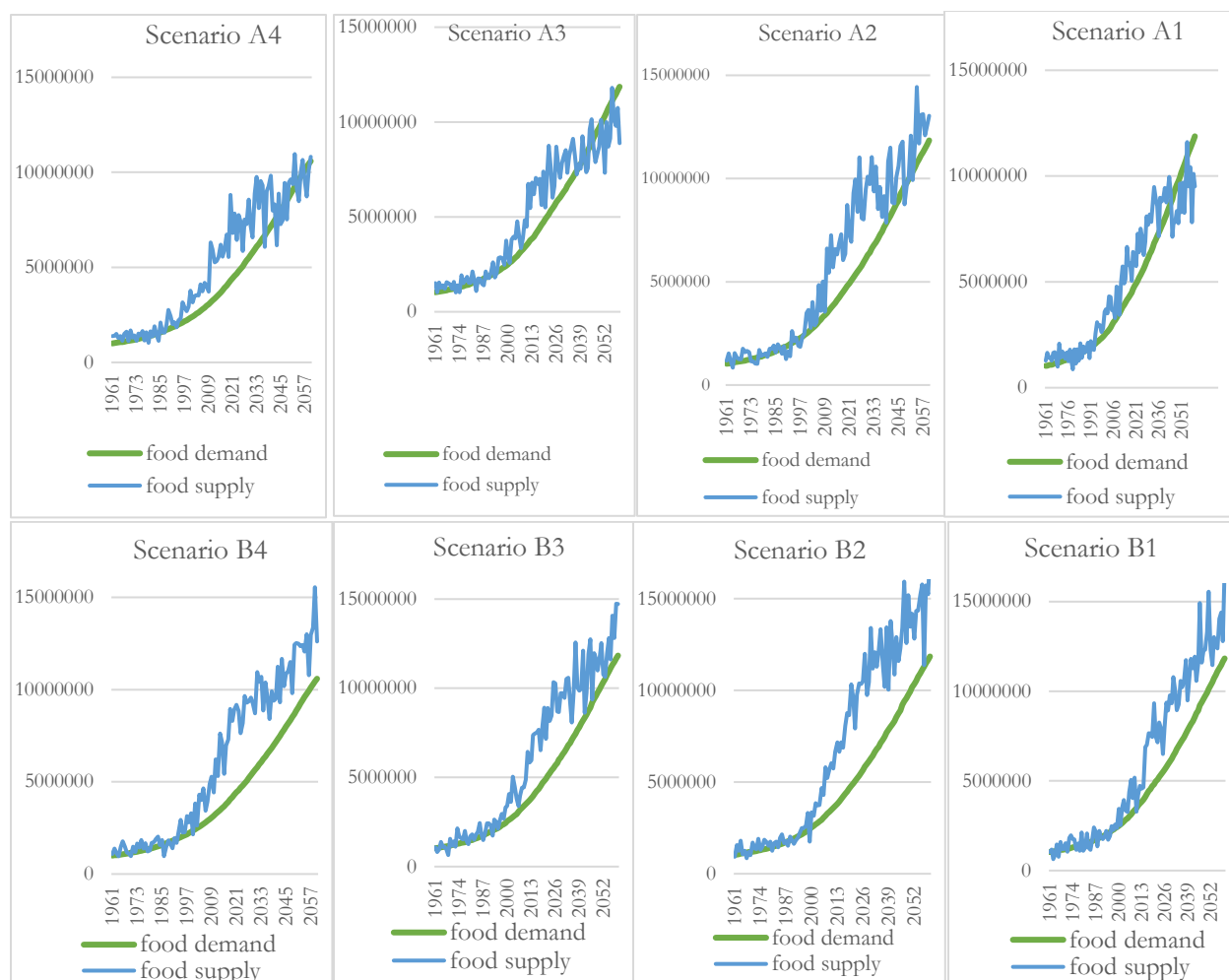


Figure 3.32. Scenario A & B 1-4- Food supply and demand (1961-2060)

5.2.3.5. Scenario A5: Fertilizer use + increased land allocation + stabilization in pastoralism decline + cereal extensification scenario

The model simulations for the “fertilizer use + increase land allocation to sorghum and millet+ stabilization in pastoralism decline + cereal extensification” scenario increases the proportion of land allocated to cereal production. However, under scenario A5, increase in land acreage of maize and rice is offset by the decline in rainfall (Figure 3.33) as opposed to Scenario B 5 (Figure. 3.34). Crop production especially for maize and rice in Scenario B5 is higher than crop production in scenario A5 (Figure 3.35 and Figure 3.36).

