IDENTIFYING LEVERAGE POINTS TO CREATE RESILIENCE TO CLIMATE SHOCKS IN DRYLAND SOCIAL-ECOLOGICAL SYSTEMS

By

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ABSTRACT

Drylands cover approximately 40 percent of the earth's land area and support more than a billion people, most of whom live in Sub-Saharan Africa (SSA), where agro-pastoralism is the major food system. Climate-related shocks such as drought, water-scarcity, diseases and pests, and food price spikes have profoundly impacted household food security among dryland agro-pastoralists, especially in Tanzania. Thus, there is a need to investigate mechanisms to ensure the future resilience of livelihoods and food systems in these regions. The goal of this dissertation is to use resilience thinking approaches to identify points of intervention in dryland SES, to manage both present and future climate risks. Resilience assessment is guided by three major questions: "resilience of what, to what, and for whom".

Paper-I explores "resilience of what, to what, for whom" through the use of systems archetypes for a Maasai dryland agro-pastoralist food system in Northern Tanzania. The paper identified three system archetypes— Escalation, Limits to Growth, and Shifting the Burden—to (1) pinpoint the elements, patterns, and relationships that make up agro-pastoralist food systems; and (2) find leverage points to address the archetypical patterns limiting food security. The paper suggests a need for institutional strengthening and polycentricity to deal with food insecurity among agro-pastoralists. Paper-II explores what shocks Tanzanian food systems are responding to and how, i.e., "resilience of what, to what". The paper used randomly sampled household data collected at national level through secondary sources to understand how different adaptive capacities influence their ability to deal with climate shocks, particularly with respect to ensuring food security, measured in terms of dietary diversity and household consumption expenditure. Through Structural Equation Modeling (SEM), the paper drew a path model that indicated investment in wealth and income diversification and investment in infrastructure were able to mediate the impact of shocks on food security. Paper-III similarly explores "resilience of what, to what" but using System Dynamics Modeling (SDM). The model allowed the exploration of feedback mechanisms and interactions between the population, livestock, and crop sub-sectors with food security in agro-pastoralist food systems in Naitolia village in Tanzania. The goal of the model was also to evaluate effectiveness of multiple policy scenarios required for food security. Out of four simulated scenarios, the model identified enhancing mechanisms for food production, along with reducing post-harvest losses and livestock predation, as most likely to result in a food sufficient scenario in the future. In creating these analyses and findings, the dissertation recommends four major leverage points to support food security through both present and future climate shocks : (1) maintaining diversity and redundancy

in income and assets that provide insurance against failures; (2) fostering connectivity between multiple actors across networks for promoting bridging social capital; (3) ensuring polycentric governance so that the right well-connected institutions at the right time can deal with both agro-pastoralist rights to food and respond to disturbance and uncertainty. The dissertation also creates methodological advancement in the understanding of food security in complex systems under climate shocks, by utilizing a variety of approaches that support system thinking - systems archetypes, statistical modeling, and simulation through a system dynamics model.

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INTRODUCTION

Background and Rationale

Climate-related shocks such as drought, water-scarcity, diseases and pests, and food prices spikes have profoundly impacted household food security in Sub-Saharan Africa (SSA) (Béné et al. 2016). Data shows that almost one in four people in SSA are food insecure, which represents one third of all people suffering from hunger globally (FAO et al. 2021). An estimated 323.2 million people in SSA faced severe (related to insufficient quantity of food, undernourishment, and hunger) food insecurity in 2020 – i.e., 57.7 million more than pre-COVID-19 levels in 2019 (FAO et al. 2021). While addressing structural inequities also need to be addressed to eradicate widespread hunger (Bjornlund et al. 2022) given the increasing impact of climate shocks there is also a need to minimize their impact (WFP and FAO 2022).

About 60 percentage of the lands in SSA are drylands, defined in terms of aridity. The United Nations Environment Programme (UNEP) defines dryland areas in terms of aridity index (AI): hyper-arid desert (<0.05 AI), arid (0.05-0.2. AI), semi-arid (0.20-0.50 AI), and dry and sub-humid (0.50-0.65 AI) (UNEP, 1992). Drylands are some of the most vulnerable social-ecological systems with high levels of food insecurity and poverty (Enfors 2013, Middleton and Sternberg 2013). Food in drylands is mostly produced through agro-pastoralism where livestock is a major part of the food system, commonly integrated with cereal and legume (Frelat et al. 2016, van Wijk et al. 2019). The existing levels of food insecurity and poverty are due to the marginalization of agro-pastoralist societies, who have historically had limited access to technology, weak institutions, and have been excluded from both development processes and political discourses (Middleton & Sternberg, 2013). Furthermore, within drylands and agro-pastoralist systems the impact of shocks is not evenly distributed and certain groups, often indigenous ones such as Maasai in Tanzania, have higher rates of food insecurity due to their higher sensitivity (degree to which system is affected by a shock) and lower adaptive capacity to shocks (Adger 2006, Butt et al. 2009). Therefore, agro-pastoralist societies, where more than half of the households are food insecure (Safari et al. 2022), are most in need of interventions to address both current food insecurity and the risk of future climate shocks (Stavi et al. 2021) .

Resilience, defined as the ability to absorb and withstand shocks through adaptation, learning, self-organizing and continue to accomplish goals notwithstanding the disturbances (Folke et al. 2010), has gained attention among policy makers and development practitioners to deal with shocks and food insecurity (Smith et al. 2015, D'Errico and Di Giuseppe 2016, FAO 2016). The capacity to accomplish goals in the face of disturbance has led to resilience theory being applied to fields such as poverty alleviation, food security, community planning, international development, and disaster management (Baggio et al. 2015). Different fields of study have defined resilience differently. For this dissertation I focus on social-ecological resilience, by basing resilience within the concept of social-ecological systems (SES). A social-ecological system is an integrated system in which humans and ecological systems are inextricably linked (Berkes and Folke 2000); each SES has a characteristic behavior that is maintained by processes and feedback loops. I use the definition by (Folke et al. 2010), "Resilience is the capacity of the social-ecological system to absorb disturbances and reorganize while undergoing change so as to still retain essentially the same function, structure, and feedbacks, and therefore identity, that is, the capacity to change in order to sustain identity." Resilience is a dynamic concept that focuses on how to persist and evolve with change (Folke 2016). This means when a dryland agro-pastoralist food system is resilient, it will have a sufficient adaptive capacity to respond to shocks in a way that ensures food security. Adaptive capacity, part of resilience that describes the ability to mobilize resources to respond shocks (Béné et al. 2014), varies between context and systems and is not equally distributed (Engle 2011). It becomes crucial to identify what builds adaptive capacity if we want to build resilience (Adger 2003, Engle 2011).

Efforts to use adaptive capacity within a broader resilience framing has resulted in array of approaches in measuring and quantifying both adaptive capacity and resilience from disciplinary silos such as social science, physical science, and ecology (Quinlan et al. 2016). However, disciplinary studies do not reflect the social-ecological resilience approach because resilient is emergent property of a SES that is maintained by processes and feedback loops between social, physical, and ecological components (Folke 2016). The complex feedback relationship is not a property of any component, but a feature of the system as a whole; therefore, does not lend itself to an easy measurement (Quinlan et al. 2016). Carpenter et al. (2001) and Quinlan et al. (2016) argue that it is difficult to measure social-ecological resilience and there exists no explicit methodology – instead they recommend assessing resilience by asking these questions: "resilience of what (what system state is being considered, drylands, for instance), to what (what disturbances are of interest; drought, for instance), and for whom" (who benefits, or losses as the result of disturbance of interest, agro-pastoralists, for instance), and focusing on deeper understanding of systems dynamics. Resilience assessment from this perspective requires a case study framing and a historical perspective to guide an understanding of the system dynamics of a given place and time to inform management interventions (Quinlan et al., 2016). Case study approach is suitable because each case study represents one system, and resilience assessment is framed around providing a degree of focus on a particular system by obtaining in-depth, about system dynamics, components, issues, and interactions within a particular system from the perspective of multiple actors.

In other words, resilience assessment needs to be context-specific and aware of present and past trajectories that differ between multiple regions and systems, and case study approaches can provide deeper understanding of a system's context, feedbacks, and interconnections over multiple periods of time. Therefore, there is a need to provide an alternative to -disciplinary approaches of resilience assessment that do not show key system variables, and dynamics, or address power and equity dynamics within the system. Especially in the dryland agro-pastoral food system, there is also a need to comprehend resilience pathways to understand what system variables, interactions and feedback lead to food security (Ambelu et al. 2017).

Research Objectives

The broader goal of this dissertation is to use a resilience-based approach to unwrap processes, elements, and feedbacks in dryland agro-pastoralist food systems in Tanzania to then identify leverage points towards food security. Tanzania serves as a noteworthy case study due its transitions in social-ecological and political systems due to unprecedented climate related shocks (Arndt et al. 2012). Against the 1960 baseline, the surface temperature has increased by 1 degrees and lead to conditions like drought, flooding, destruction of infrastructure and crops (Luhunga et al. 2018). Future projections have suggested that climate-related shocks will have more profound effects on food security in dryland and agro-pastoralist systems (Ripkey et al. 2021). Therefore, a primary goal is to identify leverage points and pathways that reduce the current cumulative impact of climate shocks and address future risks on food security in dryland food systems in Tanzania.

Studying the resilience of dryland agro-pastoralist SES already responding to shocks is challenging. First, the complexity of SES means there is a need to integrate theories and methods from different disciplines (Ostrom 2009), which demands interdisciplinarity and broad set of indicators (Quinlan et al. 2016). As mentioned earlier, this is guided by the overall question of "resilience of what, to what, for whom" which requires multiple methods to be answered fully – therefore, an interdisciplinary approach is required that incorporates expertise from ecology, and social sciences. Thus, the second objective of this dissertation is also to create methodological advance in terms of multi-method approach to data-gathering and assessment for studying social-ecological resilience, so that the opportunity to deepen understanding of system dynamics is not lost. In undertaking a detailed multi-method analysis of Tanzanian dryland agro-pastoralism, I integrate multiple tools (Systems Archetype[1], Statistical Modeling, and Systems Dynamic Modeling[2]) to explore whether their combination supports a methodological approach for identifying leverage points.

Therefore, the key research objectives of the dissertation are:

1. To strengthen the understanding of agro-pastoralist food systems in Tanzania as social ecological systems by using system archetypes and system dynamics models to identify system components and the patterns between them that are limiting food security.
2. To identify key social, economic, and structural capacities that exist to deal with food insecurity in the presence of climate shocks and intervention pathways for effective adaptation efforts.
3. To understand the dynamic behavior of dryland agro-pastoralist food systems as it responds to key changes in system components over time, to suggest policy priorities based on emerging leverage points that support decision making in attaining food security.

Research Framework

The dissertation includes multi-method approach combining resilience thinking tools - system archetypes, statistical modeling, and system dynamics modeling. As mentioned above, resilience is an emergent, systemic property that needs to be assessed against a system's desirable state so that thresholds, key feedbacks, and dynamic interactions of potential concerns that lead the system to undesirable state, such as a food insecurity, can be monitored. Therefore, the research framework for this dissertation is guided by the overall question of "resilience of what, to what, for whom". The dissertation is organized as three separate research papers with an overarching goal of identifying leverage points towards food security against climate related shocks in Tanzania, where each chapter contributes to identification of different leverage points. Paper-I answers "resilience of what, to what, for whom" question by applying system archetypes to understand dryland agro-pastoralist food system structure in a case study of a Maasai community in Naitolia village in

[1] Patterns of behavior in the social-ecological system understood through causal links between system behaviors

[2] Problem-oriented modelling approach that involves causal mapping and the simulations to understand system behavior.

Northern Tanzania. Paper-II answers "resilience of what, to what" question by using statistical modeling to access adaptive capacity against climate shocks in Tanzania at the national scale. Paper-III answers "resilience of what, to what" question by using system dynamics modeling to evaluate effective management scenarios to support food security decision making at the village scale in Naitolia, Tanzania. The agro-pastoralist food system, which contains elements, significant actors, relationships, patterns, resources, and possible shocks that affect food security, is analyzed in Paper-I and Paper-II from a historical perspective. In Paper-III, the analysis is forward-looking, exploring management solutions for achieving food security in the future. Table 1 shows how each paper, resilience questions, research questions (detail in next section) and methods fit into overall dissertation research framework.

Table 1 Research Framework with nested objectives, research objectives, resilience questions and methods used.

Overarching goal of the dissertation:	1) Identifying leverage points towards food secure futures for drylands 2) Innovating methodological approaches for resilience assessment		
Objectives	Objective 1: strengthening the understanding of agro-pastoralist as social ecological systems.	Objective 2: identifying key social, economic, and structural capacities, and intervention pathway.	Objective 3: understanding the dynamic behavior of the system and suggest policy priorities
Resilience questions	Resilience of what? Resilience to what? Resilience for whom?	Resilience of what? Resilience to what?	Resilience of what? Resilience to what?
Study Area	Naitolia village in Northern Tanzania	Tanzania	Naitolia village in Northern Tanzania
Methods used	System Archetype developed through context analysis and in-depth interviews;	Structural Equation Modeling (SEM) using secondary data.	System Dynamics Models developed through participatory diagnostic exercises

Table 1 (cont'd)

How are leverage points identified?	Identifying feedback loops that limit food security and using archetypes theory to suggest how to address the negative outcomes	Identifying variables that have higher total effect on food security	Identifying scenarios that have positive effect on food sufficiency

Paper-I: Application of System Archetypes to Understand Agro-pastoralist Food Systems in Northern Tanzania

Paper-I discusses "resilience of what, to what, and for whom", i.e., the resilience of a Maasai dryland agro-pastoralist food system in Naitolia village in Northern Tanzania. The specific research questions I am interested in answering are:

RQ1: What are the different components, patterns, interactions, and system archetypes within Tanzanian agro-pastoralist food systems that are limiting food security?

RQ2: What can we do to reverse archetypes that are preventing the achievement of food security in Tanzanian agro-pastoralist food systems?

Complex interactions and feedbacks make it difficult to understand agro-pastoral food systems; as a result, a systems thinking approach is required. Tools for systems thinking, such as causal loop diagrams (CLD) and system archetypes, are used to recognize common system structures that result in undesirable behavior as well as to identify strategies to alter the structure to produce the desired behavior. Therefore, a qualitative research design was used to collect two sets of data to create two sets of CLDs from: (1) content analysis of peer-reviewed literature, and (2) in-depth interviews. These data were used to depict connections between dynamic components and identify feedback loops and system archetypes in Maasai agro-pastoral food systems in Northern Tanzania. The paper was able to identify different system patterns and archetypes and suggest strategies to achieve food security in Tanzanian agro-pastoralist food system.

Paper-II: Using Structural Equation Modelling to identify adaptive capacity pathways to different shocks in Tanzania

Paper-II is dedicated on discussing "resilience of what, to what", i.e., resilience of Tanzanian food systems to different shocks. The research question I am interested in answering is:

RQ3: What are the key social and economic capacities that exist in Tanzania to increase resilience to climate shocks and ensure food security?

RQ4: What are the intervention pathways for supporting effective adaptation?

People are constantly responding to shocks and food insecurity, but their responses align with their capacities. A plethora of resources have been mobilized across SSA to reduce the effects of shocks and their compounded impacts. However, to undertake such practices in response to shocks and food insecurity requires identifying and strengthening adaptive capacity (Adger et al. 2005). Therefore, the goal of this dissertation chapter was to understand different adaptive capacities and their ability to deal with climate shocks, particularly with respect to ensuring food security. I followed Eakin, Lemos, & Nelson (2014)'s conceptualization of generic adaptive capacity as it provides flexibility to respond to a spectrum of both known and unknown stressors (Eakin et al. 2014, Lemos et al. 2016, Thapa et al. 2016). I used randomly sampled household data collected at national level through secondary sources to conduct principal component analysis and obtain variables for the paper. Using those variables in Structural Equation Model (SEM), I obtained latent constructs then regressed against food security and shocks. The paper was able to identify intervention pathways for supporting effective adaptation.

Paper-III: A System Dynamics Simulation Model for Agro-pastoralist Food Systems: A Case Study from Northern Tanzania

Paper-III is dedicated to discussing "resilience of what, to what", i.e., resilience of food systems to different shocks in Naitolia village in Tanzania. The research question I am interested in answering is:

RQ5: What are the effective management scenarios that support decision making in attaining food security in dryland agro-pastoral food systems?

Models that are based on systems thinking can be helpful analytical tools for researchers and decision makers to understand changes in food system components over a period of interest. To explore the feedback mechanisms and interactions between the population, livestock, and crop sub-sectors with food security output in agro-pastoralist food systems in Naitolia village in Tanzania, I constructed a system dynamics model. The model's goals are to serve as a learning tool for decision-makers to deepen their comprehension of the long-term dynamic behavior of the agro-pastoral food system and as a decision support tool to investigate realistic policy scenarios required for food security. I used structural and statistical tests to assess and validate the effectiveness of the model. The model was simulated under four scenarios to identify leverage points: Scenario 1- Enhancing food production; Scenario 2- Reducing crop and livestock losses; Scenario 3- Combination of scenario 1 and scenario 2 to provide holistic approach to deal with food security; Scenario 4- Combination of Scenario 3, along with limiting livestock sale to promote consumption from 2022 to 2050. Based on the four scenarios, the paper was able to suggest best strategy to achieve food security situation in Naitolia village.

PAPER-I: APPLICATION OF SYSTEM ARCHETYPES TO UNDERSTAND AGRO-PASTORALIST FOOD SYSTEMS IN NORTHERN TANZANIA

1.1 Introduction

Approaches to understanding food systems are challenged by their non-linear dynamics, multidimensionality, cross-scale interactions, and surprises (unanticipated behaviors such as increased frequency of extreme events, loss of soil productivity etc.) (Liu et al. 2007, Monasterolo et al. 2015). To address problems within the food systems, such as food insecurity (Thornton et al. 2011), both theoretical and methodological approaches are needed that take dynamic interactions between social and ecological components into account. Recent literature on food security has stressed the necessity of systems thinking approach to understand the complex nature, interconnections, and multiple feedbacks (Monasterolo et al. 2015, Metta 2020).

Systems thinking approaches consider feedbacks within and between the social and ecological components using tools such as Causal Loop Diagrams (CLD). CLD consists of variables connected by causal relationships, to identify recurring patterns of behavior, called system archetypes (Kim and Anderson 1998). By analyzing and understanding repetitive behavioral patterns, archetypes are both a diagnostic and prospective tool to enhance our understanding of systems and our ability to manage them effectively. Based on combinations of different recurring feedback loops, researchers (Kim and Anderson 1998, Meadows 2008) have identified eight system archetypes to understand the multitude of problems in social-ecological systems. Such an understanding can (1) be used to anticipate challenges, (2) identify points of intervention, and (3) explore why problems reappear despite multiple interventions (Braun 2002). In this regard, the system archetype appears to be a well-suited method to uncover challenges in food systems (Abson et al. 2017, Fischer and Riechers 2019). Therefore, the purpose of this article is to investigate the application of archetypes in food systems.

There are emerging examples of archetype analyses in food systems around the world. Brzezina et al. (2016) used system archetypes to understand and anticipate challenges to European organic farming, while Neudert et al. (2019) used archetypes to identify the root causes of recurring problems in the pastoral system in Georgia and Azerbaijan. Similarly, Banson et al. (2016) applied archetypes to understand the agricultural systems (horticulture, industrial livestock industry, and industrial fish industry) from an economic perspective in Ghana, West Africa. In the Asian context, Nguyen and Bosch (2013) and Bahri (2020) applied archetypes in a conservation area and water-energy-food systems respectively in Vietnam and Indonesia.

Agro-pastoralist food systems- those consisting of both crop (cereals and legumes) and livestock production (Tendall et al. 2015, Frelat et al. 2016) have historically had inadequate comprehension, marginalization, and exclusion from discussion, while providing livelihoods for the rural people on about half of the world's land area (FAO 2022). Even with the acknowledged need to focus on their sustainability, I found no examples of studies applying system archetypes in agro-pastoralist food systems. However, these food systems require further study as they are incredibly vulnerable to climate changes due to lower adaptive capacity and higher exposure (FAO 2022). System archetypes are also not applied in tribal agro-pastoralist communities like the Maasai, whose food security status is poor and has remained so despite multiple changes to policy and social-ecological systems (Reid et al. 2014, Galvin et al. 2015). I fulfill the gap by focusing specifically on agro-pastoralist food systems among Maasai tribes in Northern Tanzania, given their persistent food insecurity, and resource degradation (Baro and Deubel 2006, Diwakar and Lacroix 2021).

In Sub-Saharan Africa (SSA), where food systems are predominantly agro-pastoralist, the prevalence of severe and moderate food insecurity increased from 51.4% to 66.2% between 2014 and 2020 (FAO et al. 2021). The neoclassical cause-effect linear approaches have not been able to understand the complete dynamics of agro-pastoral food systems, as they employ short-term thinking and miss the multiple feedbacks in place (Monasterolo et al., 2015). Current studies of agro-pastoralist food security focus on smaller subsets of the food systems, such as food production and its impact mechanisms (Birhanu et al. 2017, Mubiru et al. 2018, Burian et al. 2019, van Wijk et al. 2019). When decision-makers rely on studies that investigate one element of the complex agro-pastoralist system, they risk missing trade-offs on other elements in the system. For instance, if the focus is only on the crop-production, the decision may neglect the negative impacts of intensive farming on grazing land availability for livestock (Renom et al. 2020), perpetuating sustainability challenges overall in the food system. This does not mean that previous studies are not aware of the multiple-agent concept in studying food security. Rather, earlier studies such as those (Sharif and Irani 2016, Banson et al. 2018) did not explicitly state multiple agents in their studies. This study overcomes this issue by recognizing patterns that emerge from interactions between multiple components and agents in the system.

A multidimensional approach, like the one I am proposing, is important as many of the learnings from earlier linear studies have been integrated into policy and development interventions

(Wossen and Berger 2015, Holden 2018), with little improvement in food security conditions. For instance, many of the public policies and strategies in Tanzania such as the Arusha Declaration policies (1967-97), Agricultural Sector Development Policy 2013, Tanzania Livestock Master Plan (2017-2021) and ongoing Southern Agricultural Growth Corridor of Tanzania 2010-2013) are focused on improving food security through a focus on one element of the food system - crop production, livestock production, cooperative-based marketing, and rural poverty etc. (USAID 2013, West and Haug 2017). Yet even with these strategies, food insecurity is persistent and recurring, with 20% to 30% rural population experiencing high levels of acute food insecurity in Tanzania between November 2021 to April 2022 (IPC 2022). Drylands make up nearly 60 percent of the country's total geographical area, with the Maasai who inhabit these regions reporting even higher rates of food insecurity (Nkobou et al. 2021). The lack of stability and improvement in food security (Candel 2018, Giller 2020, Nkobou et al. 2021) indicates that interventions have failed to achieve or sustain desired outcomes over time. In fact, some interventions created outcomes opposite of what was intended (Eriksen et al. 2021, Asare-Nuamah et al. 2021).

For instance, market strengthening for livestock sale offered opportunities for households coping with drought; however, this reduced the capacity to use livestock as an asset to manage future vulnerabilities (Bawakyillenuo et al. 2014). As a result, the households were locked in the vicious cycles of poverty where ad-hoc measures such as livestock sale perpetuated vulnerability, making it difficult to get out (Wilson, 2013). The Maasai are further marginalized due to limited access to technology and weakened institutions (Middleton and Sternberg 2013, Middleton 2018). However, by examining the patterns of behavior in the food systems, systems archetypes can offer a tool for deciphering dynamics and interdependencies in the system and understanding why the problems of food insecurity recur over time.

With the above-mentioned background, I set out to answer the following research questions (RQ):

RQ1: What are the different components, patterns, interactions, and system archetypes within the agro-pastoralist food systems that are limiting food security?

RQ2: What can we do to reverse archetypes that are preventing food security in agro-pastoralist food systems?

To identify the patterns of interaction and underlying system structure from which archetypal behavior originates I employ the template of eight archetypes (Meadows 2005; Kim and

Anderson 1998). System archetypes locate repeating patterns by looking at the feedback loops as opposed to articulating linear correlations. I can identify potential actions for breaking the feedback loop (i.e., that is pushing the food system toward an unfavorable state, food insecurity), after recognizing the pattern that archetypes give. In summary, by responding to the study questions, I contribute in the following ways: (1) add a new systems perspective to the literature on agro-pastoralist food systems; (2) toad more context on the Maasai, a vulnerable groups who are relatively underrepresented in the literature on systems thinking and archetypes; and (3) through the methods I am proposing, I provide nuances to the agro-pastoral food systems, such as components, patterns, interactions and feedbacks, that were not fully understood.

1.2 Methods

1.2.1 The Case Study

Following a constructionist paradigm (Lincoln et al. 2018), the study employed a case study approach. A case study was appropriate for these research questions as it provides a boundary of time and space within which to build a detailed understanding of an agro-pastoralist food system. Therefore, I sought an agro-pastoralist case study with a history of food insecurity, ideally under long-term study to provide longitudinal data as well as with a history of interventions by development practitioners and governance actors.

Naitolia village, in Monduli district in Northern Tanzania, provides an agro-pastoralist case study, as it has a history of food insecurity and undergone long term intervention through The Tanzania Partnership Program (TPP). TPP is a collaborative alliance of local and international organizations dedicated to improving local livelihoods, with one partnering village in a dryland context, Naitolia (in Monduli district, within the semi-arid Arusha region) (Tanzania Partnership Program 2020). The main ethnic group in Naitolia is Maasai (agro-pastoralists), the total population is around 1,800, and 79 percent make a living through agro-pastoralism (Tanzania Partnership Program 2020). Households are spread across two sub-villages – Ormang'wai and Engursero – with a total area of 178 square kilometers (68 square miles). Naitolia has faced seasonal food shortages for several years (Fair 2022).

Approximately 97% of people in Monduli district are Maasai that largely depend on agro-pastoralism, where over 95% of the cattle kept in the district are indigenous zebu-type (Kimaro et al. 2017). Based on meteorological and vegetation cover data between 1940-2020, the mean monthly temperature in Monduli district increased by 1.06 °C, which resulted in prolonged drought due to higher potential evapotranspiration rates (Verhoeve et al. 2021). The productivity of grazing land for agro-pastoralism closely depends on rainfall, and herd mobility is the major strategy to overcome pasture and water shortages among Maasai. However, Naitolia is on the edge of a wildlife management area, which limits mobility. As a result, the community experienced low agricultural yield, lower livestock production followed by death, food crises and water scarcity (Homeland et al. 2009, Ahmed et al. 2011). Climate change predictions in the area also suggest increased drought occurrence, which may lead to further food insecurity instances.

At the regional level, future climate simulation models project temperature in Northern Tanzania to increase by 2 to 2.4 degree Celsius (Luhunga et al. 2018). The increase in temperature highly affects agro-pastoralists because livestock change their feeding behavior and are more susceptible to heat stress (Kimaro et al. 2018). In the past, livestock in Northern Tanzania have already demonstrated reduced productivity and succumbed to disease and death following the drought of 1990-1994, due to scarcity of water and pasture, (Goldman and Riosmena 2013). The 2009 droughts also were found to increase socio-economic vulnerability of Maasai households (Theodory and Yamat 2014). In addition to drought, Maasai have also had to respond to challenges such as land ownership transition, due to establishment of new administrative areas in Northern Tanzania like the establishment of Ngorongoro Conservation Area (NCA) (McCabe et al. 2010) which reduced their access to water and pasture.

1.2.2 Research Design and Methods

To understand and identify steps for effective interventions in complex systems require methodological pluralism to provide diverse forms of knowledge. This exploratory work focuses on developing a nuanced understanding of the case study's food system. Therefore, to depict interconnections between dynamic food system components and identify feedback loops and system archetypes, a qualitative research design was employed to obtain two sets of data from which to create two CLD: (1) content analysis of peer-reviewed literature, and (2) in-depth interviews. While both datasets can be used to answer the research questions, using them together provides a deeper understanding than relying on one alone. For instance, in-depth interviews provide the context of Naitolia but may lack broader policy perspectives and changes happening at the regional level, whereas the literature in content analysis may provide that policy focus but lack the specific context of Naitolia. By combining the two I am providing a holistic approach that connects Naitolia with broader agro-pastoralist food systems while supporting multiple scales for resilience framing, and supplementing triangulation – convergence with multiple sources of information in the study (Golafshani, 2005) – and thus standards for content validity and reliability (Lincoln et al., 2018).

1.2.3 Content Analysis

To identify different agro-pastoral food system components and their interactions, I conducted an exhaustive literature scan (Rubin et al. 2010) using Scopus. In the exhaustive literature scan for relevant publications, I applied [TITLE-ABS-KEY ("Food security" OR "Food systems" AND "Naitolia" OR "Tanzania")] in Scopus as search terms and found 533 articles (as of December 2020). Each abstract was reviewed, and none mentioned "Naitolia" in their abstract. I identified and then omitted 339 publications that did not include Arusha or Northern Tanzania in their abstract, title and keywords, as I required a dataset that also referred to Maasai food systems. Naitolia lies in the Arusha region in Northern Tanzania and is home to approximately 72% of the total Maasai population in Tanzania (Joshua Project 2022). However, the Maasai are not the only group present in this region, so a potential limitation is that the content analysis findings are more broadly dryland than just Maasai.

This left 194 abstracts specifically about the focal area from which to identify key elements in the food systems; where, 129, 38 and 27 articles mentioned Northern Tanzania, Arusha, or both Northern Tanzania and Arusha in their abstract respectively. Only 48 abstracts contained drought components, of interest because initial inquiry via the TPP and agency reports mentioned drought to be a primary issue. As a second iteration of the scan, I then broadened the literature search by applying [ALL ("Food security" OR "food system" AND "Tanzania" OR "Naitolia" AND "Drought" AND "pastoralism")], with 326 articles found. I excluded 49 articles that did not include Northern Tanzania or Arusha. Out of 277 articles remaining, 251, 5 and 21 articles mentioned Northern Tanzania, Arusha, and both respectively. After both searches, a total of 471 individual abstracts were selected for coding (194 from the first literature scan plus 277 from the second).

I used inductive coding in MAXQDA, a ground-up approach where codes are derived from the data, to condense textual data into a summary format, from which I developed a framework of the underlying dryland food system structure (Thomas 2016). Initial inductive coding of 20 randomly selected abstracts resulted in 23 themes related to components of food systems. Based on the themes, a final codebook was prepared (Table 7) and used to code the selected 471 abstracts. After the abstracts were read and coded, codes were merged to identify themes. Each theme contributed a variable in the CLD, while links represented the causal relationships and were based on relationship between the themes (explained more in section 2.3). This analysis resulted in a Casual Loop Diagram ((CLD-L).

1.2.4 In-Depth Interviews

To complement the findings from the peer reviewed articles on food systems obtained from the content analysis, I carried out eight in-depth interviews as an additional explorative approach (Creswell 2014). Explorative approaches are common in field of research that generally do not have enough research (Patton 2016). I conducted in-depth qualitative interviews with stakeholders working in Naitolia as a development practitioner and governance actors. Identifying stakeholders is important as whoever will be interviewed will shape the process and outcome of the research, i.e., solutions identified will reflect the worldview and perspectives of the experts. Therefore, stakeholder identification was primarily based on criteria of legitimacy (institutional position acquired by law or task undertaken by public consent), resources (knowledge, capabilities and expertise to exert influence to manage and monitor resource), and interconnectedness with agro-pastoralism and Maasai community (number and quality of relationships with the community) (Zimmermann and Maennling 2007). The Tanzania Partnership Program (TPP) office was reached out to first, and stakeholders were then identified based on the above-mentioned criterions. Our purposive sample was then expanded as participants recommended further actors to speak with, creating a snowball sample of regional level stakeholders that met the criteria (Abubakar et al. 2015). One additional criterion was that given COVID19 and travel restrictions for the researchers, all participants were required to have access to internet or phone. The final sample represented NGOs, development practitioners, and nature conservation organizations.

All interviews were conducted virtually through Zoom and WhatsApp between May-July 2021. A semi-structured interview guide was used to ask questions that provided contextual information about Naitolia and the Maasai agro-pastoralist food system. The semi-structured approach allowed researchers to get details and richness on specific issues of interest, but also allows interviewees to bring topics and issues of their interest into the conversation (Creswell 2014). I applied the theoretical saturation model, a widespread methodological principle in qualitative research, which indicates criterion for discontinuing data collection (Saunders et al. 2018). When no additional information was found, and the researcher saw similar instances repeatedly to develop the trend, interviews were discontinued. Saturation was reached after eight interviews.

This research was determined to be exempt under the [redacted for review] IRB Board (ID [redacted for review]) and all participants provided informed consent before participating. With the additional consent of the interviewees, the interviews were recorded and transcribed manually within 24 hours of the interview, as important details maybe forgotten and could bias the result (Rubin et al. 2010). All eight transcripts were coded in three steps using MAXQDA. Firstly, an initial set of deductive codes that corresponded with the interview questionnaire were applied, which is a typical form of coding in qualitative research (Seidel 1998). Initial codes covered topics regarding food system and food security components. Secondly, inductive codes were assigned where emergent themes arose. Finally, the transcripts were recoded with the integrated codebook (i.e., including all deductive and inductive codes) to identify themes. A total of 26 (Table 8) themes were identified that correspond to the components of an agro-pastoralist food system. A Casual Loop Diagram (CLD-I) (Figure 24) was prepared, where the variable names in the CLD-I referred to the coded themes; while links represented the causal relationships between the themes, which is explained more in the following section.

1.3 Drawing Causal Loop Diagrams to Understand System Structure

The themes developed through content analysis and in-depth interviews are considered as system components or system variables. System components were combined to produce a figure visualizing how they are causally interrelated (i.e., the system structure) in the form of Causal Loop Diagrams (CLD), developed following the steps from Kim and Anderson (1998). The themes from the content analysis were used to create CLD-L whereas the themes from the interviews were used to create CLD-I. Both CLD were developed using the following process:

- The themes identified in both content analysis (Table 7) and in-depth interviews (Table 8) correspond to variables in CLD-L and CLD-I respectively. Themes inserted as variables in Stella software.
- The identified variables were linked together in Stella by representing how one variable affects the other, based on the data. The links are labeled with either a "+" or a "- ". For instance, if the literature review or in-depth interview mentioned variable "A" to move in the same direction as variable "B" (positive relation) the link from "A" to "B" is labelled as "+". Likewise, if the literature review or in-depth interview mentioned "A" to move in a different direction as "B" (negative relation), the link from "B" to "A" is labelled as "-". Inferring causality was an iterative process and only ends when one link was clearly substantiated.