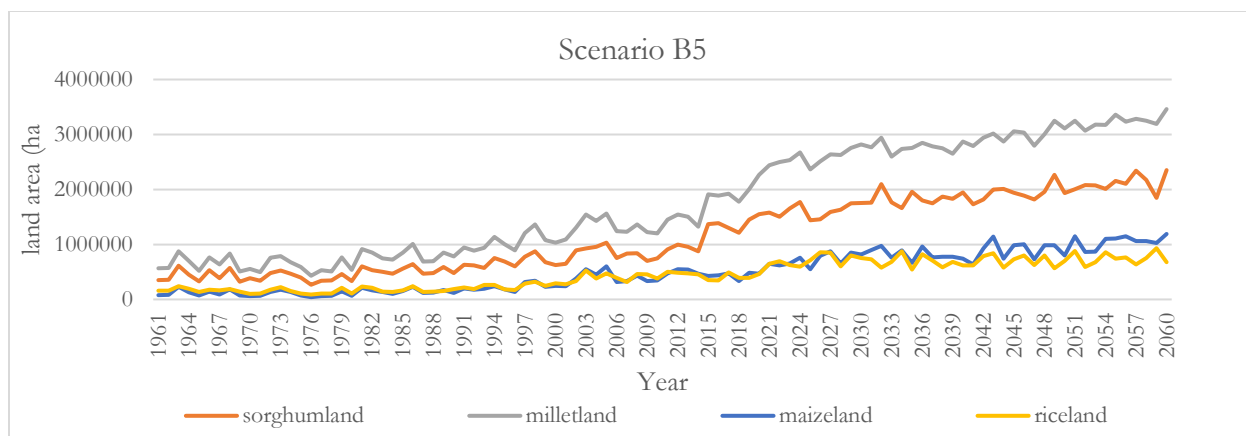


Figure 3.33. Scenario A5- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

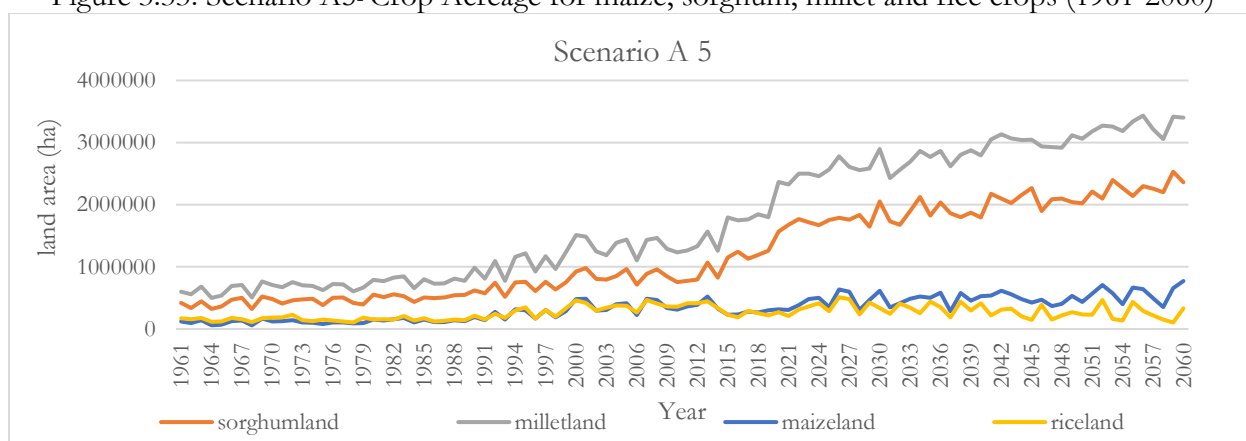


Figure 3.34. Scenario B5- Crop Acreage for maize, sorghum, millet and rice crops (1961-2060)

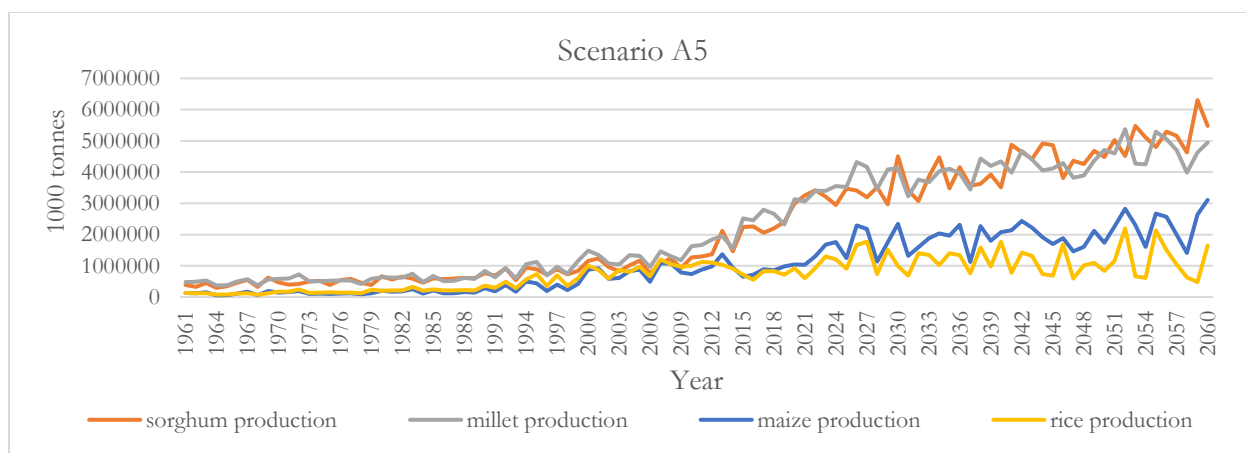


Figure 3.35. Scenario A5- Crop production for maize, sorghum, millet and rice crops (1961-2060)

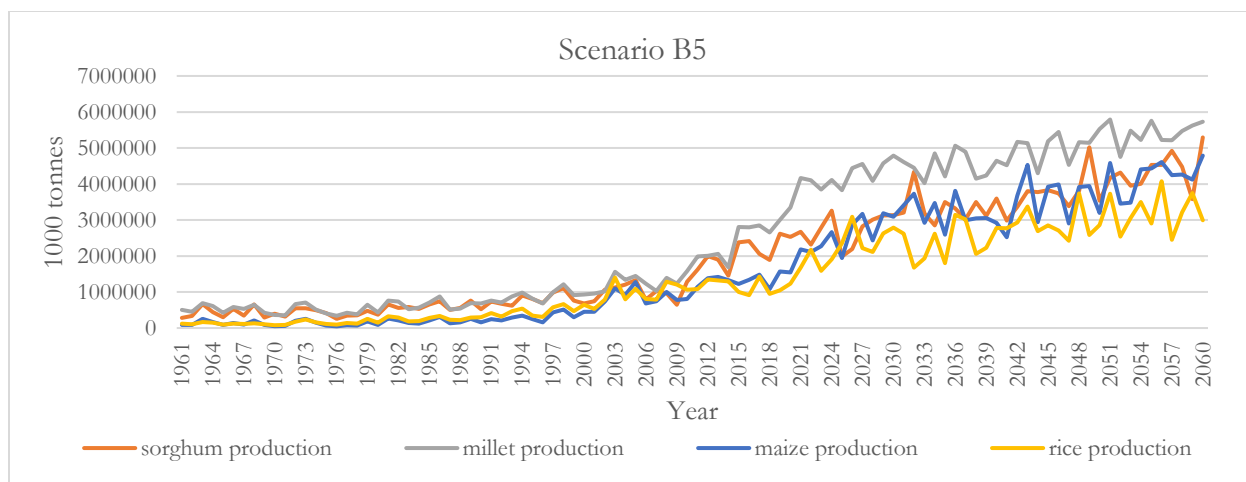


Figure 3.36. Scenario B5- Crop production for maize, sorghum, millet and rice crops (1961-2060)

5.2.4. Food security projections: Comparison for scenarios A 1-5 and B 1-5

The comparison of food security status under climate adaptation scenarios A [1-5], as a function of cereal demand and supply, for the period 1960-2060 (Figure 3.37) shows that between 1960-1990, Mali went through a period of diminishing food security where the overall supply of cereal crops such as maize, sorghum, millet, and maize barely matched the food demand of a growing and rapidly urbanizing population. Enhanced fertilizer use in maize and improved irrigation facilities in rice production improved combined with a land expansion of about 3% between 1990-2000 improved the food security status of the country. The period between 1990-present also saw an increasing trend in rainfall during the crop growing phase in the wet season which further enhanced cereal production and subsequent food security. However, the model suggests that the Malian food security will reach a tipping point by 2025 where regardless of adaptation scenarios such as fertilizer use [A2], land allocation [A3], stabilization of pastoralism decline [A4]; the system will move to a declining food security status and transition to a food deficit phase by mid-century. Expansion of cereal land through extensification [A5] is likely to delay the transition to a food deficit phase.