- Once all causal links had been added, they represent an interaction. When a causal link demonstrated a reciprocal relationship, a feedback loop was created. All feedback loops were then assembled into a causal loop diagram to create a visual model of food system.

1.4 Identifying System Archetypes

Meadows (2008) and Kim and Anderson (1998) provide a detailed guide of recurring patterns that have occurred in multiple systems with their signature dynamic of archetype based on feedback loops. To identify a particular archetype, I looked carefully at our CLDs for a systemic structure (i.e., a certain combination of feedback loops) or a story template and compared them with Meadows (2008) and Kim and Anderson (2003). I then related the archetype's storyline with the storyline in our CLD to explore typical behavior over time, looking for balancing or reinforcing feedback loops, unintended consequences and delays (Sun et al. 2014, Turner et al. 2016, Sharma et al. 2021). The system archetypes reveal patterns of events and provide more insight into the whole "story" (Sun et al. 2014).

1.5 Results

The CLDs generated through the content analysis (CLD-L; Figure 23) and in-depth interview (CLD-I; Figure 24) have many common variables and similar storylines – parts of these CLD are isolated and presented below to show structures of interest. There are eight balancing and five reinforcing loops in CLD-L, while eleven balancing and sixteen reinforcing loops in CLD-I. As shown in Table 2, three archetypes were found in both CLD-L and CLD-I.

Table 2 Summary of system archetypes found in two CLDS and used for analysis.

ARCHETYPE	GENERAL DESCRIPTION	ARCHETYPE STRUCTURE	FOUND IN CLD-L?	FOUND IN CLD-I?
LIMITS TO GROWTH	Growth levels off or declines.	Reinforcing behavior accompanied by balancing behavior.	Yes	Yes
ESCALATION	Each party considers the other party as a threat.	Two balancing feedback loops creating constant retaliation	Yes	Yes
SHIFTING THE BURDEN	Even though the fundamental solution is known, preference is given towards symptomatic solution, and must deal with side effects.	Two balancing and a reinforcing loop	Yes	Yes

The following section answers the research questions by outlining the system archetypes identified within the CLD-L and CLD-I. The first section describes system components with the help of system archetypes (RQ 1), followed by discussion on possible solutions (RQ 2).

1.5.1 RQ 1: What are the different components, patterns, and interactions within the agro-pastoralist food system that are limiting food security?

As mentioned in the earlier section, system archetypes are identified through feedback loops - causal links between connected system elements. Therefore, a system archetype contains system elements, their connections, feedback, and patterns. The archetypes found within both CLDs to influence food security were Limits to Growth, Escalation, and Shifting the Burden.

1.5.1.1 Limits to Growth

Limits to Growth archetypes occur when reinforcing behavior (the growing action) is accompanied by balancing behavior (the slowing action) that eventually limits the driving growth (Kim & Anderson, 1998). Both content analysis (Figure 1) and in-depth interviews (Figure 2) show that reinforcing behavior corresponding to food availability is balanced by drought. According to the content analysis, the historical existence of sustainable arrangements in governing agro-pastoralism in the region (herd-diversification, mobility, social capital etc.) have has positive impacts on food production, as shown in R1 loop in Figure 1. Specifically, the reinforcing loop operates as follows: by implementing traditional management practices, food production improves. As enhancement of food production in agro-pastoralism becomes more apparent, more people are likely to practice traditional management practices.

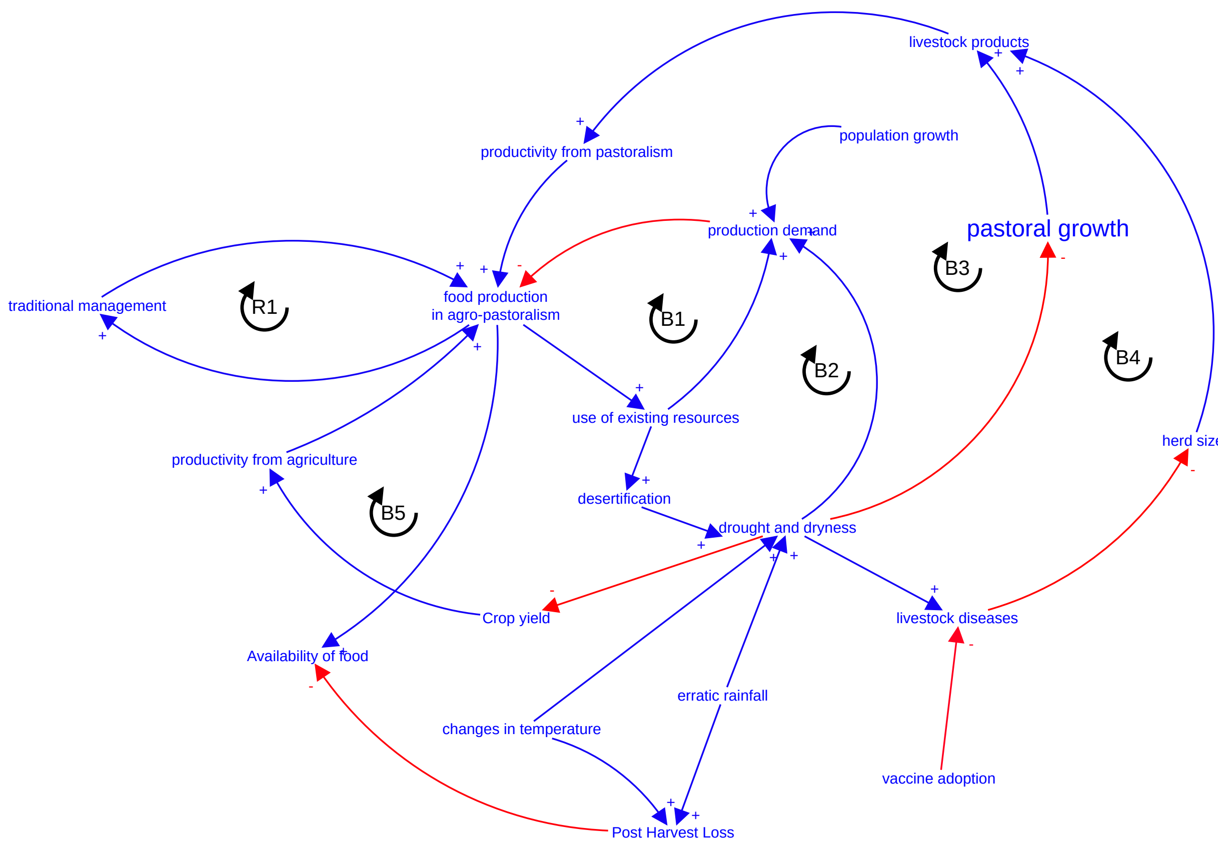


Figure 1 Limits to Growth Archetype in CLD-L (content-analysis), linking climate change to agro-pastoral food production. Loop R1 shows the reinforcing nature of food production through traditional management, while loops B1, B2, B3, B4 and B5 show slowing action due to drought and dryness. If two variables move in same direction – the link is colored in blue; if the two variables move in different direction – the link is colored in red.

In-depth interviews also reported growing food availability as both crop and livestock production complement each other as seen in loops R17 and R19 (Figure 2). As seen in Figure 2, livestock and agriculture are related. Livestock provides direct food in terms of milk and meat, where the surplus can be sold to generate income. The revenue generated is further invested in livestock herd creating a reinforcing loop (R17), where more income is generated, which further improves food access and availability. The manure from livestock is used in crop production which increases availability of food. Surplus grain is sold for household income, which are further invested in crop-production and ultimately increasing availability of food (loop R19, Figure 2).

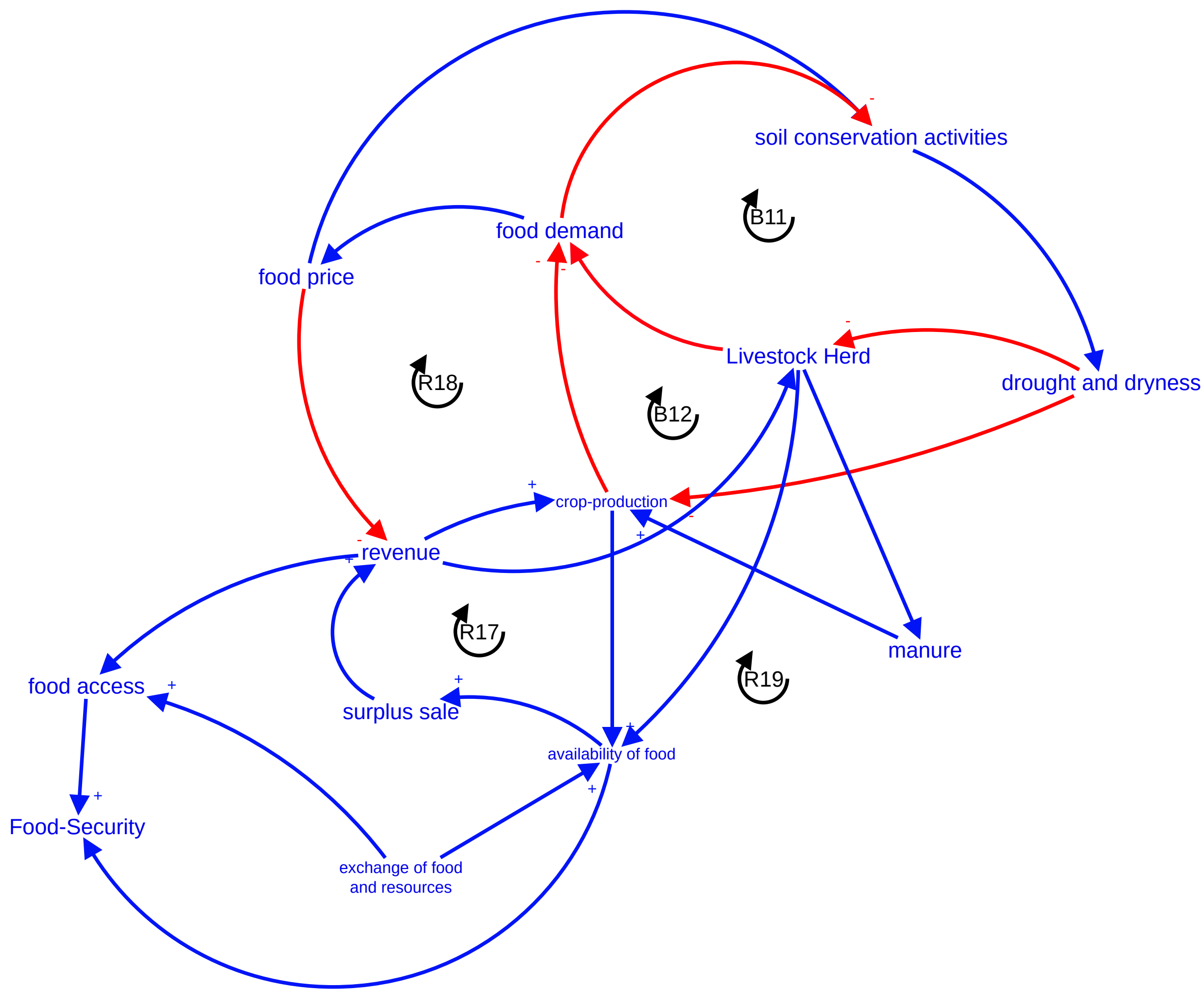


Figure 2 Limits to Growth Archetype in CLD generated through interview: Linking climate change to agro-pastoral food production. Loop R17 and R18 shows reinforcing nature of food production through integration of crop and livestock, while loops B11, and B12 show slowing action due to drought and dryness. If two variables move in the same direction – the link is colored in blue; if the two variables move in different direction – the link is colored in red.

However, there are balancing feedback loops in both figures, which are slowing the food production. The first and second balancing loop in Figure 1 (B1 and B2) relates to resource degradation and demand. In loop B1, to produce more food, there is more use of existing resources, which leads to increase in production demand as resources become scarcer and population increases.

As a result, food production cannot keep up with the increase in production demand in loop B1. In loop B2, as more existing resources are used there are chances of over-exploitation which may lead to soil degradation and desertification that increases the incidences of drought and dryness. This in-turn affects production demand, ultimately reducing the food production in loop B2, while in loop B3, with production demand, there is more use of existing resources- those results in desertification and drought and dryness. As a result of increased drought and dryness, pastoral growth is reduced ultimately leading to lower livestock products and productivity from pastoralism. The loop B4 illustrates that as livestock diseases increase, herd size reduces due to disease- related mortality, which then reduces milk and animal products, ultimately impacting food production. The fifth balancing loop in Figure 1 (B5) highlights the dynamics of drought crop production and yield. As drought increases, crop yield decreases which further affects productivity and food production. In combination, the five balancing loops (B1, B2, B3, B4 and B5 Figure 1) limit the growth of food production in the agro-pastoralist food system.

The interviews also validate the results in CLD-L: with increased drought CLD-I shows there is less crop (B12, Figure 2) and livestock (B11, Figure 2) production, which ultimately reduces food availability and access and increases food demand. To fulfill the increased demand of the food, disorganized use of resources is undertaken, leading to overgrazing. Given the loss of a soil's moisture holding capacity during a drought, when it does rain runoff increases, creating channels across lands which further washes away soil, the cycle continues resulting in worsening gullies with no vegetation.

1.5.1.2 Escalation

The system archetype Escalation refers to a situation in which actors are a part of a non-cooperative game (as per game theory; competition between multiple actors (Kim and Anderson 1998)). When actor A perceives a threat from actor B, and actor A responds to the threat by an activity. When that activity by actor A is perceived as a threat by actor B, actor B responds again, which is again perceived as a threat by actor A. Therefore, when both actors take action to maximize their outcome, they create a vicious loop where both actors put more and more effort to surpass the threat from the opponent. The archetype is represented by two balancing feedback loops which interact to create growth behavior like a reinforcing loop. Therefore, Escalation archetype is also described as one linked reinforcing loops.

Both CLDs demonstrate the Escalation archetype given a constant struggle for land. The archetypes generated from content-analysis (CLD-L) focus on the competition between agro-pastoralism, settled farming with no transhumance pastoralism (referred here as cropping communities), and conservation (Figure 3), while interview-generated archetypes in CLD-I focus more on the conflict between agro-pastoralism and conservation (Figure 4).

CLD-L shows two balancing loops (B7 and B8), extracted in Figure 3, which interact to create a reinforcing loop of ongoing conflict between cropping communities, conservation actors, and agro-pastoralists. B7 illustrates that cropping communities and government perceive encroachment of farming lands by pastoralists as a potential threat. They respond to the threat by increasing land-privatization for crop cultivation, which is evident through more support for policies on livestock domestication and commercial crop production, and ultimately leads to the expansion of cropland.

As a response to the threat of losing access to critical grazing land, agro-pastoralists are compelled to encroach conservation areas (loop B8), which likely leads to loss of biodiversity and habitat. To deal with the threat of encroachment, stringent fortress conservation policies are created that result in the expansion of conservation areas and further loss of critical grazing lands for pastoralists. From the cropping community's perspective (loop B7), policy on conservation and wildlife can be a threat to agriculture, to which agricultural agents responds through expansion of cropping land and the cycle continues. In a wider sense, these two feedback loops (B7 and B8 Figure 3) undermine pastoral mobility. The co-occurring processes of increased climate change impacts, sedentarization, and conflict with conservation and agriculture is affecting food security of agro-pastoralists.

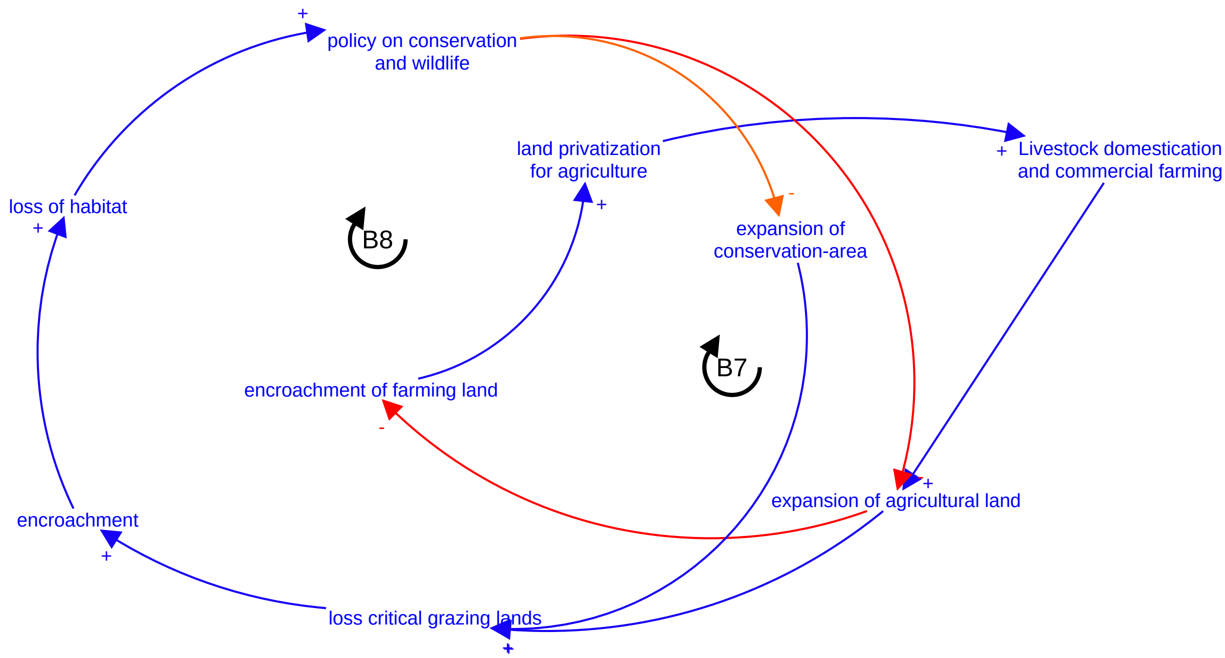


Figure 3 Escalation archetype in CLD-L: the cycle of conflict between agriculturalists, pastoralists, and wildlife (B7 and B8) as identified through content analysis. If two variables move in same direction- the link is colored in blue; if the two variables move in different direction – the link is colored in red.

Likewise, Figure 4 shows an Escalation archetype in CLD-I, generated through interviews, that is more focused on the interactions between agro-pastoralism and conservation. As mentioned in the earlier paragraphs, Escalation archetype is generally shown by two balancing loops, which can be translated as a single reinforcing loop. In Figure 4, the Escalation is shown by reinforcing loop R12, as two balancing feedbacks interacts to create a single reinforcing loop; can be redrawn to figure eight, with two balancing feedbacks. In loop R12, if there is surplus food available, and no food deficit among agro-pastoralists then nothing will happen. If there is food deficit among agro-pastoralists increases, they will interact in such a way that agro-pastoralist's uncertainty over food, adds threat in wildlife and conservation area. The wildlife and conservation assume that the agro-pastoralists would break the rules, to overcome the food deficient situation and perceives the agro-pastoralist's actions as demographic and institutional risks. The perceived risk is overcome by stringent wildlife conservation policies, which in turn creates perceived threats such as fragmentation and loss of access to grazing land for agro-pastoralists. The agro-pastoralists undertake deforestation and degradation activities through illegal entry in conservation area, which creates political instability resulting in the similar food deficit situation and the cycle continues (loop R12 - Figure 4).

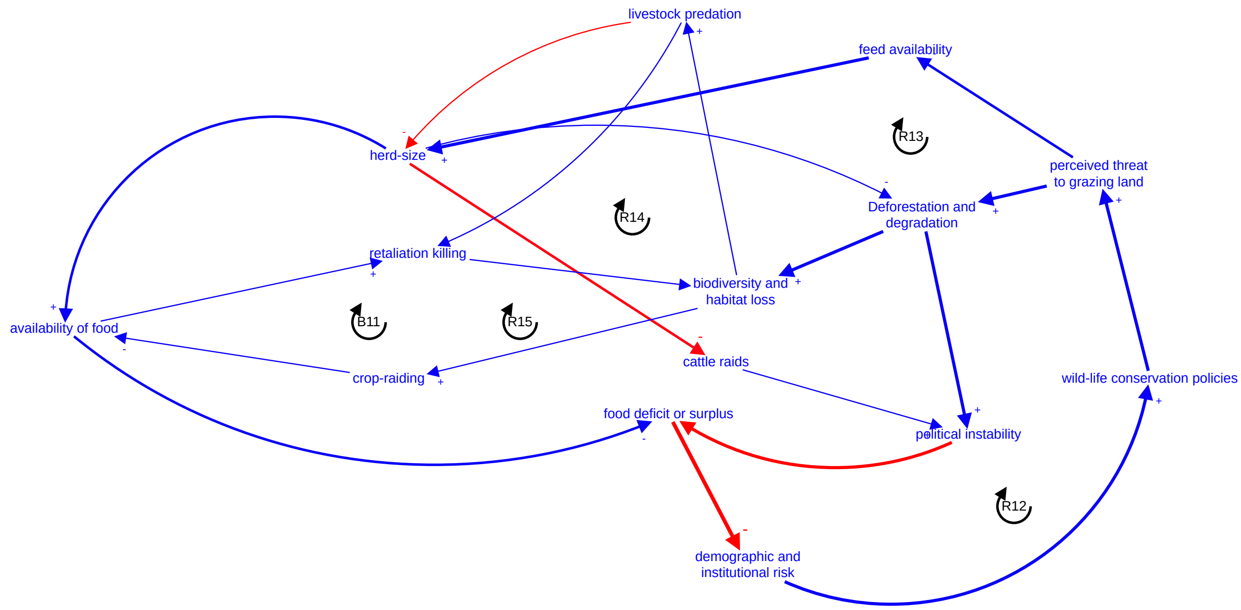


Figure 4 Escalation archetype in CLD-I: the cycle of conflict between agro-pastoralism and wildlife (R12, R13 and R14) as identified through in-depth interviews. If two variables move in same direction- the link is colored in blue, if the two variables move in different direction they are colored in red.

One of the interviewees, with knowledge of natural resource management in Naitolia and Tanzania, stated-

> *"It is not exactly encroachment, but changes in pastoral land tenure that pastoral communities are not made aware [of]. There were many conflicts between communities and Serengeti National Parks because of this."*

The interview data contained more depth on implications of conflict between agro-pastoralists and conservation actors, as shown in loop R13 on Figure 4, where perceived threat to grazing land affects feed availability and herd size, and ultimately increasing deforestation and degradation. Loop R14 outlines resulting human-wildlife conflict, as deforestation and degradation increase biodiversity and habitat loss also increases. With habitat loss and fragmentation, the wild animals are likely to attack domestic animals, which sparks retaliation killing spree among agro-pastoralists and further decreasing biodiversity. As noted by (Kaswamila et al. 2007, Kaswamila 2010), there are numerous instances of crop destruction, livestock depredation by wild animals, loss of agricultural land to conservation, and insufficient buffer zones. Livestock and crop loss was confirmed by one of the interviewees, who has worked in Naitolia for more than four years, during the interview-

> *"The wild animals destroy crops, kill livestock and chicken. This is a sad situation. First, they can't grow most of the things due to lack of water, and even if they grow- the wild animals destroy them."*

The above explanation shows that there are three connected land-uses (agro-pastoralism, conservation, and cropping) within agro-pastoralist food systems. The Escalation archetype shows that food system management has not been approached in a systemic way, given the vicious cycle of conflicts which influence food availability.

1.5.1.3 Shifting the Burden

The archetype Shifting the Burden relates to a situation where the symptoms of a problem are addressed by an 'easy fix' without fundamentally addressing the core problem, which requires significant time, effort, and political will (Braun 2002). Eventually the problem reappears, sometimes much bigger, and the cycle continues where a symptomatic solution is prioritized over a fundamental solution (Braun 2002). The shifting burden archetype is represented by two balancing and at least one reinforcing loop. The first balancing loop denotes the relationship between symptomatic solution and problem symptom, while the second balancing loop denotes the relationship between problem symptom and fundamental solution. The reinforcing loop denotes the solution-induced side effect when a symptomatic solution is prioritized over a fundamental solution.

To address food availability challenges, both decentralized and centralized commercial plantation models have been introduced, with the aim of pursuing positive socio-economic growth, resulting in increased food availability (Van Eijck et al. 2014). The solution is considered as a quick fix as agricultural yield would replace food produced through subsistence crop and livestock production. However, undertaking plantation cultivation would mean permanently settled livestock raising, a large cultural shift for subsistence agro-pastoralist households, in addition to a different crop cultivation model, as they lack skills, knowledge, and know-how on commodity farming. As the result, the cycle of food insecurity continues as observed in balancing loop (B5) in Figure 5.

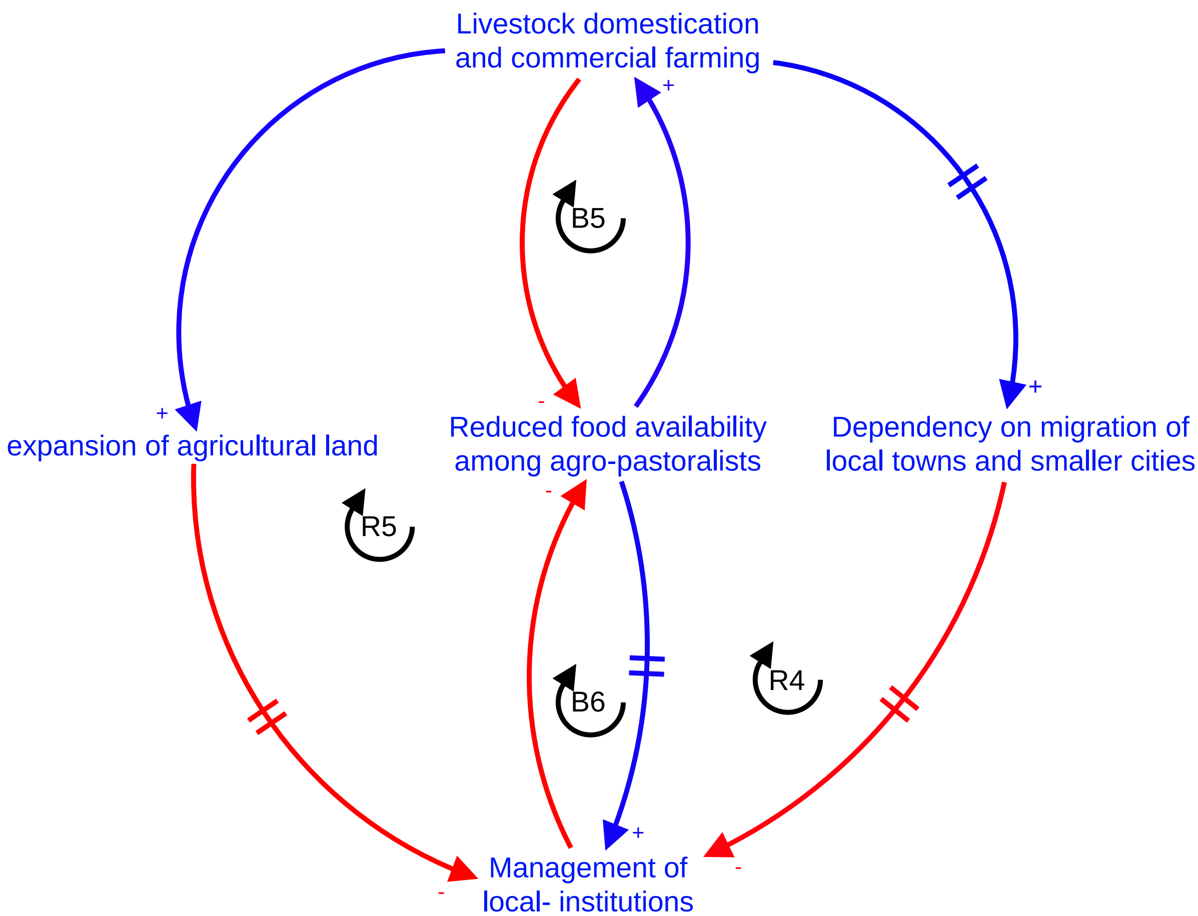


Figure 5 Shifting the Burden archetype as identified in CLD-L through content analysis. Loop B1and B2 shows the relationship between symptomatic solution, problem, and fundamental solutions, whilst loop R4 and R5 shows unintended consequences. If two variables move in the same direction the link is colored in blue.

Many authors perceive the fundamental solution to food availability challenges is traditional institutional strengthening. Barham and Chitemi (2009) argue that strengthening local pastoralist institutions and collective action minimizes food insecurity through risk sharing, labor and resources pooling and trust building. If we look at it through the Shifting the Burden lens, this means they advocate for strengthening the balancing loop B6. The loop illustrates that if food availability is reduced, the more the need to strengthen and empower local institutions and innovation. In turn, as the collective action through local institutions increases, food availability is likely to increase. However, there is a delay in the balancing loop B6 as it takes considerable amounts of time, effort, and resources at the institutional level to achieve this.

Figure 5 also shows two reinforcing feedback loops that leads to increased migration (R4) and reduced pastoralist production due to expansion of agricultural land (R5). As more government interventions are targeted towards commoditized agricultural development, the loop R4 arises as agro-pastoralists migrate in search of land, jobs and opportunities, given their lack of interest and skills in commodity crop production, which in turn, disrupts traditional agro-pastoralist institutions. As migration increases, the local agro-pastoral institutions are deteriorated as greater integration of agropastoralism into broader migration economy decreases contributions to public goods in the presence of collective risks such as availability of food. The second reinforcing loop (R5) also emerges from the interplay between farming and pastoralism. As more agro-pastoralists are settled and undertake cropping activities, there is likely to be competition for arable land. In most of the cases, the requirement for arable land is fulfilled by farming in areas that were traditionally used for pastoralism, concurrently deteriorating local agro-pastoralism institutions.

In combination, short term solutions to decreasing food production are resulting in increasing migration and cropping land expansion, which R4 and R5 show are vicious circles that disrupts local institutions, thereby increasing the need to undertake more permanent settled agriculture and livestock production in dryland food systems.

The system archetype Shifting the Burden is also noted in the interview generated CLD-I but with a different narrative (Figure 6). Each interview highlighted water scarcity as the major issue influencing food security, and that this has been addressed through input support from NGOs and programs such as TPP. The input support (B1) has temporarily reduced symptoms to some extent but have diverted attention away from the implementation of fundamental solution, i.e., policy and institutional strengthening. However, these interventions are not sufficient to solve the water scarcity problems both in terms of quantity and quality year-round because of ongoing changes in climate and loss of traditional livestock management practices. Policy and institutional strengthening are likely to be the fundamental solution (Pretty 2003).

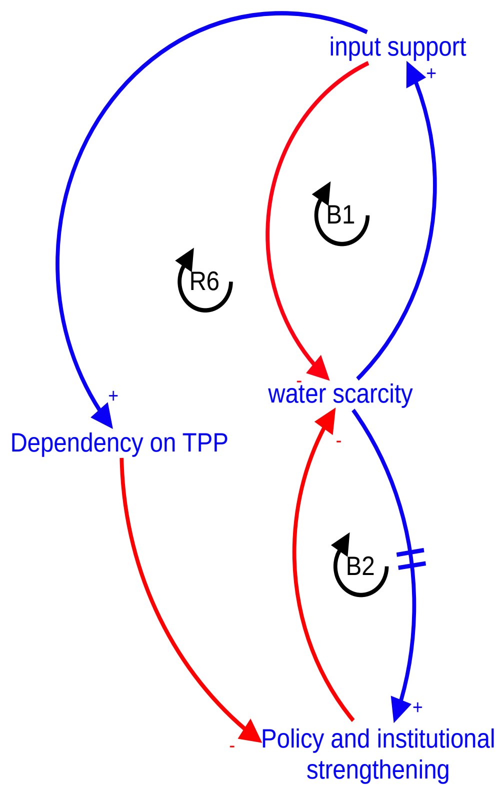


Figure 6 Shifting the Burden archetype identified in interview generated CLD-I. Loop B1 and B2 denotes temporary and fundamental solution to the water scarcity problem in Naitolia. If two variables move in same direction- the link is colored in blue; if the two variables move in different direction – the link is colored in red. The two lines in a loop is the time delay.

When asked if TPP is institutionally sustainable in long run and whether they contribute to ensure self-reliance in the future, many interviewees expressed their concerns regarding long-term sustainability and longevity of TPP. According to one of the interviews, the community's dependency towards NGOs and TPP have reached to the point where community demands help in activities pursed independently over the years such as resource appropriation and monitoring (Loop R6, Figure 6). An expert, a lecturer at TPP partnered university in Tanzania, stated-

> *"The people at Naitolia want help with so many things. It's difficult to say no-but also, we cannot make false promises. It is easier for them to ask us than to the local government because TPP is here for so long".*

1.5.2 RQ2: What can we do to reverse archetypes that are preventing the achievement food security in agro-pastoralist food systems?

As a diagnostic tool, system archetypes allowed us to investigate underlying structure and understand where problematic system outcomes emerge. Therefore, they allow us to identify where and how solutions can be implemented by identifying the causal relationships between variables, feedbacks and patterns that are causing the problem. Through doing so, we may pinpoint the specific actions that have the best chance of transforming the system's structures from unwanted to desirable consequences, following Meadows (2008) work on archetypes. Meadows (2008) also discussed the concept of leverage points, i.e. places in the system where minor interventions can change the system outcomes from undesirable to desirable. In examining the feedback loops and elements within the archetype, I highlight relevant leverage that can shift the system structure from food insecure to food secure. The paragraphs below pinpoint various leverage points by examining the system structure and patterns.

Both the interviews and content analysis show the Limits to Growth archetype. There will always be Limits to Growth, as no system can grow forever, however, if limiting constraints, like drought, livestock diseases, post-harvest losses etc., go unaddressed, the loop can lead to a rapid decline because continued growth reaches the threshold of the system's capacity – i.e., 'overshoot and collapse' (Kim and Anderson 1998, Meadows and Sustainability Institute 1999, Ford 2000, Meadows 2008). Therefore, to prevent this, we should: (1) address the balancing phases that are affecting the agro-pastoral growth; and (2) implement an equilibrium method to prevent "overshoot and collapse" and keep the system within the carrying capacity.

The balancing phases in Figure 1 (loops B1 and B2 (production demand), B3 (drought), B4 (livestock diseases) and B5 (post-harvest losses)) and Figure 2 (loop B11 and B12 (drought) do not allow the agro-pastoral food systems to flourish, which in many cases go unnoticed or are delayed because potential constraints in the system may arise from slow variables. The leverage point lies in addressing the potential constraints; for instance, Figure 1 shows that the underlying limit on food production is drought (loop B3). Common responses by agro-pastoralists to address drought include, increasing pastoral mobility or investing more time, knowledge, and resources to adapt (Béné et al. 2014) i.e., building water storage facilities for cows to drink to reduce future failure of the livestock production or fundamentally change the system of land by adoption of agroforestry. These strategies address drought while subtly advancing the agro-pastoral food system.

The agro-pastoral food system, however, can only support a certain amount of cattle without causing environmental deterioration. This archetype also shows that leverage for increasing food production in agro-pastoralist systems does not necessary lie in accelerating growth, because it may cause 'overshoot and collapse' and permanently degrade the carrying capacity of the traditional food system. Therefore, the second leverage point lies in reducing the pressure of the herd on the carrying capacity in a particular geographic location by implementing an equilibrium method on key variables, which is livestock numbers. The most extreme leverage point for supporting food production in times of drought could be destocking of livestock in agro-pastoralist communities so that the livestock do not reach their carrying capacity in terms of pasture availability and water. Emergency destocking with the external government or NGO support has gained popularity in recent years (Nkuba et al. 2019, Dika et al. 2022). It involves giving pastoralists more incentives to sell animals or lifting restrictions on selling animals during the early stages of a drought. Simultaneously, the state could facilitate and promote organized herd movements, and rotational grazing interventions that allows enough time for pasture to generate during droughts and disturbances. Eakin et al. (2014) and Lemos et al. (2016) both highlight that responding to drought both in terms of coping and adaptation is inseparable from a development context. In addition to the community-level responses, additional solutions are available in the policy sphere, i.e., finding appropriate ways to remove constraints to and enable adaptive management. Policy should recognize agro-pastoralists' goals for adaptation, risk avoidance, and the need for productivity enhancement and stress tolerance. Scenario planning with the local agro-pastoral Maasai community will help to prioritize research goals and make contingency plans for drought conditions.

Both datasets reported Escalation archetypes are affecting food security. Conflict between the agro-pastoralists, cropping communities, and conservation actors (i.e., loop B7 and B8, Figure 3) is leading to Escalation because each respond to actions by the others to protect their access to land, although given, Maasai communities are relatively disadvantaged and resource poor (Middleton and Sternberg 2013), they are likely to break down and be further marginalized in the conflict. According to Meadows (2008), the best way to get out of Escalation trap is by negotiating and creating a situation whereby one-party refuses to compete, and as such interrupts the reinforcing loop.

In the Naitolia context, given that the parties have been engaged in conflict for so long it may require a fourth party, such as the NGOs and academicians, to put an end to Escalation. Much research on common-pool resources has shown that conflict resolution is about bringing parties face-to face to map perceived threats and their sources, before discussing and negotiating acceptable solutions (Sarker and Itoh 2001, Fleischman et al. 2014, Rommel et al. 2015, Baldwin et al. 2018a). Given much of this conflict is related to access and use of land, and use of resources such as water, the success of conflict resolution is grounded upon the government's capacity to produce or control rules and arbitrate conflicts along with recognizing local property rights. Successful conflict resolution can also be translated into collaboration with proper rights and regulation enforcement (Chaudhary et al. 2015). The process requires stakeholder engagement, participatory planning and knowledge sharing, trust building and power sharing (Fleischman et al. 2014, Rommel et al. 2015). Regarding the conflict between conservation and agro-pastoralists, third-party intervention can help in negotiating for technical, cognitive, and economic interventions that reduces human-wildlife conflicts (Baynham-Herd et al. 2018). Technical interventions include wildlife control, buffer zone creation, surveillance system, and livelihood training (Lute et al. 2018). Cognitive interventions include building awareness of conservation and regulatory benefits. Most importantly, economic interventions (for example, providing agro-pastoralists to work as park rangers, or eco-tourism) that weaken the balancing loop of retaliation killing and wildlife attack are required, including compensation and insurance for crop raiding and livestock predation, payment for ecosystem services, direct employment, education, infrastructure development, and alternative livelihood (Ravenelle and Nyhus 2017). Current policies do not adequately address complex situations and as a result there is conflict between the different users, this calls for the need of conflict resolution mechanisms. The state needs to recognize the precarious land tenure and unequal power relations that have undermined agro-pastoral food systems. It is then the government's duty is to create formal institutions that guarantee the access to dependable sources of water, especially during the dry season for agro-pastoralists.

The shifting burden archetype revealed that incidences of food insecurity have been addressed by symptomatic solutions, which work for a time. Given they have led to improvements in food production and security, I am not advocating for discontinuing such programs – they are a relevant coping strategy. But the leverage point here is to also focus on the root cause of the problem and work on fundamental solutions. One fundamental solution as strengthening traditional agro-pastoral institutions to strengthen the balancing loop (B5- Figure 5). The role of the state is to recognize Maasai's right to design their own rules and institutions without being undermined by other authorities. This is particularly important considering the prevalence of top-down decision making and incidences of government actors undermining Maasai rights to resources. In addition, given the complexities between multiple actors (as explained in Escalation archetype), all the activities such as provisioning resources, monitoring, rules enforcement, and conflict resolution must be nested as multiple layers within higher-level governance. Likewise, if we look at Figure 6 and Figure 7 simultaneously, policy and institutional strengthening is likely to increase bonding (such as sharing resources and information between kinship) and bridging capital (interactions between communities), which in turn enhances collective action (Pretty 2003). Collective action further strengthens policy and institutions (McGinnis and Ostrom 2014, Pahl-Wostl and Knieper 2014) creating a reinforcing loop (R7 and R8), which acts as the means of delivery of external resources and technology to deal with water scarcity situations (Agrawal 2008).

1.6 Conclusion

System structures offer a framework to address unsustainable behavior. I used system archetypes as a diagnostic tool to identify different components and interactions in agro-pastoralist food systems in Naitolia, Northern Tanzania. As a prescriptive tool, the goal was to use system archetypes to frame leverage points as the strategies that would reverse feedbacks that are currently preventing achieving food security in agro-pastoralist food systems. With the knowledge of system archetype and leverage points, stakeholders participating in managing agro-pastoralism can apply tailored strategies at specific places in the system, some of which are listed above, to solve potential pitfalls leading to food insecurity.

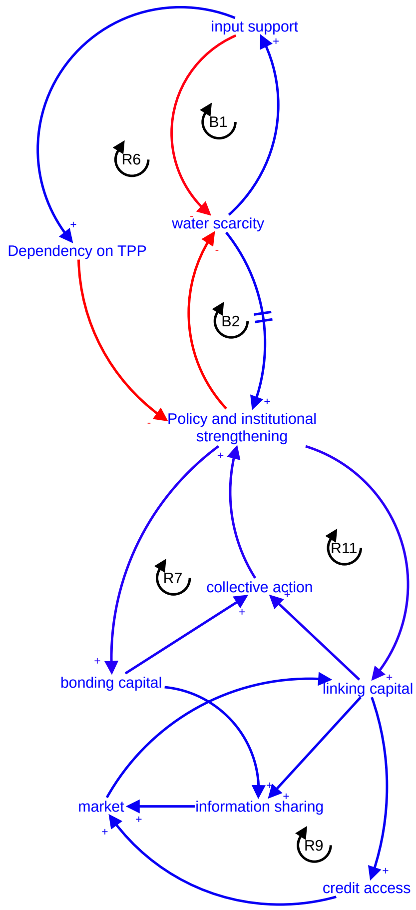


Figure 7 Shifting the Burden archetype identified in interview generated CLD-I. Loop B1 and B2 denotes temporary and fundamental solution to the water scarcity problem in Naitolia. Loop R6 denotes unintended consequences, while loop R7, R11, and R9 shows possible impact of promoting policy and institutional strengthening.

Given the lack of application of systems archetypes to study food security in agro-pastoralist systems, I have added this to the literature for Maasai agro-pastoralist systems, using multiple methods (content analysis and in-depth interviews) to create a holistic overview of the food system via Causal Loop Diagrams in a new case study, Naitolia, Northern Tanzania. There are three main types of land use in the Tanzanian agro-pastoral food system under study - agro-pastoralism, cropping and wildlife conservation. Exploring archetypes within the CLD allowed the interactions between agro-pastoralism, crop production, and wildlife to be demonstrated, along with the socio-political and environmental components within and interacting with food systems The multiple methods approach helped to provide diversity of information, empowerment, and attention to the context. My datasets provide a summary of the system structure and behavior for future research and development in Naitolia and Northern Tanzania.

Failure to understand the complexity (components, structure, behaviors, interactions) behind food security has led to a breakdown in understanding of cause-effect relationship and encouraged looking for a approaches that focus more on the symptoms at the abstract level and follow linear cause and effect sequences (Gohari, Mirchi, & Madani, 2017). As a result, food insecurity is persistent and the linear attempts to address it have led to many unintended consequences, such as migration and increased external dependency on programs such as TPP. By using two complementary datasets generated by content analysis and in-depth interview, I was able to map out the system components and interactions, to then explore involved parties, patterns visible through system archetypes, and implications for food security.

The datasets presented three system archetypes: Limits to Growth, Escalation, and Shifting the Burden. It is worth noting that the different datasets provided differences in narratives within the same archetype. For instance, the CLD-L shows tri-party Escalation between wildlife conservation, agro-pastoralism, and cropping, while CLD-I reflects Escalation between agro-pastoralism and cropping. Likewise, Shifting the Burden archetype in CLD-L reflects livestock domestication, reduced food availability, expansion of agricultural land, while CLD-I shows water scarcity and dependency of external support such as TPP. These differences show that food system is conceived slightly differently at different scales and different methods allowed us to recognize this. Therefore, another contribution of this paper is CLD developed through methodological pluralism which captures more holistic and textured analysis, that allows for complete understanding of the situation to redress the differences and limitations inherent in any single CLD development method. The content analysis literature more commonly studies food systems at the regional scale, where changes in policy at the state stimulate changes in the pattern and processes of food system, resulting in different narratives (for instance, livestock domestication and migration in Shifting the Burden in CLD-I). On the contrary, but not surprising given our case study framing, in-depth interview's conception of food systems is at the village level. Policy support for land expansion and settled livestock raising is occurring at the national level with the impact at the lower level. There is also a delay in the system, to see that at local level, and requires long term research and monitoring to link policy changes to food security. Perhaps, for the content analysis, they can see this cross-scale interaction even though they don't know nuances at local level. Therefore, combining both methods allowed us to see actions required across scale to address problems in a more complex way, addressing root causes across multiple scales.

Overall, the study showed that the long-history of Maasai culture and sustainable agro-pastoralism is not integrated in the current policy scenarios, and as the result, the system elements have constantly changed with changes in environment and socio-political changes. The changes may be irreversible, but our study was able to capture them through the elements of feedback and system archetypes. Building on the archetype analysis, I was able to identify some ways to address the root cause of food insecurity problems by addressing the feedback loops that are creating imbalance in the food system. Most of the leverage points lie require action by the state to recognize and support traditional food systems by emphasizing the contribution agro-pastoralism makes to ensuring food security in drylands. The state could acknowledge agro-pastoralists' right to the resources and allow them to continue with their own rules and collective choice processes without being undermined by the external government authorities. Agro-pastoralism not only reflect elements of food, but also the manifestation of Maasai cultural identity. In this context, a food systems' purpose should not be profit maximization, but rather improving food access in ways that are fair to the marginal groups.

Our findings also outline the need for institutional strengthening in the village and beyond at the regional/national scales, to which Ostrom (2009) refers as polycentricity. Polycentricity, a governance system with interacting bodies that formulate and enforce rules within specific policy area, is touted to be best ways to achieve sustainability in the face of disturbance and change (Aligica and Tarko 2012, Heikkila et al. 2018, Baldwin et al. 2018). Given our analysis identifies food insecurity challenges result from other underlying structures (drought caused by climate change, land degradation, changes in land tenure, and changes in social capital) I suggest that additional ongoing research is required to fully understand sustainability challenges in agro-pastoralist food systems in Naitolia and beyond. A key limitation was that COVID-19 prevented us from including agro-pastoralist perspectives, which need to be incorporated in future studies as their first-hand experience of reality and challenges is critical. Given the complexity of the agro-pastoralist food system it is imperative for researchers to conduct systems-based research in a transdisciplinary manner to understand and tackle issues surrounding food insecurity.

PAPER-II: USING STRUCTURAL EQUATION MODELLING TO IDENTIFY ADAPTIVE CAPACITY PATHWAYS TO DIFFERENT SHOCKS IN TANZANIA

2.1 Introduction

Climate change is expected to adversely affect sub-Saharan Africa though increased drought, reduction in crop yields, increased incidences of diseases and pests, and increased water stress which ultimately leads to food insecurity (Dasgupta and Robinson 2022). Evidence has also shown that the burden of climate change is much heavier for resource-poor communities residing in arid and semi-arid areas which are vulnerable to rainfall (Middleton 2018). The changing climate leads to stressed food systems that results in a vicious cycle of food insecurity and hunger as the compounded impact of decreased food production and resource deterioration reduces food access and increases in those mal- or under-nourished (Vermeulen et al. 2012). The welfare cost of climate shock is therefore often significant in arid and semi-arid regions and going to increase in severity, thus demanding increasing humanitarian and policy attention. Responding to these shocks is imperative to protect natural resource-based livelihoods and ensure food security.

The resultant impacts of climate shocks (events that outstrip the capacity to cope with such as drought, floods, heat waves, etc.) are therefore particularly important for countries like Tanzania, where the poverty rate is 25.7 percent and approximately 75 percent of labor force depends on agriculture and natural resources for their livelihood (World Bank 2022). Communities affected by climate change in Tanzania already face slow-onset and persistent stress such as drought, and extremities such as heat waves, gully erosion and flash floods (Achten et al. 2008) and many studies have highlighted such shocks will be even more severe in the future (Sawe et al. 2018, Said et al. 2019, Näschen et al. 2019). In recent years, Tanzania experienced a massive food insecurity crisis because of increased in temperature and erratic rainfall (Arndt et al. 2012, Kimaro et al. 2018).

A study found that the North-East of Tanzania is most impacted by climatic shocks that have led to food insecurity. Within the North-East regions, Longido and Monduli are currently the most severely impacted districts, with 30% and 25% of the population experiencing food insecurity, respectively (IPC 2022). Prolonged dry periods, anticipated to have started in October 2021, and irregular rainfall throughout the rainy season in 2021, have resulted in a below-average crop and the death of more than 62,000 animals (Gebre and Rahut 2021, IPC 2022). The failure of the harvest has increased the cost of foods like maize, rice, and beans, which has decreased household purchasing power. The Northern part of the country is also home to Maasai, an indigenous group, facing severe food insecurity. Likewise, resource poor households mostly relying on subsistence farming, wage income, remittance, and other natural resources particularly in regions of Manyara, Ruvuma, Arusha, tanga, Pwani and Dodoma are also considered highly vulnerable to food insecurity (Nkobou et al. 2021, Gebre and Rahut 2021, IPC 2022). Therefore, households in Tanzania are frequently responding to the climate shocks and food insecurity. A plethora of practices have been documented across Tanzania that are employed by people to reduce the effects of climate change and its compounded impacts (Eriksen et al. 2005, Osbahr et al. 2008). However, to undertake such practices in response to climate change and food insecurity requires identifying and strengthening adaptive capacity.

Adaptability, adaptation, and adaptive capacity are used concurrently in climate change literature. Adaptability is the capacity of a defined system (for instance, forest system, or agricultural system) to change whilst maintaining certain elements of system identity by adjusting its responses and institutions by learning, combining experiences, knowledge, and innovation to changing external and internal drivers and processes (Folke 2016). Adaptability is demonstrated through "adaptation" actions and "adaptive capacity" (Smit and Wandel 2006, Nelson et al. 2007). Adaptation is the ability to adjust or modify a pre-existing process (Nelson et al. 2007, Engle 2011) and requires adaptive capacity. Adaptive capacity is the precondition required to "enable people to anticipate and respond to change, to minimize the consequences, to recover, and take advantage of new opportunities" (Cinner et al. 2018, p. 118). However, decision makers and researchers struggle to identify and expand adaptive capacity that bolsters practices into potential actions, as adaptive capacity is context specific and understanding it requires rich and in-depth studies (Oberlack 2017). We can only understand the reactions to shocks by comprehending the already-existing adaptive capacity in Tanzania and how it is used to facilitate responses to climatic shocks. From such an understanding we can then unpack the mechanisms for improved delivery of interventions to foster adaptive capacity. Therefore, the goal of this dissertation chapter is to assess adaptive capacity among Tanzanian households to deal with climate stress, particularly with respect to ensuring food security.

To understand adaptive capacity in detail, I follow Eakin et al. (2014)'s notion of generic adaptive capacity. As noted by Lemos, Lo, Nelson, Eakin, & Bedran-Martins (2016), to achieve food security in the Global South, a combination of interventions that not only address the impact of particular shock but also structural deficits (such as education, employment, development etc.) that shape vulnerability to climate shock is required, which they term as "generic adaptive capacity".

Lemos et al. (2016) also argue that a lack of capacity to manage climate shocks has its foundation in structural underdevelopment as it influences the choices made to respond to the stressors. In affluent societies found in Global North, climate shocks and food insecurity may be buffered by the national development processes; however, in the Global South, especially in the under and least developed countries, national development interventions are less prioritized and thus do not provide such a buffer (Middleton, 2018; Middleton & Sternberg, 2013). As a result, managing climate shocks becomes a part of daily livelihood activities, but factors such as income, access to basic services, access to assets, education level, and household income are often conflated with climate responses, reflecting these structural shortcomings rather than the household's capacity for knowledge and innovation (Eakin et al. 2014). Such structural shortcomings can place households into poverty traps from which recovery becomes difficult (Adger 2006, Eakin et al. 2014, Lemos et al. 2016). Therefore, to build responses against a range of climate shocks, it becomes imperative to assess, strengthen and build such structural capacities at the household level (Nelson et al. 2007).

Most of the adaptive capacity and food security studies are focused on potential yield impacts from climate change while empirical evidence examining social and structural considerations has been less numerous, and mostly examined through place-based case studies (Cassidy and Barnes 2012, Brown and Sonwa 2015, Burchfield and Gilligan 2016). One of the limitations of such approaches is that they cannot capture the ways in which shocks and food security may cut across different sectors such as housing conditions and access to public services (Gershon and Ansah 2019). If adaptive capacities must be strengthened in vulnerable households in Tanzania, evidence based adaptive capacity pathways considering social and structural needs to identify and promoted. However, I am unaware of any large-scale studies employing household level empirical data to assess relationships between shocks, food insecurity using structural development factors in Tanzania that builds long term adaptive capacities to the range of climate shocks (Gershon and Ansah 2019). Therefore, this study uses household data collected across the nation that shows the inter-relationship between different generic adaptive capacities and the potential pathways to develop long-term responses to climate shocks and food insecurity. The key research questions the paper seeks to answer is as follows: (1) what generic adaptive capacities exists with to deal with food insecurity in the presence of climate shocks? (2) what are the intervention pathways for effective adaptation building efforts?

2.2 Methodology

2.2.1 Study Area

The United Republic of Tanzania is an East African country divided into 30 regions, with twenty-five on the mainland, three on Zanzibar Island and two on Pemba Island. Tanzania has a tropical climate that varies across regions influenced by regional heterogeneity. The seasonality is mostly associated with Inter-Tropical Convergence Zone (ITCZ), Western Indian Ocean, monsoon winds and tropical waves(Black 2005). As a result, Tanzania has two types of rainfall patterns: unimodal and bimodal, which is influenced by the movement of ITCZ southwards in October and reverses Northward in March-May. This movement makes Southern, Central and Western parts of the country to receive unimodal rainfall patterns from October to May. The northern highlands, and Victoria basin also receive two types of seasonal rainfall: the short rainfall season, with higher variability, from October to December *(Vuli),* and long rainfall season *(Masika)* from March to May (Luhunga et al. 2018). The total amount of rainfall in these two seasons generally ranges from 50 to 200 mm per month but significantly varies across regions.

Studies that have used General Circulation Models (GCMs), a type of climate model, have projected that rainfall over southern Tanzania is likely to be decreased, while northern highlands and Victoria basin is likely to be increased (Luhunga et al. 2018). It is projected that growing season temperature (January to June) in the early 21st century is likely to be higher than the late 20th century by approximately 0.2 to 1.11 degrees, as the concentration of greenhouse gases (GHG) increases (Ahmed et al. 2011). Climate trends in Tanzania show that the average temperature of the country will increase up to 2.2 degrees by the end of 21st century (Agrawala et al. 2003). This change in temperature and precipitation is assumed to have an impact on water resources, crop and livestock production (Ripkey et al. 2021). The higher temperature is likely to create wilting in plants, increase pest and disease infestations, reduce crop yields and thereby increasing the cost of crop production (Sawe et al. 2018). This increase in temperature is likely to break animal diseases and casualties (Ripkey et al. 2021). The projected changes in rainfall pattern is likely to create soil erosion, influence nutrient leaching, and create disease havocs that would correspond to lower crop yields and affect food security (IPCC et al. 2012).

To prepare for climate shocks, the Tanzanian government should focus on generic adaptive capacity. This study attempts to account for the key social, economic, and institutional determinants in terms increasing climate responses and food security among Tanzanian households. The study will be based on the secondary data focused on Tanzania collected by World Bank's household survey program National Panel Survey, Uniform Panel Dataset that covers Northern-coast, Lake Zone, Central Zone, Southern Zone, Eastern Zone, Dar es Salaam Zone and a separate zone for Zanzibar (The World Bank 2019). To undertake the analysis, I used national scale household data because more than 60 percent of the Tanzania's surface area is covered by arid and semi-arid zones, which are delineated into patches. Because each arid and semi-arid zones are different in terms of ecology, geography, and social structure, would have been excluded if study was conducted at a local or smaller scale. By undertaking a national level study, I am attempting to incorporate representative of entire arid and semi-arid zones. Arid and semi-arid zones are the most vulnerable areas in Tanzania because climate shocks have threatened food security due to their lower adaptive capacity.

2.2.2 The Data Set:

The National Panel Survey (NPS), a publicly available dataset, used in this study is collected by World Bank as a part of Living Standards Measurement Study (LSMS) (The World Bank 2019). The NPS dataset is a nationally representative household surveys that collected information on topics including non-farm income, agricultural production, consumption expenditure, housing conditions, wealth, poverty, and other socio-economic characteristics. The datasets have been explicitly combined, used, and validated through in multiple studies; likewise, the basis of FAO's resilience framework is based on the dataset (FAO 2016). The surveys have both individual, household, and community modules administered to the entire sample. At the individual level the questionnaire collects data on individual income and education. At the household level the questionnaire collects data on labor market, socio-demographic characteristics, assets and family wealth, and information on different types of shocks experienced by the household. The community level questionnaire involves community demographics and infrastructures, distances to health and educational infrastructure etc. Regarding food security, the database contains household information on consumed food, purchased food and received food, which can be easily converted into dietary diversity index, and food consumption expenditure as a proxy for food security (The World Bank 2019). This dataset was mainly chosen for study because it has been used several times in developing resilience-based research and developing methodological guidelines (D'Errico and Di Giuseppe 2016, World Food Program 2017, d'Errico et al. 2018). On the contrary, other government-based data are not available free of cost and have not been extensively used for resilience-based approaches as the NPS dataset.

2.2.3 Dataset cleaning

The dataset contained 40 modules, each containing different observations and variables collected in 2012/2013. Ideally, it is best to study adaptive capacity over time to address changing responses to repeated shocks, however, due to the data availability and time limitations, this analysis uses one-time point. The available data was prepped by cleaning that involved identifying, correcting, and removing inconsistent data for analysis purposes for the datasets from all four rounds. The dataset cleaning involved the following process: (1) checking structural errors- checking for mislabeled variables, faulty data types, non-unique household/individual identification numbers, and string inconsistencies; (2) checking for data irregularities- invalid values and outliers; (3) checking for missing values. The observations/rows with data irregularities, inconsistencies and missing values were dropped as algorithms will break if used with missing values. After dataset cleaning, relevant modules were merged based on the "inner join" method that only keeps observations and variables that match "unique identifier" provided in each 40 modules (The World Bank 2019). As some of the modules such as education and health used individual-person ID (UPI) as a unique identifier while other modules used household-ID (UPHI), a lot of data were lost during the merge process, unfortunately from areas with food insecurity, including Arusha, Dodoma, Kilimanjaro, and the Manyara region. As a result, there was an imbalance in the representation of observations in the dataset, with a significantly higher number of observations coming from places like Dar es Salaam and Mwanza. For some areas like Mara and Lindi the observations were below 100, which is not enough to undertake the analysis; therefore, the study was not controlled for region. Therefore, the study is a macro-level study without controlling for region undertaken at one-time point with fixed effect of climate shocks.

2.2.4 Statistical Analysis

Many studies have assessed adaptive capacity based on structural deficits with focus on food insecurity, successfully capturing of shocks and responses (Alinovi et al. 2010a, D'Errico and Di Giuseppe 2016, Tambo 2016, d'Errico et al. 2018). The quantitative approaches used in these studies to assess generic adaptive capacity are ex ante rather than actual results, which focuses on identifying proxy indices of household adaptive capacity based on observable variables (Alinovi et al. 2008, 2010b, Bahta et al. 2016, d'Errico et al. 2018, Mekuyie et al. 2018). Baseline information from secondary household surveys were quantitatively modelled as a latent variable or measured by using an observable variable as a proxy, for example Alinovi, D'Errico, Mane, & Romano (2010) and

Alinovi, Mane, & Romano, (2008) used cross-sectional household data from Kenya and Palestinian public perception survey. Alinovi et al. (2008, 2010) assessed adaptive capacity using social safety nets, public service accessibility, assets, income, and stability as the structural capacities, which mimics Eakin et al.'s (2014) concept of generic adaptive capacity. All dimensions (social safety nets, public service accessibility, assets, income and food access, stability, and specific "adaptive capacity") were expressed as latent variables through a two-stage factor analysis (Alinovi et al., 2010, 2008). Similar steps were followed by Bekele et al. (2022) to measure adaptive capacity to shocks that causes food insecurity in Ethiopia using a panel data at household level. The study used two-stage principal component analysis that included components like education, assets, and social networks (generic adaptive capacity). Other studies have used similar approaches (Carter et al. 2006, Mekuyie et al. 2018). FAO later refined the approach by integrating some other proxy variables for institutional environment (D'Errico and Di Giuseppe 2016, FAO 2016).

This study follows the proxy latent variable method as explained in the literature above, by Structural Equation Modeling (SEM). SEM combines factor analysis with the regression, termed as "measurement model" and "structural model" respectively. SEM uses measurement model/factor analysis to measure the latent variable through observed variable, whilst simultaneously conducting regression (structural model) to identify relationship between latent variables. SEM can also be used in non-normally distributed data like the NPS.

To explain the statistical analysis process, the hypothesized SEM model for this study is shown in, Figure 8 which will be tested and confirmed during data analysis. There are two components in SEM as shown in Figure 8, the measured component and the structure component. The square boxes denote the measured component, which are observed. The measured components are linked to latent constructs which are shown in oval boxes. The latent constructs are not measured but translate the measured variables through linear equations. The coefficients linking the latent and measured variables are called loadings. The structural component of the model links multiple latent variables.

Therefore, analysis will be conducted in two steps: (1) Constructing indices of observed variables through principal component analysis (PCA) and weighted averages. There are more than 50 variables in the dataset that can affect adaptive capacity, and PCA detects the correlation between multiple variables and projects it onto a single index if correlation is high, whist retaining most information from these variables. (2) Running a SEM model on variables and indices identified in step 1 to analyze structural relationship with the dependent variables. There are three dependent variables in the Figure 8: adaptive capacity (also a latent variable), Dietary Diversity and Food consumption. Shocks are considered as a control variable in the analysis. In all analyses, p-value <0.05 is considered as a cut off point for statistical significance. The analysis was conducted in R statistical software.

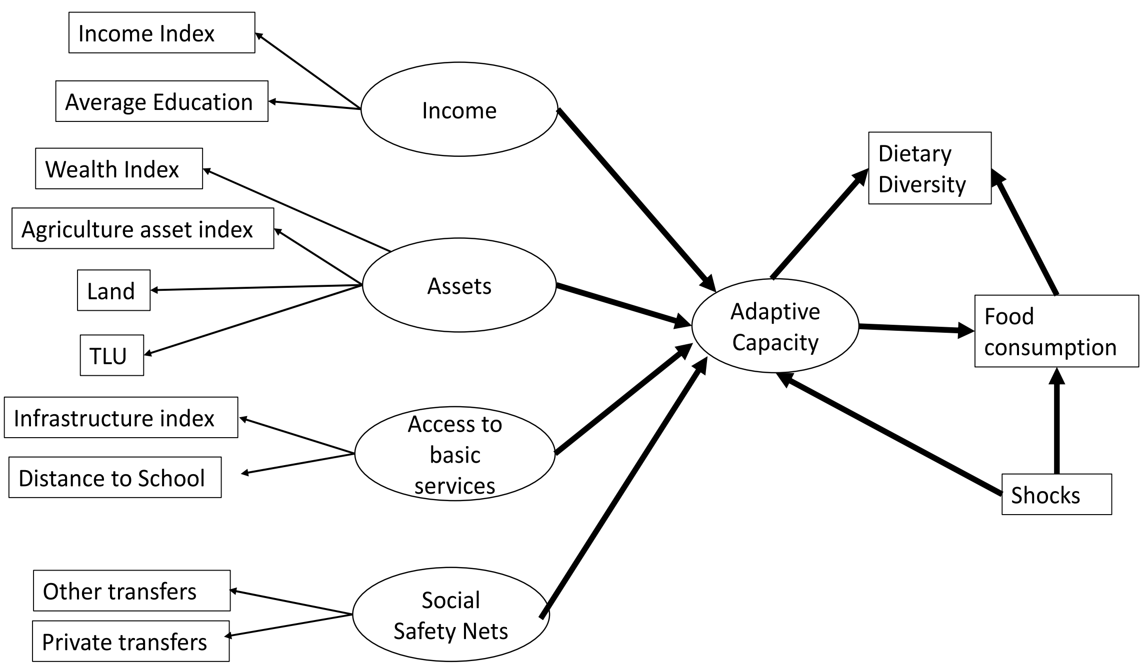


Figure 8 Hypothesized SEM Path diagram showing relationship between adaptive capacity dimensions, latent variables, shocks, and food security based on (Alinovi et al. 2010b, d'Errico et al. 2018).

2.4.1.1 Identifying and summarizing observed variables

Food security indicators

Household Dietary Diversity Score (HDDS): HDDS can be defined as the variety of different food groups eaten by a household at a given time (Verger et al. 2019). A modified HDDS was calculated for each household by counting the number of twelve food groups consumed and is proposed as an indicator of the access dimension of food security. A guideline for calculating HDDS is based on household consumption of different food groups over the previous 24 hours (Verger et al. 2019). However, due to lack of 24 hours recall data on the NPS dataset, this modified HDDS was calculated by summing the number of unique food groups consumed during last 7 days. In the past many studies based on secondary data have also resorted to 7 days recall period due to lack of 24 hours recall data (Englberger et al. 2004, Zezza and Tasciotti 2010, Jones et al. 2014, Verger et al. 2019). The food groups include cereals, fruits, vegetables, meat, eggs, fish and seafood, roots and tubers, pulses and nuts, dairy and dairy products, sugar, oil and fats, and condiments. The modified HDDS is a continuous score from 0 to 12, with each food group weighted evenly with a score of 1.

Food consumption per household: Expressed in monetary value (US dollars), the NPS contains monthly household food consumption based on expenditure on food as well as the monetary value of self-produced food, food gifts, and stored food. The food consumption per household further represents household access to food (Pangaribowo et al. 2013, d'Errico et al. 2018).

Infrastructure index

Following d'Errico et al. (2018), I constructed an infrastructure index as a composite index using PCA. The index combines six dummies, each of which equals to one having a home, concrete cement roof, brick walls, toilets, running water and electricity. Higher value of index indicates better dwelling conditions. Higher infrastructure provides better adaptive capacity to risks and shocks (Burnham and Ma 2017).

Distance to school

Distance to school is calculated in kilometers and it represents access to social services (Alinovi et al. 2008, 2010b). Lower distance to school represents better access to social services.

Agriculture Asset Index

The agriculture asset index is a composite index constructed using PCA (Alinovi et al. 2010a, d'Errico et al. 2018, Gershon and Ansah 2019). The index is created through combining dummies, each of which equals to one owning a coffee pulping machine, fertilizer distributor, hand milling machine, harrow, harvesting and threshing machine, hoes, milking machine, plough, power tiller, reapers, and spraying machine. Higher value of index indicates higher productive asset.

Wealth Index

The wealth index is a composite index constructed using PCA (Alinovi et al. 2010a, d'Errico et al. 2018, Gershon and Ansah 2019). The index is created through combining dummies, each of which equals to one having an animal drawn cart, beds, bicycle, boat/canoe, books (not schoolbooks), carts, chairs, music system, computer, cooking pots (cups and other kitchen utensils), cupboards (chest, boxes, wardrobes, bookcases), dish antenna, electric gas stove, air-conditioner, mosquito net, motor vehicles, motorcycle, other stoves, outboard engine, radio and radio cassette, sewing machine, sofas, tables, telephone (landline), telephone (mobile), television, and tractor. Higher value of index indicates higher wealth.

Livestock

Livestock numbers were standardized based on tropical livestock unit (TLU). TLU represents weighted sum of domestic animals owned. To get the TLU, the conversion factors were: 1-camel, 0.50-donkeys, 0.60 for cattle, 0.1-goat/sheep, 0.01-poultry (Rothman-Ostrow et al. 2020).

Land owned

Total hectares of land owned per household (d'Errico et al. 2018).

Income Index

PCA constructed index with dummies for income from wages, farming, fishing and livestock, and business. Higher value of index indicates higher wealth.

Average education

Average education among household members (adult and child) based on average years of education. Higher value indicates higher level of education.

Transfers

The monetary value of assistance received in terms of cash, food or in-kind support converted into US dollars from private sources (Alinovi et al. 2008, d'Errico et al. 2018). The monetary value of assistance received in terms of cash, credit, pensions, food, or in-kind support converted into US dollars from government or other non-governmental organizations. This amount is different from income that is received as a salary, wages, and business income.

Climate-related shocks

The sum of total number of climate shocks the household faced in the two years. The climate shocks accounted for the study are disease crop and pests, drought or floods, fire, failure of agricultural business, price drop for agricultural products, livestock died or stolen, loss of land, and severe water shortage.