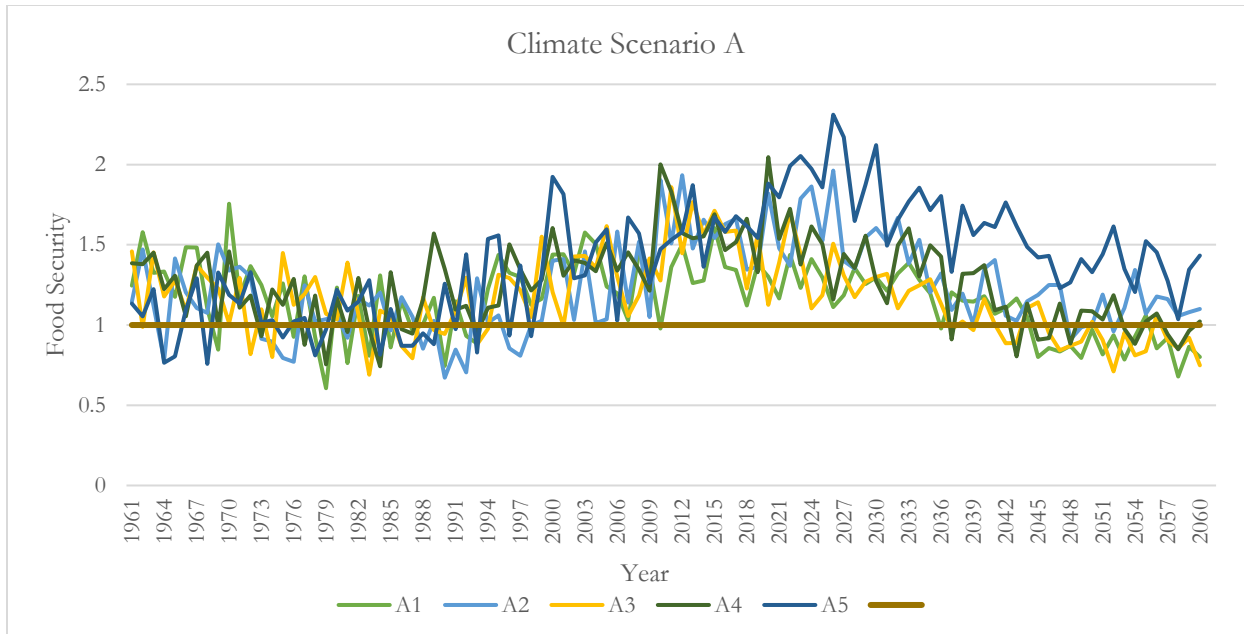


Figure 3.37. Comparison of food security under Climate Adaptation Scenarios (A1-5) (1961-2060)

Food security projection under Climate Scenario B shows that no decline in rainfall trends in the growing phase would prevent Mali from a food deficit phase until the end of the century (Figure. 3.38). However, despite the trends in rainfall, trends of food security over time show a similar pattern as in climate scenario B where food security reaches a tipping point by 2025 and declines subsequently.

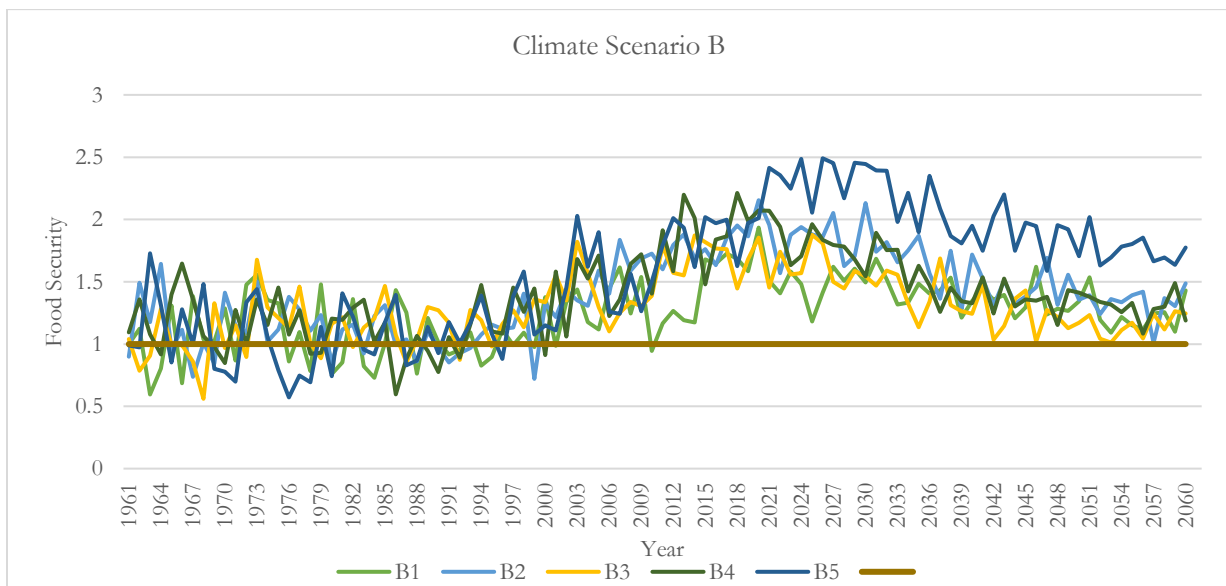


Figure 3.38. Comparison of food security under Climate Adaptation Scenarios (B1-5) (1961-2060)

5.3. Sensitivity analysis results

The results of the sensitivity analysis show that the rate of temperature change in sowing season exhibited the maximum sensitivity to food security outcomes in the region (Figure 3.39) while the rate of temperature change in growing and maturing season (Figure 3.40 & Figure 3.41) showed little or no sensitivity to food security outcomes respectively. On the other hand, the rate of precipitation change in growing season (Figure 3.43) showed maximum sensitivity to food security outcomes while the rate of precipitation change in sowing and maturing seasons showed no sensitivity to food security behavior over time (Figure 3.44 and Figure 3.45). Sensitivity runs for urbanization and cereal extensification rates (which increases the land allocated for sorghum and millet crops) show small numerical sensitivities due to change in coefficient values but no major shifts in trends or behaviors over time.(Figure 3.46 and Figure 3.47) These tests suggest that temperature during sowing season and precipitation during growing season are the key drivers that influence food security outcomes in the region.

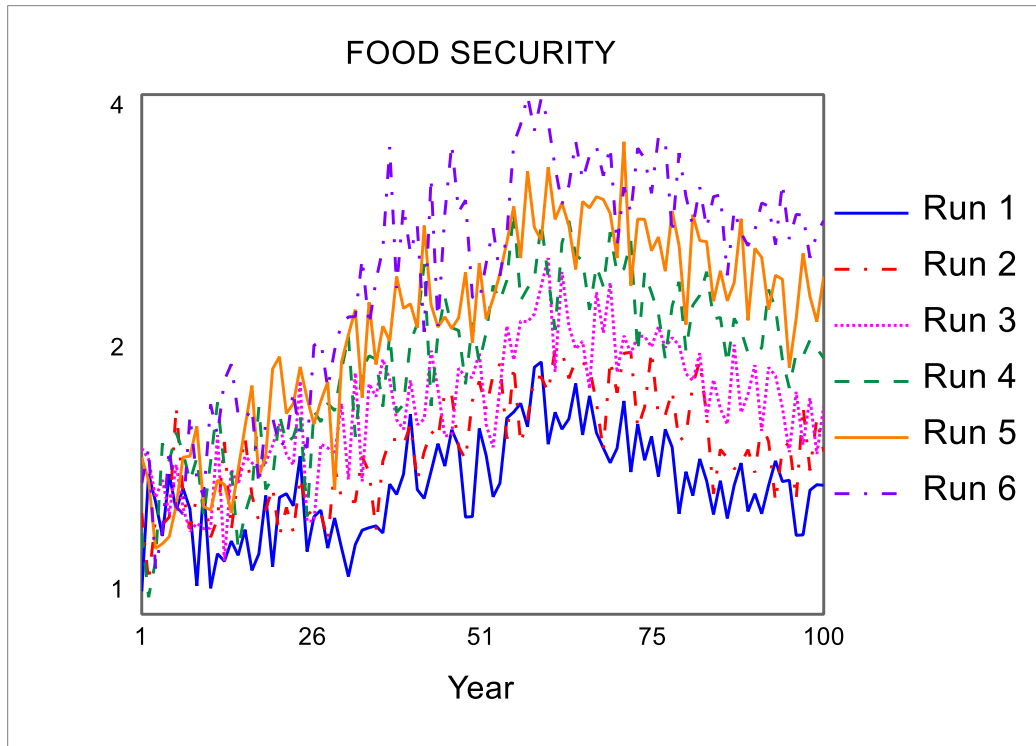


Figure 3.39. Sensitivity runs for rate of change in sowing temperature

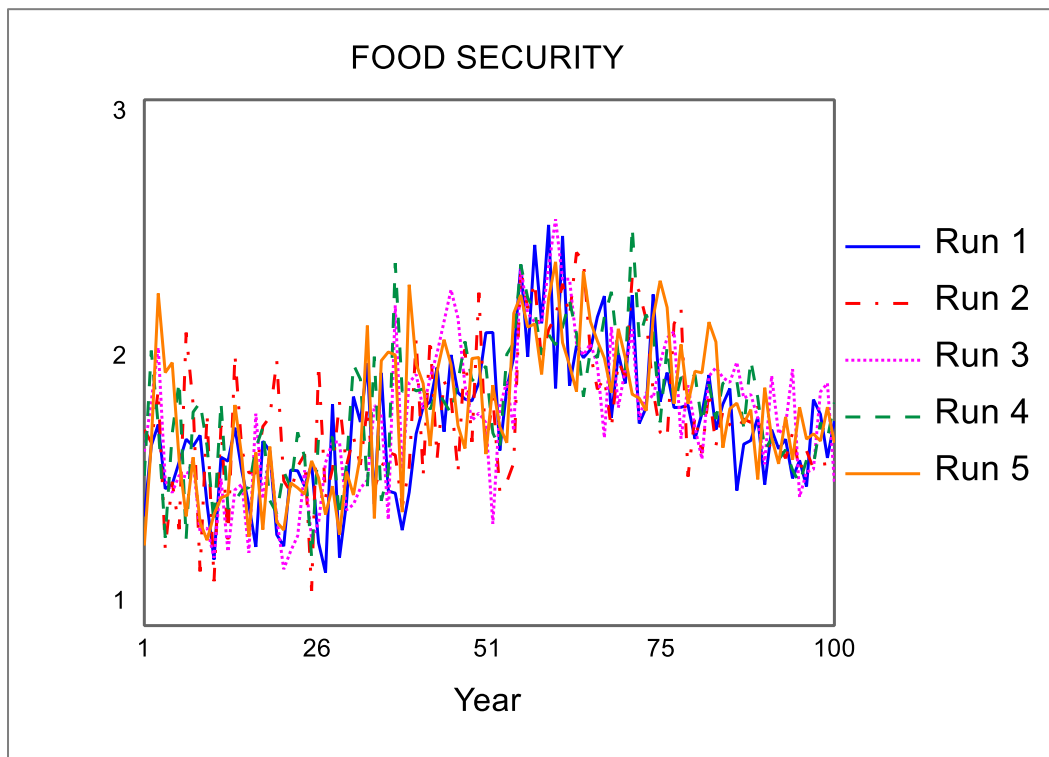


Figure 3.40. Sensitivity runs for rate of change in growing temperature

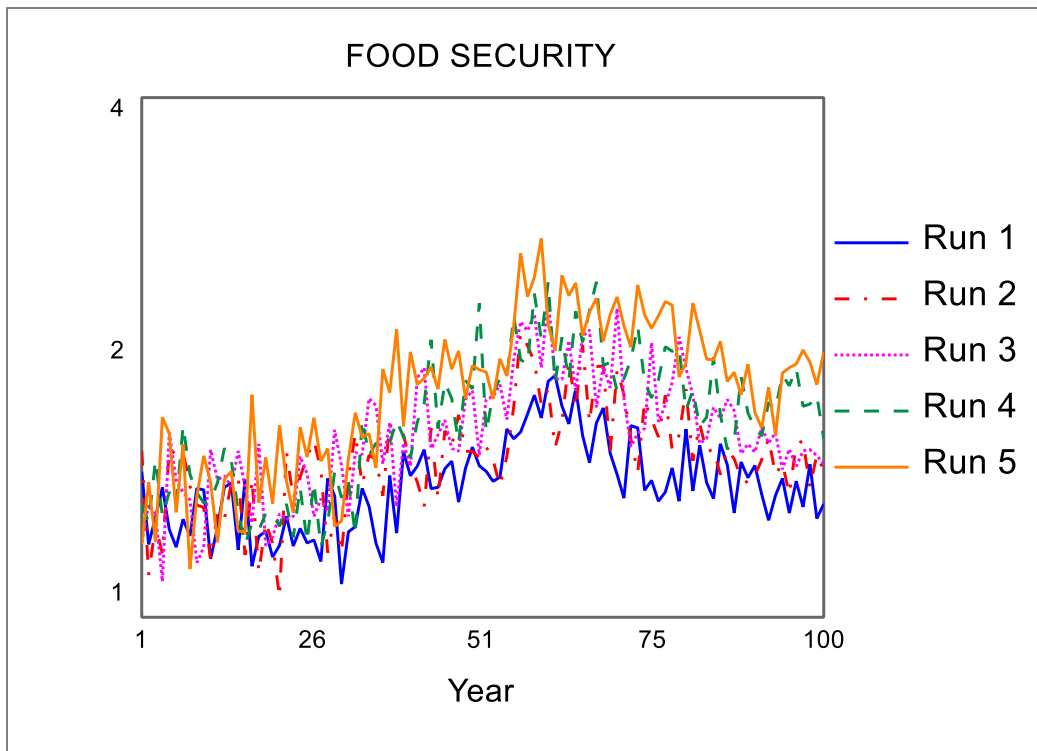


Figure 3.41. Sensitivity runs for rate of change in maturing temperature