2.2.5 Structural Equation Modeling

I applied maximum likelihood-structural equation modeling approach to estimate the interrelationships among these observed variables, latent constructs, and their effect on dependent variables (Schumacker, R. E., & Lomax 2004). SEM is a widely used approach to quantify complicated relationships among multiple factors (Hair 2009). SEM is also well-suited to exploratory research for studies with non-normally distributed data (Schumacker, R. E., & Lomax 2004).

The model is identified through "block recursive" models (Schumacker, R. E., & Lomax 2004). The maximum likelihood estimation is used to solve this SEM. I carried out the estimation in two procedures: estimation and validation of the measurement model associated with the latent variable and the structural model. I assessed the reliability of the estimates and the validity of both measurement models and SEM test using robust goodness of fit measures, particularly SRMR (Standardized root mean squared residual), and root mean square error of approximation (RMSEA), supplemented by Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) (Hu and Bentler 1998). Finally, I interpreted path coefficients that explain the direct, indirect, and total effects of predictors on food security indicators.

I determined the total effects of the structural equation model, which are the sum of the direct and indirect effects, using the structural model's inter-correlated links. The identification of indirect effects, according to Schumacher and Lomax (2004), can assist in determining whether secondary effects increase or moderate structural connections between variables. As a result, examining the total, direct, and indirect impacts of variables might help us gain a better understanding of the interrelationships between variables.

2.3 Results

2.3.1 Observed variables

The results of PCA analysis of observed variables are given in the Appendix in Appendix F: Result of Principle Component Analysis Table 9, which shows that wealth, infrastructures, income diversification, assets and access to public services are the generic adaptive capacities present in Tanzania that builds the ability of households to cope and respond to the wide range of shocks and stressors. The infrastructure index is produced by two underlying components which jointly explained 51 percent of the total variance, where the first and second component explained 0.29 and 0.22 percent variance significantly. Likewise, three components explained wealth index, which jointly explained 31 percent of the total variance. In case of agriculture asset index, three components explained 51 percent of the total variance, where each component explained 32.4, 10.5 and 10.2 percent of the variance respectively. Similarly, three components in income index explained 65.7 percent of the total variance between the three components. The summary statistics for different variables are given below.

Table 3 Summary statistics of different adaptive capacity dimensions used in the study.

Variable	**Notes**	**Mean**	**Standard Deviation**	**Min**	**Max**
Household Dietary Diversity Score	Continuous score from 0 to 12	7.3	2.76	0	14
Food Consumption Expenditure Per Household	In US dollars	10471	11868.14	0	155340
Infrastructure index	Obtained through PCA	0.0518	0.427	-0.5426	1.2029
Distance to School	In Kilometers	4.50	2.60	0.00	9.00
Agriculture Asset Index	Obtained through PCA	-5.515e-05	0.030	1.066e-01	1.096e-01
Wealth Index	Obtained through PCA	0.006483	0.313	-0.44	1.31
Livestock	Converted to TLU	3.18	10.35	0.00	498
Land owned	Hectares	1.433	1.60	0.00	12
Income Index	Obtained through PCA	0.009	1.041	-1.40	1.11
Average Education	Continuous	7.00	2.60	0.00	14
Private transfers	In US dollars	0.004	0.911	0.00	34.00
Other transfers	In US dollars	0.992	1.02	0.00	28.00
Shocks	Continuous variable	0.14	1.00	0.00	4.34

2.3.2 Path diagram for adaptive capacity using SEM

The pathway model constructed through structural equation model depicts the relationship between different observed variables and dependent variables. The study used 5000 observations in the SEM model, which was constructed in R using lavaan package. The chi-square was significant at 0.05. The root mean square error of approximation (RMSEA) was 0.076; values closer to 0 represent a good fit. The standardized root mean square residual (SRMS) was 0.058, SRMS less than 0.80 is considered a good fit. Likewise, Comparative Fit Index (CFI) should be greater than 0.90 for a good fit. CFI for our model is 0.90. Figure 9 shows path diagrams with standard path coefficients.

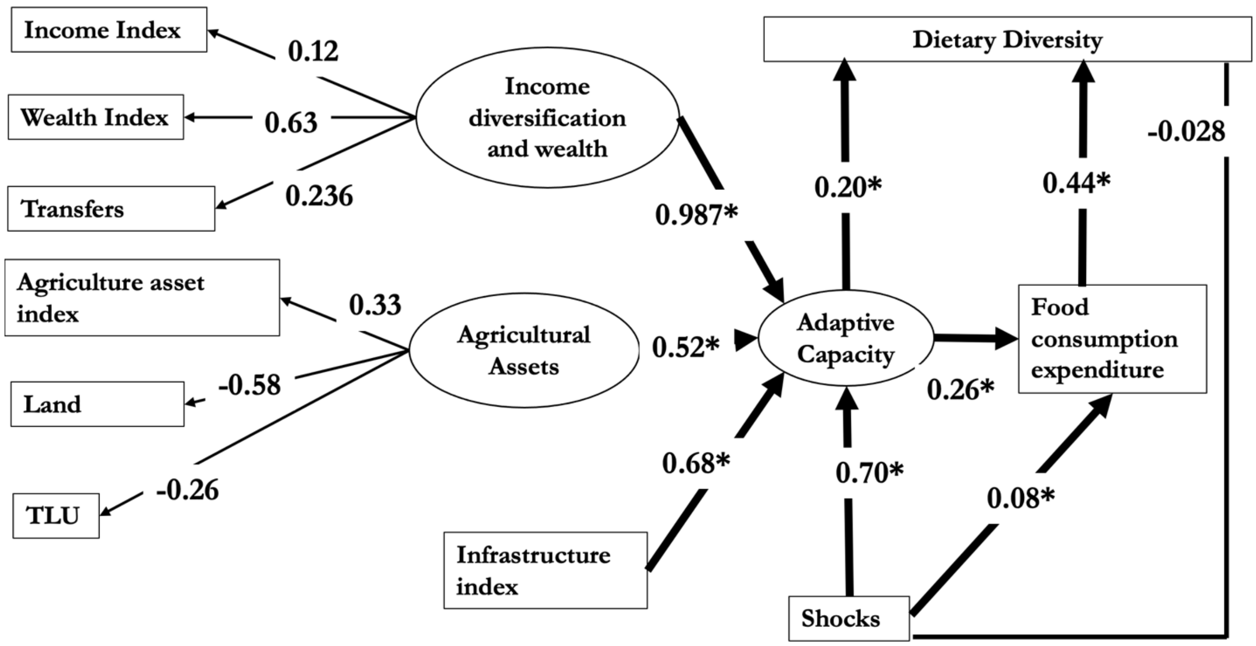


Figure 9 Path diagram of direct and indirect effect of adaptive capacity dimensions on dietary diversity and food security.

The left side of Figure 9 shows the relationships between the measured variables (income index, …. TLU) and the latent variables (income and wealth diversification, agricultural assets, access to basic services) and represents the measurement model. The numbers in the measurement model represents the standardized coefficients or the factor loads on latent variable, which indicates the magnitude of relationship between the measured variables and the latent factors. The standardized coefficients range from 0.12 to 0.63 indicating that the magnitude of the relationship between the measured variable and latent factors are not adequate based on the dataset. The income index is particularly low (0.12). Income diversification and wealth are explained by income index (0.12), wealth index (0.63) and transfers (0.236). Likewise, agricultural assets are explained by agricultural asset index (0.33), land (-0.58) and TLU (-0.26). The variables, distance to school and average education, hypothesized in Figure 8 did not contribute to any of the factors. Even though popular literature (Liu 2019, Yang and Bansak 2020) supports stronger correlation of education and distance to school with income, wealth and infrastructures, the data did not show the correlation between these factors. Literature have touted the role of education and education infrastructure in terms of reducing vulnerability to shock, enhancing adaptive capacity, and accelerating socio-political changes (Feinstein and Mach 2019).

The right side of Figure 9 shows the relationship between independent (Income diversification and wealth, Agricultural assets, Infrastructure index) variables and dependent variables (Adaptive capacity, Dietary Diversity, and Food consumption Expenditure). The values represent standardized regression coefficients that represents the strength of the relationship between the dependent and independent variables. Since the values are standardized, it is interpreted as the amount change in the dependent variable given a unit standard deviation change in the independent variable. These are further explained below.

2.3.3 Relationship between latent variables: adaptive capacity, income diversification and wealth, agricultural assets, and infrastructure index

I found a significant positive relationship between income diversification and wealth with adaptive capacity. The standardized coefficient of 0.987 indicates that with one standard deviation change in income and wealth, the adaptive capacity index increases by 0.987. The income diversification provides insurance against failure in one activity by reducing in average production cost from an increase in range of activities undertaken (Wuepper et al. 2018). Greater financial access reflects a better ability to offset the possible negative impacts of climatic variability and to recover from material loss (Chepkoech et al. 2020). Moreover, different employment delivers more opportunities to minimize risk if shocks affect a particular type of occupation (Chepkoech et al. 2020). Likewise, rich households can mobilize their wealth to enhance their adaptive capacity in the time of shock (Burnham and Ma 2017). Complementary incomes such as transfers from social safety nets from the government and remittances also led to diversification of economic activities that leads to better protection from shocks (Macours et al. 2012).

Similarly, there is a positive relationship between agricultural assets and adaptive capacity. One standard deviation change in agricultural asset increases adaptive capacity by 0.58. Agricultural asset is important to Tanzanian household because agriculture contributes to nearly 30 percent of country's gross domestic product and provides livelihood to more than 75 percent of its population (World Bank, 2022). Land and agricultural assets are productive- assets in Tanzania as focusing on agriculture means achieving economic growth. Greater financial resources enable farmers to typically employ a sufficient labor force on their fields. Ample agricultural labor resources enable farmers to carry out farm tasks on schedule and test out novel technology, both of which necessitate a labor investment. Owning a land also means having tenure which is shaped by institutions and socioeconomic processes (Antwi-Agyei et al. 2018). Land ownership can act as a collateral to access resources that can be used to implement adaptation practices against climate shocks (Antwi-Agyei et al. 2015). Likewise, livestock plays an important role in Tanzanian household as majority of the country's surface area lies in semi-arid zone, where agropastoral is the major food system. The arid and semi-arid areas are mostly inhabited by the Maasai household who support themselves by subsistence agriculture and animal husbandry. Livestock is the major source of income, while also providing saving, insurance during climate shocks and maintaining stronger social capital.

There is also a positive relationship (0.68) between adaptive capacity and infrastructure index. Infrastructure index emphasizes the role of access to different social services and infrastructures. Poor developed physical infrastructures and social services, for instance water resources, have shown to trigger violent conflicts due to competition and limited resources (Birhanu et al. 2017). Infrastructure improves human capital, which in turn improves adaptive capacity. According to (Ambelu et al. 2017) availability of infrastructure also enhances economic opportunities.

2.3.4 Relationship between adaptive capacity and dietary diversity, food consumption, and shocks.

I found a significant positive relationship between adaptive capacity index and dietary diversity. The value 0.20 indicates that with one standard deviation change in adaptive capacity index, dietary diversity increases by 0.20 units. There is also an indirect effect (Table 4) of adaptive capacity to dietary diversity (calculated through multiplying coefficients of adaptive capacity > food consumption expenditure>dietary diversity, i.e., 0.26*0.44 in Figure 9) and the total effect of adaptive capacity on dietary diversity is 0.314. Likewise, I found a significant positive relationship between shocks and adaptive capacity index. The value 0.70 indicates that with one standard deviation change in shocks, adaptive capacity index is activated by 0.70 units. This means that as the effect of shocks grows, so are income and wealth, infrastructure, and agricultural assets used that contribute to adaptive capacity. There is low and non-significant negative relationship (-0.028) between shocks and dietary diversity, with a total effect of 0.112. Since, the total effect of adaptive capacity is more than shock in dietary diversity, this indicates that in the presence of shocks, adaptive capacity helps to balance dietary diversity.

This finding is in line with Murendo et al. (2020)'s research from Malawi, where they found adaptive capacity positively associated with household dietary diversity in the presence of shocks.

Their results suggest that adaptive capacity has the potential to balance food consumption during period of higher shocks through income, wealth, and access to infrastructures. It can be assumed that promoting activities that enhances adaptive capacity such as financial access, promotion of additional sources of income and livestock management is essential to deal with different types of food consumption in the time of shock.

Likewise, a positive relationship between food consumption expenditure and adaptive capacity is found. The value of 0.26 indicates that with one standard deviation change in food consumption expenditure, adaptive capacity increases by 0.26. The findings are in line with a study conducted in China that found that farmers with higher storage infrastructure stored crops when the food prices were low and used the storage grains when the prices were high, thereby indicating that when food consumption expenditure increases, household's adaptive capacity increases (Rasaily et al. 2010). Similarly, a positive relationship between shocks and food consumption expenditure is found (0.08), however, the total effect of both adaptive capacity index and shocks on food consumption expenditure is found the same, 0.26.

Table 4 Direct, indirect, and total effects of key predictors on food security.

Variable Relationship	**Direct effect**	**Indirect Effect**	**Total Effect**
Shock-> Dietary Diversity	-0.028	0.14	0.112
Shock -> Household Food Expenditure	0.08*	0.18	0.26
Shock-> Adaptive Capacity	0.70*	0	0.70
Adaptive Capacity ->Dietary Diversity	0.20*	0.1144	0.314
Adaptive Capacity -> Household Food Expenditure	0.26*	0	0.26
Income diversification and wealth-> Dietary Diversity	0	0.19	0.19
Income diversification and wealth-> Household Food Expenditure	0	0.25	0.25
Agricultural Assets -> Dietary Diversity	0	0.10	0.10
Agricultural Assets-> Household Food Expenditure	0	0.13	0.13
Infrastructure Index -> Dietary Diversity	0	0.13	0.13
Infrastructure Index -> Household Food Expenditure	0	0.17	0.17

*Note: * indicates value significance at 5%*

2.4. Discussion and Conclusion

The path model developed through the SEM is shown in Figure 9, which illustrates the relationship between multiple adaptive capacity variables and their relationship with food security measured in terms of dietary diversity and household consumption expenditure. Income diversification and wealth, agricultural assets, infrastructure index, adaptive capacity, dietary diversity, and food consumption expenditure showed significant (<0.05) relationship to each other. However, the relationship between shocks and dietary diversity was not significant. Accordingly, adaptive capacity index is the basis for dealing with shocks that affects food insecurity in Tanzania. Within the adaptive capacity, the path analysis showed that income diversification and wealth had stronger effect than infrastructure index and agricultural asset. Even within the income diversification and wealth latent variable, wealth had the stronger factor loading. This indicates that poverty alleviation programs should be promoted because in absence of wealth, a resource-poor household is likely to spend majority of their income on food, leaving them vulnerable to price volatility and shocks.

In addition, improvement of infrastructures such as housing, transportation, schools, storage facilities etc. could improve adaptive capacities in Tanzania. According to Ambelu et al. (2017), infrastructures are related to peace and prosperity to improve the living and economic condition of the people. For example, lack of water infrastructures is the major source of conflict in many places in the world, and conflict affects everything including food security (Ambelu et al. 2017). Infrastructure, such as storage facilities, are a key buffering strategy in agricultural development that allows for delayed consumption of the food. As production and storage capabilities increase above subsistence needs, the surplus accumulation may direct towards market-oriented farming and progressive decoupling between agricultural dependency and shocks (Angourakis et al. 2015, Balbo et al. 2016).

The paper helps assess the relationship among multiple adaptive capacity variables. The variables are first identified from the earlier studies and then revised to specify possible intervention pathways. However, it is not able to include important factors such as crop and livestock production due to the lack of production data in the dataset. Likewise, there may be some statistical and data cleaning errors because of which few structural and development related variables such as distance to school and education did not load into the factors, therefore Figure 8 (hypothesized) did not match with Figure 9. Perhaps, in the future attempts should be made to conduct exploratory factor analysis with much broader variables and compatible datasets to provide more holistic analysis of adaptive capacity. Additionally, according to the analyzed dataset, major shocks in Tanzania are related to climate change such as drought, floods, lack of sufficient water, fire, disease and pest, loss of livestock and market prices. Even though the path analysis showed that current adaptive capacities can balance these shocks at national level, there may be other shocks such as human-wildlife conflicts which are not included in our analysis, and which should be included in future analyses. Likewise, some factors like "migration" can be both a shock and adaptive capacity, which needs to be included in the model.

The use of macro data meant I was able to quantitatively assess several theoretical hypotheses and paths using structural equation modeling. For instance, I was able to examine the contributions that land, livestock, assets, and income make to the capacity to adapt to climate shocks in Tanzania that has been highlighted by significant theoretical works on the subject (Devereux 2001, Adger 2003, Agrawal 2008, D'Errico and Di Giuseppe 2016, FAO 2016). This predictive analysis on food security, grounded in theory, can then inform policy to support Tanzania's development of adaptive capacity to climate-related shocks. I was able to demonstrate the fundamental factors that contribute to adaptive capacity in Tanzania through path analysis and PCA. This study can be used by Tanzanian policymakers to formulate tailored policies that focus on the main contributors to adaptive capacity.

The adaptive capacity path analysis has indicated that adaptive capacity is multi-dimensional and complex with varying degrees of interactions and relationships. Adaptive capacity is not one variable or one relationship within the entire path diagram; in fact, the entire path analysis constituting interaction between observed variables, latent constructs, and dependent variables composes adaptive capacity. The path analysis has shown various sequences that lead to underlying observed variables, outcomes in the form of latent constructs and impacts in terms of food security. Therefore, promoting poverty alleviation and asset building programs, income diversification, livestock production, promoting tenure arrangements, and investing on infrastructure building reduces the risk of shocks on household food insecurity. Thus, generic adaptive capacity building should focus on variables and constructs that portray stronger effect on adaptive capacity and food security.

The paper also connects with the broader dissertation goal of identifying leverage points for influencing system behavior to food secure future. Following Meadows (1999) and Abson et al.

(2017)'s notion of leverage points, income and wealth, infrastructure, and agricultural assets are the important leverage points and should be invested in. All the three components (income and wealth, infrastructure, and agricultural assets) are critical for supporting generic adaptive capacity and thus attaining food security in the presence of shocks, evident through their total effect on dietary diversity and household food consumption expenditure. However, such interventions may not be easy in the current paradigm, characterized by low income and wealth due to structural deficits, and may require transcending the current paradigm. However, as we learned in Paper-I, to do so can be aided by understanding the causal pathways within the system and routinely evaluating the effects of these intervention points to make sure the causal relationship has not changed over the time.

PAPER-III: A SYSTEM DYNAMICS SIMULATION MODEL FOR AGRO-PASTORALIST FOOD SYSTEMS: A CASE STUDY FROM NAITOLIA VILLAGE IN THE NORTHERN TANZANIA

3.1 Introduction

By 2030, it is anticipated that up to 70 percent of people living in drylands (nomadic, transhumant, and smallholder agro-pastoralists) (The World Bank 2018, Stavi et al. 2021) may have to deal with increasing food insecurity as multiple shocks coupled with land degradation and land tenure changes, results in lower crop and livestock yields (Schmidt and Pearson 2016, Kabote et al. 2017, Zampaligré and Fuchs 2019). By 2050, it's expected that dryland agricultural production would drop by 10–20%, which will result in a rise in food demand due to the ensuing population growth (IPCC et al. 2012). Dryland inhabitants, already in the risk of food insecurity, are likely to be further marginalized due to limited access to technology, weak institutions, and exclusion from both development processes and political discourses (Middleton and Sternberg 2013, Middleton 2018). Therefore, dealing with food insecurity in drylands, particularly in sub-Saharan countries, and predicting the effect of a management decisions is challenging because of complexities arising from varied and interacting components such as precipitation patterns, socio-political factors, and values of diverse stakeholders (Stavi et al. 2021). Hence, tools that allow us to simulate the complex behavior are needed to provide the ability to make predictions to increase food security and reduce unintended consequences.

Livestock is a major part of dryland food systems, commonly integrated with cereal and legume crops within agro-pastoralism (Frelat et al. 2016, van Wijk et al. 2019). Dryland agro-pastoral food systems are social-ecological systems (SES) – integrated systems where humans are part of nature (Berkes et al. 1998). Our inability to develop solutions to food insecurity challenges is grounded in the lack of understanding about dynamic interactions between multiple components within the social-ecological systems. In SES, identifying feedbacks is a key requirement for resilience because the interactions between different variables influence the capacity to adapt and transform in the face of change. However, less attention is given to feedback mechanisms because there are financial and technical constraints to their monitoring (Biggs et al. 2015). Many scholars have highlighted the need for a holistic view that includes feedbacks and dynamic interdependencies between social and ecological components, for better future anticipation and decision making in the food systems such as agro-pastoralism (Ericksen 2008, Thornton et al. 2011). According to Tendall et al. (2015), to address food insecurity, our management should anticipate and be informed by food system dynamics. Being able to reflect on the combined effect of social-ecological components in dynamic food systems also reduces possibilities of unintended consequences and side-effects of management interventions.

System Dynamics Modeling (SDM) has emerged as an innovative method that enables a holistic analysis of complex social-ecological systems, including food systems. Many recent studies have utilized SDM to understand the complexity of food insecurity and simulate models for future interventions in agricultural, energy, and water systems (Kopainsky and Nicholson 2015, Paterson Guma et al. 2016, Kotir et al. 2016, Kopainsky et al. 2017, Song et al. 2021, Vildan Serin and Çelik 2022). The application of SDM has led to an improved understanding of system dynamics and resulting behavior.

However, most food system SDMs are focused on food security in arable systems rather than agro-pastoralist food systems, and rarely a total perspective on food security. For example, there are SDMs examining dryland food security, but they are mostly focused on food production, availability, and access (Turner et al. 2016). While there are SDMs in pastoralism on pasture and livestock production, and disease infestations, food system articles are almost absent that integrate livestock with crop production (Oniki et al. 2018, Odoemena et al. 2020, Queenan et al. 2020). Even within these articles, the focus is on livestock production, whereby livestock consumption and sufficiency are rarely included and quantified. As a result, the knowledge is limited and understanding long-term behavior of dryland food systems is also incomplete. Therefore, a holistic view of the dryland food system is missing, as is an understanding of feedback mechanisms and system dynamics in agro-pastoralism, which includes both crop components and livestock components. This article offers such a system dynamics model to explore sustainable management of dryland agropastoralism food systems and food security.

3.2 Agro-pastoral Food System Model (AP-FSM)

Many seminal articles have highlighted the need for integrated approaches that combine socio-political and biophysical process in a coupled manner for accessing and managing for future food security outcomes (Stephens et al. 2012, Turner et al. 2016, Rojas-Downing et al. 2017). The articles have also highlighted the need to generate predictions of a range of possible outcomes with associated probabilities to explore the risk and potential impacts of extreme events over longer time horizons. Therefore, the recognition of interactions and dynamic feedback between multiple socio-political and bio-physical components, along with simulation over a long period of time, are fundamental to the development of the Agro-Pastoralist Food Systems Model (AP-FSM) described in this article. The goal of this paper is to evaluate multiple management scenarios that I derived from the recommendations from past studies to support decision making in attaining food security in dryland agro-pastoral food systems. We are particularly interested in knowing which management scenarios would yield the highest outcomes in terms of food sufficiency, food consumption and food availability because these variables are proxy for food security, which is one of the outcomes of food systems.

3.3 Study context and scope

The study employed a case study approach as it provides a boundary of time and space within which dynamic patterns, structural relationships between feedback loops, levels and rates of primary variables can be observed. Model building is an iterative process and requires evaluation in every step to acquire confidence. Case studies can provide longitudinal understanding of system variables to quantify and evaluate the model variables at every steps. Therefore, we sought a dryland agro-pastoralist case study to provide longitudinal data to develop basic models and conduct basic validation test, which are described later in the paper.

We selected Naitolia, an arid/semi-arid village in Moduli district in Northern Tanzania with the history of food insecurity. Approximately 97% of people in Monduli district are Maasai that largely depend on agro-pastoralism, where over 95% of the cattle kept in the district are indigenous zebu-type (Kimaro et al. 2017) . Human-wildlife conflict, disease and pest infestation, lack of infrastructure such as grain storage facility and lack of employment opportunities are the common factors affecting food insecurity in Naitolia (Fair 2022). Access to water for drinking, livestock and crop production is a major issue in Naitolia.

In the last two decades, the whole northern part of the country, including Arusha region, suffered from low arable yields and lower livestock production, followed by food crises and water scarcity (Verhoeve et al. 2021). A drought occurred across the Horn of Africa in 2010/2011, also impacting people in Monduli district where food and water shortages were prominent. Therefore, there are food insecurity events in recent history to explore in Naitolia and the anticipation of their increasing in the future. The productivity of grazing land for agro-pastoralism depends on rainfall, and herd mobility is the major strategy to overcome pasture and water shortages among Maasai. However, Naitolia is on the edge of a wildlife management area, which limits mobility. Wildlife often passes through and raid and trample crops, resulting in human-wildlife conflicts. Agro-pastoralists are experiencing shrinking pastoral land, forcing them to look for alternative livelihood opportunities. Consequently, decreased livestock production due to diminished pastoral production and crop yields is prevalent, with increased human-wild life conflicts. Households lose an average 10 livestock annually due to dehydration and 11 livestock due to livestock depredation (Fair 2022).

For under-represented agro-pastoralism systems such as in Naitolia, the scarcity of data creates challenges in developing a household or community level model. As a result, most of the modeling efforts are either at larger regional or national scales (Oyo and Kalema 2016, Paterson Guma et al. 2016, Kotir et al. 2016). However, as a unit of land management, the village scale is critical for understanding food systems and behavior over time under different strategies. We use Naitolia to explore this interacting land, and management dynamics with the assumption that there will be lessons for other dryland agro-pastoralist villages. Given the availability of basic data such as population, and land use and land cover, the data sets from the national and regional level can be summarized and calculated in the efficient and cost-effective manner.

3.4 Methods

Agro-pastoralist food systems, as complex adaptive systems are difficult to comprehend as they are non-linear and cannot be explained using traditional linear methods. A useful method for understanding the dynamics of the cross-scale interactions, feedbacks and interdependences between the social sub-system and ecological sub-system are SDMs. SDM create an understanding of feedback and interdependencies and are grounded in the theory of non-linear dynamics and feedback mechanisms (Ford 2000). SDM assumes that time delays, systems feedback, processes, and nonlinearities can be more significant in determining the aggregate systems behavior than individual components alone (Meadows 2008). They are based on the structure of an adaptive complex system (i.e., agro-pastoralist SES, for instance) and the pattern of behavior it generates over the time (Cavana and Ford 2004, Maani and Cavana 2007, Badham 2010).

SDM have been used in variety of fields including agricultural systems, water resource management and food systems to build tools for supporting management decisions that are simpler than large scale physically based global climate models but retain the behavior of those original models (Cumming and Collier 2005, Kelly et al. 2013, Kopainsky et al. 2017, Ding et al. 2018, Li et al. 2022). SDM have been used for analyzing complex processes with multiple actors and the feedbacks among their behavior (Kopainsky et al. 2017). The technique is designed to visualize non-linear complex systems through a framework that utilizes stocks, flows, and feedbacks to understand how those influences interact with different stimuli (Ford 2000, Van den Belt 2004). The stimuli can arise from the interaction of internal system structure to the external factors, and SDM tries to predict changes dynamically.

In the past decade, there have been an increasing number of system dynamics models of food systems in African drylands. For instance, Oyo and Kalema (2016) used SDM to investigate the enabling factors that determined successful responses to shocks and stresses for obtaining sustainable food security in sub-Saharan Africa. Likewise, Kopainsky et al. (2012) used SDM to evaluate the effectiveness of social trust and reciprocity in adoption of improved crop varieties among small holder farmers. Paterson Guma et al. (2016) used SDM to evaluate policies and interventions strategies for better livelihood and food security at household level. However, as mentioned above, food system SDM is both scarce in agro-pastoralism and absent in Naitolia, a gap filled by this paper.

3.4.1 Causal Loop Diagram Development

A system dynamics model starts with development of a conceptual model, which is called a Causal Loop Diagram (CLD), which is then converted into a stock and flow diagrams (Kotir et al. 2016). CLDs are analytical tools for representing relationship between different system components that produce dynamic structures. The CLD for AP-FSM is shown in Figure 10, developed with stakeholders using a participatory modelling approach (Voinov et al. 2018). Engaging with the stakeholders took place in three phases.

In Phase 1, transect walks, participatory resource mapping, stakeholder mapping, and institutional analyses were conducted from August-October 2021, all with the same group of male and female community leaders from Naitolia. The goal of transect walk with the community was to get familiar with the case study and triangulate information available in the literature. Participatory resource mapping exercise (as per (Hodbod et al. 2019)) helped in outlining the system boundaries by marking key land use types, resources, and infrastructure. This exercise was also able to show community's perceptions of changes in ecosystem services. To supplement the ecosystem knowledge, we mapped out social systems within Naitolia with institutional and stakeholder mapping exercises. Building on both the natural resource and stakeholder mapping, community elders identified key resources or ecosystem services they rely on and explained how these have changed over the last 30 years, also outlining which shocks (both positive and negative) led to what impacts for which types of households through the behavior over time graphs in the second phase. These exercises supported fact finding and process orchestration (Voinov et al. 2018).

While participatory diagnostic exercises in earlier phases were carried out with a group of both male and female community leaders, Phase II used homogenous groups. The process of selecting participants was purposive, supported by community leaders, to ensure representation of both men and women, and richer and poorer households (as indicated by livestock holdings, given livestock are a key indicator of wealth (Nkedianye et al. 2019). The resulting six groups were: women belonging to rich households (many livestock); women belonging to poor households (few livestock); men from rich households; men from poor households; male youth from all wealth backgrounds; and male and female village committee members. The purpose was to ensure diversity and inclusion of multiple opinions while making sure village members are comfortable during the focus group discussions. A total of 6 focus group discussions were carried out with a maximum of 10 participants in each group, for a total up to 60 participants. During the focus group discussion, which was facilitated by the third author, a translator and note taker were present.

Both participatory exercises from Phase I and the focus group discussions from Phase II were recorded and transcribed in Phase III. The transcriptions were read to inductively identify key system variables and problems that affect the agro-pastoralist food system and food security. The goal was to integrate community's problem descriptions, solutions, and activities to represent shared representation of the reality. Subsequently, we used the group discussion information, expanded notes, and transcription to develop a preliminary conceptual model (CLD) in STELLA representing the qualitative feedback structure of Naitolia food system. The model was refined and validated with Tanzania Partnership Program (TPP) members in four zoom meetings. TPP is long-term collaboration of local and international organizations dedicated to improving local livelihoods through by supporting education, water, economic development, agriculture and food security, human and animal health and community empowerment, through an integrated development approach. The goal of this partnership is to co-create a model of sustainable community development and build academic connections with Tanzanian academic institutions, scholars, and development practitioners. TPP has been working in Naitolia for over a decade and the final CLD shown in Figure 10 was discussed with TPP members for validation.

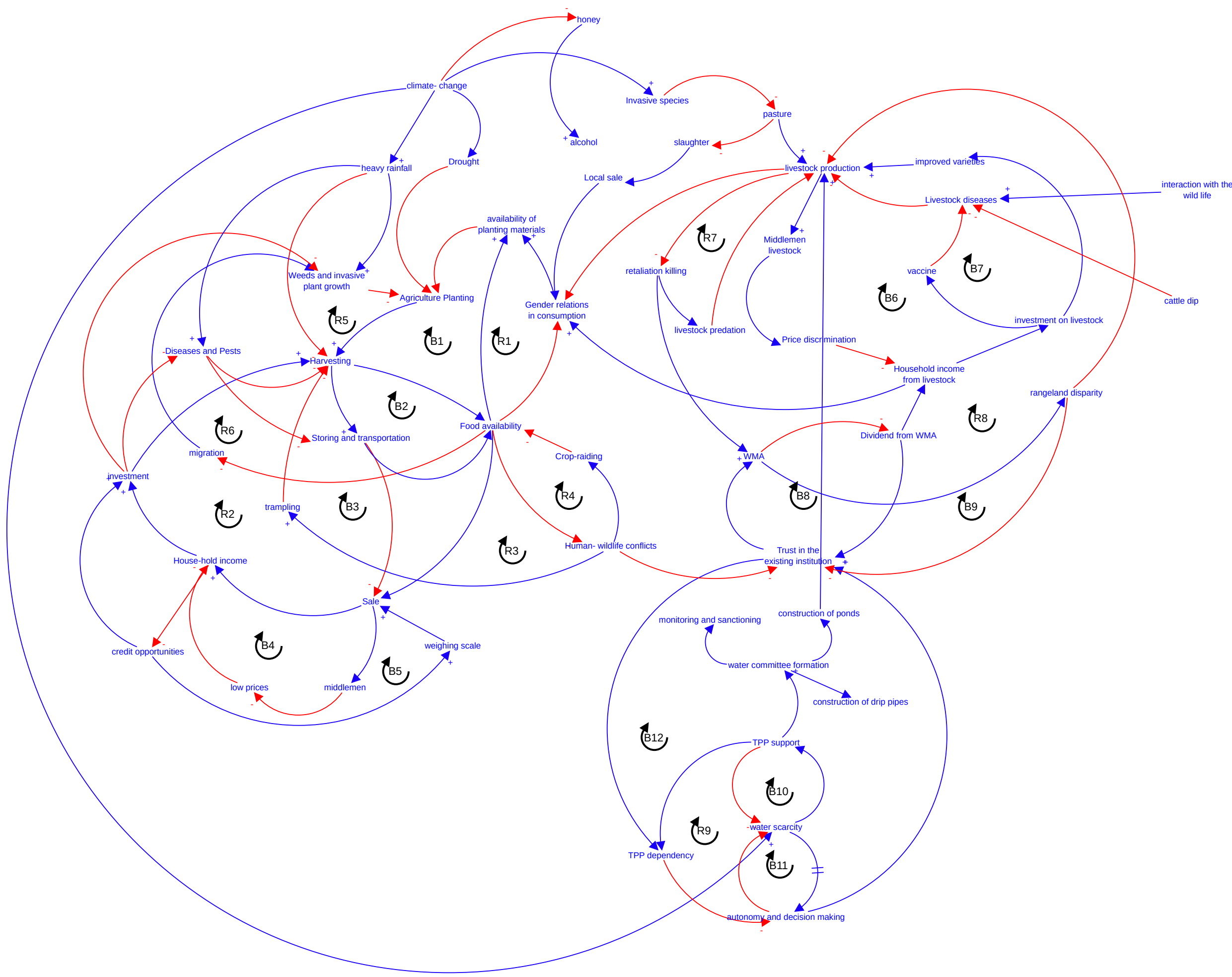


Figure 10 Conceptual model of the AP-FSM. The link colored in blue and red indicates positive and negative link respectively. R denotes reinforcing feedback loop, while B denotes balancing loop. // denotes delay.