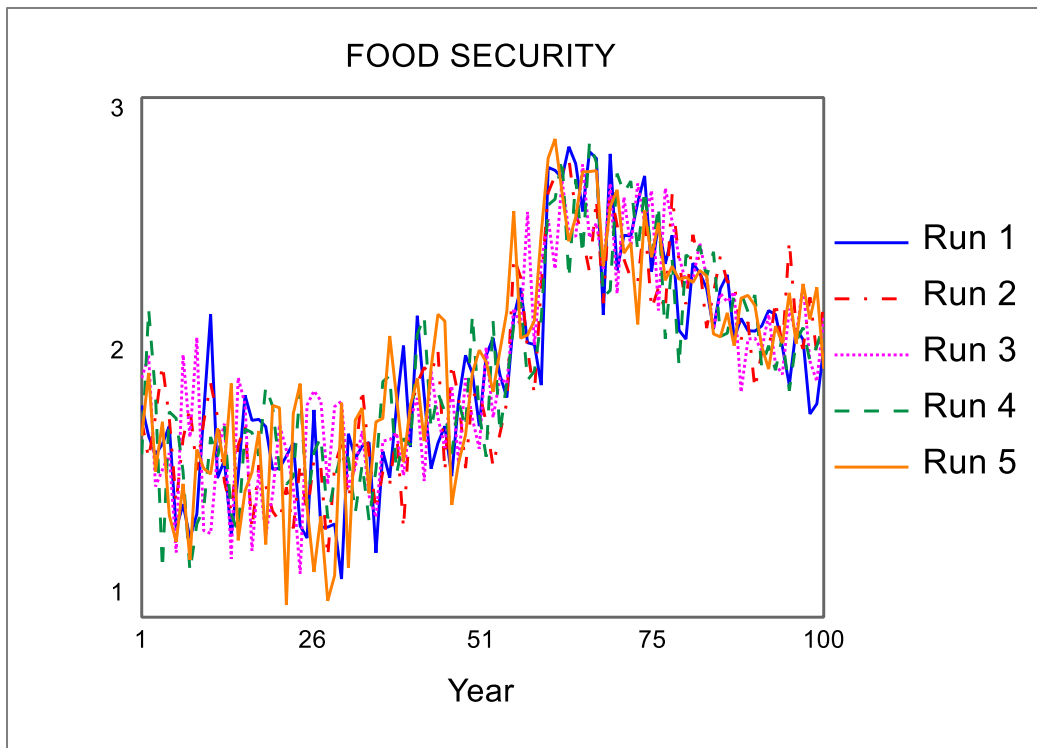


Figure 3.42. Sensitivity runs for rate of change in sowing season precipitation

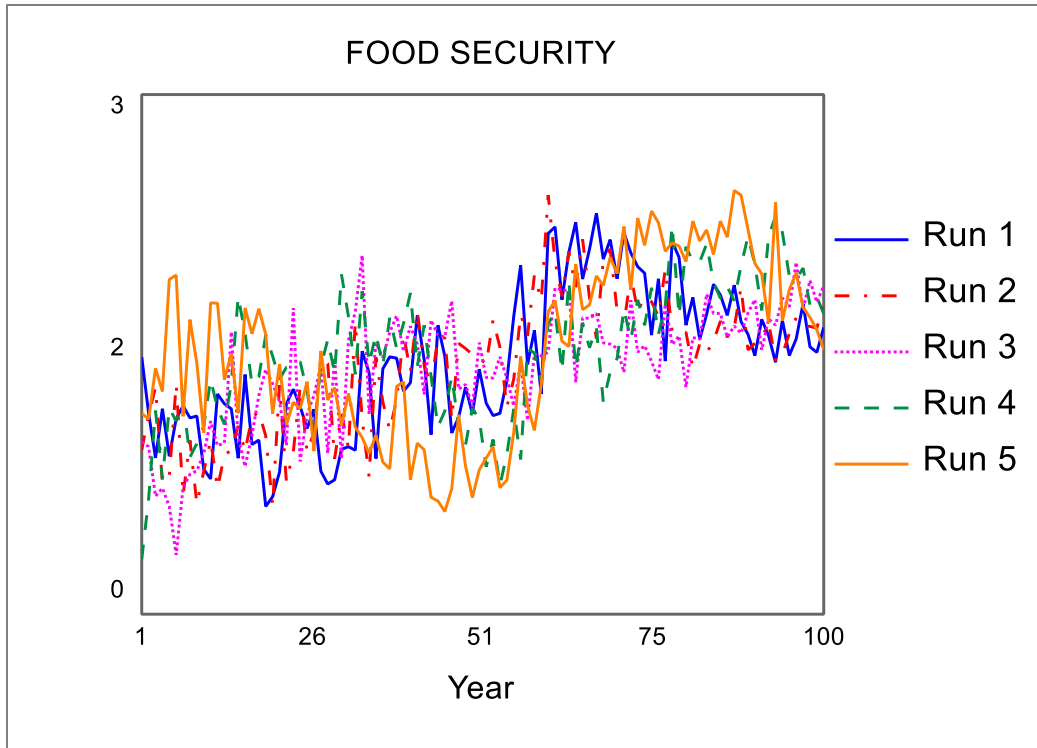


Figure 3.43. Sensitivity runs for rate of change in growing season precipitation

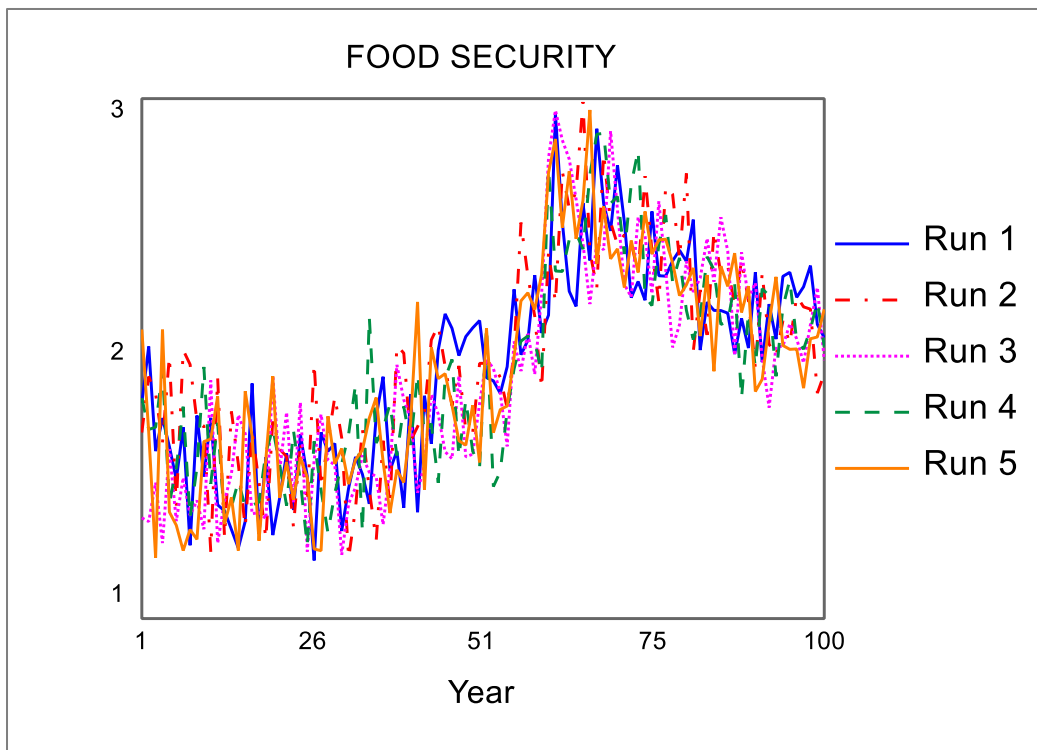


Figure 3.44: Sensitivity runs for rate of change in maturing season precipitation

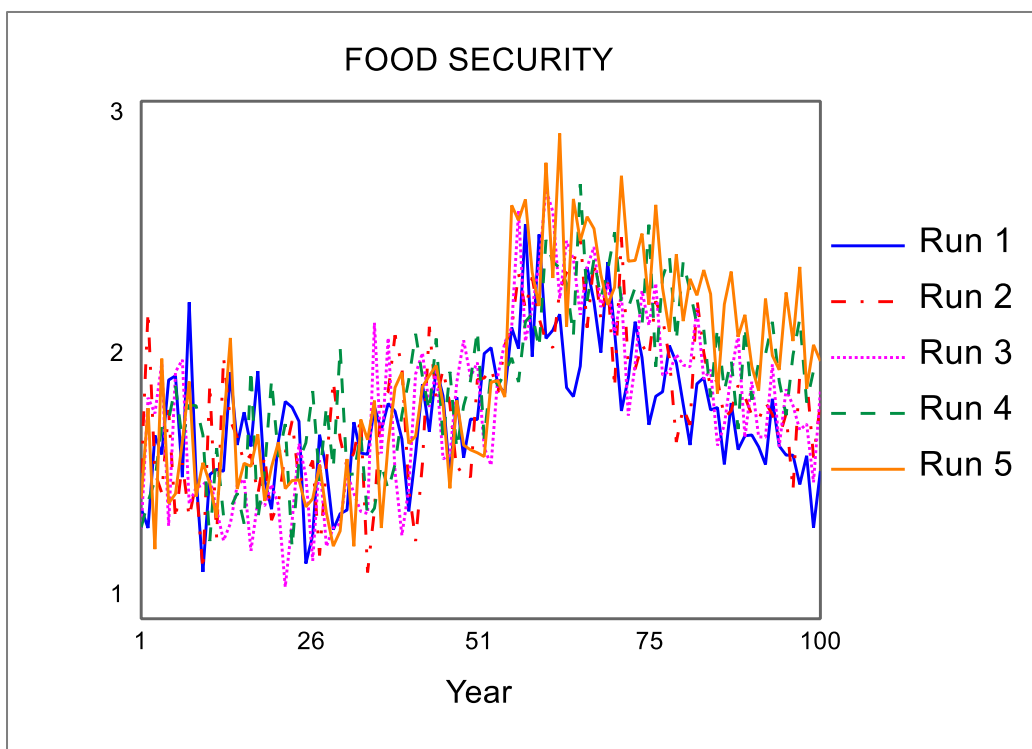


Figure 3.45. Sensitivity runs for urbanization rates

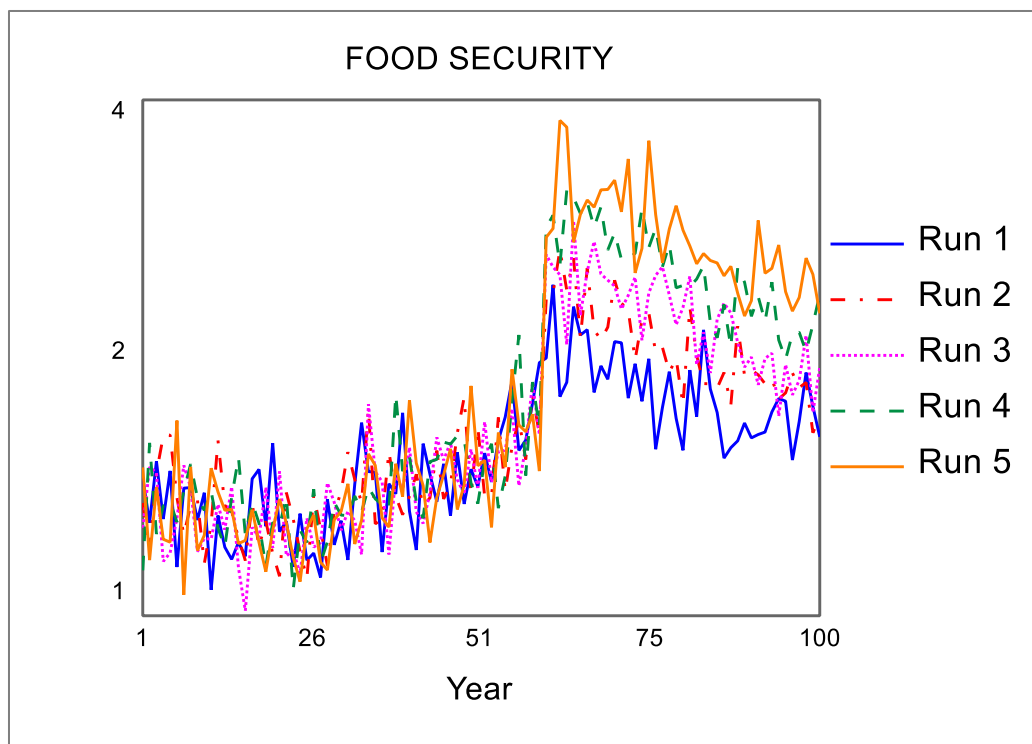


Figure 3.46. Sensitivity runs for cereal extensification rates

6. Conclusion

According to Haraldsson (2000), the intention of creating system dynamics models is not to capture the whole reality in one model, which is a particularly daunting task for complex systems. Capturing ‘dynamic complexity’ which represents the important dynamics functioning in the system is more important than capturing the “detailed complexity” (Haraldsson, 2000). The Mali-SES model incorporated the key aspects of agricultural socio-ecological systems in Mali in terms of land use, climate patterns, crop production, cattle production, crop management, population change, urbanization trends, poverty trends, and food consumption. The analysis of model scenarios and sensitivity analysis shows that the key drivers influencing food security in Mali are sowing season temperature and growing season precipitation trends over time. Increase in sowing season temperature over time is likely to improve yields of sorghum, millet, maize, and rice crops while the increase in growing season precipitation is likely to improve yields of millet, maize and rice and reduce the yield of sorghum crops. The increasing trend in growing season precipitation in the future will also likely lead to an increase in land acreage and subsequent production for maize and rice crops. Alternatively, decreasing trends in growing season precipitation will lead to an increase in yield of sorghum crops while yields of millet, maize and rice will decrease. These changes are exogenous to the internal dynamics within the agricultural socio-ecological systems in Mali and influenced by increases in overall sea surface temperature in the Atlantic and Pacific Ocean due to global warming and subsequent changes in West African monsoon patterns. This suggests a presence of system gridlock where the high likelihood of a further increase in global temperatures and highly variable rainfall patterns in the future as predicted by the General Circulation Models (GCM) will likely lead Mali to another famine and food insecurity phase by mid-century. According to the IPCC report (2007) even if all emissions were stopped and atmospheric greenhouses gas concentrations are kept at a constant at the current level, the climate will continue to change in the future with significant impacts on the ecosystem. The

only response available to cope with these impacts (in the shorter term) is adaptation before mitigation efforts become effective (Stern 2007). This calls for policy-making which provides a range of adaptation options for greater flexibility in adaptation strategies regardless of the direction of climate trends and an enhanced resiliency in the socio-ecological system.