The links in Figure 10 are either colored red or blue, signifying the direction of change one variable enforces on the other. The blue color links indicate a reinforcing relationship where an increase or decrease in Variable X would impose change in the same direction in Variable Y. The red color links indicate a balancing relationship where an increase/decrease in Variable X would lead to a decrease/increase, respectively, in Variable Y. The combination of links creates reinforcing or balancing feedback loops. If left unchecked, a reinforcing loop results in growth or decline, while a balancing loop opposes change. For example, as, crop raiding increases, food availability is reduced, which encourages retaliation killing or attacking animals (Loop R4, Figure 10). Lack of transportation and storage facilities increase post-harvest loss leading to less sale, creating a loop B3. Overall, the CLD consists of 43 variables that are connected to each other through over 55 links. The combination of positive and negative links generates 12 balancing feedback loops and 9 reinforcing loops.

3.4.2 SDM setting and description

Even though CLDs represent variables and their connections, feedback loops and interactions, they are mostly conceptual and cannot be used to simulate behaviors. However, they can be quantified when converted into stock and flow diagrams which form a foundation for SDMs, where stocks are accumulations and flows are rates (Meadows, 2008). Materials, information, or energy can move through flows and accumulate in a stock. Ideally, the entire CLD shown in Figure 10 could be simulated. However, due to lack of observed and historical data, the AP-FSM only captured essential components in the system for which there was data, i.e., livestock sector, crop production, and population sector, described in detail in the next section. For instance, we left out water resource management because the amount of water used for drinking, livestock feed, and amount stored through rainwater harvesting, etc. was not available. As more data becomes available in the future, the entire CLD can be quantified and simulated. Therefore, in this paper, the CLD was broken down into four sectors, each of which was quantitatively structured as stock and flow diagrams in STELLA. All three stock and flow diagrams were then linked together in a single SDM, AP-FSM, simulating food security over 30 years. The time frame of 30 years was chosen for the purpose of long-term planning and simulation. The section below describes logic of the model followed by description of each of the four sectors in the model.

3.4.3 Logic of the Model

INPUT	MODEL	OUTPUT
Participatory diagnostic exercises- transit walk, participatory mapping, focus group discussions. Causal Loop Diagram ↓ Validation ↓ Validation with TPP ↓ Stock and flow diagram ↓ Parameterization and Calibration: FAO and World Bank Data ↓ Sensitivity Analysis ↓ Simulation for 28 years	<u>Management scenarios:</u> 1. Increasing crop productivity and decreasing livestock mortality. 2. Decrease post harvest losses and human wildlife conflict. 3. Combination of 1 &2 4. Decrease livestock sale	• <u>Total Food Available</u>: sum of total livestock production + crop (cereal) harvest. • <u>Food Demand</u>: Expressed in FAO recommended amount. • <u>Food Consumption</u>: Actual consumption of food, different than the recommended amount. • <u>Food Sufficiency</u>: Difference between Food Demand and Food Consumption

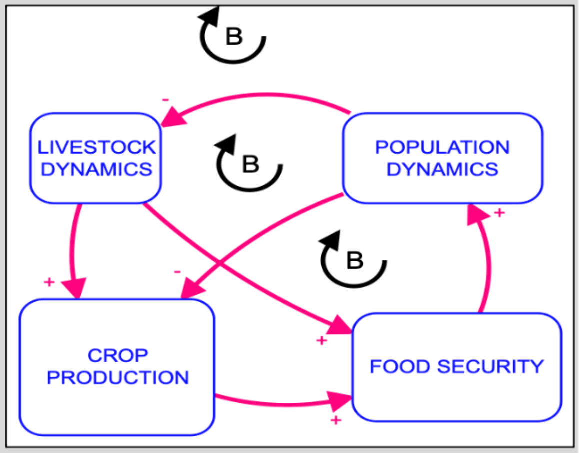


Figure 11 Logic of the Model.

Figure 11 shows the graphic illustration of the relationship between inputs used in AP-FSM development, model-AP-FSM, and the intended output of the model. The AP-FSM was developed through a step-by-step relationship under the heading “input” as already explained above; the parameterization and calibration will be explained in the next section. The outline of the integrated SDM, AP-FSM is shown in Figure 11 under the heading “MODEL”. The integrated AP-FSM consists of four different sectors: Population Dynamics, Livestock Dynamics, Crop Production and Food Security. With increase in livestock production, there is an increase in crop production due to availability of livestock-manure for the crop. Both livestock production and crop production contribute to food security in terms of : (1) <u>Total Food Available</u>- sum of the livestock production and crop harvest for the community as a whole; (2) <u>Food Demand</u>- total amount of food recommended by FAO per community; (3) <u>Food Consumption</u>- actual consumption of food (livestock production + crop harvest) per community; (4) <u>Food sufficiency</u>- the difference between the recommended amount (food demand) and food consumption per community. Food Consumption amount is commonly different than the recommended amount of food (Food

Demand) - if food consumption is higher than food demand, the assumption is consumption is sufficient. If food consumption is lower than demand and not sufficient, population decreases due to migration in search of income, jobs, employment, and food. The model assumes an inverse relationship between population dynamics and livestock dynamics- as the population increases, there is more demand for resources and the pressures for livestock production increases. Similar relationship is assumed between population dynamics and crop production. The output of this model is “total food consumed”, “total food available” and “total food sufficiency”. The next section describes each sector in detail.

3.4.4 Dissection of Sectors used in the Model

3.4.4.1 Population sector

The population sector of AP-FSM is shown in Figure 12, where population is influenced by birth, death, and migration. Therefore, the variable of interest is “population”, “net-migration”, “death rate” and “birth rate”. The definitions of these variables are given in Table 10.

We deliberately kept this sector as simple as possible, and not all factors that influence population dynamics were incorporated, due to lack of historical and observed data. Population growth is the most important socio-economic factor for food security because pressure on resources is driven in part by population growth. For instance, increased demand for food from increased population leads to increased expansion of farming land, destruction of forest resources, etc.

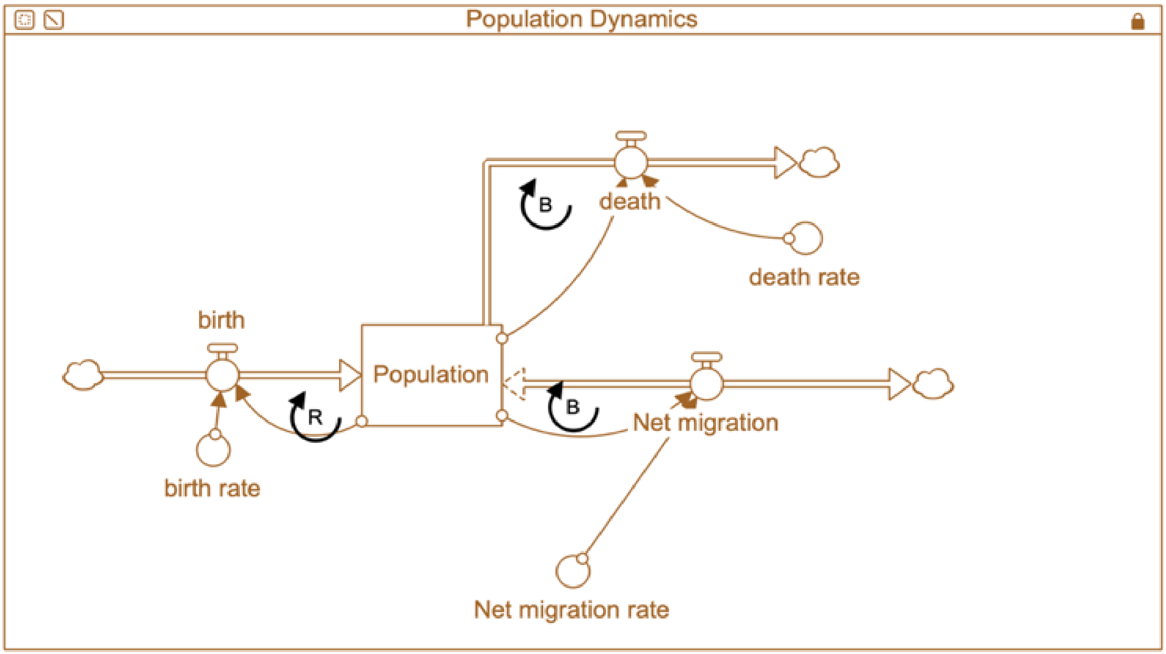


Figure 12 Stock and flow diagram of population sector in AP-FSM.

3.4.4.2 Livestock sector

The assumption of the livestock sector is as follows: (1) Livestock production is dependent on calving rate, calf survival, and livestock mortality (Odoemena et al. 2020); and (2) the produced livestock is either sold, saved in the form of asset, or consumed (Menghistu et al. 2020). The livestock sector models these assumptions in AP-FSM in Figure 13.

In Figure 13, the stock "calves", which denotes young cow, is dependent upon the flows "calving" and "calf mortality". "Calving" refers to birth of the young cows, while "calf mortality" refers to the death of young cows. The flows "calving" and "calf mortality" are dependent on the converter "calving rate" and "calf mortality rate" respectively. The "calves" that survive grow up to become adult cows, represented by the stock "livestock population", capable of reproduction and producing milk and milk products. The stock "livestock population" has the outflow "livestock mortality" which causes decline in the number of adult cows. The flow "livestock mortality" is dependent upon the converter "effect of rainfall on livestock" and "livestock mortality rate" which denotes natural death of adult cows and death due to diseases and dehydration. The remaining cows, represented by the stock "expected livestock stock", is either sold through the flow "livestock sale", or saved in the form of asset though the flow "asset building", or consumed through the flow "livestock consumption". The flows "livestock sale", "asset building" and "livestock consumption" are dependent upon the converters "percentage sale", "percentage saved in the form of asset", and "per capital consumption of livestock and livestock products".

In the study area, cattle are the most common livestock. The death rate is influenced by high calf mortality rates as the calves are subjected to many digestive, respiratory, and reproductive disorders, which accounts for approximately 58 percent of total known deaths (Gebremeskel et al. 2019). Even as adult cattle, the livestock population is subjected to many different diseases which results in livestock mortality. Livestock survival also depends on the grazing land availability. Since grazing lands are frequently converted to other land uses such as wildlife management areas, reduction in grazing land leads to the poor survival of livestock. Livestock are an important family asset in agro-pastoralist households, contributing to both status and wealth. Livestock fulfill multiple roles that range from maintaining family status, draught power, performing rituals, assets for sale or dowry, to selling dairy products for household income. According to the focus group discussions, the milk and dairy products are both consumed by the household and sold in the market. On the contrary, the livestock are rarely slaughtered for household consumption of meat; they are mostly sold in the market as a live animal. However, there is little data on how much is sold and consumed in AP-FSM for calibration and validation.

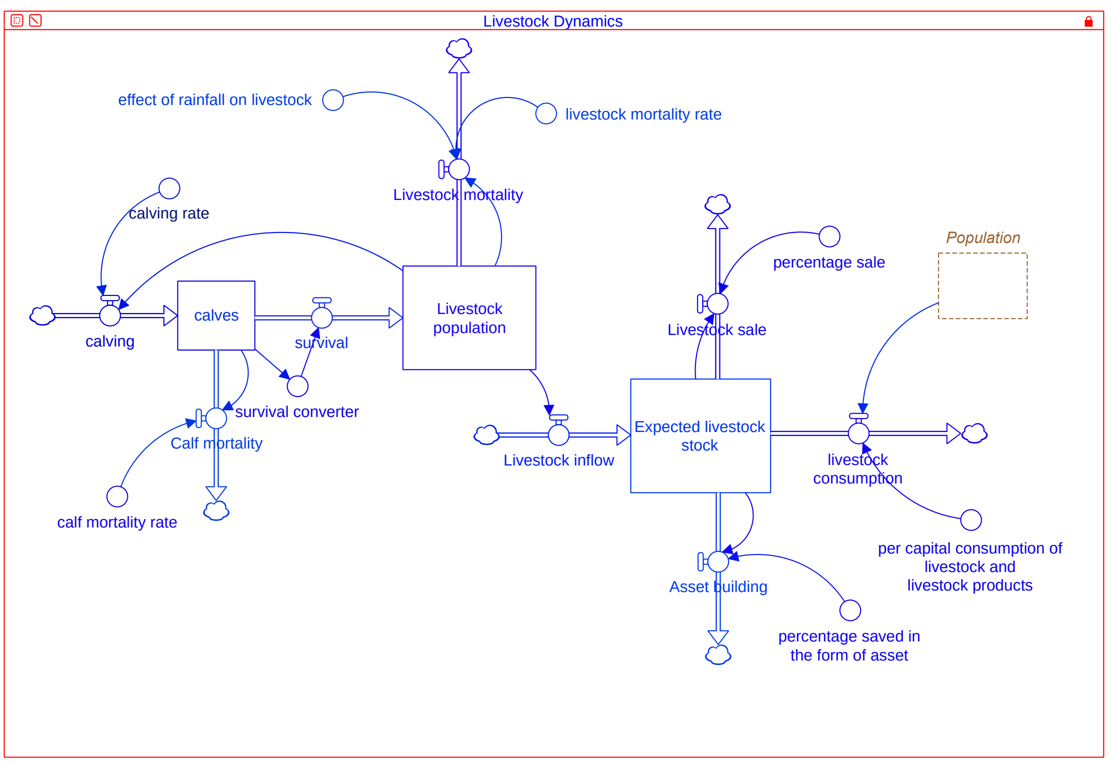


Figure 13 Stock and flow diagram of livestock sector in AP-FSM.

3.4.4.3 Crop production sector

The assumption of the crop sector is as follows: (1) Crop production is affected by rainfall (Tarnavsky et al. 2018); (2) Crops in the study areas are destroyed by wildlife, mostly on the field (Kalyahe et al. 2022); (3) Post harvest losses are rampant (Pittelkow et al. 2014); (4) Crops are then either consumed, sold or saved as seeds for the next growing season (Kopainsky et al. 2012, Grabowski et al. 2019). The crop sector models these assumptions in AP-FSM in Figure 14.

In Figure 14, the stock "area under harvest" represents the total cereal harvested area in Naitolia, which is dependent on the flow "flow for area" and the converter "annual area under harvest increase rate". The converter "cereal production" which represents the total cereal production is the function of the total cereal harvested area "area under harvest" and cereal productivity "productivity" (function of "effect of rainfall on cereal" and "potential productivity"). The converter "cereal production" affects the flow "plantation or production" which denotes planting of cereal crops which grows up to become the stock "crop harvest". The stock "crop harvest" affected by the flow "loss due to raiding and trampling" which denotes crop loss due to wildlife. The remaining crop is harvested which is then prone to post harvest losses and the remaining crop, denoted by the converter "remaining after losses" is available as a food through the flow "expected crop stock inflow". The stock "expected crop stock" denotes total crop available, that is either consumed, sold or saved, denoted by the flows "crop consumption", "crop sale" and "seeds for future" respectively.

Arable production in most dryland agro-pastoralist systems is 95% rain-fed (FAO 2022). Cereals are the major crop type, with maize the major crop produced throughout Naitolia. However, cereal productivity is relatively low given the low rainfall in the area. As a result, increases in cereal production are mostly due to expansion of area under harvest. However, there are challenges producing enough cereals for household demand, given the variable rainfall and crop raiding and trampling by wild animals, such as elephants. Since Naitolia lies in wildlife management area, next to Serengeti National Park, human-elephant conflict is significant. According to Pittiglio et al. (2014), the damage from elephant trampling and raiding can lead to approximately 33% loss in crop. Additionally, it was revealed through the focus group discussions, post-harvest there is also loss of crop due to poor storage and transportation. With the remaining crop, the priority is to use the cereal crop for household consumption, with the remainder sold, exchanged, or saved as seeds for future plantation.

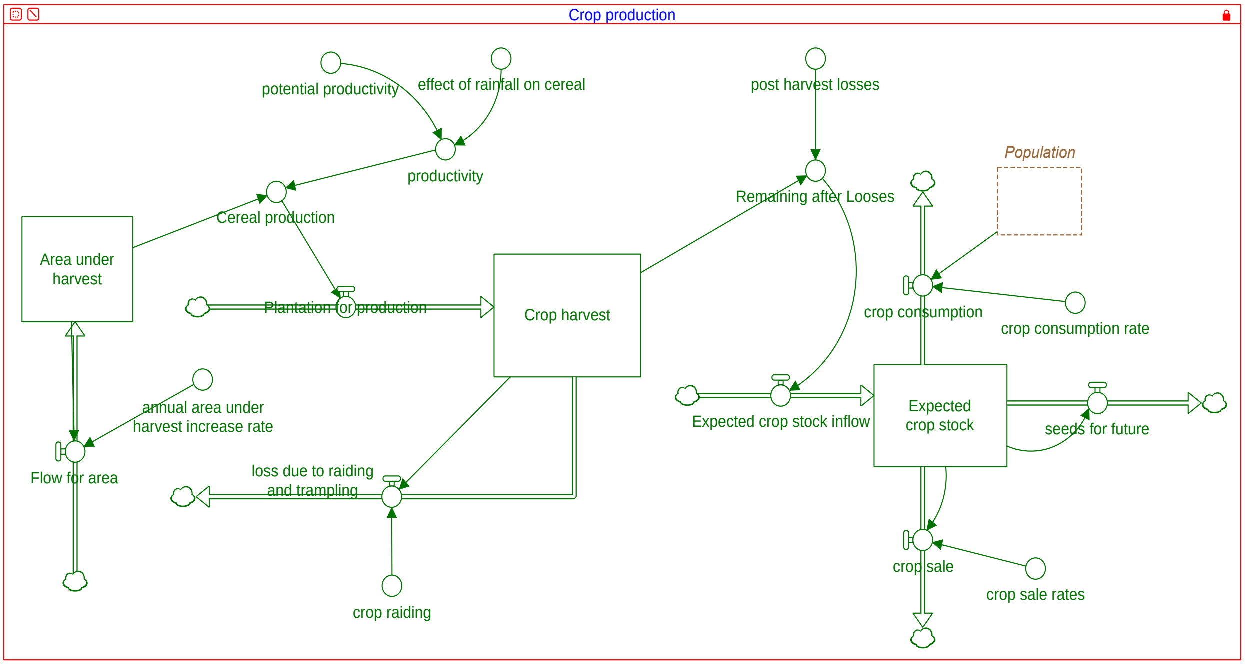


Figure 14 Stock and Flow diagram of crop production sector in AP-FSM

Food security outcomes in the AP-FSM

The assumption of food security outcomes is as follows : (1) Not all food available (sum of food available for livestock and crop harvest) is consumed, some are sold while others are kept for asset building; (2) Cattle represents a fundamental asset in an agro-pastoral society; (3) In general, dryland inhabitants such as Naitolia consume less than FAO recommended amount; (4) If consumption of food is higher than the recommended amount (Food Demand) it is assumed as sufficient. These assumptions are modeled in food security sector as shown in Figure 15.

Figure 15 depicts food security sector created by integrating the three sectors above to outline the food system structure that influences food security. The converter "total food available" is the total of the stock "crop harvest" and "livestock population". "Total food available" denotes amount of food available for consumption through livestock and crop production. Likewise, the converter "total food consumed" denotes the number of livestock and crop consumed along with amount of food purchased. It is "calculated by adding the variables "livestock consumption" and "crop consumption" and "purchased". Food demand is a function of the rates of demand and population, denoted by the variables "annual rate of demand" and "population". For this study, food demand is considered as FAO recommended yearly intake of food for a population. Food consumption, on the other hand, is the actual consumption of food, which is differeent than the recommended amount (food demand). "Food sufficiency" occurs when the variable "total food consumed" is higher than total "food demand". Likewise, when demand of food is higher than consumption, it denotes food deficits.

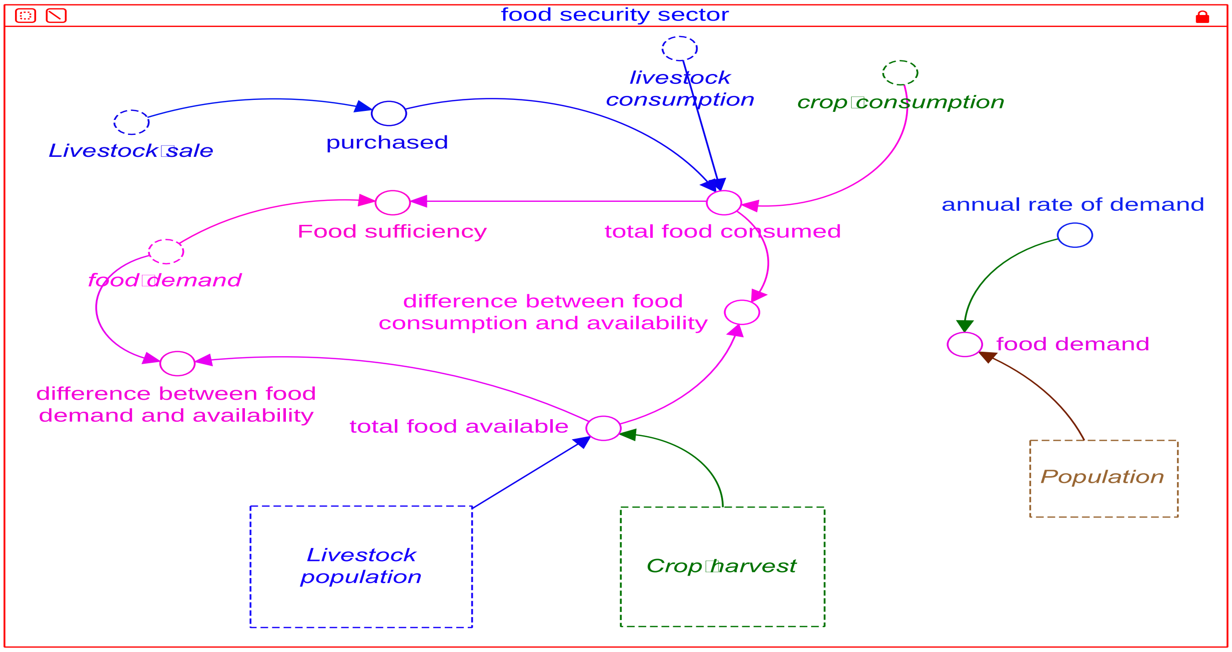


Figure 15 Stock and Flow diagram for the AP-FSM, outlining food security inputs from the crop production, livestock, and population sectors in green, blue, and brown respectively.

3.4.5 Input data and model parameterization

As mentioned earlier, agro-pastoralist food systems in Naitolia are under-researched. Therefore, specific data for each variable within AP-FSM are not easily available for the model. Like Kotir et al. (2016), most of the data used to parameterize AP-FSM are national in scope and have been averaged and summarized to represent conditions of Naitolia (Appendix G: Data used for System Dynamics Model Table 10). Population and demographic figures were parametrized based on World Bank database (World Bank 2022). Crop yield, area under harvest, wildlife areas, food production etc. were obtained from FAOSTAT (FAO 2022). Population and crop data were available from 1961 to 2020, while livestock data was only available from 1990-2018. For easy comparison and interpretation, the AP-FSM model was parameterized with data from year 1990-2018, with key parameters described in Appendix G: Data used for System Dynamics Model Table 10.

3.4.6 Model testing and verification

The AP-FSM was tested by as per Ford (2000) and Kotir et al. (2016). A parameterconfirmation test was performed to measure how accurately the model replicates the patterns and behaviors in the real system. The observed data obtained from World Bank databank and FAOSTAT from 1990 to 2018 was used to validate the model by examining its ability to reproduce historic behavior (Wu et al. 2013).

The parameters used in the model for determining behavioral patterns based on the long-term data availability were Population, Area under harvest, Crop harvest, and Livestock population (cattle). To evaluate how close the model is with the observed data, three statistical measures were calculated: coefficient of determination (R2), maximum relative errors (MRE), and Nash-Sutcliff efficiency coefficient (NSE) as suggested by Kotir et al. (2016) and Wu et al. (2013). The coefficient of determination is the number between 0 to 1, which measures how close model predicts an outcome - R2 values closer to 1 indicate the model is a good simulation of the system (Wu et al. 2013). On the other hand, the MRE indicates the relative difference between simulated and observed data - values close to 0 are considered good (Wu et al. 2013). NSE describes the quality of simulation results and values range from $-\infty$ to 1 - the closer the NSE value is to 1, the more accurate the model.

3.4.7 Sensitivity analysis

A model can often include both certain and uncertain parameters, however due to the model's credibility, it is uncommon to include highly uncertain parameters. Sensitivity analysis examines how uncertainty in model inputs translates into uncertainty in important outcomes. In other words, sensitivity analysis aids in understanding how the model responds to changes in the parameters or how variables behave within the model. Therefore, sensitivity analysis provides a way to systematically reduce impact of uncertainties on the model (Sahin et al. 2015). The sensitivity analysis was performed 50 times with parameters that were thought to have an "incremental" distribution.

3.4.8 Scenario design

Scenarios in SDM are projections for the future in which dynamic effects associated with endogenous and exogenous variables and rates of change interact and playout. Scenarios reveal how much acceleration or reversal in what factors induces change in the outcome variable. For instance, applying different scenarios in an SDM can show what pathways lead to a 50 percent reduction in food production and when, as a function of rate of change in system components, feedbacks, and non-linear interactions.

The scenarios in this paper are designed based on two frameworks: (1) Ericksen (2008)'s food system framework and (2) Béné et al. (2014)'s conceptualization of disturbance/shock intensity and responses. Ericksen (2008) describes a food system in terms of major activities and food system outcomes. Activities include production, retailing, storage etc., while outcomes are food security, social welfare, and environmental welfare. Bene et al. (2014) state that different responses are needed for different intensities of shock or change. For instance, if the intensity of drought or food insecurity is lower, a household may resist or absorb its impact by making small adjustments such as re-planting the wilted plant or adapt by planting high yielding varieties or building water storage facilities to reduce failure of crop. However, if making these adjustments did not reduce the intensity of impact from food insecurity and drought, the system may fundamentally change the property of land use, for instance by adoption of agroforestry. Based on the food system framework and intensity of change conceptualizations, four scenarios and the business-as usual scenario (base-run) are designed to simulate Naitolia's agro-pastoralist food system and food security in terms of food availability, food consumption, and food sufficiency between 2022 and 2050.

3.3.7.1 Base Run

The base run is used to the business as usual (BAU) scenario with no interventions. The base run assumes that existing trends of population growth as well as agricultural and livestock growth trends will continue in the future.

3.3.7.2 Scenario 1: Increasing crop productivity and decreasing livestock mortality.

Scenario 1 is based on food availability, where we increase food production ((Ericksen 2008) through making adaptive adjustments (Béné et al. 2014). In this scenario we focus on the production side, increasing the cereal productivity from 0.6 to 0.8 tonnes/ha and the livestock calving rate from 0.55 to 0.60.

Food production is the major activity in the food system (Ericksen 2008), and many dryland studies have touted increasing productivity through application of organic and plant-based fertilizers, planting climate resilient varieties, and intercropping with multifunctional plants such as pigeon pea (Glover et al. 2010, 2012, Kopainsky et al. 2012, Antwi-Agyei et al. 2014, Grabowski et al. 2019). Mixed cropping and home-gardens, a holistic system that focuses on soil health, and uses local input is shown to be admirable fit for drylands (Watson and Eyzaguirre 2002, Manaye et al. 2021).

3.3.7.3 Scenario 2: Decreasing post-harvest losses and losses due to human-wildlife conflict.

Scenario 2 is based on food availability, where we reduce losses occurring during production (Ericksen, 2008) and storage through some incremental adjustments within existing agro-pastoralist livelihoods (Béné et al., 2014). Under this scenario, we reduce livestock mortality from 0.50 to 0.44; reduce crop trampling and raiding from 0.33 to 0.15; and reduce post-harvest loss from 0.20 to 0.05.

Livestock vaccinations and cattle dip programs are active in Naitolia and Northern Tanzania and intended to reduce mortality but could be scaled up. Though a lot of resources, motivation, awareness, and policy changes are required (Kalyahe et al. 2022). There are a number of studies that recommend potential strategies to reducing crop losses due to wildlife raiding and trampling. A study conducted in Gaurishankar Conservation Area (GCA) in Nepal recommends investing in community-based wildlife monitoring, and fair and quick crop loss compensation as some of the ways to reduce impacts of post-harvest losses due to wildlife (Awasthi and Singh 2015). Likewise, a meta-analysis on human-wildlife conflict suggests that if protection of livestock and crop against wildlife is put on place, it can improve food security (Seoraj-Pillai and Pillay 2017). In case of post-harvest losses, it needs holistic approaches that pay attention to: agricultural extension and rural credit services; post-harvest handling technologies; strengthening cooperative marketing; and improvement of local market and infrastructures (Zhang et al. 2022, Debebe 2022).

3.3.7.4 Scenario 3: Increasing production and decreasing post-harvest losses.

In this scenario we combine both Scenario 1 and Scenario 2 as many scholars have recommended integration of multiple strategies is required to deal with food security situation in dryland food systems (Mawdsley et al. 2009, Lobell et al. 2013, Charles et al. 2014, Pittelkow et al. 2014). Therefore, Scenario 3 recommends adaptive actions to influence both food availability via increased production and decreased loss.

3.3.7.5 Scenario 4: Decreasing crop and livestock sale.

Scenario 4 builds on scenario 3 to increase food availability (by increasing food, production and reducing food losses) while also making structural (i.e., more transformative) adjustments to agro-pastoralist livelihood (Béné et al. 2014). In this scenario, we intend to look if reduction in livestock sale translates into food consumption. We combine Scenario 3 with a reduction in livestock sales, from 0.30 to 0.15.

Tanzania's poverty reduction strategy was judged to be successful by the World Bank, given that between 2000 to 2015 poverty was reduced by 3.2 percent (ASAI et al. 2019). The poverty reduction was achieved by prioritizing food and humanitarian aid (i.e., food consumption), institutional strengthening and good governance, and strengthening additional income through employment and empowerment programs that focused on commercial agriculture, manufacturing, and tourism. The program lifted thousands out of poverty and made it the seventh-largest economy in Africa; however, it is not clear if it positively impacted agro-pastoralists, particularly in Naitolia. In this scenario 4, we assume that if additional livelihood and income resources are available, households will produce the increased amounts of crops and livestock, lose less, and reduce their sales – as a result food consumption will increase.

Cattle represent fundamental asset in traditional Maasai society. Maasai communities accumulate large herds to demonstrate wealth and status. Accumulating large herd is the cultural norm, so it is common for cattle to change hands as part of diplomatic relations between clans, pay the bride price, and as a gift. Therefore, it makes sense to simulate if reduction in livestock sale translates into asset building or consumption.

3.5 Results

3.5.1 Model testing

The results simulated by the model follows trends like the observed values, which specify that the model is calibrated to make a prediction. The model testing results are shown in Figure 16, Figure 17, Figure 18, and Figure 19. The statistical values for R2, MRE and NSE are listed in Table 5 and indicate that the model satisfactorily fits the available data. The MRE parameters for crop harvest and area under harvest are lower (<0.10), while population and livestock population are relatively high (up to <0.15). The higher MRE values may indicate uncertainty due to model assumptions. The R^2 of Livestock (cattle) population, Area Under Harvest, and Population are in the ranges between 0.89- 0.98 respectively, indicating that simulation values correspond to the observation. The values for NSE range from 0.67 to 0.99. Even though the NSE for livestock population and crop harvest is relatively lower, 0.67 and 0.76 respectively, they have higher R^2.

Table 5 Statistical Parameters of Validation.

Variables	MRE	R2	NSE
Livestock (Cattle) Population	0.12	0.93	0.67
Crop Harvest	-0.08	0.93	0.76
Area Under Harvest	-0.07	0.89485311	0.99
Population	-0.15	0.98	0.99

According to Kotir et al. (2016) the aim of a simulation model is to understand pattern behavior over the time, and not to make accurate predictions related to system variables. Rather, the models are formulated to predict patterns (Kelly et al. 2013), which the model has successfully accomplished.

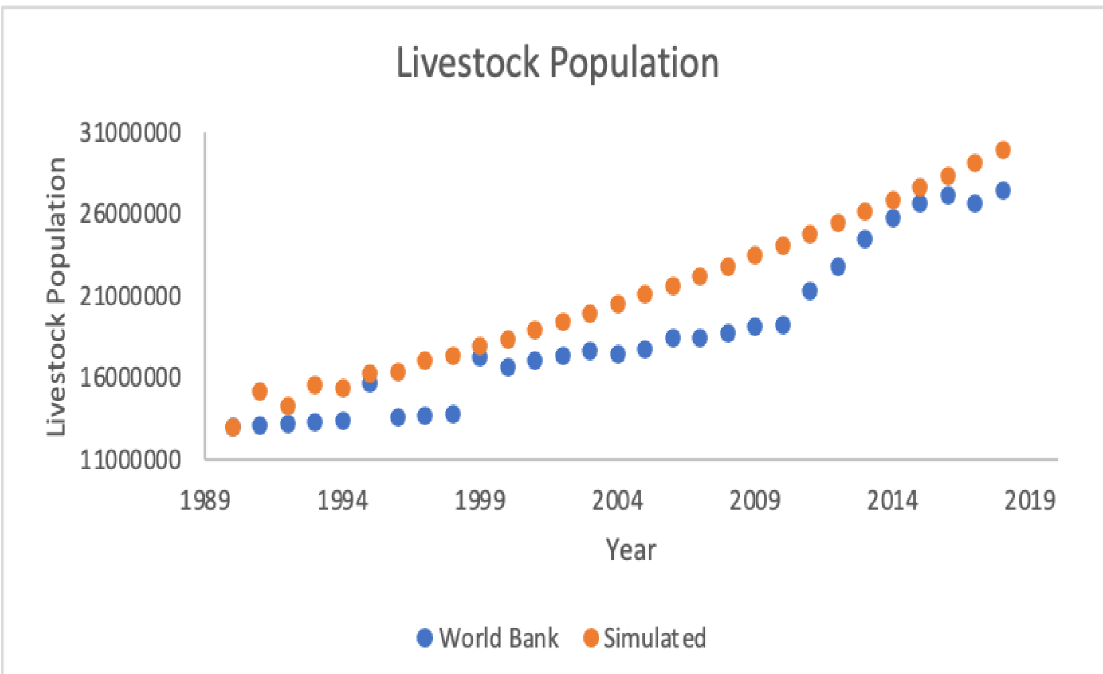


Figure 16 Comparison between observed and simulated data for Livestock (cattle) population between 1989 and 2018.