The Mali-SES model assessed the effectiveness of various future climate and adaptation scenarios such as enhanced crop management, land-use change, stabilization of increased trends in internal migration and urbanization in the country and cereal land extensification in enabling the country to avoid another food deficit and famine situation in the future. The analysis of the various scenarios for these adaptation strategies suggests that at best, these solutions will help in delaying the effects of declining food security as projected for 2025-2060. Cereal intensification measures are most likely to be effective in delaying food deficit in the future. Hence, policy interventions that target effective land security and rights rural farmers in Mali are likely to be more effective in aiding cereal land expansion in the future.

The process of expansion of land is ultimately related to land tenureship (Becker, 1990). There exists a high degree of uncertainty about land rights in Mali with a very low percentage of land in the West African region held by written title (Becker, 1990). Land use rights are usually allocated through local social relationships where village chiefs have the authority to implement the rules governing the access and use of land. The distribution of rights is based on the socio-political system and on family relationships where households are settled by village chiefs and given control over the land allocated to them. According to Delville (1998), these socially determined land-use rules are flexible and evolve over time based on new ways of farming, alterations of social relationships, or changes in conditions of production. In Mali, land governed by socially determined land-use rules is not recognized legally although usage rights are tolerated *unless the land is needed for another purpose*". Existing policy interventions with regards to land tenureship in Mali show a sliver of hope in the positive direction

towards food security in an otherwise gloomy future as predicted by the Mali-SES model. In 2017, the Malian government developed a new law that set aside a share of government-managed land for women to farm. The new law facilitated exclusive access of 10 percent of government-managed land leased to women farmers at a cost of 65,000 CFA francs (\$105) per year. As I elaborated in Chapter 2, insufficient access to land and credit acts as a key barrier to women in cultivating desired crops such as sorghum and millet. A two-pronged policy intervention which enhances land tenureship and credit access among women is likely to be effective in two ways: first, increasing the acreage of sorghum and millet crops which are genetically more resistant to increased temperatures and variable rainfall; thereby increasing food availability of a growing rural population and second, improving the access to credit among sorghum and millet will allow farmers to invest in fertilizer use which will improve the yield of the crops.

The imposition of alternative ways of production, such as agricultural policies that favor cash crops (cotton) cultivation, promotion of maize and rice cultivation, increased dependency on global market prices, etc. have enabled Mali to enhance production in recent decades and improve food availability. However, these structures have also led to a shift in the agricultural systems in Mali where rice and maize dominate the production the agricultural systems. This has important implications for the future resilience of food systems in Mali, one, as demonstrated by the Mali-SES model in Chapter 3, rice and maize production are expected to decline in the future due to an increase in temperature and decline in precipitation during the crop growth phase in the wet season. Second, annual variability in maize and rice productions will be higher than sorghum and millet production, thereby increasing farmer's sensitivity to climate risks. According to Sultan et al (2013), traditional cultivars of millet and sorghum used by local farmers for centuries are more resilient to future climate conditions than modern cultivars with high yield potential. Social structures that favor collective agricultural production within large households; gift-giving within and among villages, collective labor

associations, etc. are forms for risk-sharing and community-based adaptation measures. As observed from Malian past, mutual cooperation, sharing, and collective action were one of the key reasons for the resilience of Malian socio-ecological landscapes to the Sahelian droughts in the 1960s. Leveraging the social capital among rural inhabitants of Mali will be key in bringing forward the role of human agency in the resilience of the Malian future.

In conclusion, this paper highlights the fact that small incremental adaptive changes within the agroecological systems are likely to delay an eventual system collapse in the short term. However, unless there is a transformative change in the system where we challenge the status quo of who adapts, how and in what way, the system cannot prepare itself to be resilient to impending changes. This includes challenging notions of gender-based roles in Malian agriculture where the communal land rights within the household give men the power to hold ownership rights to land and women the role of laborer and supporter in farming activities. Such transformative practices need to create policies and avenues where women can exercise autonomy and ownership of land and food production and move the system to a resilient future. While incremental adaptation measures such as enhanced crop management and land-use change may delay impending food insecurity and famine; long term resilience of the system will depend on structural transformations in the agricultural systems in Mali.

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CONCLUSION

This dissertation makes a significant methodological advance towards systems-based assessment of the complex processes that influence food security as well as human decision making under uncertainty through a novel mixed methodology of historical process tracing and participatory simulation game design that inform the construction of a system dynamics model. This approach builds on important works by Aquino et al. (2002); Barreteau & Abrami (2007); Becu, Bousquet, Barreteau, Perez, & Walker (2003); Bousquet et al. (2002); Briot, Guyot, & Irving (2007); d'Aquino & Bah, (2013); Naivinit, Le Page, Trébuil, & Gajaseni (2010); Reckien & Eisenack (2013); Voinov & Bousquet (2010) who leveraged the advantages of participatory role-playing games among groups of diverse stakeholders to inform decision-making and behavior in computational agent-based models of natural resource management. In the initial phases of 'Food and Farm' game conceptualization, I envisioned that the outcomes of the 'food and farm' game would inform a descriptive agent-based model of how farmers made agricultural decisions in the context of climate risk and uncertainty and how these decisions influenced food security and climate resilience of farming households in the system. Thus, the game would have facilitated not only the collection of qualitative data on the decision-making heuristics or algorithms implemented by farmers but also quantitative data that can be used to calibrate the decision heuristics in an agent-based model. With this goal in mind, the first version of the game was a cooperative multi-player role-playing board game where each player represented a decision-making actor in a collective farming framework where the players cultivated in a collective farming plot for collective food harvest and consumption. However, during the pilot testing of the game in Mali, I realized various implementation challenges in the game, most of which stemmed from the cultural contexts in the game. According to the feedback from pilot farmers, land use and labor conflicts within collective plots was a sensitive issue in the household. Many younger

men farmers were unwilling to challenge the authority of their fathers (elder men) within the game in order to maintain the respect of their elders in front of external researchers and to avoid conflicts in the household after the game was over. Taking into consideration the concerns of cultural appropriateness and sensitivity within a collective multi-player game, the final version of the game was subsequently revised into a process-based single-player game which focused on individual perceptions, preferences, strategies and decision structures around food production and climate change adaptation, designed such that it gave the participants the flexibility to co-design the game as they played in a way that matched their reality.