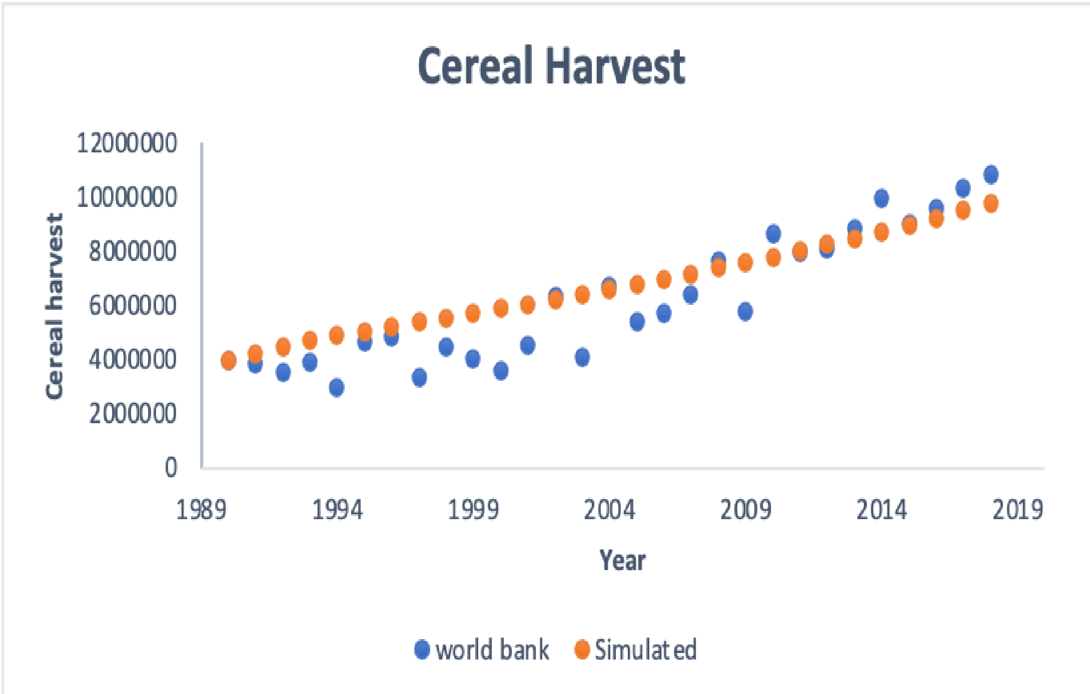


Figure 17 Comparison between observed and simulated data for crop harvest between 1989 and 2018.

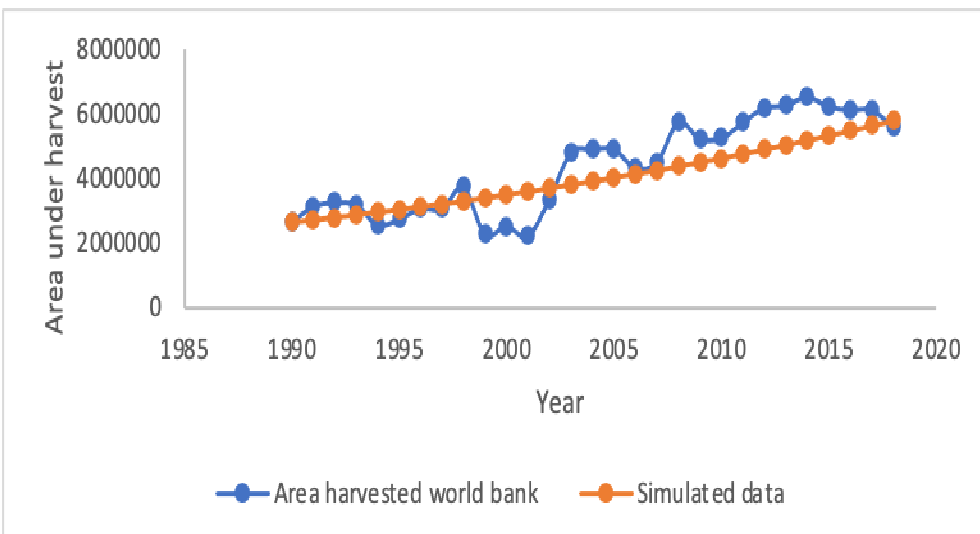


Figure 18 Comparison between observed and simulated data for Area under harvest between 1989 and 2018.

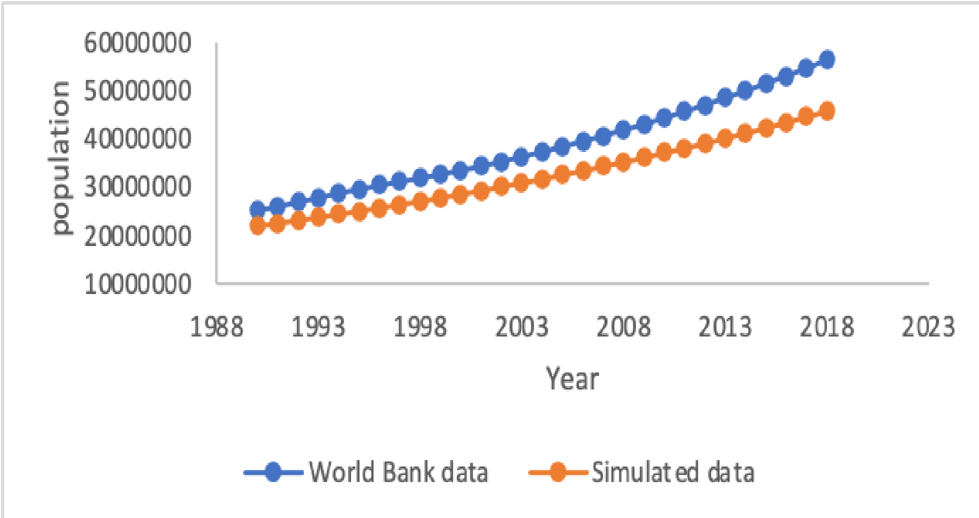


Figure 19 Comparison between observed and simulated data for cattle population for population between 1989 and 2018.

3.5.2 Sensitivity Analysis

Sensitivity analysis conducted on four stocks: “livestock population”, “expected livestock stock”, “Crop harvest” and “Expected crop stock” shows that these stocks are highly sensitive to the variables. With each unit change in each variable, there is a concomitant change in the stocks. The results of the sensitivity analysis are included in the appendix (Figure 25, Figure 26, Figure 27, Figure 28).

3.5.3 Scenario Analysis

3.5.3.1 Base Model Run

The future simulation in the base model (business as usual) is shown in Figure 20. The parameters used in the base model are shown in Appendix G: Data used for System Dynamics Model Table 10. If we assume a situation where climate change and other management practices are likely to remain the same, the crop harvest and livestock population is likely to increase (Figure 20) because of the progressive expansion of the agricultural area and the reinforcing action of the calving rate in livestock. Therefore, total food availability is also likely to increase, while total food consumption is likely to be similar because the population of Naitolia, which is expanding at the same time, consumes the amount generated. Food demand (as recommended by the FAO and a function of the Naitolia’s population) is likely to increase, and food sufficiency is likely to decline because not all the food that is available is consumed; part of it is sold or kept as assets and seeds (in the case of livestock) (in case of crops). By 2050, food demand is likely to reach 650 tones in Naitolia, while food sufficiency is likely to decline by 150 tones. The increase in food demand, reduction in food sufficiency and steady consumption patterns indicate that food consumption does not increase even with increases in livestock population and crop harvest.

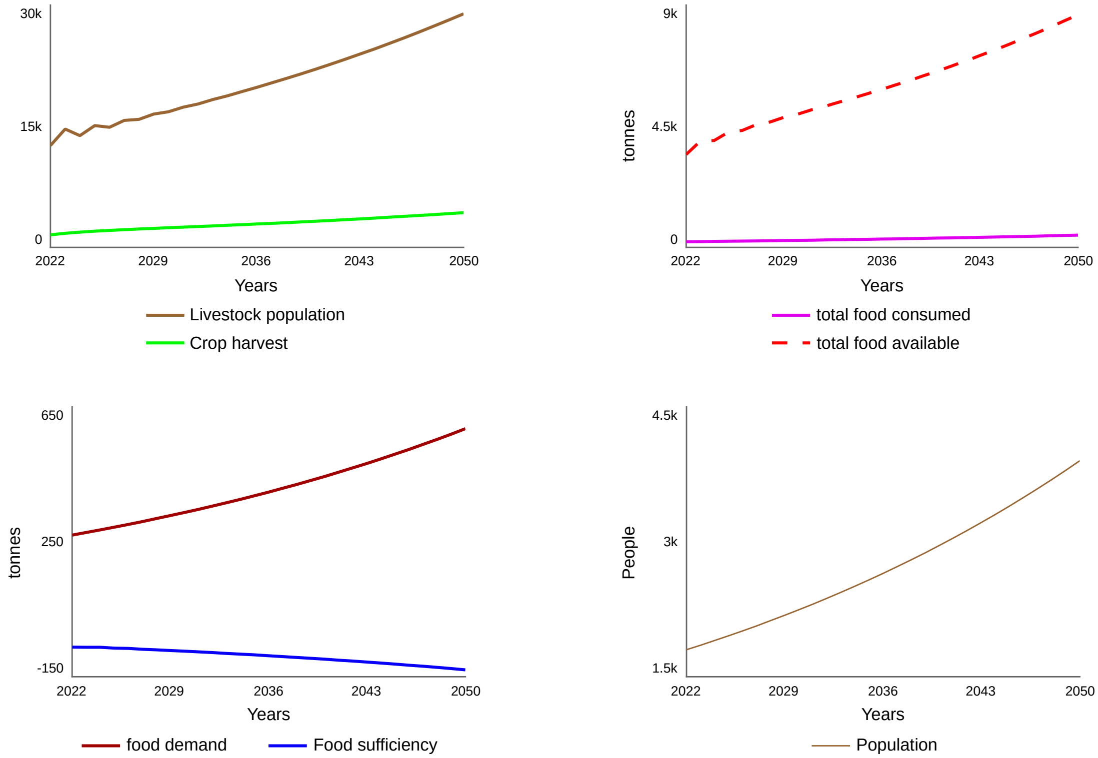


Figure 20 Base run simulation from 2022 to 2050.

3.5.3.2 Scenario outcomes

The behavior of each selected variable under the four scenarios is shown in Figure 21. Crop harvest, Livestock Population, Crop Sale, Livestock Sale, Asset Building, Food Demand, Total Food Consumption, and Total Food Available show positive trends and are likely to increase by 2050 in all four scenarios. However, food sufficiency only increases in Scenario 3. In Scenarios 1, 2, and 4 sufficiency shows downward trends culminating in even more negative sufficiency in 2050 than in the present, but not as low as the base run shows. Through Scenario 3, the combination of increased production and reduced loss lead to food demand needs being met from Naitolia's own agro-pastoralist production, rather than purchasing food from outside and to the degree which results in a food surplus, the only scenario to do so.

Scenario 4 results in, the maximum growth in Livestock Population, Crop Harvest, Crop Sale, Asset Building, and Total Food Available by the year 2050. However, Total Food Consumed, Livestock Sale, and Food Sufficiency are likely to be higher in Scenario 3. Given the only difference is a reduction in Livestock Sale in Scenario 4, it leads to Asset Building (as shown in Figure 21) rather than increased consumption and sufficiency.

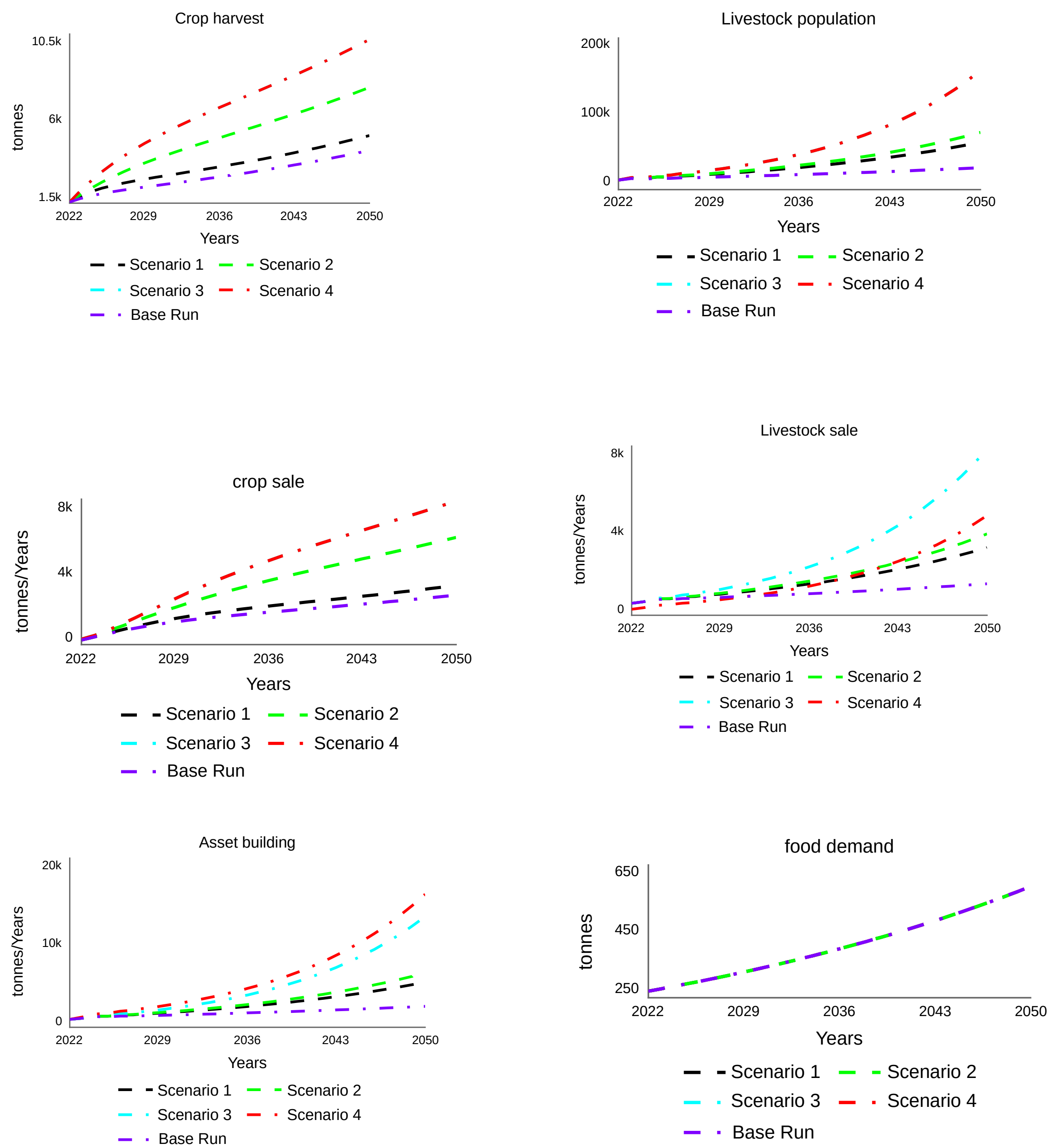
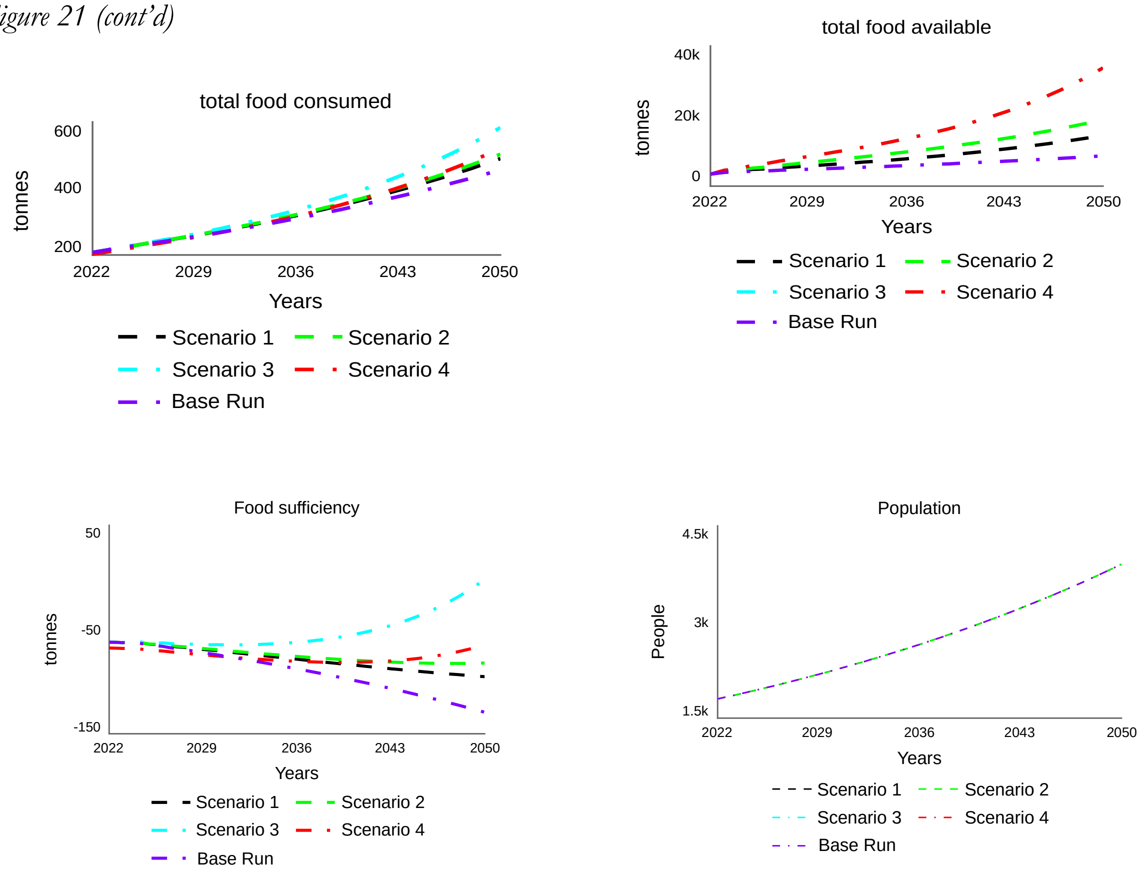


Figure 21 Prediction of variables under different scenarios.

Figure 21 (cont'd)



3.6 Discussion

The results indicate that in case of AP-FSM, only focusing on crop or livestock production is likely to yield scenarios like Scenario 1 and is not adequate to enhance sufficiency and thus food security. Therefore, the popular conjecture that to increase food security in drylands, productivity should be boosted (E Beza 2017, Tian and Yu 2019, Qaim 2020), is incomplete and not sufficient for Naitolia. Historically, enhancing productivity has resulted in many unintended consequences such as increasing greenhouse gas emissions and decreasing biodiversity. Since the outcome of food systems is also social and environmental welfare, intensification has led to neither increased food security nor sustainability (Ericksen, 2008). Therefore, focusing on closing yield gaps or improving productivity alone with the aim to obtain food sufficiency reflects an inability to understand the dynamic interactions between multiple components within the food system and may not be sustainable in long run.

The model suggests that Scenario 2, reducing pre-harvest losses due to human-wildlife conflicts and post-harvest losses during storage are also not sufficient alone to enhance food production, availability, consumption, or sufficiency. Even though a large portion of food at production and storage stages is lost in countries like Tanzania (Ngowi and Selejio 2019), Scenario 2 shows focusing only on minimizing losses does not eliminate hunger. However, post-harvest strategies to reduce loss during harvesting, storage, and transportation still need to be prioritized to preserve the food to address environmental and social welfare (Ngowi & Selejio, 2019). Likewise, crop raiding and trampling also needs to be addressed, as seen in Figure 10. A further increase in crop damage could intensify the human-wildlife conflicts in the form of retaliation killing, as shown in recent studies (Seoraj-Pillai and Pillay 2017, Siljander et al. 2020). Such conflicts further reduce the stock of food that would otherwise be consumed or sold.

Simulation results from Scenarios 1 and 2 indicate that a sector-scale interventions are insufficient and system-wide intervention strategies must be a part of Naitolia's food system to achieve food security. Scenario 3, combining interventions that enhance productivity and reduce losses, seems to be the most beneficial in terms of livestock population growth and crop harvest, which results in higher food availability, consumption, and sufficiency than the base run and Scenarios 1 and 2. Given the linkages between production, yield losses, human wildlife conflicts, and food security, which cross-cut the ecological and socio-economic realms, implementing scenario 3 could provide positive impact on income and health. Both ecological determinants such as climate, soil conditions, ecosystem stocks and socio-economic determinants such as availability of planting materials, technology, cultural preferences etc. play a huge role in food production (Ericksen, 2008). While implementing scenario 3, focus should be on conservation agriculture, rotational grazing, and intercropping with leguminous crops that could be incorporated in the food system that reduces environmental and biodiversity impacts (Chen et al. 2018). Then, culturally appropriate awareness and information on wildlife, capacity building on technology for reducing post-harvest losses and institutional arrangements could preserve the already produced food (Awasthi & Singh, 2015; Seoraj-Pillai & Pillay, 2017; Siljander et al., 2020). Together, scenario 3 presents a more holistic approach of linked systems in which both social and ecological process are important (Thornton et al. 2011).

Scenario 4 showed that reducing the percentage of livestock sales on top of the actions in Scenario 3 does not translate available food into consumption. Rather it is converted into an asset, which aligns with Maasai culture. Traditionally, cattle are more than just a livelihood for the Maasai, but also a key indicator of wealth, status, and success (Nkedianye et al. 2019). The number of cattle a family own is an indicator of socio-economic status which is important for bride wealth payment and exchanged during ceremonies (Quinlan et al. 2016). Cattle are also converted into cash to purchase household necessities. Therefore, Maasai households go lengths to own cattle, rather than slaughtering them for food. In terms of livestock products, Loos and Zeller (2014) found per person milk consumption between Maasai groups in Eastern Tanzania that sale milk with those who do not to be markedly similar. They concluded that income generated through the sale of livestock products do not increase the quantity of food consumed but rather invest in diet diversification. For similar reasons, scenario 4 did not result in increased food consumption and sufficiency in comparison to scenario 3. Perhaps, the future research on food consumption should base our work to include focus on dietary diversity among agro-pastoralists. Coming back to Bene et al. (2014)'s framework, with the assumption that the variables are held constant, adjusting the current food systems (those mentioned in scenario 3) is likely to increase food consumption, and food sufficiency.

The trends found in our study are consistent with other food security studies in other drylands in that food security is likely to decline, while the food demand is likely to increase (Oyo and Kalema 2016, Paterson Guma et al. 2016). These studies show that interventions focused on food should also be complemented by addressing demographic challenges that are associated with high-levels of population growth and food demand- a lack of health care, education, livelihood security, institutional strengthening, and mobility etc. (Lemos et al. 2016). However, given the relatively lower food sufficiency in scenario 4, these factors should not alter Maasai norms. Rather, focus should be in terms of increasing stress tolerance, income and dietary diversification and capacity building that are exogenous to the system.

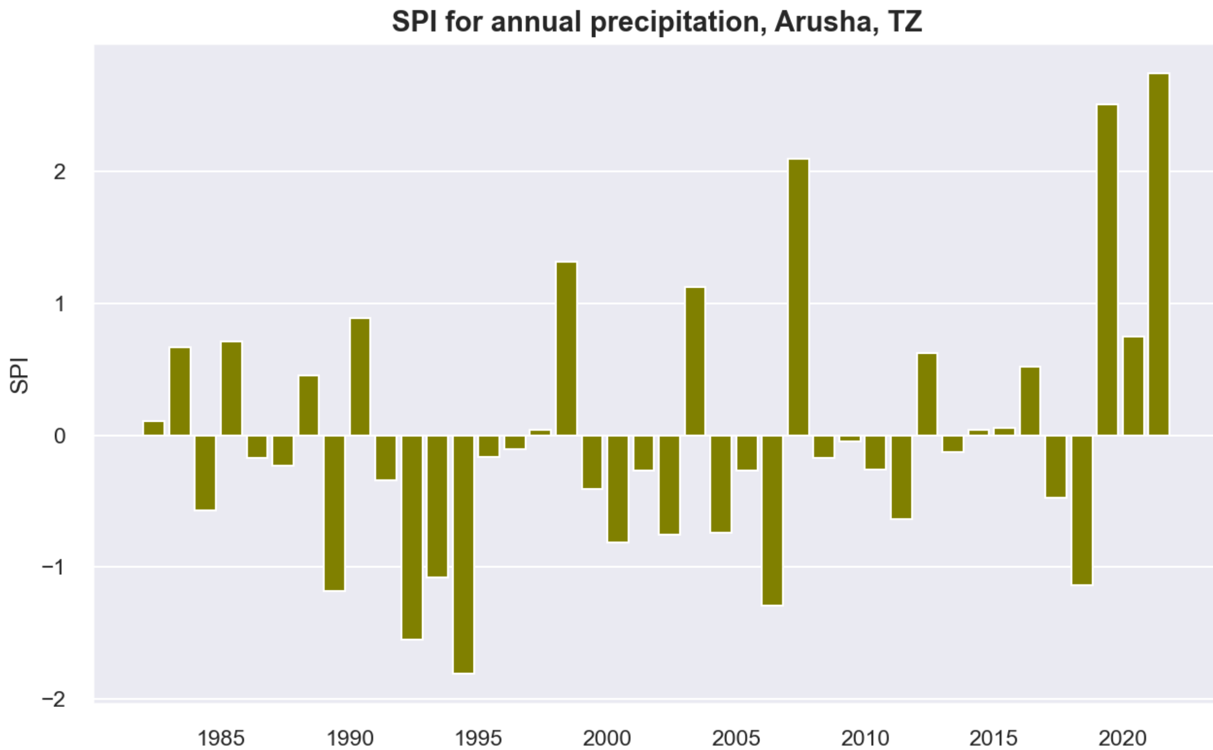


Figure 22 Standardized Precipitation Index (SPI) for annual precipitation of Arusha region between 1981-2020 based on daily rainfall data.

Due to the disparity between published climate literature and calculated data, one of the major drawbacks of AP-FSM is the absence of a climate component. Studies by Ahmed et al. (2011), Kabote et al. (2017), and Luhunga et al. (2018) discuss how climate change is affecting Tanzania, particularly how severe the drought has been in the past and forecast that the drought and climate change will become more severe in the future. Figure 22 shows the Standardized Precipitation Index (SPI) I generated for Arusha region using daily rainfall data from CHIRPS for the 30 years (1981-2020). SPI values between 0 to -0.99, -1.00 to -1.49, -1.50 to -1.99 and greater than -2.00 considered as mild drought, moderate drought, severe drought and extreme drought respectively (Mckee et al. 1993). Arusha suffered two moderate droughts in 2007 (SPI value =-1.3) and 2017 (SPI value= -1.2) and two severe droughts between 1990 and 1994 (SPI value between -1.5 to -1.99) throughout this 30-year span. Contrary to what the literature claims, even though the area has been relatively dry and arid for the past 30 years, SPI indicates that drought hasn't worsened. On the other hand, between 1981 and 2020, annual precipitation increased at a rate of 2.22 mm per year; nevertheless, the Mann-Kendall test did not show any significance. The Walsh and Lawler seasonality index has a value of

0.69, indicating that seasonality may play a role in climate fluctuation and drought. So, future studies can use AP-FSM and Figure 22 as a starting point and add more seasonality-related variables to their models.

The scenarios projected in the AP-FSM are not a strict prescription, rather a display of potential long-term trajectories of the system that decision makers should be aware of. The AP-FSM, like other models is incomplete and not perfect. Trying to model a complex system such as dryland agro-pastoralist system is very challenging in terms of defining each component and subsystem. While we have taken a first step to develop a decision support tool for understanding and managing dryland food systems, the study did not contain a detailed investigation on dietary diversification, food utilization, water resource management, institutions, and governance due to data availability limitations and system uncertainty. Therefore, future work it is important to further expand the AP-FCM.

3.7 Conclusion

The goal of this article was (1) to construct a system dynamics model of the Naitolia agro-pastoralist system to understand the key system components, drivers, and dynamic behavior including feedbacks for its food system, and (2) to simulate the food security situation under different scenarios to support decision making in food security planning at village level. The process of developing AP-FSM was participatory with inputs from the community. The AP-FSM model was tested using statistical matrices such as coefficient of determination (R2), maximum relative errors (MRE) and Nash-Sutcliff efficiency coefficient (NSE). The model was simulated under four scenarios: Scenario 1- Enhancing food production; Scenario 2- Reducing crop and livestock losses; Scenario 3- Combination of scenario 1 and scenario 2 to provide holistic approach to deal with food security; Scenario 4- Combination of Scenario 3, along with limiting livestock sale to promote consumption from 2022 to 2050. The model indicates that food demand will increase in future, based on population growth. Even though all the scenarios showed improved food security (in terms of food available, consumption, and sufficiency) when compared to the business-as-usual scenario, scenario 3 is the only one to result in a positive food consumption and sufficiency and thus increase food security.

The paper also connects with the broader dissertation goal of identifying leverage points (action points) for influencing system behavior to create food secure futures. Given the linkages between production, yield losses, human wildlife conflicts and food security, which crosscut the social-ecological realm of food system, scenario 3 indicates the importance of complex interactions and dynamics in social-ecological system. The inability of scenarios 1 (which focuses on production) and 2 (which focuses on reducing losses) to achieve food sufficiency also points to the ineffectiveness of sector-specific policies and calls for system-wide action to achieve food security. Therefore, the leverage point is in making system-aware interventions that consider the intricate and unpredictable web of relationships and linkages between production, losses, and food security in Naitolia.

Our results were able to show what combination of variables lead to positive food consumption and sufficiency. Our work also proved SDMs as useful tool – they acknowledge the dynamic interconnections between system components, allowing the replication of non-linearity and unintended consequences. Future work should take this paper as a foundation to add more system components such as dietary diversity, food utilization, water resource management, land use changes, climate change, gender dimensions and socio-political settings. Structural changes like education, health care, livelihood and governance could also be expanded.

Even though many SDMs are developed to simulate food security, SDMs focused on agro-pastoralist food systems are scarce. On the contrary, other studies on food security in agro-pastoralist systems are reductionist, linear, and do not provide context of how variables and components interact in the system. After creating an SDM for an agro-pastoralist context, we provide the first system-based insights for Naitolia, Tanzania, building on information through community's input. Our approach, using participatory approaches to inform a CLD and then SDM, can be parameterized by others for other agro-pastoralist contexts. However, if a similar study is undertaken with different stakeholders such as the government or non-governmental organizations, the resulting system structure and range of scenarios may vary. Nevertheless, our study indicates that SDMs are a good method to explore such a complex issue as food security and provide a decision-making tool to test what-if situations when making management plans for food systems.

CONCLUSION

The dissertation significantly advances our understanding of Tanzania's agro-pastoral food systems as social-ecological systems by highlighting system elements and patterns within the dryland agro-pastoralist food systems that are posing a threat to food security. Through the identification of important social, economic, and structural capacities that exist to deal with food insecurity in presence of climate shock, the dissertation was also able to suggest intervention pathways for effective adaptation building efforts. The dissertation was also able to identify management priorities based on a variety of scenarios to aid in the decision-making process for achieving food security. In creating these analyses and findings, the dissertation also creates methodological advancement in the understanding of complex processes that affect food security under climate shocks by utilizing a variety of approaches that support system thinking - systems archetypes, statistical modeling, and simulation through a system dynamics model. With this both objectives and overarching goal of the dissertation, as explained in the introductory section of the dissertation, is fulfilled. In the sections below, I discuss resilience questions, and overarching goal of the dissertation - identifying leverage points; and innovating a multi-method approach to resilience assessment.

Resilience assessment requires identifying what will be made resilient to what, for whom (Carpenter et al. 2001). The goal of the first paper was to answer, “resilience of what, to whom”, i.e., resilience of dryland agro-pastoral food system for Maasai living in the Northern Tanzania. The paper’s methodological innovation was to use system archetypes as a diagnostic tool to identify the elements and interactions in the agro-pastoralist food systems in Naitolia and then as a prescriptive tool to find leverage points to counteract feedbacks that are impeding the achievement of food security in agro-pastoralist food systems. Since there is little study on agropastoralism in Naitolia, Northern Tanzania that focuses on ensuring food security, I used a variety of techniques (including context analysis and in-depth interviews) to produce Causal Loop Diagrams (CLD) that give a comprehensive picture of the food system in Naitolia. The use of mixed methods helped to offer a variety of knowledge, empowerment, and context awareness. The mixed methods approach was also able to capture more holistic and nuanced analysis and enabled better understanding of food system structure. For instance, the CLD developed through content analysis shows tri-party Escalation between wildlife conservation, agro-pastoralism, and cropping, while CLD developed through interviews reflects Escalation between agro-pastoralism and cropping. If I had used either one of the data collection techniques, I would have overlooked a key conflict situation with an implication to food security. Likewise, Shifting the Burden archetype in content analysis reflects livestock domestication, reduced food availability, expansion of agricultural land, while interviews show water scarcity and dependency of external support such as TPP. Using two methods have led to more thorough understanding of unintended consequences occurring in Naitolia and in Northern Tanzania by revealing information on cross-scale interactions that happens in agro-pastoral food systems.

Together, the use of two datasets helped in mapping how stakeholders and actors engaged in the food system in terms of competition and Escalation. At the end of the analysis, I was also able to demonstrate that the existing policy provisions (such as livestock domestication, and agriculture and conservation area expansion based on The Wildlife Conservation Act, Agriculture Sector Development Strategy, and Livestock Master Plan (USAID 2013)) do not consider the long history of Maasai culture and sustainable agro-pastoralism, and as a result, system components have undergone continuous modification in response to environmental and socio-political changes. As a result of this experience, I can recommend that the system archetype and CLD tools could be utilized widely in resilience assessment because they aid in creating the conceptual model of a SES focus system, identifying associated resources, stakeholders, and problems, and therefore answering "resilience of what, to what, and for whom".

While system archetypes are excellent at identifying the root cause of a problem at the spatial scale, they fall short in demonstrating the relationship between system variables and feedback at the temporal scale. In the Escalation archetype in Paper-I, for example, through the balancing loops that produced the conflict situation, I was able to demonstrate the intensity and strength of the conflict between multiple land uses, but the archetype offered no information regarding the frequency and timing of the conflict. For instance, the dispute might be still going on or might have happened a year or ten years ago. Likewise, the conflict situation may not be as straightforward as illustrated in Paper-I, and there may be additional interrelated problems related to poverty, equity, and inequality leading to the conflict that I have not considered in my analysis due to study constraints. Meadows (2008) used poverty and drug addiction example in the US to show this complexity in real life.