While there are many other methodologies that can effectively help researchers understand human decision making such as case studies, oral histories, ethnography, field and behavioral experiments, laboratory observations, etc. , participatory game design offers several advantages over other methods: one, a real-time discussion and dialogue between the players of the game allows the modeler to identify the boundaries of the system, the rules that govern the system, institutions that manage the system and roles of the users in managing the system and insights into how management regimes affect the system. Second, it enables the modeler to gain insights into the decision-making heuristics of the players. Often, these heuristics are so ingrained into the mental models that we are often not aware of using these heuristics. This often leads to a false assumption that agents make ‘reactive’ and not deliberative decisions. An anecdotal support for this claim comes from one of the players from my fieldwork. As I prepared myself to play the game with my first female farmer participant, I had requested the chief of the village to introduce me to a woman who owned or had access to plot of land, assuming that only women who cultivated or had prior experience to farm management would be able to play the ‘Food and Farm’ game. As I began the game, the pre-game questionnaire revealed that she did not own a plot of land and had never worked in her own field. I decided to play the game nevertheless as I did not want to turn her away, but as the game progressed, she showed remarkable

acuity and foresightedness in the gameplay. When the game ended, I asked her why she didn't cultivate when she knew so much about farming and cultivation, she mentioned that she was the younger wife of the chief of the household and therefore, was expected to contribute as a laborer in the collective family plot as opposed to the elder wife who had access to a small plot of land. She further elaborated on how she was teaching herself to grow rice in a tiny patch of land in a corner of the collective plot so that when the time came, she would grow her own crops. The conversation with this respondent planted the seed of what is now the second chapter in this dissertation on barriers to food security and climate adaptation. This anecdote serves as a reminder that sometimes, researchers come with their own sets of biases and assumptions when trying to assess a phenomenon that they think they have knowledge on. The game design methodology was a way to eliminate those biases as much as possible by letting the players take ownership of the game design.

This insight had important implications on the construction of models on decision-making within socio-ecological systems as well. According to Livet et al (2008, 2010) model construction is an exercise which is dependent on an 'etic' analysis of a system where the study of SES is framed through an 'external' lens of the properties of the subject in the system instead of the 'emic' analysis which frames the response of the system from within the subjects which are being studied. The etic approach fails to consider the social and normative positions of individuals within the system which influences how the conceptualization of "resilience of what" and "resilience to what" questions. As a result, each 'etic' model becomes subject to the 'knowledge framework' of the modeler which comprises not only on the implicit ontologies of the modeler but also the specific theories and conceptualizations, formalized representations and empirical data chosen by the modeler (Livet, Muller, Phan, & Sanders, 2008, 2010). This knowledge framework may lead to different modelers to construct ontologically different models to assess the same phenomena, potentially leading to different interpretations of the models. This makes the comparison of socio-ecological models particularly difficult (Livet et al. 2010).

Efforts towards minimizing such ontological assumptions or make them more explicit are likely to improve the evaluation and comparisons of computational models (Livet et al., 2010; Livet, Phan, & Sanders, 2008). In this research, the participatory game-based methodology was used in a way that allowed me, as the researcher/ modeler to step out of my ontological frameworks and design the system dynamics model based on the insights generated from games combined with a careful assessment of trends over time to development of testable hypothesis/theory that emerged from the data.

Finally, this research is an effort towards improving the transparency of model- building processes and addressing concerns of uncertainties in modeling environmental and social processes (Ascough et al. 2008). Funtowicz and Ravetz (1990) define uncertainty as a situation with three kinds of incomplete information: inexactness, unreliability, and ignorance. Knowledge uncertainty, that stems from a lack of adequate understanding and knowledge of the system; combined with data or parameter uncertainty often leads to mistrust in the model results among its users (Ascough et al, 2008). Care was taken to validate the model with historical data for over 55 years to ensure that the model was valid. As much as possible, this dissertation tried to avoid linguistic uncertainty in the vagueness of key concepts and terms by explicitly stating the definition of key terms used in the analysis.

A key limitation of this study is the inability of the system dynamics model to incorporate cross-scalar heterogeneity within the various social and ecological components of the system. Complex social-ecological systems are composed of multiple systems operating at different scales across both space and time (Gunderson & Holling, 2002). Fast variables (land use and allocation, population change, migration, crop production), are in part influenced by slowly changing variables (implementation of irrigation structures, soil fertility, groundwater availability etc.) in response to external drivers such as changes in temperature and precipitation patterns (Walker 2012). Incorporation of dynamics of slow variables such as the decline in soil fertility due to agricultural intensification and the corresponding

decline in crop yield was difficult in a national-scale model of agricultural production and hence, was excluded in the Mali-SES model.

Research on the historical impact of long-term climate change on preindustrial era societies across the Middle East, China, Europe and other countries in the Northern Hemisphere have shown a high correlation between trends in temperature change and frequencies of war, famines, population decline (Zhang et al. 2011) leading to collapse of societies (Weiss and Bradley 2001). Examples of such climate-driven societal collapse were seen with the Harappan civilization in the Indus Valley (South Asia) (Weiss and Bradley 2001), the Mayan civilization in Mesoamerica in the 9th century (Haug et al. 2003) and the Anasazi agriculturist societies in North America in the 13th century (Tainter 2006). Past paleoclimatic records show that such societal collapses coincided with the onsets of multidecadal and multi-century length droughts, impacting agrarian societies who had limited technical or social capacity to adapt to the changing climate conditions (Weiss and Bradley 2001). Rural landscapes in Mali are similar to pre-industrial era agrarian societies in their dependence on climate, low use of agricultural mechanization and high utilization of manual labor and draught power for agricultural activities. However, implying that Malian societies might be subject to similar collapse in the future due to climate change-induced droughts and famine, would mean subscribing to the idea of ‘environmental determinism’, a belief that “observed cultural transitions can be causally related to the magnitude of climatic change” (Coombes & Barber, 2005). Proponents of this view often use the ‘population-resources’ framework based on the Malthusian Crisis theory which suggests that demographic pressure on a finite pool of resources would ultimately lead to stagnation and decline (Curtis, 2012). Such a linear, deterministic view precludes the complex ways in which socio-ecological interact with and influence each other, as demonstrated in this study. This dissertation attempts to highlight the complex feedback and interactions between social, economic, environmental and institutional dynamics with Malian SES as a response to external climatic drivers and brings forward

the role of ‘human agency’ in building resilience to socio-ecological and climatic change. As we see in Chapter 1, high inter-annual rainfall variability, with variable onset of the rainy season, is not a new phenomenon in the Sahelian regions. As a result, agrarian societies in Mali have historically developed various adaptation strategies that have allowed them to cope with climatic variability and avoid collapse.

The IPCC Fifth Assessment Report defines transformation as “adaptation that changes the fundamental attributes of a system in response to climate and its effects”. Incremental adaptations, on the other hand, are actions where the goal is to maintain the essence and integrity of a system or process at a given scale. This dissertation offers a window towards the Malian future (but also applicable elsewhere) where climate change has already caused irreversible changes in the climatic patterns in temperature and precipitation in West Africa, it is likely that incremental adaptation will only enable the Malian-SES to delay the adverse impacts of these changes. Hence, it is imperative that we move beyond adaptation and focus on transformative changes that will enable a more resilient future not only for us but the generations after us.

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