Paper-I recommends ways of reversing system archetypes through destocking and undertaking conflict resolution mechanisms etc., which may entail altering the system's rules, power distribution, goals, and ultimately, its paradigm. These adjustments reflect the most difficult types of leverage points (Meadows and Sustainability Institute 1999, Abson et al. 2017, Fischer and Riechers

2019). They require investing time, effort, and money, which are often not done until after the crisis has passed (Meadows 2008). Therefore, system archetype analysis creates results that are idealistic and often difficult to achieve without challenging existing goals, power structure, and rules of the system such as incentives and constraints.

One method for addressing temporal concerns is to add behavior over time (BOT) graphs to system archetype analysis, which demonstrates a pattern of change and how problems increase and decrease over time. BOT graph is also one of the fundamental tools for modeling and comprehending various systems (Calancie et al. 2019). Understanding complexities calls for repeated research that uses multiple methodologies to consider multiple system elements. For instance, the community's input was not incorporated in Paper-I; further research can use this work as a baseline and add the community's input via qualitative data collection and participatory modeling to account for a variety of concerns and feedback. With regards to changing system goals, power structure, and rules of the system, it is important to strengthen the relationship both within and between communities, land uses, and the government. It opens opportunities to those belonging to less powerful or excluded groups by fostering trust and reciprocity between multiple groups (Pretty 2003). Nevertheless, the outputs from system archetypes are still useful when planning for future resilience, and system archetypes could be used to identify recurring patterns of behavior that either build or erode resilience and inform appropriate management.

Likewise, the Paper-II is dedicated to discussing “resilience of what, to what”, i.e., the past resilience of Tanzanian food systems to different shocks. The Paper-I is based on secondary data collected in 2013/2014 to create a structural equation model that depicted the association between various adaptive capacity factors with dietary diversity and consumption expenditure. In general, this method was statistically able to identify factors that had direct and indirect effect on the dependent variables, i.e., dietary diversity and household food consumption expenditure. Regarding "resilience of what," I learned about Tanzania's socioeconomic factors at the national level through this research, including infrastructure, residential development, assets, income, etc., which were not discussed through system archetypes. In addition, I discovered that there are more diverse sorts of shocks reported at the national level than were present in Naitolia, such as fire, floods and land loss, providing an opportunity of creation of a shock index that contained a variety of shocks. Importantly, the method could also determine whether the effects of shock could be reduced by adaptive capacity, and it discovered that adaptive capacity mediates the impact of shock on food security at the national scale. Overall, SEM can test theory-based inferential studies, like this one where I tested adaptive capacity components based on the earlier literatures, that can direct policy formulation to concentrate on pertinent response mechanism based on path diagrams.

Even though SEM have excellent predictive power, they fall short in illuminating underlying causes of behavior such as why wealth and income contributes differently to adaptive capacity even though statistically, they may be explainable in terms of correlation. The method of using secondary data also did not provide the complete understanding of the system, it missed out most of the ecological variables. The fact that dataset did not specifically have the variables such as crop, and livestock production, water use, stakeholder's information etc. is a significant drawback of using secondary data as it did not provide all the desired information about the system. Since I have no control over the information in the data set because I did not gather the data, the lack of certain data types frequently restricted the analysis and changed the initial questions I was trying to address related to the system structure and components. Nevertheless, having access to secondary dataset during COVID-19 pandemic meant I could continue the study even when I couldn't travel to study area for data collection. Furthermore, if mixed with other qualitative and participatory data within the same study, secondary data is valuable and can probably provide various viewpoints and provides another option for triangulation or provides a bigger sample than I could collect by myself. I am not against using macro-level studies based on secondary data for resilience studies, but since the NPS dataset lacked several of the variables I wanted to utilize in my research, I would suggest exploring for other datasets that did. To achieve the analytical goals, it is also a possibility to combine two or more datasets. However, in my situation, I was unable to purchase datasets like the Tanzanian census data since I lacked the necessary funds. Therefore, in the future I would also recommend prioritizing the participatory and qualitative methods as they are more likely to better support a case-based approach where information on system structure, components, issues, cross-scale interactions, adaptive governance, institutions, and social networks can be attained which helps to answer the question of "resilience of what and to what".

Paper-III is dedicated to discussing "resilience of what, to what", i.e., resilience of Tanzanian food systems to different shocks but with a future-facing focus compared to Paper-II. The paper used System Dynamics Modeling (SDM) to demonstrate system structures, feedbacks, and interactions within the food system, clearly answering "resilience of what" question. The findings were also able to demonstrate which factors work together to increase food consumption and sufficiency. The Causal Loop Diagram developed through focus group discussion was able to draw connections between multiple shocks and socio-political dimensions also answering the question of "resilience to what" as post-harvest losses, and food losses due to human-wildlife conflict. My research also demonstrated the value of SDMs as an important resilience assessment tool since they recognize the dynamic relationships among system elements, enabling the replication of nonlinearity and unexpected effects.

SDMs look forward and explore the outcomes of different actions in the SES. The process of developing SDM involves constructing a CLD and then translating it into a stock and flow diagram. Sometimes the significance of stock accumulation processes is overlooked because the value of feedback structure in shaping behavior is overemphasized. According to Richardson (1986), the way to avoid this situation is by taking a step back and trying to figure out how the stock variable will behave over time. Multiple researchers, members of the community, etc. can participate in the same activity to observe how the stock variable reacts over time. We will begin to comprehend the stock's accumulation process as we repeat this activity. This does not exclude us from using CLDs to understand system structures, as they are the most effective means of conveying feedback and system structures, but we must use caution when doing so.

Likewise, there are hard and soft variables in the CLDs - hard variables are easily measured and the data is easily available (Sterman 2000). On the contrary, soft variables are mostly related to factors such as goals, aspirations, trust, etc. for which numerical metrics are not available. As a result, most of the soft variables are difficult to translate into stock and flow diagrams due to a lack of data availability (Sterman 2000). In addition to the challenge of data availability with soft variables however, there was also a lack of context-specific Naitolia-level data to verify the model's hard variables, particularly regarding socio-political dimensions such as gender, institution, governance, health care, education, and climate related shocks such as drought, erosion, disease, and pests. Therefore, a solution is to integrate primary data from the case study.

The overall goal of this dissertation is also to identify leverage points to create resilience to shocks in dryland agropastoral system. For agro-pastoralism, resilience is not a one-time need to deal with a specific type of shock, but rather the idea of continuously learning and self-organizing to develop capacity to decrease food insecurity with recurring and unforeseen shocks (Folke, 2016). To put these ideas into practice, I summarize the leverage points identified from each chapter and then list the learnings for agro-pastoral food systems in general and contextualize those for Naitolia in

Table 6. The findings from each paper are briefly summarized in the first column with the header "Paper." The design goals, which I define as - where or how one wishes to be in comparison to where they are right now in the present, identified in each paper are displayed in column two. One requires actionable points to change to transition from the present condition to the future state. Therefore, the leverage points that are actionable at the relevant scale—Naitolia—are broken down in column three. Theoretical insights into the agro-pastoral food system's resistance to food insecurity are presented in column four, which expands on the resilience tenets proposed by Biggs et al. *(2015).*

Table 6 Summary of design goals and leverage points for Naitolia, Tanzania and learning for agro-pastoral resilience to food insecurity in drylands.

Paper-I showed three archetypes: Limits to Growth, Escalation, and Shifting the Burden	Addressing feedback loops to tackle Limits to Growth.	• Destocking to avoid overshoot and collapse. • Grazing land management that ensures adequate recovery period.	Food system's carrying capacity, resource demands, and motivation affects longevity of the system
	Conflict resolution mechanism to reduce Escalation.	• Participatory planning and community engagement exercises with multiple land uses that is facilitated by NGOs and academia. • Introduce multi-sectoral policies (within the department of agriculture, livestock development and wildlife conservation) that incorporates concerns about agro-pastoralism. • Ensuring tenure security for agro-pastoralism by assessing and then strengthening the agro-pastoral rights to resources (pastoral land and water) in terms of (1) access and withdraw, (2) manage, (3) exclude, (4) Alienate (Schlager and Ostrom 1992).	Unequal power relations among resource users undermine access to resources that create vicious cycle of inequality and marginalization in the system. Fostering platforms for multiple actors to connect promotes linking capital and reduces conflict.

Table 6 (cont'd)

	Addressing problems through fundamental solutions than symptomatic solutions.	• Establish community-based activities like cooperative farming and cooperative livestock raising that encourage risk and profit sharing, knowledge and information sharing, and community empowerment and bonding through the provision of resources (inputs and money) and trainings. • Establish cooperatives at the village level that enables agro-pastoralists easy access to loans and savings through providing monetary input, and trainings on cooperative by laws, good governance, record keeping and monitoring. • Establish polycentric governance units to ensure cooperation for agro-pastoral issues in all subsidiary jurisdictions.	Strengthening institutional strengthening promotes bonding social capital. Having multiple governance units addresses agro-pastoral food insecurity problems at the right time at the right scale by the right agency.

Table 6 (cont'd)

Paper-II showed relationship between adaptive capacity and food insecurity in the presence of shocks.	Increased adaptive capacity (income, wealth, and infrastructure)	• Prioritize and deliver funding for poverty alleviation and asset generating programs. • Budget allocation for capacity building (training and extension) so that households can diversify income. • Build infrastructures such as food storage, drinking water and transportation etc. • Increase access to credits and loans establishing cooperatives and loan agency at the local level followed by creating awareness and capacity building.	Income diversification, wealth and access to resources through infrastructures provides insurance and fallback mechanism during times of stress and shocks.
	Frequently testing and understanding the causal relationship between adaptive capacity and food insecurity		Given the dynamic complexities due to shocks and social-ecological variables, knowledge of the system is incomplete; therefore, requires continuous learning and experimentation.

Table 6 (cont'd)

Paper-III showed the combination of increased production and reduction in losses results in food sufficiency	System wide intervention that acknowledges the relationship between social-ecological components from production to consumption of food.	• Increase production of multi-functional and climate resilient crops such as pigeon pea, promote inter-cropping practices and promote drought resilient cattle adaptive to local conditions. • Allocate budget and research priorities for infrastructure and capacity building to reduce post-harvest losses • Increase community awareness of wildlife monitoring, crop-livestock insurance schemes and infrastructure building. • Introduce organic farming; and integrated pest management practices for increasing production, whilst also reducing losses due to diseases and pests. • Livestock vaccinations, cattle dip programs.	Stress tolerance and diversification provides both persistence and flexibility towards shocks. Foster complex adaptive thinking to understand web of connections between system components, and relationship between actors and multiple land uses.

The learnings from the column four in Table 6 is summarized into seven theoretical insights for building resilience in agro-pastoral food systems that are elaborated in the section below. The theoretical insights have been organized to correspond with Biggs et al. (2015)'s resilience principles because I am interested in building desirable resilience with the leverage points in Table 6 and they offer a framework for doing so.

4.1 Addressing system's carrying capacity and feedback loops.

This theoretical insight correspondents with (Biggs et al. (2015)'s resilience principle on "manage slow variables and feedback". SES exist in a variety of self-organizing configurations or "regimes" that are sustained through feedbacks (Brock and Carpenter 2010). The Limits to Growth archetype identified in Paper-I suggests that one of the key leverages for sustaining food security is to monitor feedback loops and ensure that the carrying capacity is not exceeded. Otherwise, it will result in an "overshoot and collapse" scenario that will cause irreversible change to the agro-pastoralist system (Ford 2000) such as the pastoral ecosystem transforming into a desert or another environment where an agro-pastoral system cannot subsist (Foley et al. 2003, Biggs et al. 2018). The archetype has shown that leverage for moving forward with food production in agro-pastoralist systems does not necessary lie in accelerating the growth, but rather anticipating and building resilience to the pressures that are building in the system (Braun 2002). Likewise, it is important to monitor the balancing phase, which in many cases go unnoticed or delayed because potential constraints in the system may arise from slow variables like drought or land degradation. If the limiting constraints, like drought, go unaddressed, the loop can lead to a rapid decline because the system's capacity is outstripped by continued growth. Therefore, addressing feedbacks is an important design goal for keeping food systems functioning, by identifying them before they can pass from food secure to food insecure state.

In case of Naitolia, to achieve this goal the leverage point of destocking of livestock can address the overshoot and collapse situation. Throughout the world, many payments for ecosystem services (PES) have successfully compensated agro-pastoralists for destocking through direct payments, input support and insurance mechanisms (Roche et al. 2021, Yang et al. 2022), which can be replicated in Naitolia. Simultaneously, the state should facilitate and promote organized herd movements, and rotational grazing interventions that allows enough time for pasture to generate during droughts and disturbances.

4.2 Fostering platforms for multiple actors to connect across networks by promoting bridging social capital.

This theoretical insight correspondents with Biggs et al. (2015)'s resilience principle on "manage connectivity". Through Escalation archetype in Paper-I, I've demonstrated how unequal power dynamics among resource users have hampered access to resources, creating a vicious cycle of inequality and marginalizing of agro-pastoralists in the system. As seen in most of the conflict situation in common-pool resources, the lack of platforms to map their perceptions of threat and collaborate to prioritize everyone's demands to find a resolution to the conflict may be one of the causes of conflict (Mwangi 2007, Fleischman et al. 2014, Rommel et al. 2015).

Therefore, the design goal lies in promoting social capital between multiple land-uses which Pretty (2003) calls "bridging social capital". The leverage point for achieving the design goal involves stakeholder engagement, participatory planning and knowledge sharing among multiple land users for trust building and power sharing (Fleischman et al. 2014, Rommel et al. 2015). Since bridging capital enhances communication between actors across networks or land-uses to make informed decisions about each other's needs, perceived threats and may enhance in developing trust and reciprocity and simultaneously reducing conflict situation (Pretty 2003), which concurrently helps to build resilience.

At the Naitolia scale, to achieve this design goal, the leverage point lies in stakeholder engagement and participatory planning activities which may be facilitated by NGOs and academicians to map threats and prioritize solutions. At the national level, multi-sectoral policies must be developed along with the establishment of a governance structure tailored toward agro-pastoral needs that go beyond the traditional boundaries of individual sectors like agriculture, livestock, and conservation, etc., to foster relationships between various land uses and reduce conflicts. This governance structure can evaluate and strengthen the tenure arrangement for agro-pastoralism, which can be defined in terms of access (right to use resources such as pasture and water), manage (right to control how pasture and water can be used), exclude (right to choose who will have access), and alienate (right to lease management rights) (Schlager and Ostrom 1992).

4.3 Strengthening institutional strengthening for promoting bonding social capital.

This theoretical insight also correspondents with Biggs et al. (2015)'s resilience principle on "manage connectivity". The first paper of this dissertation noted that one of the ways to deal with Shifting the Burden archetype is through strengthening the agro-pastoralist institutions that focus on the fundamental solution to managing water scarcity rather than symptomatic solutions. Strengthening of traditional agro-pastoral institutions is likely to increase bonding (such as sharing resources and information between kinship) which in turn enhances collective action (Pretty, 2003). Collective action further strengthens policy and institutions (McGinnis & Ostrom, 2014; Pahl-Wostl & Knieper, 2014) which acts as the means of delivery of external resources and technology to deal with food security problems (Agrawal, 2008). Social connectivity can enable fair distribution of burden of shocks and adaptive capacity across all sectors for leveraging positive adaptive responses against food insecurity.

As a result, one of the design goals in dealing with food security is to encourage bonding capital, as it helps to facilitate resource and knowledge sharing to increase cooperation and collective action to various shocks within the agro-pastoral group. (Adger, 2003; Adger et al., 2009). Establishing collective activities like collective farming and livestock raising practices that promote risk and benefit sharing, knowledge, and information sharing, and building trust and reciprocity by offering resources and trainings is the leverage point for achieving this design goal at the village level in Naitolia. These initiatives will encourage local food production and encourage people to share resources when necessary. As a result, the dependency toward external sources such as migration may be reduced. Like this, encouraging credit and saving facilities at the local level boosts economic engagement within the community and gives residents more power by giving them a safety net when taking risks.

4.4 Promoting polycentric governance to addresses agro-pastoral food insecurity problems at the right time at the right scale by the right agency.

This theoretical insight also correspondents with Biggs et al. (2015)'s resilience principle on "promote polycentric governance system". Polycentricity is a governance system with multiple nested and overlapping centers of decision making or governing entities with autonomy to formulate and enforce rules within a specific socio-political setting (Heikkila et al. 2018). The role of polycentric governance as a leverage point, is seen throughout Paper-I, Paper -II and Paper-III, to fulfill design goal of addressing problems through fundamental solutions. Leverage lies in creating well-connected governance units that can deal with both agropastoral rights over food and respond to disturbance and uncertainty as they are addressed by the right stakeholders and actors at the right time. Such multi-scalar governance is commended for maintaining and restoring diversity, connectivity, learning, and participation for equitable and sustainable management of resources that has implications for resilience (Thompson et al. 2009, Ojha 2014). Because polycentric governance enables greater policy innovation and diffusion across multiple organizational units, through regulatory instruments like financial incentives for destocking, or self-regulation, polycentric systems provide opportunity to address food insecurity at the various level. In comparison to monocentric governance, polycentric governance is thought to offer greater chances for representation of various social actors. Because of this, its inclusivity might be seen as a more righteous style of government

(Aligica and Tarko 2012). Polycentric governance can facilitate the creation of custom, purpose-fit solutions by fostering innovation and experimentation across several organizational divisions (Lebel et al. 2006). It also offers a degree of adaptability and quickness that conventional hierarchies might not be able to offer. Additionally, polycentric governance is thought to be more reliable because several other portions of the system can take over if one part of the system fails (Cox et al. 2010). Therefore, polycentric governance is an important leverage point in dealing with food security – the right well-connected institutions at the right time can deal with both agro-pastoralist rights to food and respond to disturbance and uncertainty,

In case of Tanzania, it will be crucial to comprehend and coordinate the direct interactions between the centers in a polycentric governance system. This includes everything from acknowledging institutional integration and the interdependence of various actors (such as those operating within the Ministry of Agriculture, Ministry of Livestock and Fisheries, and Ministry of Natural Resources and Tourism) to strategically planning interactions between actors with various preferences and capacities (e.g., via transfer and compensation schemes such as insurance for destocking).

4.5 Diversification of income, resources, and infrastructure to provide insurance against shocks.

This theoretical insight also correspondents with Biggs et al. (2015)'s resilience principle on "maintaining diversity and redundancy". In the Paper-II of this dissertation, it was discovered that wealth and income diversity made significant contributions to the adaptive capacity index and were able to lessen the effects of shocks on household consumption spending and dietary diversity. Diversification of income and resources is one of the design goals for achieving food security since the existence of numerous income sources and assets provide insurance by allowing components to make up for the loss or failure of others. Tanzania should prioritize asset development and poverty reduction initiatives at the national level as a leverage point for boosting food security resilience. The leverage points here are to prioritize and allocate budget and resources for asset building programs, capacity building, and developing infrastructure building so that households could have access to additional income sources, which provides fallback mechanisms during time of stress.

The only scenario that led to a reduction in crop losses and an increase in food production is Scenario 3 in Paper-III, which also produced more food. Naitolia relies on maintaining diversity by adopting mixed cropping in dryland agro-pastoral households, such that the loss of any one crop will not have a catastrophic impact on access and availability of food. This is the leverage point for achieving household food insecurity. Mixed cropping and home-gardens, a holistic system that focuses on soil health and uses local input, is shown to be admirable fit for drylands (Watson and Eyzaguirre 2002, Manaye et al. 2021). By allowing components to make up for the loss of other components, the presence of functional redundancy, or several components that carry out comparable functions, provides insurance within a system.

4.6 Learning and capacity building.

This theoretical insight also correspondents with Biggs et al. (2015)'s resilience principle on "encourage learning". The agro-pastoral food system as a social-ecological system is dynamic and are constantly changing, which demands constant revision in existing knowledge and capabilities (Folke, Hahn, Olsson, & Norberg, 2005). Therefore, learning and capacity building is an important design goal to enhance resilience that must be supported by continuous testing and experimentations as a leverage points. For instance, Paper-II was able to show a relationship between adaptive capacity components and food insecurity, however the relationship may change due to changes in severity and intensity of shocks. Therefore, learning, experimenting, articulating, and evaluating through is a crucial design goals for dealing with such uncertainty and change (Hodbod, Barreteau, Allen, & Magda, 2016). The leverage point here lies in community engaged research, working collaboratively with agro-pastoral households to constantly learn about the systems components, feedback loops, how the rules of the system such as incentives, punishments and constraints have affected certain group over the other in terms of food security.

In addition to the community engaged research, making informed decisions in the cases of Tanzania and Naitolia will depend on collaboration with academic institutions and research organizations to conduct studies on developing and testing technologies such as cattle dip programs to fightt against cattle parasites, or stress tolerant crop varieties. In the same way, measures to reduce human-wildlife conflict must be tested and evaluated while utilizing adaptive management (highlighted in Paper-I). Similar to this, boosting integrated pest management, animal disease management, and dryland farming (Paper-III) necessitates learning by doing by putting alternative management strategies to the test under the leadership of research organizations. In addition to learning by doing, the leverage point is knowledge exchange among various actors, communities, and the prioritization of best practices in policy making. Institutional strengthening and polycentric governance, as described above, can allow the cross-scale learning and capacity building amongst actors.

4.7 Understand complex interactions between social and ecological components.

This theoretical insight also correspondents with Biggs et al. (2015)'s resilience principle on "foster complex adaptive systems thinking". Understanding the complex relationship that exists between actors and resource systems helps to understand the web of connections and interdependencies and to recognize barriers to cognitive change that would foster resilience, therefore it is one of the design goals. Both Paper-I and Paper-III in this dissertation made it clear that there are multiple sub-systems like agro-pastoralism, crop-production, and wildlife conservations that are always interacting within the larger dryland agro-pastoral food systems. Within these sub-systems, it is crucial to recognize the interconnection of agro-pastoralists' need for mobility and water during the dry season.

The leverage point for promoting complex interactions between social and ecological components lies in institutional restructuring from sector- and geographical based institutions to landscape-based and multi-sectoral institutions that match the social-ecological conditions. As seen in Paper-I, the agro-pastoral system extends beyond the village level and can be a threat to other land-uses. A landscape-based institution can simultaneously achieve social, economic, and environmental objectives within a landscape, where multiple land uses, people, institutions, and values can interact. Establishing a landscape-based institution is a leverage point because involves applying multiple tools, methods, concepts, and approaches to understand and manage interconnections between different land uses to achieve diverse objective and secure benefits for diverse stakeholders. The resilience of agro-pastoral food system can be improved by management that is based on this model because it will acknowledge the linkages between social and ecological components and the frequently complicated dynamics they produce.

Abson et al. (2017) ranks leverage points based on four 'realms of leverage': (1) Modifications to parameters; (2) Modifications to feedbacks; (3) Modifications to the system's design (design objectives); and (4) Modifications to the system's intent. The 'realms of leverage' is based on Meadows (2008), where distinction between leverage points are made based on importance—where interventions are simple but have little chance of bringing about transformative change (modifications to parameters) to interventions that are challenging but have a lot of chance of bringing about transformative change (Modifications to the system's intent). I tried to rank the design goals in order of importance based on Abson et al. (2017)'s four 'realms of leverage'; because Abson et al. (2017) especifially talks about leverage points and not the design goals, I also bring in

Ostrom (2009). Ostrom (2009) asserts that implementation of action points may also be affected by the size and scale of the system (agro-pastoralism) and the users (agro-pastoralism, cropping, wildlife conservation etc.). For instance, the leverage point of undertaking stakeholder engagement, and participatory planning under the design goal of 'Fostering connectivity between multiple actors across networks for promoting bridging social capital' may be more effective at a village or community scale than at a regional scale because the impact of users size on transaction costs of self-organization tends to be negative given the higher costs involved in bringing users together and reaching consensus on change. Very vast territories are also unlikely to self-organize in land-related resource systems, such as pastoral land, due to the high costs associated in defining boundaries (such as by surrounding with signs or fences), monitoring use patterns, and gaining ecological knowledge. Smaller regions also do not produce significant flows of valuable goods.

Although each of the seven design goals is essential to achieving resilience in dryland agro-pastoral systems, I've chosen to focus on only three of them here for the sake of implementation priority:

(1) Diversification of income and resources because diversification provides insurance against failures.
(2) Fostering connectivity between multiple actors across networks for promoting bridging social capital.
(3) Ensuring polycentric governance so that the right well-connected institutions at the right time can deal with both agro-pastoralist rights to food and respond to disturbance and uncertainty.

To conclude, this dissertation used multi methods approach and mixed-scale analysis where Paper-I is scaled at regional level, and Paper-II and Paper-III are scaled at national and village levels respectively. The dissertation provides a model for resilience assessment in food systems.

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APPENDIX A: CODEBOOK DEVELOPED FOR THE CONTENT ANALYSIS

Table 7 Codebook for the Content Analysis.

Theme	Code	Definition	Rule for applying Code	Example when the code applies
R and D for agriculture development	RESEARCH_A	creative and systematic work undertaken to increase the stock of knowledge	Apply anytime document mentions collection, organization, and analysis of information to increase understanding of food security and drought for agriculture.	The focus is on capacity building and input support in agriculture.
R and D for pastoral development	RESEARCH_L	creative and systematic work undertaken to increase the stock of knowledge	Apply anytime document mentions collection, organization, and analysis of information to increase understanding of food security and drought for livestock production.	A lot of vaccine research is undergoing to manage livestock diseases.
Livestock domestication and commercial farming	LIVESTOCK	A domesticated animals raised in an agricultural setting to produce labor and commodities and sale.	Apply anytime document mentions rearing animals for commercial and market perspective.	The changes in *livestock production* have had important implications for economic efficiency, and sustainable livelihood
Herd Size	HERD	A crowd of livestock raised together.	Apply anytime document mentions number of livestock raised together	Reported herd size among the pastoralist group is 2-400 livestock.
Livestock Production/ products	CATTLE	Livestock products or livestock used primarily for household consumption; and only surplus sale.	Apply anytime document mentions livestock products or livestock used primarily for household consumption, and only surplus sale. Apply anytime document mentions rearing animals both by landless and small and marginal people.	

Table 7 (cont'd)

Biodiversity and habitat loss	BIODIVERSITY	Loss of different species, habitat, and ecosystem	Apply anytime document mentions loss of any plant / animal species, habitat, or ecosystem that affects pastoralism.	There are no more indigenous cattle.
Policy and institutional support for food security	POLICY	Pertinent policy supporting food security	Apply when a document mentions any training, material, monetary or policy help to alleviate food security	Government supports agriculture over livestock.
Productivity from agriculture	CROP	the produce of cultivated plants, especially cereals, vegetables, and fruit. the amount of such produce in any season.	Apply anytime a document mentions growing any cereals, legumes, vegetables etc.	The agriculture production is mostly due to expansion not due to intensification
Food availability	AVAILABILITY	enough quality food from domestic agriculture production or import.	Apply anytime a document mentions food production, distribution, and exchange.	Drought makes it difficult to grow food.
Drought or dryness Merged with increased temperature and erratic rainfall	DROUGHT	Lack of rainfall over a larger period from weeks to years.	Apply anytime a document mentions dryness in soil and air exacerbated by extreme heat and wind.	The soil is very dry; difficult to grow.
Pastoral mobility	MOBILITY	Pastoral mobility implies that pastoralists can move to areas with pasture for their livestock.	Apply anytime document mentions pastoral mobility because of unforeseen events, e.g., outbreak of disease, bush fire, locust. attack, can be mitigated.	

Table 7 (cont'd)

Soil fertility	SOIL	Fertile soil provides essential nutrients to plants, while supporting a diverse and active biotic community that helps the soil resist environmental degradation.	Apply anytime document mentions soil's ability to sustain plant growth by providing essential plant nutrients, as a habitat for plant growth.	
Pastoral productivity	GRAZE	A field covered with grass or herbage and suitable for grazing by livestock.	Apply anytime document mentions about pasture, and pastureland, common land, commons - a pasture subject to common use.	The pastoral land is decreasing because of the focus on settled agriculture.
Livestock disease	DISEASE	Abnormal condition that affects livestock production and health	Appy anytime the document mentions livestock diseases and health	The diseases associated with cattle include ringworm, Q fever, chlamydiosis, leptospirosis.
Post-harvest loss	LOSS	loss (PHL) of food crops, during or after harvest,	Apply anytime the document mentions the degradation in both quantity and quality of a food production from harvest to consumption.	Post-harvest losses and quality deterioration of horticultural crops are mostly caused by pests, microbial infection, natural ripening processes and environmental conditions such as heat, drought and improper post-harvest handling.

Table 7 (cont'd)

Traditional management	INSTITUTIONS	Shared rules that prescribe, permits, or advises actions or outcomes for individuals/ actors regarding use and management of land/resources/ pasture etc.	Apply anytime document mentions formal or informal ruling that individuals have used when interacting within a wide variety of repetitive and structured situations at multiple levels of analysis regarding use and management of land/resources/ pasture etc.	
Migration	MIGRATE	the movement of people from one place to another with intentions of settling, permanently or temporarily, at a new location (geographic region)	Apply anytime the document mentions movement to another place, often of a large group of people.	Push factors "push" people away from their home and include things like war. Pull factors "pull" people to a new home and include things like better opportunities. The reasons people migrate are usually economic, political, cultural, or environmental.
Expansion of agricultural land	EXPAND	extension of a land for the purpose of agriculture	Apply anytime land is extended for the purpose of agriculture by law	
Land privatization	PRIVATE			

Table 7 (cont'd)

Wildlife policy	W_POLICY	Pertinent policy supporting wildlife or conservation	Apply when a document mentions any training, material, monetary or policy help to national park or conservation	
Conservation area expansion	EXPAND-WILD	extension of a national park/conservation	Apply anytime national park and conservation areas are expanded by law	

APPENDIX B: CAUSAL LOOP DIAGRAM DEVELOPED THROUGH THE CONTENT ANALYSIS

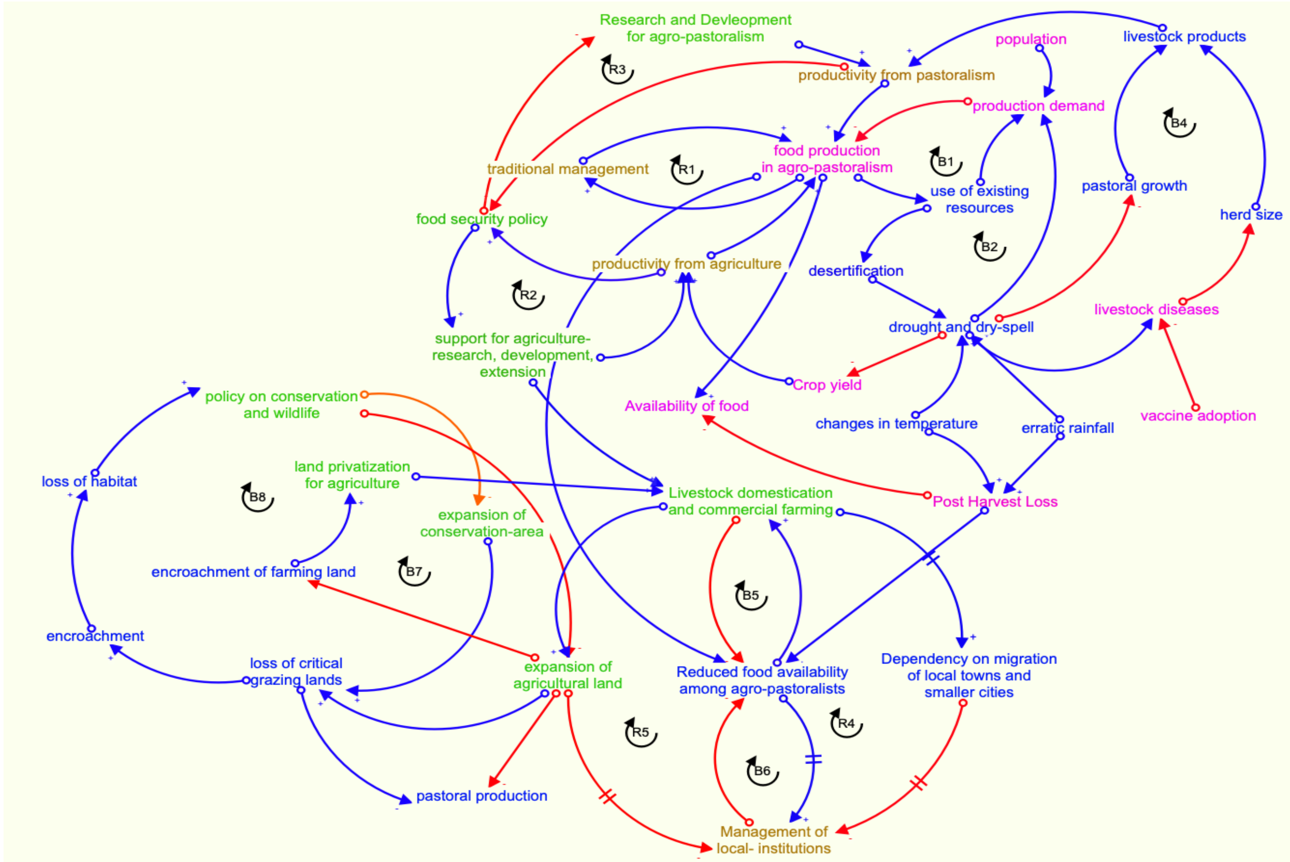

Figure 23 Causal Loop Diagram (CLD) developed through content-Analysis. The variables are interacting either locally, regionally, both locally and regionally, or nationally, as indicated by the variables' respective colors of pink, blue, brown, or green. The linkages between two variables are positive if they are blue; otherwise, they are negative. Reinforcing feedback loops are represented by loops R, whereas balancing feedback loops are represented by loops B.

APPENDIX C: PROTOCOL FOR AN IN-DEPTH INTERVIEW

Interviewee (Title and Name):

Date and Time:

Institution: Michigan State University

Interviewer: Shubhechchha Sharma

Introductory Protocol

My name is Shubhechchha Sharma, and I will interview you today as a part of my PhD dissertation. The goal of my dissertation is to find leverage points, point of intervention, in dryland food systems to deal with drought risks. In order to find the leverage points, I have done extensive literature review in the subject area and would like to validate and clarify those findings with you as an expert as you have intensively worked on North Tanzanian Drylands, Naitolia.

You have been identified as an expert given your deep competence, knowledge and experience through research and involvement in the related field.

The inputs from your interview will be transcribed, coded and will be used to develop a Causal Loop Diagram (CLD) and System Dynamics Model (SDM), which will be used for long-term, strategic modeling and simulation.

As a form of notetaking, I would like to record the interview. Only the researcher (interviewee and her advisor) will have privy to the recorded information and will be destroyed after they are transcribed and coded. During transcription your identity will be replaced with codes. *Essentially, this document states that (1) all the information from your interview will be held confidential; (2) your participation is voluntary, and you may skip the question or may stop at any time if you feel uncomfortable; and (3) there aren't any risks or benefits involved in this interview, but you contribute to the research which will help dryland inhabitants to deal with drought risks.*

The interview will last no longer than an hour. During this time, I have several questions regarding food security and Tanzania in general/Naitolia in particular that I would like to cover. Your agreement to continue with this interview indicates your verbal consent for interview and recording – are you happy to proceed? I appreciate you for agreeing to participate in the interview process. Do you have any questions? If there aren't further questions- I would like to begin the interview process. Let me know if you need a minute or so to get ready

[Note: the interviewer will use probes such as "Could you expand more", "Could you provide more details?", "Could you provide some examples?" to obtain more rich and deep information when required.]

A. Interviewee Background

To start the interview: Please describe your current role (researcher, community engagement, etc.) in the related field of study (food systems, dryland, drought)?

Follow up: Could you tell me how long you have been working in this field of study

Probes: How did you get involved in Northern Tanzania /Naitolia?

When was the last time you went to Naitola/Tanzania?

B. General description of the dryland food system in Naitolia; Drought, Disturbance and Uncertainty.

Based on your involvement - how would you describe Naitolia to me? In terms of people, occupation and climate?

So, we're on the same page, I think of food systems are formed of biophysical and social factors linked through feedback mechanisms which at a minimum comprise of the activities related to food production, processing and packaging, distribution and retail, and consumption. Given this definition,

1. Can you describe what are the components of food system at the Naitolia?
   Probes: biophysical (abiotic and biotic factors), social, production/processing/distribution/consumption
   a. Did you notice on how did the people get their food? I assume they did grow their own food, right?
      - What crops and livestock are grown in Naitolia?
   b. If they do not grow their own food, how do they get their food?
      - Probe: What proportion of food do people grow themselves vs. buy/trade/earn by labour?
      - Probe: Can you name few off-farm activities (other than farming and raising livestock) in Naitolia that contributes to obtaining food?
         i. Follow up: How?
   c. How would you describe food security in Naitolia [over recent years]? Probe: 5 years?

- [If there is an annual pattern] Which months are considered severe in terms of food scarcity?

  Probe: Can you tell me in terms of months where there is reduced quantity and quality of food available and consumed?

    - Probe: Food production, availability and consumption.
- When there isn't enough food, what are common responses? (Coping strategies)
- How have NGOs and government programs influenced food security?

d. Is Naitolia any different from food systems in the surrounding region (Northern Tanzania)?

2. What are the current challenges surrounding food systems in Naitolia? i.e., challenges that influence the availability and production of food or food security?

b. How frequent are the droughts? (Probe: how many droughts did you think Naitolia experienced in past 10 years?)

1. How did drought affect the food system?
    a. Probe: Can you explain in terms of pastoral growth, livestock mobility, water availability.
    b. Probe: Can you explain in terms of rainfed agriculture, cereal yield.
    2. Has there been any mortality due to drought?
        a. Probe: Human mortality, livestock mortality.
    3. How about economic losses due to drought?
    4. Other impacts?
2. How did the people respond to the drought in the past?
    1. How effective were they in terms of reducing the duration, severity and frequency of drought?
    2. What worst would it happen, if the people didn't respond to the drought?
    3. What are the TPP activities that have helped?
3. Are there any non-drought challenges that food system in Naitolia is currently facing? Probe: such as diseases, lack of information etc.

1. How prevalent and severe is this challenge?
2. If it happened in the past, how did you solve it.
    a. Probe: Changes in the system of governance, policy changes, economy changes, conflicts?

C. **<u>Ownership and Tenure arrangement</u>**

a. I'd like to understand the governance system in Naitolia. What is the land tenure system in Naitolia?
    1. Who owns the land in Naitolia? Agriculture land, pastoral land?
        1. Probe: Can you clarify in terms of access (can enter), withdrawal (have rights to use), manage the resource, right to exclude others, and full ownership?
    2. Has there been any conflict related to differences in these rights in Naitolia?
        1. Why and with whom did the conflict happen?
            a. Was the conflict due to how pastoral land were allocated?
            b. Has conflict led to more hunger and food insecurity?
        2. How was the conflict solved? (Probe: on their own, from external support.)
            a. Were there any agreements? If so,
                i. What is the monitoring process for compliance?
                ii. What is the sanctioning process for non-compliance?
        3. How likely is it for the conflict to happen again?

b. (Recap answers from a above) Did these rights affect how people respond to the drought in the past?
    1. Probe: Did conflict affect how people respond to the drought in the past?

c. I'd like to ask you something about the institutions. Institutions are shared rules that prescribes, permits or advises actions or outcomes for individuals/ actors. Institutions are both formal and informal. (on the contrary- organizations are corporate actors).
    1. Are there any particular informal local institutions (in Northern Tanzania/Naitolia? Is the local institution recognized by the authority? (Probe: local and national level authority).

Informal institutions are ruling that individuals have used locally when interacting within a wide variety of repetitive and structured situations at multiple levels of analysis.

2. Is decision-making concentrated within a single group or institution, or is a diversity of institutions accepted by stakeholders?
    1. What is the arrangement of this institution with other community? Who establishes the agreement?
3. Have the informal local institutions enhanced or constrained flexibility to address to drought? How?

D. <u>Review section for non-policy experts.</u>

a. Apart from (summarize from above) what are the other reasons for food unavailability and hunger in Naitolia?
b. What are the "top three things" that need to happen in order to solve food security situation in Naitolia?

Is there anything else you think I should know about food systems and drought in Naitolia?

E. <u>Socio-political settings (Note this section is for policy experts)</u>

Finally, I'd like to talk about policy. Can you tell me broadly- what are the existing federal or regional policies that concern food systems and food security in Tanzania?

a. How critical are these policies in terms of achieving food security goals? Probe: What events necessitated creation/changes in the policy?
b. What scales are policies being made at?
    1. How has the broader natural resource policy affected the food system at the local level such as Naitolia.
c. How has government perceived and approached drought risk reduction? Can you explain in terms of food availability and production?
    1. What is the focus of these policies?
        a. Probe: research, providing input, capacity building, development. Can you rank them in terms of priority?
        b. Do you think this is the right order? What should have been the priority?

2. Literature has shown that there are number of laws and policies that overlap with each other making it difficult to implement. What are your thoughts in this?
    a. How clear is the policy in terms of beneficiary household, livelihood groups, interventions and goals?
    b. To what extent do the laws recognize differences in property rights and tenure arrangements?
    c. How about availability and adequacy of information, technology, tools and organizational resources across individuals belonging to different property rights?

2. Are there any social protection strategies that government and agencies are undertaking to deal with droughts?
3. Which agency looks over food system and food security concern in Tanzania?
    1. Is this the same agency that looks after agro-pastoralism?
    2. If the agencies are different, to what extent are they mutually supportive and how clear are their working mandates?
    3. Is the available budget enough to deal with food security concerns across these agencies?

d. How consistent are the laws with international obligations and commitments? Can you explain in terms of market strengthening and infrastructure development?

e. Are there any policy-practice gaps when it comes to achieving food security against the drought?
    1. Are there any best practices at local level that needs scaling up at the national level?

f. Are there any private sector led food initiatives? How are they impacting agro-pastoralists?

Post Interview Comments or Leads:

____

Thank you for giving me your time.

APPENDIX D: CODEBOOK DEVELOPED FOR IN-DEPTH INTERVIEWS

Table 8 Codebook for the interview

Theme	Code	Definition	Rule for applying Code	Example when the code applies
Grazing land (forage biomass)	GRAZE	A field covered with grass or herbage and suitable for grazing by livestock.	Apply anytime an interview mentions about pasture, and pastureland, common land, commons - a pasture subject to common use.	The pastoral land is decreasing because of the focus on settled agriculture.
Feed	FEED	*Food* given to domestic animals, especially livestock, during animal husbandry. There are two basic types: fodder and forage.	Apply anytime an interview mentions fodder and forage.	The good quality of fodder comes during the rainy season.
Herd Size	HERD	A crowd of livestock raised together.	Apply anytime interview mentions number of livestock raised together	Reported herd size among the pastoralist group is 2-400 livestock.
Livestock Production	LIVESTOCK	A domesticated animals raised in an agricultural setting to produce labor and commodities and sale.	Apply anytime person mentions rearing animals both by landless and small and marginal people.	The changes in *livestock production* have had important implications for economic efficiency, and sustainable livelihood
Deforestation and Degradation	FOREST	Act of cutting/destroying trees and shrubs. Purpose clearing of land	Apply anytime interview mentions degrading forest or shrublands by cutting, fire, trampling or eating young branches haphazardly. Apply anytime a person mentions cutting down the trees for agriculture, livestock, settlement etc.	When there is no grazing land available; the cattle destroy the forest by trampling and eating young branches. The area is very dry and few trees that were there are cut down for fuel.

Table 8 (cont'd)

Biodiversity and habitat loss	BIODIVERSITY	Loss of different species, habitat, and ecosystem	Apply anytime a person mentions loss of any plant / animal species, habitat, or ecosystem that affects pastoralism.	There are no more indigenous cattle.
Policy and institutional support	POLICY	Pertinent policy supporting pastoralism and pastoral traditional institution.	Apply when a person mentions any training, material, monetary or policy help.	Government supports agriculture over livestock.
Social capital; bonding capital; linking capital	SOCIAL; BOND; LINK	Network of relationships among people living in Naitolia. Bonding capital occurs among pastoralists; Linking capital occurs among pastoralists with other actors.	*Apply anytime a person mention* links, shared values and understandings in society that enable individuals and groups.	The shared value about livestock is reducing as young people want to go to cities.
TPP Dependency	TPP	a collaboration program working independently of any government, typically one whose purpose is to address a social or political issue.	Apply anytime a person mentions TPP that are not affiliated to the government.	TPP has done a lot of good stuffs in Naitolia.
Institutional and demographic risks	RISK	Possibility of something bad happening	Apply anytime a person mentions risks that allows not meeting the goals or objectives due to age, sex, social economic status, government's policy etc.	The major risk is illiteracy and lack of education.

Table 8 (cont'd)

Collective Action	COLLECTIVE	Collective action refers to action taken together by a group of people whose goal is to enhance their condition and achieve a common objective	Apply anytime a person mentions doing any project or activities together with other agro-pastoralists to achieve a common objective such as water management or pasture management.	The grazing lands were collectively managed by the traditional rules.
Crop Production	CROP	the produce of cultivated plants, especially cereals, vegetables, and fruit. the amount of such produce in any season.	Apply anytime a person mentions growing any cereals, legumes, vegetables etc.	The agriculture production is mostly due to expansion not due to intensification
Human wildlife conflicts	WILDLIFE	when animals pose a direct and recurring threat to the livelihood or safety of people	Apply anytime when a person mentions wild animals attacking livestock and humans, or raiding crops, and retaliation killing.	A lot of what is produced is destroyed by wild animals as the area is close to the national park
Political instability	INSTABILITY	A serious disagreement and argument between different parties	Apply anytime a person mentions clash or dispute.	The situation of conflicts is likely to increase if the government is not clear about their policies.
Food security	SECURITY	having, always, both physical and economic access to sufficient food to meet dietary needs for a productive and healthy life.	Apply anytime an interview mentions not being able to live in hunger or fear of hunger.	After the rainy season, the family doesn't have to worry about food.
Food availability	AVAILABILITY	enough quality food from domestic agriculture production or import.	Apply anytime an interviewee mentions food production, distribution, and exchange.	Drought makes it difficult to grow food.

Table 8 (cont'd)

Food access	ACCESS	Food accessibility refers to the access by individuals to adequate resources for acquiring appropriate foods for a nutritious diet.	Apply anytime a person mentions affordability, location, and allocation of preferred food.	Older people make jewelries, which can be used to obtain food.
Drought or dryness	DROUGHT	Lack of rainfall over a larger period from weeks to years.	Apply anytime a person mentions dryness in soil and air exacerbated by extreme heat and wind.	The soil is very dry; difficult to grow.
Gully erosion	GULLY	the removal of soil along drainage lines by surface water runoff.	Apply anytime the erosion occurs due to heavy rainfall that occurs along drainage lines.	There is an extended period of dryness followed by heavy rainfall that have caused number of gullies.
Over grazing	GRAZE	Grazing without sufficient regeneration time	Apply anytime overgrazing is mentioned due to lack of pasture or mobility	They have no choice; but to return to the same patch of land even before the grasses regenerate.
Food surplus	SURPLUS	quantity of food more than its needs	Apply anytime a person mentions excess food than required for the household.	Maize and beans are sold when there is a surplus.
Manure applied	MANURE	Livestock dung used for fertilization	Apply anytime a person talks about using livestock dung directly or indirectly through biogas production in their field.	The biomass slurry is used for crops.
Input support	INPUT	Receiving in-kind support	Apply anytime a person mentions in-kind support such as seed, money, livestock, crops, food, building material or any other resources.	We have received material support for building water storage ponds from TPP.

Table 8 (cont'd)

Credit access	CREDIT	Access to affordable loan for agro-pastoralists.	Apply anytime a person mentions borrowing money or resource from a cooperative or a bank or any formal/informal organizational setting.	They have no credit facility.
Exchange	EXCHANGE	Exchange of resources, food, kinship, labor, knowledge.	Apply anytime a person mentions exchanging/ sharing of gifts, resources, food, labor, knowledge etc.	I give what I have, and they do the same.

APPENDIX E: CAUSAL LOOP DIAGRAM DEVELOPED THOUGH THE IN-DEPTH ANALYSIS

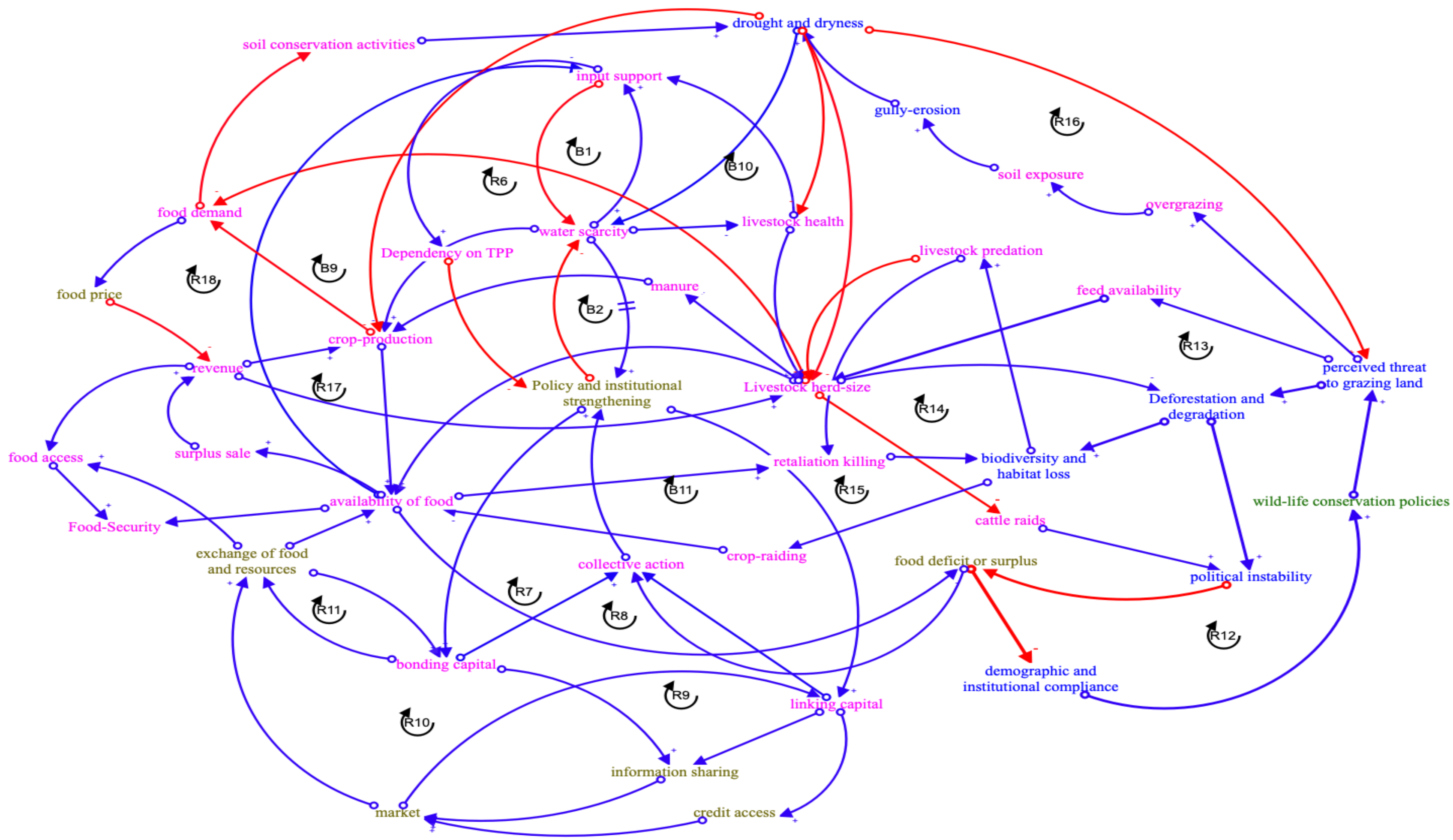

Figure 24 Causal Loop Diagram developed through in-depth interviews. The variables are interacting either locally, regionally, both locally and regionally, or nationally, as indicated by the variables' respective colors of pink, blue, brown, or green. The linkages between two variables are positive if they are blue; otherwise, they are negative. Reinforcing feedback loops are represented by loops R, whereas balancing feedback loops are represented by loops B.

APPENDIX F: RESULT OF PRINCIPLE COMPONENT ANALYSIS

Table 9 Principal Component Analysis of different adaptive capacity components.

Selected variables in the respective dimensions	**Principal components**		
	1	**2**	**3**
Infrastructure index			
Having a home	0.620		
Concrete cement floor		0.684	
Brick walls	0.561		
Toilets		0.676	
Running water	0.525		
Electricity	0.781		
Percentage of variance explained	**0.29**	**0.22**	
Wealth index			
Animal drawn cart			0.436
Beds		0.479	
Bicycle			0.380
Boat/Canoe			0.475
Books (not schoolbooks)		0.397	
Carts			0.267
Chairs		0.488	
Music system	0.418		
Computer	0.589		
Cooking pots and other kitchen utensils		0.226	
Cupboards etc.	0.479		
Dish antenna/Decoder	0.690		
Electric gas stove	0.640		
Fan/Air-conditioner	0.725		
Mosquito net		0.462	
Motor vehicle	0.577		
Motorcycle			0.242
Other Stove		0.459	
Outboard Engine			0.518
Radio and radio cassette		0.546	
Sewing machine	0.323		
Sofas	0.582		
Tables		0.641	

Table 9 (cont'd)

Telephone (landline)			0.338
Telephone (mobile)		0.543	
Television	0.770		
Tractor			0.480
Proportion of variance explained	**0.156**	**0.099**	**0.058**
Agriculture Asset Index			
Coffee pulping machine	0.468		
Fertilizer distributer	0.929		
Hand milling machine	0.382		
Harrow	0.619		
Harvesting and Threshing Machine	0.956		
Hoes			0.620
Milking Machines	0.971		
Plough etc.			0.673
Power Tiller	0.143		
Reapers	0.844		
Spraying Machine			0.614
Iron (charcoal / electric)		0.772	
Lanterns		0.771	
Proportion of variance explained	**0.324**	**0.105**	**0.102**
Income Index			
Wages		0.748	
Farming		0.720	
Livestock and Fishing		0.530	
Business	0.982		
Transfers			0.350
Remittance			0.903
Others	0.982		
Proportion of variance explained	**0.304**	**0.198**	**0.155**

APPENDIX G: DATA USED FOR SYSTEM DYNAMICS MODEL

Table 10 Data Sources and values used in the model.

Variable	Definitions	Initial Value for calibration	Units	Data Source	Initial Value for Base-run for Naitolia.	Source
Population	Individuals or inhabitants	22030000	People	World Bank Dataset	1800	(Pearson et al., 2017)
Birth rate	Number of live births per year per 1000	35/1000	People per 1000	World Bank Dataset	35/1000	Same as model calibration
Net migration rate	Difference in the rate between number of immigrants and emigrants	1/1000	People per 1000	World Bank Dataset	1/1000	
Death rate	Number of deaths per year per 1000	6/1000	People per 1000	World Bank Dataset	6/1000	
Area under harvest	Total crop sown area	2628757	ha	World Bank Dataset	1300	(Pearson et al., 2017)
Annual area under harvest increase rate	Annual rate of expansion in total crop sown area.	2.85/100	percent	Calculation, World Bank Dataset, FAOSTAT	2.85/100	Same as model calibration
Potential productivity	Most efficient production performance of crops	0.6	Tons/ha	Calibrated	0.6	Same as model calibration
Effect of rainfall	Rate at which rainfall affects potential productivity.	0.90	percent	(Sawe, Mung'ong'o, & Kimaro, 2018; Tarnavsky, Chavez, & Boogaard, 2018)	0.90	Same as model calibration

Table 10 (cont'd)

Crop harvest	Total cereal harvested in tons	3960300	Tons	Calculated based on FAOSTAT	1560	Calculated based on FAOSTAT and Pearson et al., 2017
Crop raiding	Annual rate of wild animals damaging or feeding standing crops	33/100	percent	(Pittiglio et al., 2014)	33/100	Same as model calibration
Post-harvest losses	Food loss between harvesting and consumption	20	percent	(Ngowi & Selejio, 2019); (Pittiglio et al., 2014)	20	
Crop sale rates	Rate of annual crop sale	20	percent	(Shane & Mtaki, 2018; Timpati, 2015)	20	
Seeds for future	Rate of annual seeds saved	0.01	percent	assumption	0.01	
Crop consumption rate	Rate of annual consumption of croop	0.05	Tons/Per person/year	(Shane & Mtaki, 2018; Timpati, 2015)	0.05	
Livestock Population	Number of cattle	13046835	number	Calculated, FAOSTAT	(de Glanville et al., 2020)	Calculated.
Calving rate	Number of calves produced by cattle divided by number of potential calves	0.55	percent	(Odoemena et al., 2020; Queenan et al., 2020)	0.55	Same as model calibration

Table 10 (cont'd)

Calf mortality rate	Rate of deceased calves	0.30	percent		0.30	
Calves	Young domestic livestock	calving_rate*Livestock_population*calf_mortality	percentage	(Odoemena et al., 2020; Queenan et al., 2020)		
Survival	Number of calves survived	calving_rate*Livestock_population* calf_mortality	percentage	(Odoemena et al., 2020; Queenan et al., 2020)		
Effect of rainfall on livestock	Seasonal and environmental factors affecting survival	0.77	percent	(Gebeyehu, Snelder, Sonneveld, & Abbink, 2021)	0.77	
Livestock Mortality rate	Rate of deceased cattle	0.50	percent	(Odoemena et al., 2020; Queenan et al., 2020)	0.50	
Asset Building	Gather livestock for economic well-being rather than consumption and sale.	0.50	percent	(Borgerhoff Mulder et al., 2010; Nkedianye et al., 2019; Quinlan et al., 2016)	0.50	
Percentage sale (livestock)	Total amount of livestock sold.	0.30	percent	(de Glanville et al., 2020)	0.30	

Table 10 (cont'd)

Per capita consumption of livestock and livestock products		0.059 (milk=47 kg; meat=11 kg; others=1.2 kg)	Tons/person/year	(Galié, Farnworth, Njiru, & Alonso, 2021; Wang et al., 2022)	75 (milk=61.8; meat=12; others=1.2)	Same as model calibration.
Annual rate of demand	Recommended daily intake of food calculated in terms of tons/year.	150/1000	Tons/person/year	Calculated based on calorie requirement by FAO	150/1000	Calories converted to tons.
Food demand	Recommended yearly intake of food multiplied by population	Population*annual_rate_of_demand	Tons/year	Calculated based on calorie requirement by FAO	150/1000	Calories converted to tons.
Food consumption	Actual consumption of food. The amount is different than the recommended amount of food (food demand)	livestock_consumption+crop_consumption+purchased	Tons/year			
Food sufficiency	Difference between the recommended intake and consumption of food	total_food_consumed-food_demand	Tons/year			

APPENDIX H: RESULTS OF SENSITIVITY ANALYSIS

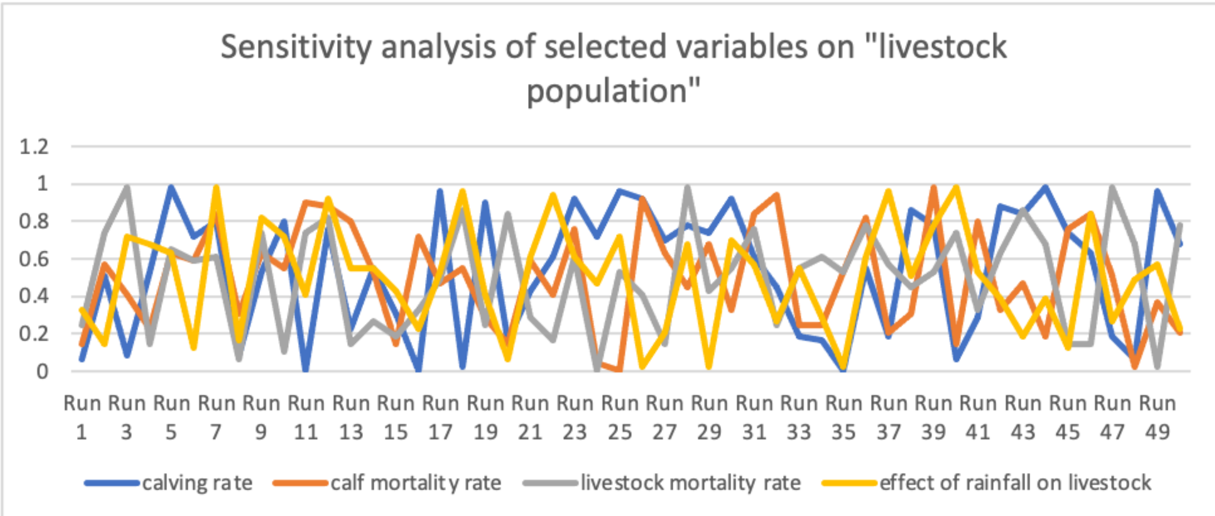

Figure 25 Sensitivity analysis of "calving rate", "calf mortality rate", "livestock mortality rate" and "effect of rainfall on livestock" on "livestock population".

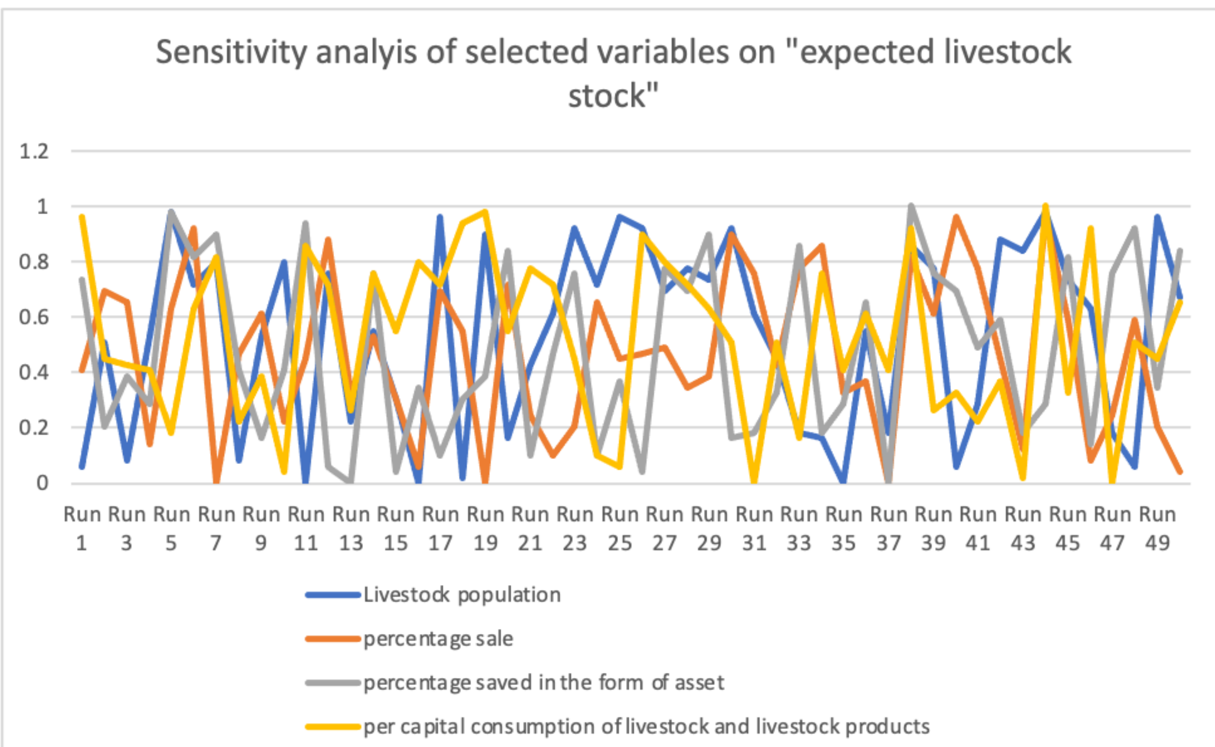

Figure 26 Sensitivity analysis of "livestock population", "percentage sale", "percentage saved in the form of asset" and "per capital consumption of livestock and livestock products" on "expected livestock stock".

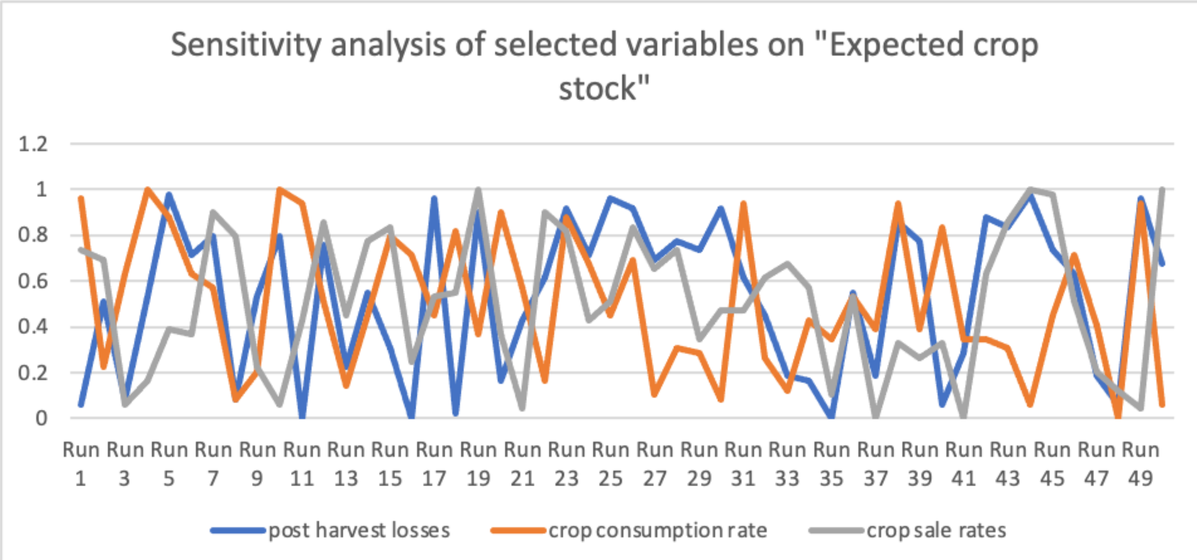

Figure 27 Sensitivity analysis of "post-harvest losses", "crop consumption rate" and "crop sale rates" on "Expected crop stock".

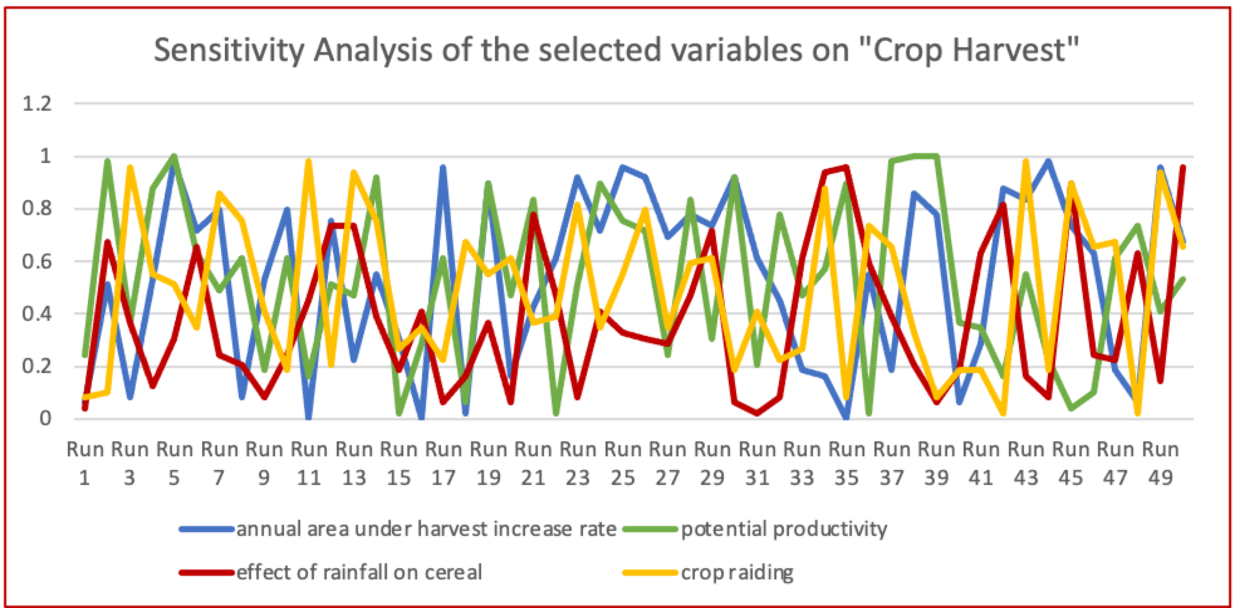

Figure 28 Sensitivity analysis of "annual area under harvest increase rate", "potential productivity", "effect of rainfall on cereal" and "crop raiding" on "Crop Harvest".